SCREENING LEVEL COST-BENEFIT ANALYSIS FOR PLUTONIUM CLEANUP LEVELS AT THE NEVADA TEST SITE

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U.S. Department of Energy
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1.0 Introduction

In September 1993, the U.S. Environmental Protection Agency (EPA) published an issues paper on radiation site cleanup regulations (EPA, 1993). EPA intends to promulgate standards for cleaning up sites contaminated with radionuclides in order to ensure consistent, protective, and cost-effective site remediation. The issues paper explores a variety of issues and invites comment on them.

In an effort to better understand the issues with the perspective of how they might apply to conditions at plutonium contaminated sites in Nevada, the Department of Energy (DOE) undertook this cost-benefit analysis. This study, which was concluded within a period of roughly six weeks, evaluated the consequences of adopting a range of alternative cleanup levels for plutonium (Pu) in soil for an area including three southern Nevada sites: the Nevada Test Site (NTS), Nellis Air Force Range (NAFR), and Tonopah Test Range (TTR) (Figure 1-1). On these three sites, which encompass a total area of approximately 6,000 square miles, aboveground nuclear and non-nuclear tests were conducted. These tests were of two types: safety shots and atmospheric tests of nuclear devices. At the locations of the safety shots, nuclear devices were exploded with conventional explosives to determine whether the device could attain criticality. These tests resulted primarily in the dispersal of Pu over miles of desert. The atmospheric testing of nuclear devices also resulted in the dispersal of Pu as well as fission products. As a consequence of these testing activities, Pu is widely dispersed in the soil on parts of the NTS, NAFR, and TTR.

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1.1 Approach to the Cost-Benefit Analysis

This study examined the relationship between the costs that would be incurred to clean up Pu-contaminated soil and the public health risks that would be averted by doing so. In addition, the risks to workers that would be incurred by conducting the remediation were estimated. The study was divided into four domains; committees with appropriate expertise conducted each part of the study. These committees consisted of an area/volume committee, a cost committee, a risk committee, and an integration committee. Each committee was tasked with providing realistic estimates of the parameters relevant to their part of the problem. In addition, they provided explicit estimates of uncertainty to provide upper (pessimistic) and lower (optimistic) bounds for the integration analysis. These bounds were intended to provide

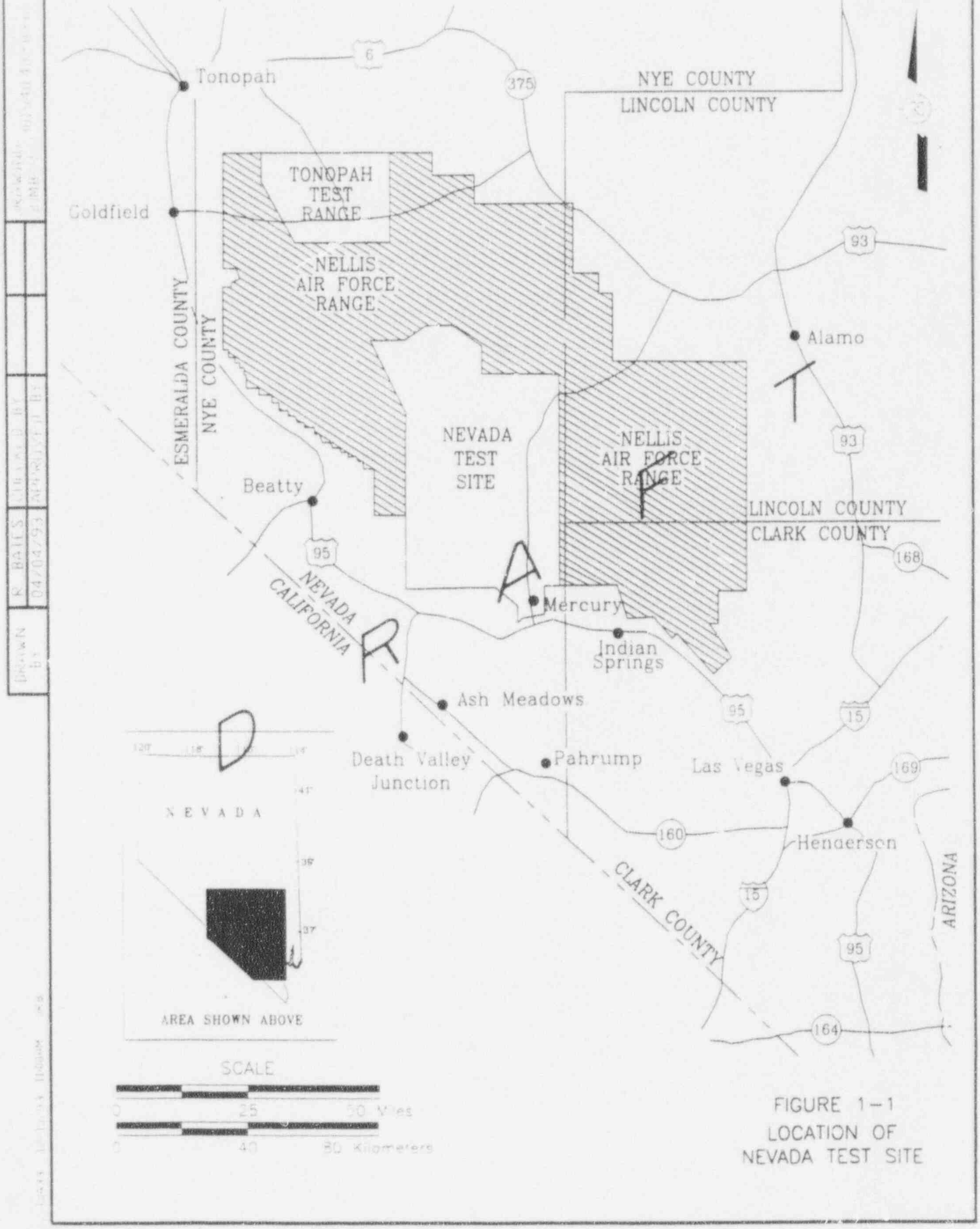

FIGURE 1-1
LOCATION OF
NEVADA TEST SITE

90 percent confidence intervals for the parameter ranges, which were then utilized in the uncertainty analysis.

1.2 Organization of the Report

The area/volume committee examined existing data to estimate the areal extent and volumes of contamination exceeding 10, 40, 100, 150, 200, 400, and 1,000 pCi/g. Results of the area/volume analysis are presented in Section 2.0. The cost committee provided estimates of the costs, both variable and fixed, of conducting remediation of the soil to each of the several potential cleanup levels. Section 3.0 presents the cost estimates. The risk committee estimated the risk averted to a population occupying currently contaminated land. Remediation workers would be exposed to Pu and to the risk of industrial accidents; those risks were also estimated. Risk estimates are presented in Section 4.0. The uncertainties in all estimates and their implications for the cost-benefit comparisons were analyzed by the integration committee. These integrated results of the analysis, along with an examination of the value of information that could be sought to reduce the uncertainties in the various estimates, are presented in Section 5.0.

2.0 Volume Estimates of Plutonium-Contaminated Soil

This section provides information from currently available data on levels of soil radioactivity at contaminated sites on and near the NTS, and an estimate of volumes of soil that may require treatment and/or removal. The specific task is to estimate the area and volume of soil that has levels of $^{239,240}Pu$ (henceforth denoted as Pu) exceeding 10, 40, 100, 150, 200, 400, and 1,000 pCi/g.

These concentrations were selected to provide information at reference levels of interest. Forty and 400 pCi/g were cleanup goals for Pacific Island tests. The 10 pCi/g level represents the lower bound of data availability (very few soil data exist at or below this level at NTS). The range from 100 to 200 pCi/g represent government agency historically recommended cleanup levels.

2.1 Data for Contaminated Sites on the NTS

The data used to estimate the size of the Pu-contaminated areas on the NTS were obtained during the Radionuclide Inventory and Distribution Program (RIDP) in the early 1980s. The RIDP's objective was to estimate the total amount and the distribution of all manmade radionuclides in NTS surface soil. The primary measurement technique used in the program was in situ spectrometry. This technique consists of recording the gamma-ray spectrum obtained with a Ge (Li) detector suspended 7.4 m above the ground, then analyzing the spectrum to determine the concentrations of various gamma-emitting radionuclides. More than 3,700 in situ measurements of soil radioactivity were made on the NTS during the RIDP. The program's methods and results are summarized in McArthur (1991); that report cites five earlier reports that give more complete details.

Because Pu does not emit a strong gamma ray, it is not easily quantified by the in situ system. Concentrations of Pu were therefore inferred from the measured concentrations of ^{241}Am (henceforth Am). Earlier studies had shown that the ratio of Pu to Am in soil is nearly constant in a given test area, though it varies from one area to another (Gilbert et al., 1975).

Evaluation of Pu contamination of the NTS began with the retrieval of the Am measurements from the RIDP data files. The surface Pu activity per unit mass at each measurement location was then calculated in two steps:

$$\text{Pu (nCi/m}^2) = \text{Am (nCi/m}^2) \times \text{(Pu/Am ratio)} \tag{2-1}$$

$$\text{Pu (pCi/g)} = 0.1 \times \text{Pu (nCi/m}^2) / 1.5 \times \ell \tag{2-2}$$

The parameter ℓ in Equation 2-2 is the relaxation depth (in cm); it originates from an assumed exponential relationship of radionuclide concentration to depth in the soil:

$$S_m(z) = S_m^0 \; x \; \exp[-z/\ell], \tag{2-3}$$

where $S_m(z)$ is the activity per unit mass of soil at depth z and S_m^o is the activity per unit mass at the surface. The relaxation depth is the depth at which the concentration has decreased to 37 percent of its value at the surface.[1] The 1.5 in Equation 2-2 represents the density of the soil in g/cm^3.

Both the relaxation depth and the Pu/Am ratio were estimated with data obtained from soil samples collected at each contaminated area surveyed during the RIDP. The estimated values are listed in Table 2-1. The methods of soil sampling, sample analysis, and calculation of relaxation depth (actually the reciprocal of the relaxation depth) are described in the RIDP reports (McArthur and Mead, 1989; McArthur and Mead, 1988; McArthur and Mead, 1987; McArthur and Kordas, 1985; and McArthur and Kordas, 1983).

About 60 percent of the RIDP Am measurements were "less than" values; for purposes of data analysis, these were converted to 0 pCi/g of Pu. Virtually all of the nonzero Pu values come from a few regions:

- Schooner (Area 20)
- Palanquin/Cabriolet (Area 20)
- Danny Boy (Area 18)
- Little Feller I and II (Area 18)
- Buggy (Area 30)
- GMX (Area 5)

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[1] Analysis of the in situ spectra requires a mathematical model of the tendency of manmade radionuclides to decline in concentration with depth in the soil (as opposed to natural radionuclides, whose concentrations normally do not change with depth). The exponential relationship of equation 2-3 has proven useful for this purpose. It is not necessarily useful for other purposes, such as calculating how deep one would have to dig to remove a specified fraction of the plutonium present.

Table 2-1
Pu/Am Ratios and Pu Relaxation Depths from Contaminated Areas on the NTS (early 1980s)

		Relaxation Depth (cm)	
Area/Event	Pu/Am	Near Ground Zero	Far Field
Yucca Flat			
Galileo	5.0	1.7	1.7
Kepler	6.0	1.7	1.3
Whitney	9.9	1.3	1.3
Diablo	5.6	1.3	1.3
Baneberry	3.9	1.7	1.7
Smoky	7.2	1.7	1.7
Oberon	6.7	1.7	1.7
Sedan	5.5	20.0	2.5
Wilson	21.0	1.7	1.7
Quay	7.5	1.0	1.0
Hornet	8.1	2.5	2.5
Schooner	0.69	10.0	1.7
Palanquin	2.6	2.5	2.5
Cabriolet	0.90	2.5	2.5
Little Feller I	5.7	10.0	2.0
Little Feller II	5.7	2.0	10.0
Danny Boy	4.0	20.0	3.3
Buggy	4.4	5.0	2.0
Plutonium Valley	5.9	1.7	1.7
GMX	7.2	2.0	2.0
Frenchman Flat	8.2	10.0	2.5

- Plutonium Valley (Area 11)
- Frenchman Flat (several overlapping sites)
- Yucca Flat (many overlapping sites).

2.2 Analysis for Contaminated Sites On the NTS

The data analysis began with the creation of a data file for each of the nine regions listed above. Each record in a file contained location information (east and north Nevada Grid Coordinates) and a Pu value. The files were then loaded into the Arc/INFO geographic information system for further processing.

The analysis was carried out using the TIN (Triangulated Irregular Network) module of Arc/INFO. The TIN data structure is based on two basic elements: a set of points with three-dimensional coordinates and a series of edges joining these points to form triangles. The triangular mosaic forms a continuous faceted surface, with each facet describing the behavior of a portion of the network's surface.

The first step in the surface modeling was to create a TIN surface for each contaminated region from the Pu data. The spatial distribution of the sample locations was usually irregular and often characterized by clusters of locations with large intervening areas containing no data. To improve the model, the density of data was artificially increased by adding data points to the original set. The added points were "null" points, initially with no associated Pu concentration values. These points were added at regular x and y intervals, defining a background lattice of points with the original collection of data points superimposed. The number of additional points ranged from 27 to 125 depending upon the frequency and size of data gaps in each region.

Pu concentration values were then interpolated for the newly added data points using a bivariate quintic (fifth-order) polynomial interpolation. The advantage of this interpolation algorithm is that it considers the surface model to be continuous, without abrupt or well-defined breaks between values, and smooth.

Isopleths of Pu concentration were then drawn using an Arc/INFO contouring algorithm. The TIN triangles were each divided into 100 subtriangles. Plutonium values for the subtriangle nodes were derived using bivariate quintic interpolation, further smoothing the isopleths.

Finally, the polygonal surface areas enclosed by each isopleth of interest were calculated. The resulting sets of isopleths were checked for gross inconsistencies with the original data.

The final Pu isopleths are shown in Figures 2-1 through 2-9. Cumulative totals of the calculated areas shown on the figures are tabulated in Table 2-2.

Table 2-2
Estimated Sizes of Areas Exceeding Certain Concentrations of Plutonium on the NTS

	Area (hectares) exceeding X pCi/g of Pu						
Site X =	1000	400	200	150	100	40	10
Yucca Flat	73	230	470	730	1,600	7,800	26,000
Schooner	0	0	0	8	35	77	230
Cabriolet/Palanquin	18	30	68	83	120	240	580
Little Feller I & II	28	77	120	140	170	280	480
Danny Boy	2	5	10	13	17	29	51
Buggy	5	14	19	22	25	35	51
Plutonium Valley	13	28	73	110	210	580	820
GMX	0	1	2	3	5	15	81
Frenchman Flat	0	0	1	1	3	16	91
Total	140	400	760	1,100	2,200	9,100	28,000

2.3 A Discussion of Contaminated Sites On the NTS

The uncertainty associated with the estimation of area is relatively large due to the nature of the existing data. Although it is difficult to quantify some of the sources of error, the main sources of error and their probable magnitude are discussed in the following paragraphs.

The original Am measurements were made using well-established procedures for detector calibration and data collection, and there are no known problems with the quality of the data set. Nevertheless, the measurements are not without error and include the random nature of radioactive decay, an intrinsic source of variation in any measurement of radioactivity. At the

Figure 2-1
Approximate Areas of Plutonium Contamination

YUCCA FLAT

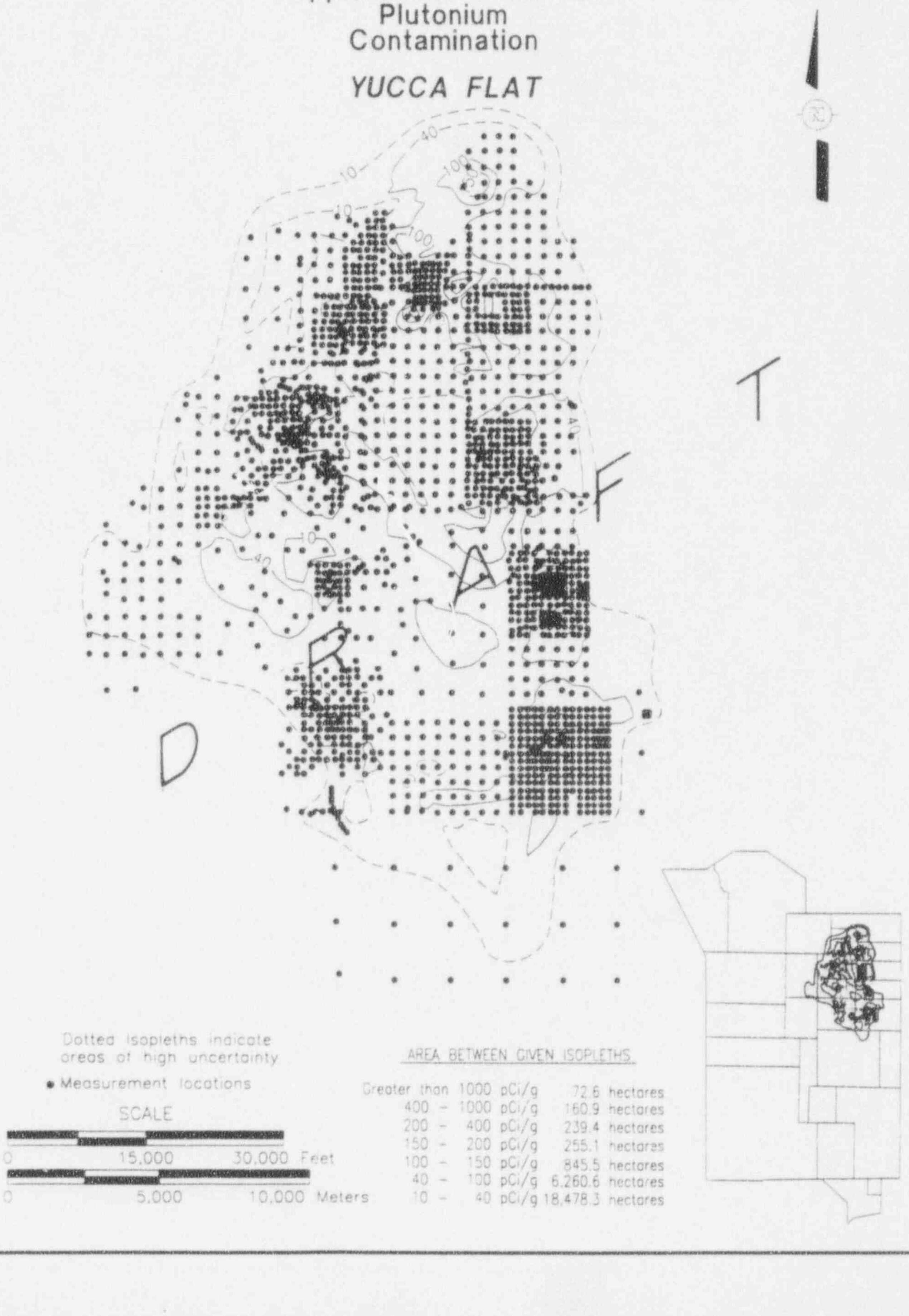


Figure 2-2
Approximate Areas of Plutonium Contamination
Schooner
Area 20

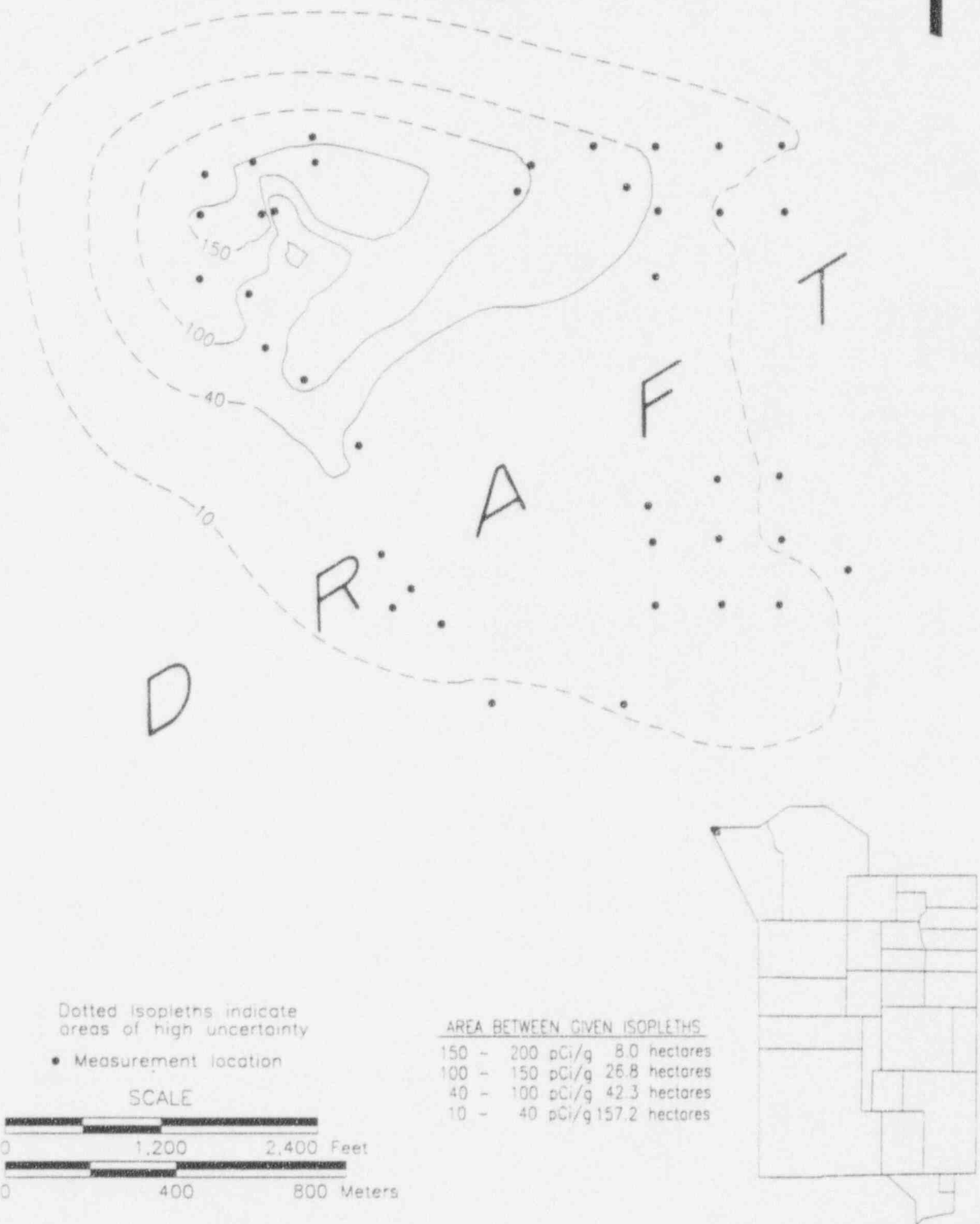


Figure 2-3
Approximate Areas of Plutonium Contamination
Cabriolet Area 20

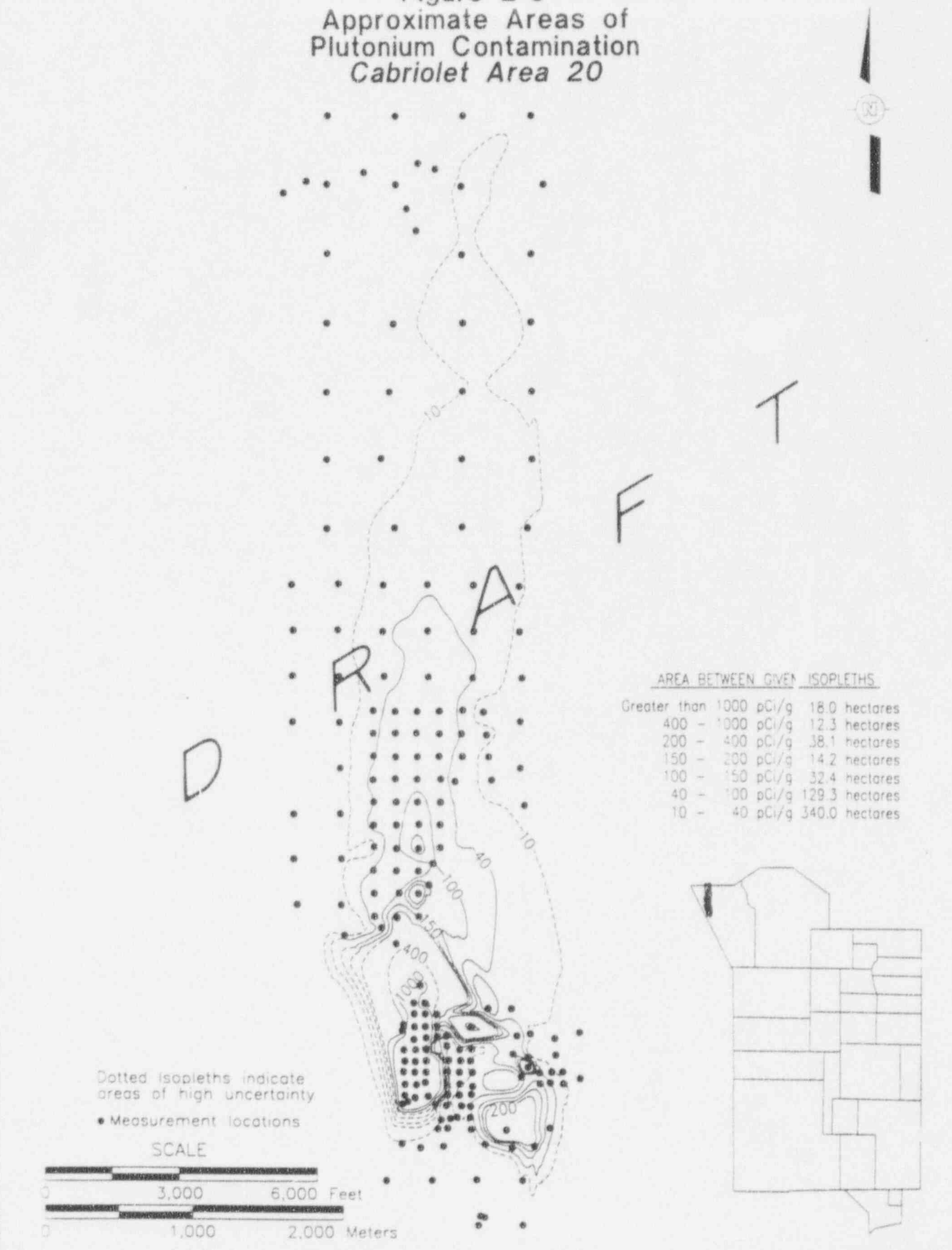


Figure 2-4
Approximate Areas of
Plutonium Contamination

Little Fellers I & II
Area 18

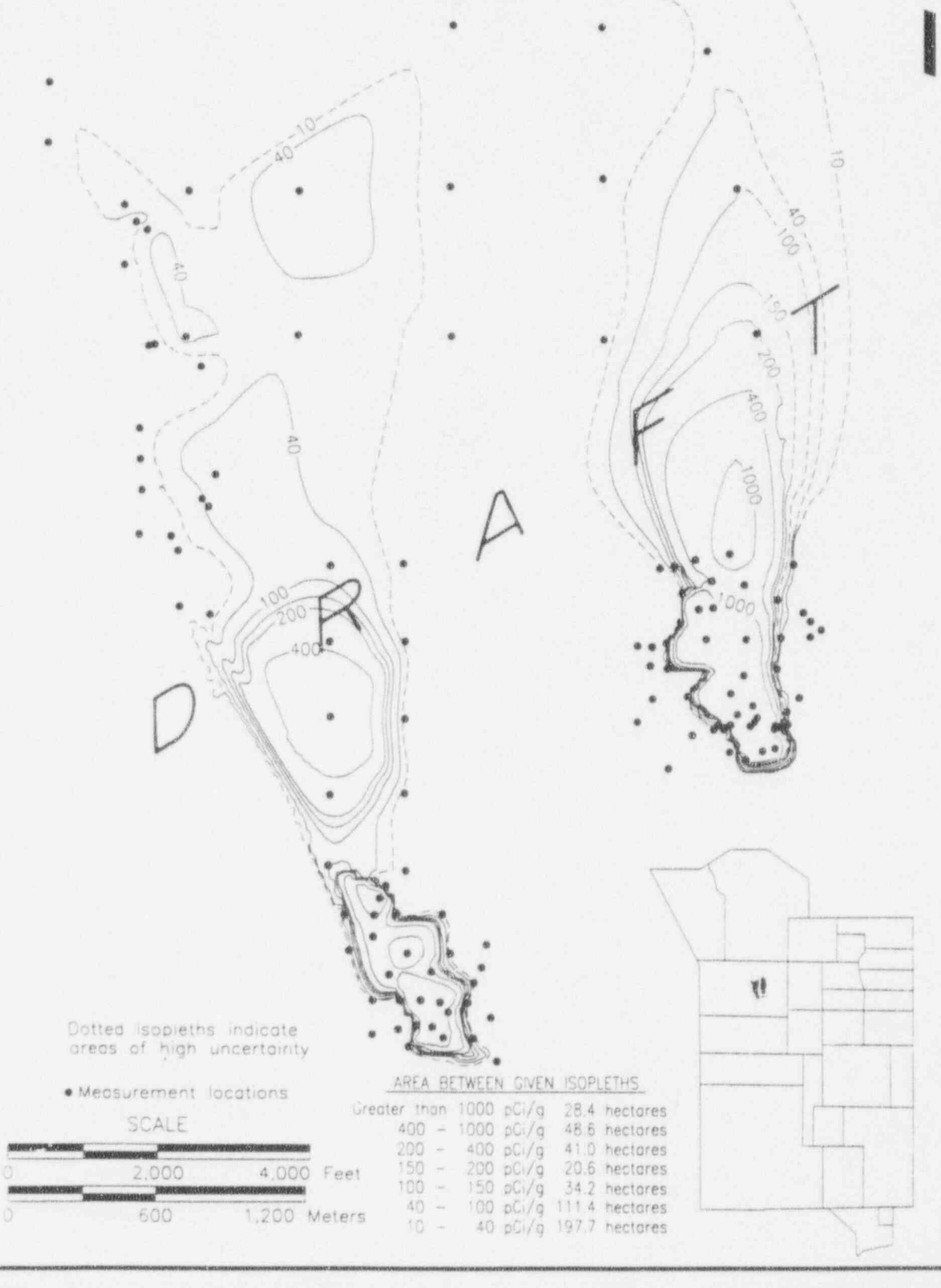


Figure 2-5
Approximate Areas of Plutonium Contamination

Danny Boy
Area 18

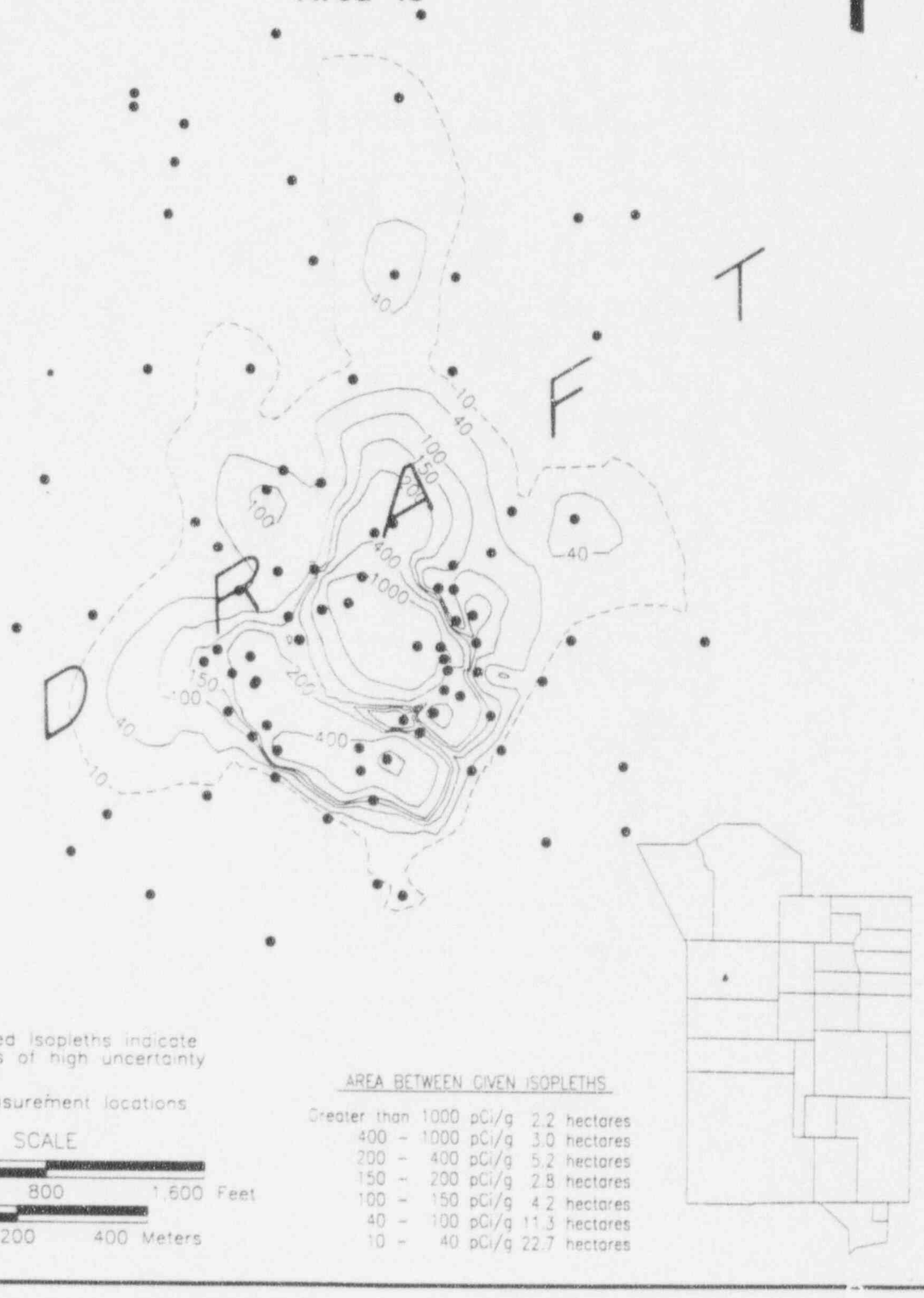
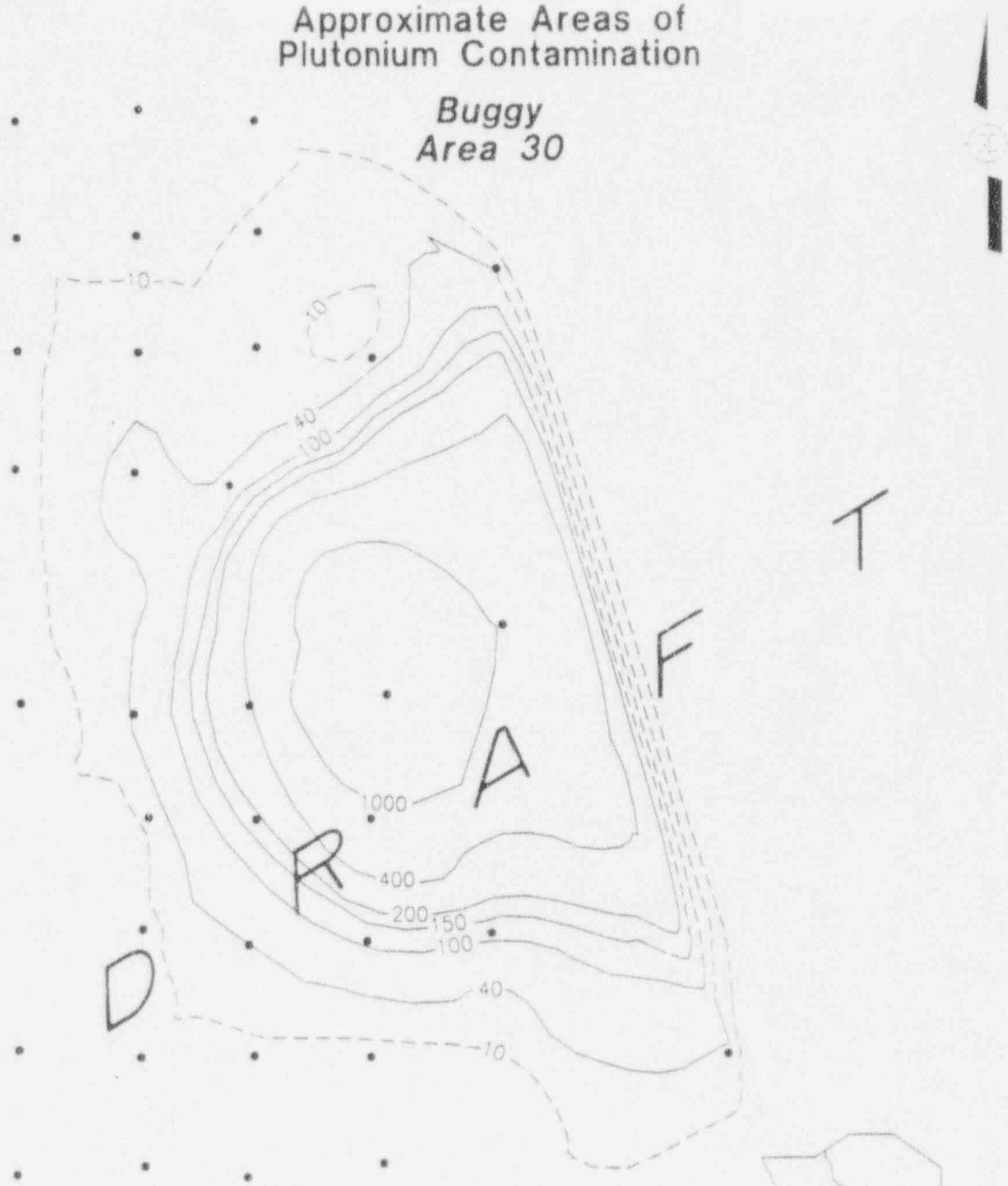
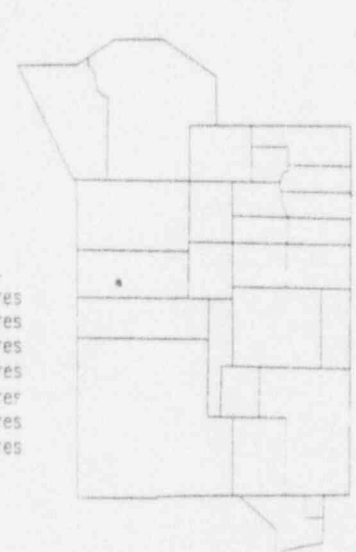


Figure 2-6
Approximate Areas of Plutonium Contamination

Buggy
Area 30





Dotted isopleths indicate areas of high uncertainty

• Measurement location

SCALE

0 600 1,200 Feet

0 200 400 Meters

AREA BETWEEN GIVEN ISOPLETHS	
Greater than 1000 pCi/g	4.6 hectares
400 – 1000 pCi/g	9.2 hectares
200 – 400 pCi/g	5.5 hectares
150 – 200 pCi/g	2.3 hectares
100 – 150 pCi/g	3.7 hectares
40 – 100 pCi/g	9.3 hectares
10 – 40 pCi/g	16.3 hectares

Figure 2-7
Approximate Areas of
Plutonium Contamination
Plutonium Valley
Area 11

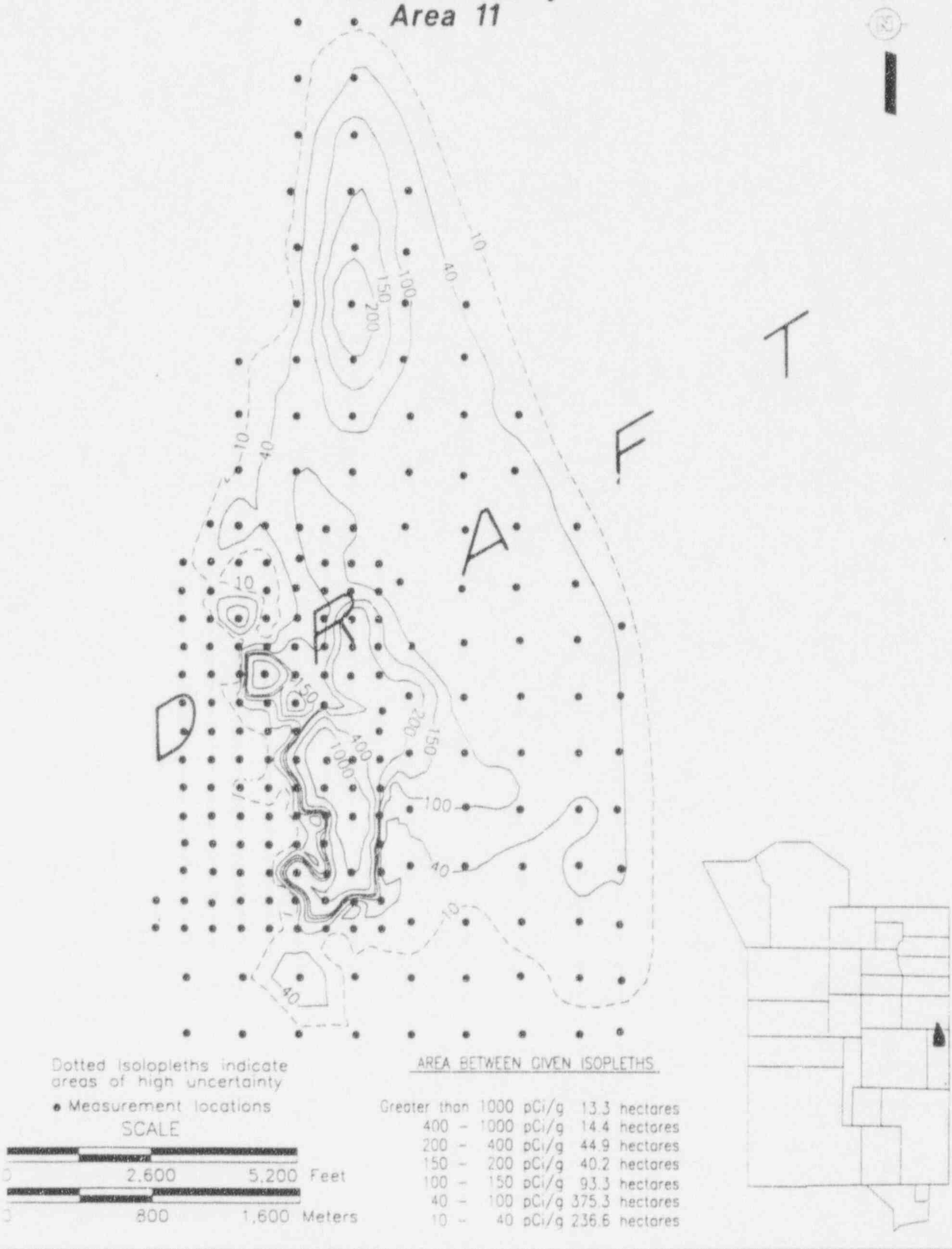


Figure 2-8
Approximate Areas of
Plutonium Contamination
GMX
Area 5

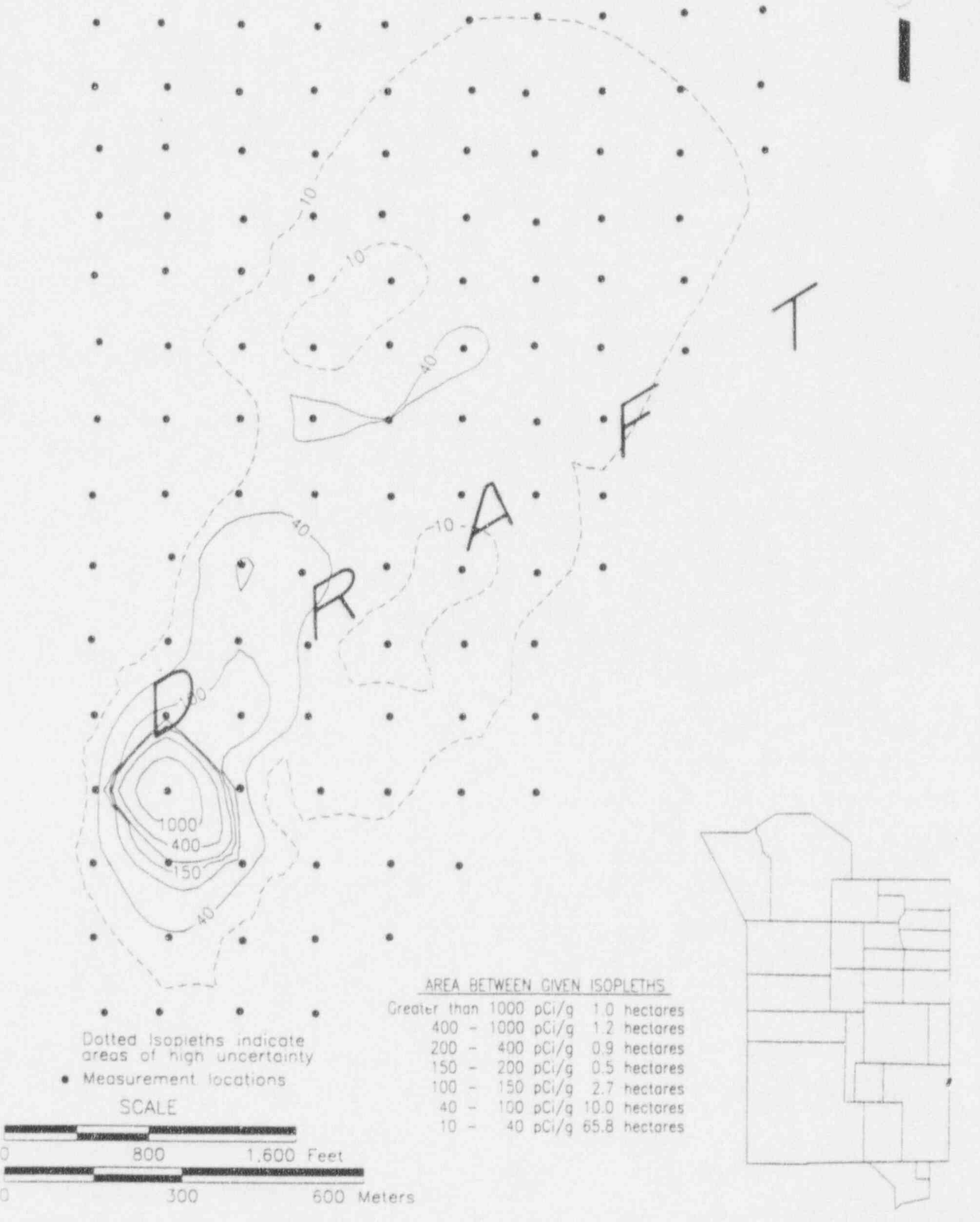
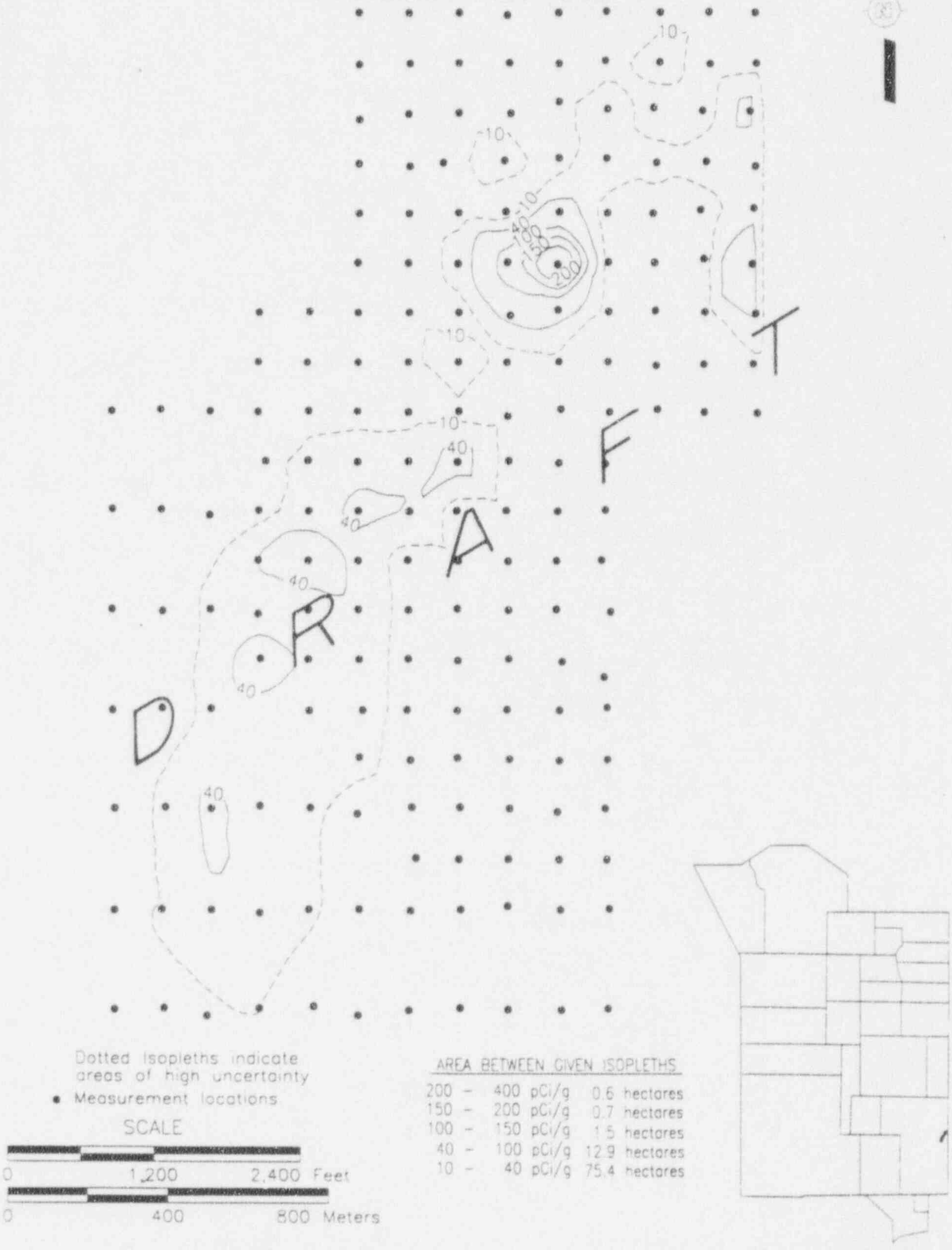


Figure 2-9
Approximate Areas of
Plutonium Contamination
Frenchman Flat Area 5



lower limits of Am detection with the in situ system (30 to 50 nCi/m^2), this counting error can reach 50 percent or higher. The spectral analysis program takes into account physical parameters such as air and soil density which were not measured at every area. Differences between the assumed values and the actual values could cause an error of a few percent in the calculated activities. Computed activities are extremely sensitive to the value of relaxation depth, especially at low energies. The relaxation depths used in the analysis were averages of several values calculated from soil profiles (usually four increments to a depth of 15 cm). The individual values were usually quite variable, so choosing a single representative value entails a high degree of uncertainty.

Calculation of Pu in pCi/g from the Am data again uses the soil density and relaxation depth. It also uses the ratio of Pu to Am, which, like the relaxation depth, was estimated from soil samples at a few locations in each area. Because the variability in the measured ratios was usually large, the average value has a high uncertainty. The assumed relationship of Pu to Am is linear, so a 25 percent error in the average ratio will cause a 25 percent error in the calculated Pu concentration.

Regardless of the quality of the individual measurements, the data set itself is of marginal utility with respect to the lower Pu concentration. Only about 70 of the 1,400 Pu measurements are less than 10 pCi/g, primarily because the Am levels corresponding to 10 pCi/g of Pu are near the lower limit of what the measurement system could quantify. It is likely that some locations considered here to have no Pu actually have 10 pCi/g or more.

In addition, the RIDP surveys at all sites except Schooner and Danny Boy did not cover a large enough region to completely determine some of the isopleths of interest. In many cases, the terrain prevented the survey vehicles from covering a greater region; in other cases, measurements were not made farther from a ground zero because the levels of radioactivity were so low. The isopleths drawn in these regions are based upon best professional judgment.

The contouring was done with Arc/INFO to meet the time constraints of this project. No claim is made that Arc/INFO's interpolation and contouring algorithms are better than other systems. The results represent one possible interpretation of the data, but many other interpretations are possible, especially for the regions where data are sparse or non-existent.

McArthur (1992) estimated the area of land surface on the NTS that exceeded 10 pCi/g from hand-drawn isopleths that incorporated information from aerial surveys and best professional judgement. Those isopleths enclosed an area of about 37,000 acres (15,000 hectares). McArthur also stated that an additional 50 square miles or so (13,000 hectares) on Yucca Flat might exceed 10 pCi/g, but uncertainty was high. The 10 pCi/g isopleth on Figure 2-1 includes most of this additional area. The total estimated area on the NTS that exceeds 10 pCi/g is shown on Figure 2-10.

2.4 Data for Contaminated Sites near the NTS

Five of the contaminated areas near the NTS are sites of safety shots (experiments in which high explosives were set off near assemblies of plutonium to see if fission would occur) conducted in 1957 and 1963. Fission did not occur at these sites, but plutonium was dispersed over tens to hundred of acres.

All five sites (Area 13-Project 57, Double Tracks, and Clean Slate 1, 2, and 3) were studied intensively by the Nevada Applied Ecology Group (NAEG) in the late 1970s. One objective of the NAEG studies was to estimate the amount and distribution of Pu in the soil. Numerous samples of surface soil (top 5 cm) were collected, dried, ball-milled, and sieved through a 10-mesh screen. A 10-g aliquot of the fine fraction was then analyzed chemically for Pu. The numbers of Pu analyses available from each site are as follows:

- Clean Slate 1 71
- Clean Slate 2 88
- Clean Slate 3 78
- Double Tracks 65
- Area 13 180

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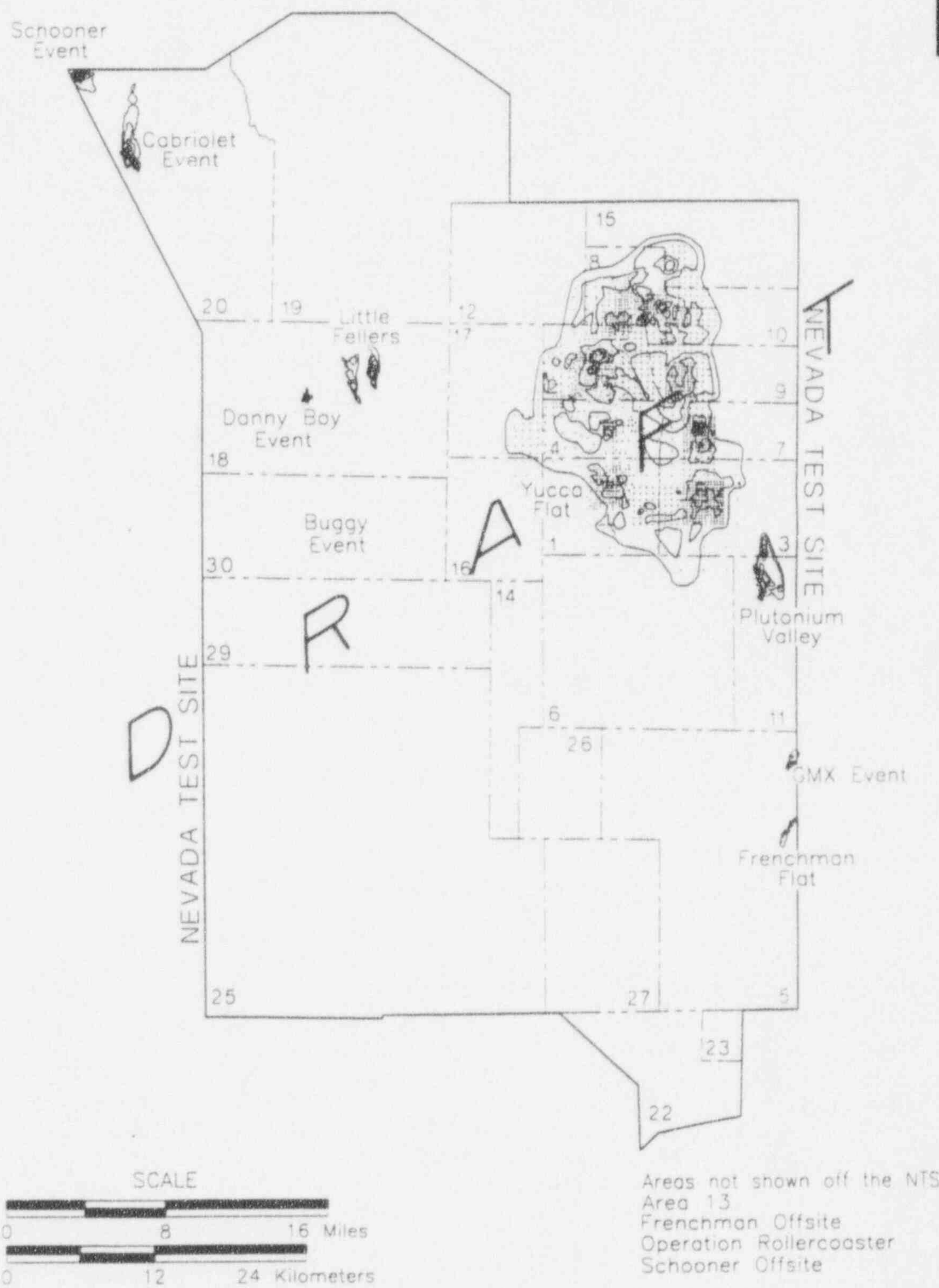
The Pu inventories calculated from the data are given in Gilbert (1977).

Many soil profiles (10 increments to a depth of 25 cm) were also collected during the NAEG studies. Although plots of a few individual profiles were published (e.g., Essington et al., 1976), relaxation depths were not calculated. In almost all profiles, Pu was detected in the 25-cm increment. Pu was also found down to 32.5 cm in deeper profiles from Clean Slates 1 and 3 (<1 pCi/g) (Essington, 1987).

Figure 2-10
Approximate Areas of Plutonium Contamination Exceeding 10 pCi/g at The Nevada Test Site



Areas not shown off the NTS:
Area 13
Frenchman Offsite
Operation Rollercoaster
Schooner Offsite

Additional information from the three Clean Slate sites is provided by aerial surveys made in 1993 by EG&G Energy Measurements, Inc. (Figures 2-11 through 2-13). The survey aircraft contained an array of eight NaI (Tl) detectors and flew over the sites at an altitude of 100 feet along lines 150 feet apart. As with the ground-based in situ system, the aerial system measures Am and other gamma-emitting radionuclides. The concentration of Pu was inferred using a Pu/Am ratio of 10.

Two other off-site areas of contamination were also surveyed using the aerial system. One is a plume extending north from the Schooner site in the far northwest corner of the NTS (Figure 2-14); the other is a plume extending east from the Smallboy site on Frenchman Flat (Figure 2-15). The survey methods were basically the same, though different Pu/Am ratios were assumed: 5 for the Smallboy plume and 0.7 for the Schooner plume.

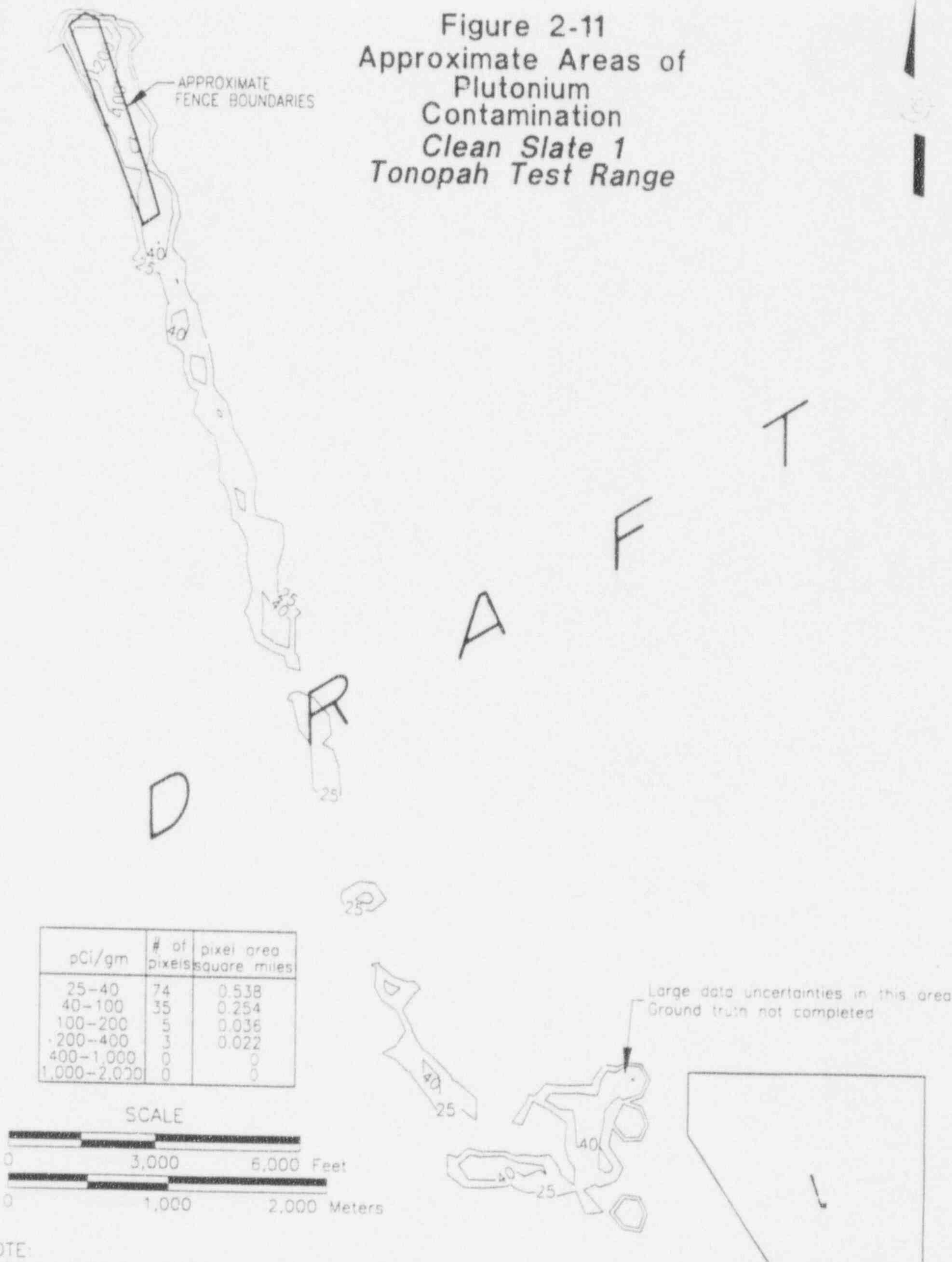
2.5 Analysis for Contaminated Sites Near the NTS

For the three Clean Slate sites, the areas enclosed by various isopleths in Figures 2-11 through 2-13 were calculated by EG&G as part of the analysis of the aerial survey data. The calculation was made by counting the number of 450-by-450-ft pixels within each isopleth.

The lowest isopleth on the aerial survey maps was 25 pCi/g, the limit of detection of the aerial system. The area that would be contained between a 10 pCi/g isopleth and the 40 pCi/g isopleth was estimated by multiplying the given 25 to 40 pCi/g area by a factor of 5 for Clean Slate 1, 2 for Clean Slate 2, and 3 for Clean Slate 3. These factors were based on visual inspection of the maps, especially the area covered by the 25 to 40 pCi/g isopleth and the distance between the 40 and 100 pCi/g isopleths. The maps also did not show a 150 pCi/g isopleth. The areas between the 100 and 150 pCi/g isopleths and between the 150 and 200 pCi/g isopleths were estimated by partitioning the area between the 100 and 200 pCi/g isopleths in approximately a 3:1 ratio.

To obtain estimated areas for Double Tracks and Area 13, the NAEG soil data from those sites were initially analyzed with Arc/INFO in the same manner as was done with the RIDP data. However, the data were not amenable to the contouring package because of their areal distribution. The Area 13 isopleths were modified by hand to make them generally consistent with the estimated isopleths of Gilbert et al. (1975, Figure 2-16 of that report). No previous attempts to contour the Double Tracks data have been published. The data locations are

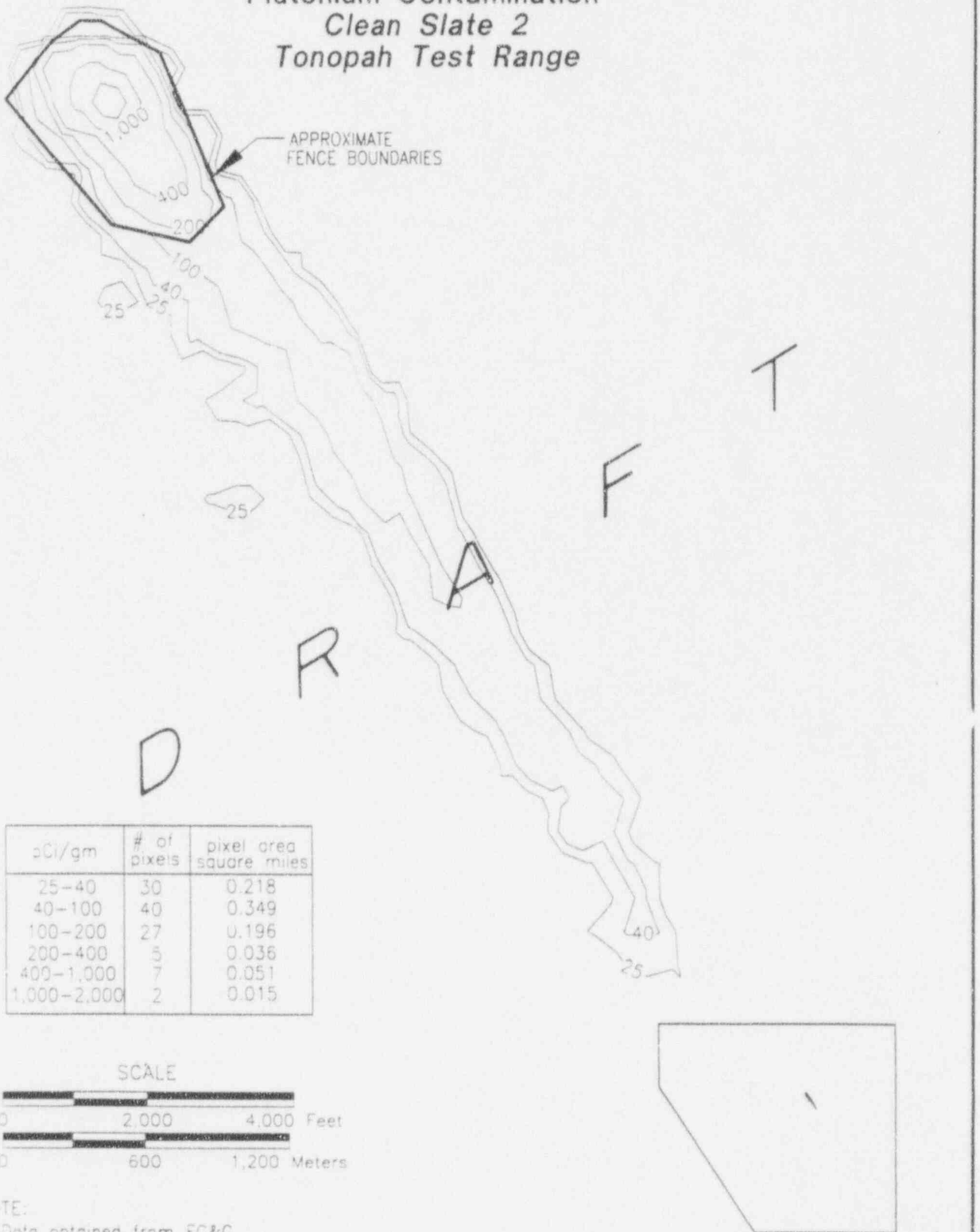
Figure 2-11
Approximate Areas of Plutonium Contamination
Clean Slate 1
Tonopah Test Range



pCi/gm	# of pixels	pixel area square miles
25-40	74	0.538
40-100	35	0.254
100-200	5	0.036
200-400	3	0.022
400-1,000	0	0
1,000-2,000	0	0

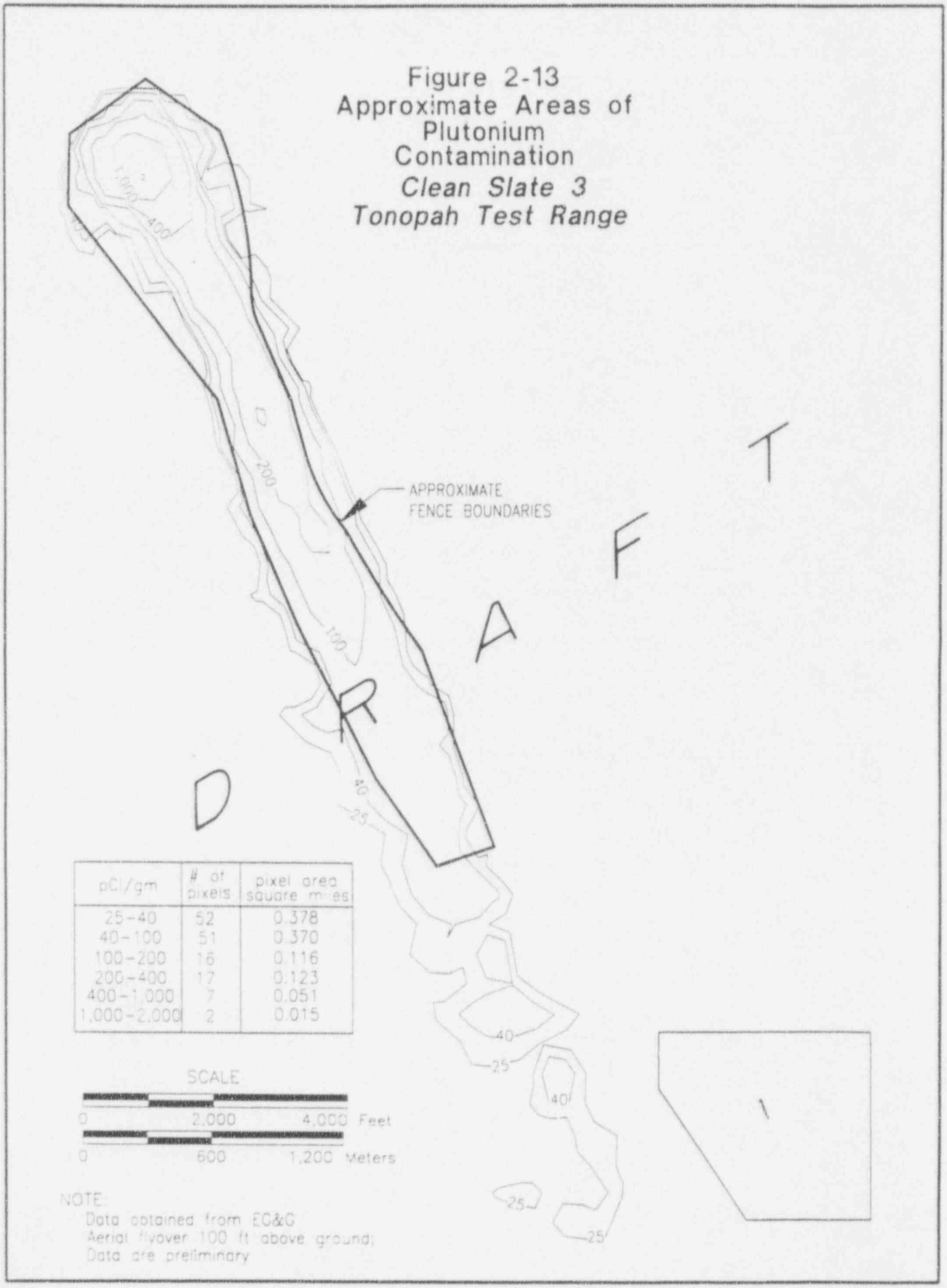
NOTE:
Data obtained from EG&G
Aerial flyover 100 ft above ground;
Data are preliminary

Figure 2-12
Approximate Areas of
Plutonium Contamination
Clean Slate 2
Tonopah Test Range



pCi/gm	# of pixels	pixel area square miles
25–40	30	0.218
40–100	40	0.349
100–200	27	0.196
200–400	5	0.036
400–1,000	7	0.051
1,000–2,000	2	0.015

NOTE:
Data obtained from EG&G
Aerial flyover 100 ft above ground;
Data are preliminary



pCi/gm	# of pixels	pixel area square miles
25-40	52	0.378
40-100	51	0.370
100-200	16	0.116
200-400	17	0.123
400-1,000	7	0.051
1,000-2,000	2	0.015

Figure 2-13
Approximate Areas of Plutonium Contamination
Clean Slate 3
Tonopah Test Range

Figure 2-14
Approximate Areas of
Plutonium
Contamination
*Plume North of
the Schooner site*

Figure 2-15
Approximate Areas of Plutonium Contamination

Plume East of Smallboy site

LEVEL	MEASURED CTS/SEC	AMERICIUM CTS/SEC	Pu pCi/g R = 3 cm S = 3 cm
A	0–55	0–92	0–36
B	55–170	92–283	36–111
C	170–550	283–917	111–360
D	550–1700	917–2833	360–1112

R = Relaxation depth (cm)
S = Soil sample depth (cm)

SCALE

0 8,000 16,000 Feet

0 3,000 6,000 Meters

NOTE: DATA OBTAINED FROM EG&G AERIAL FLYOVER 100 FT ABOVE GROUND. DATA ARE PRELIMINARY

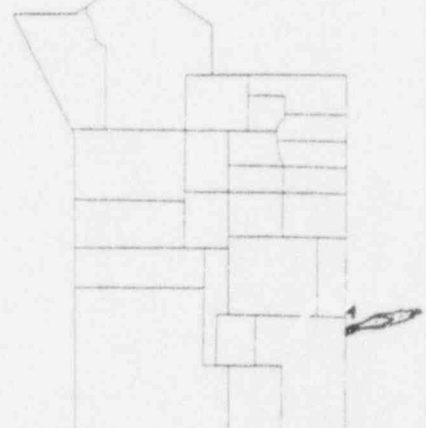
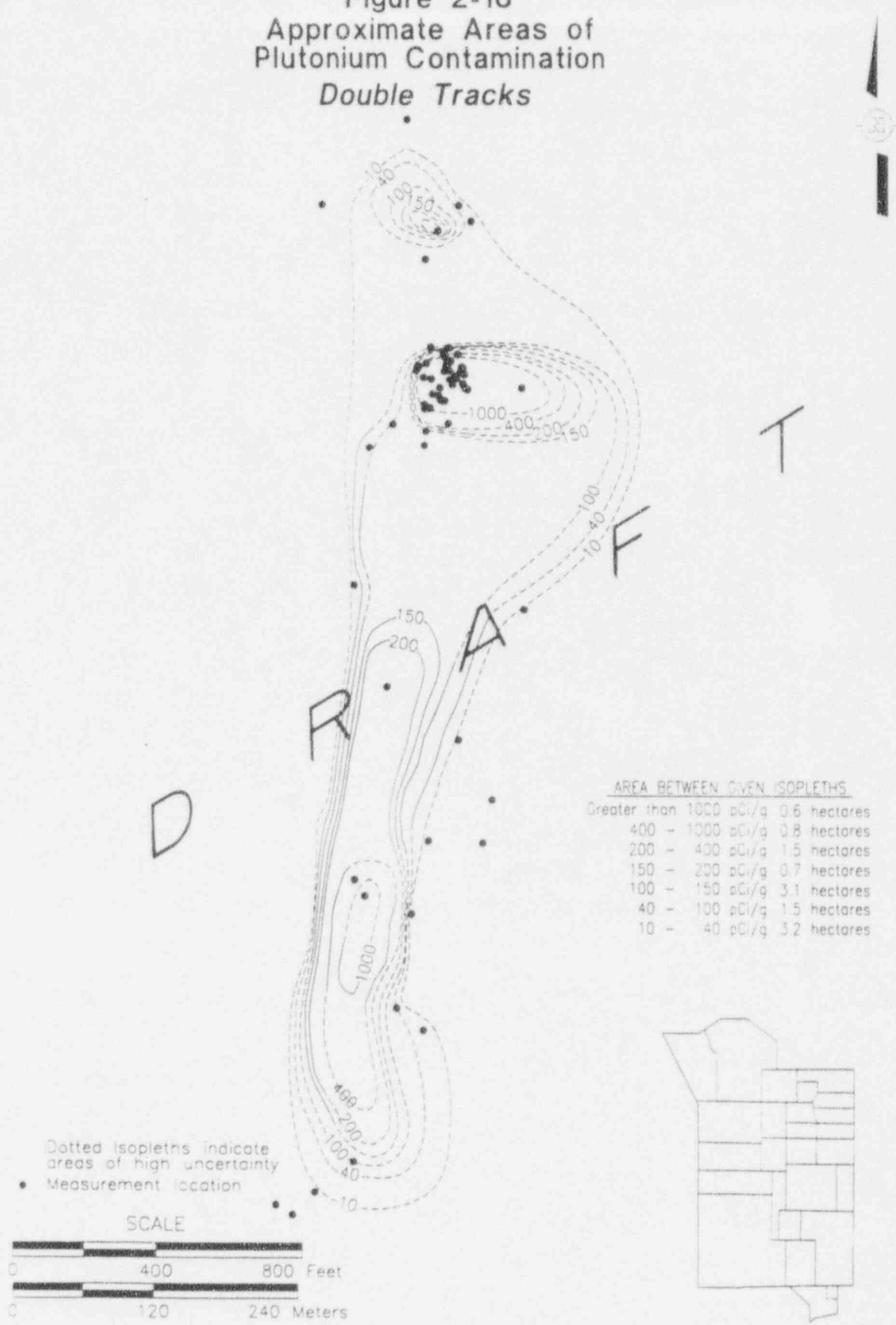


Figure 2-16
Approximate Areas of Plutonium Contamination
Double Tracks



widely scattered except for one cluster near the ground zero, and within that cluster the Pu concentrations at locations less than 30 feet apart sometimes differ by a factor of more than 10,000. The estimated isopleths presented for both regions (Figures 2-16 and 2-17) should be considered gross approximations.

The results of the aerial surveys of the two plumes crossing the NTS boundary do not include estimates of areas. The Schooner plume was not used in the analysis because the area is small and the Pu/Am ratio is less than one. The Smallboy plume, on the other hand, covers a sizeable region. Estimates of the area within the various isopleths (assuming a relaxation depth and soil sample depth of 3 cm) were obtained by the analytical technique of carefully cutting up a photocopy of Figure 2-15 and weighing the pieces. The three isopleths were taken to represent 40, 100, and 400 pCi/g instead of the nominal 36, 111, and 360. The area between 100 and 400 pCi/g was divided in thirds to give values for the intermediate levels of 150 and 200 pCi/g. The area exceeding 1,000 pCi/g was estimated to be 10 percent of the 400 to 1,112 pCi/g area, while the area exceeding 10 pCi/g was estimated to be about three times as large as the 40 to 100 pCi/g area.

The resulting areas contained within the various isopleths at the off-NTS sites are tabulated in Table 2-3.

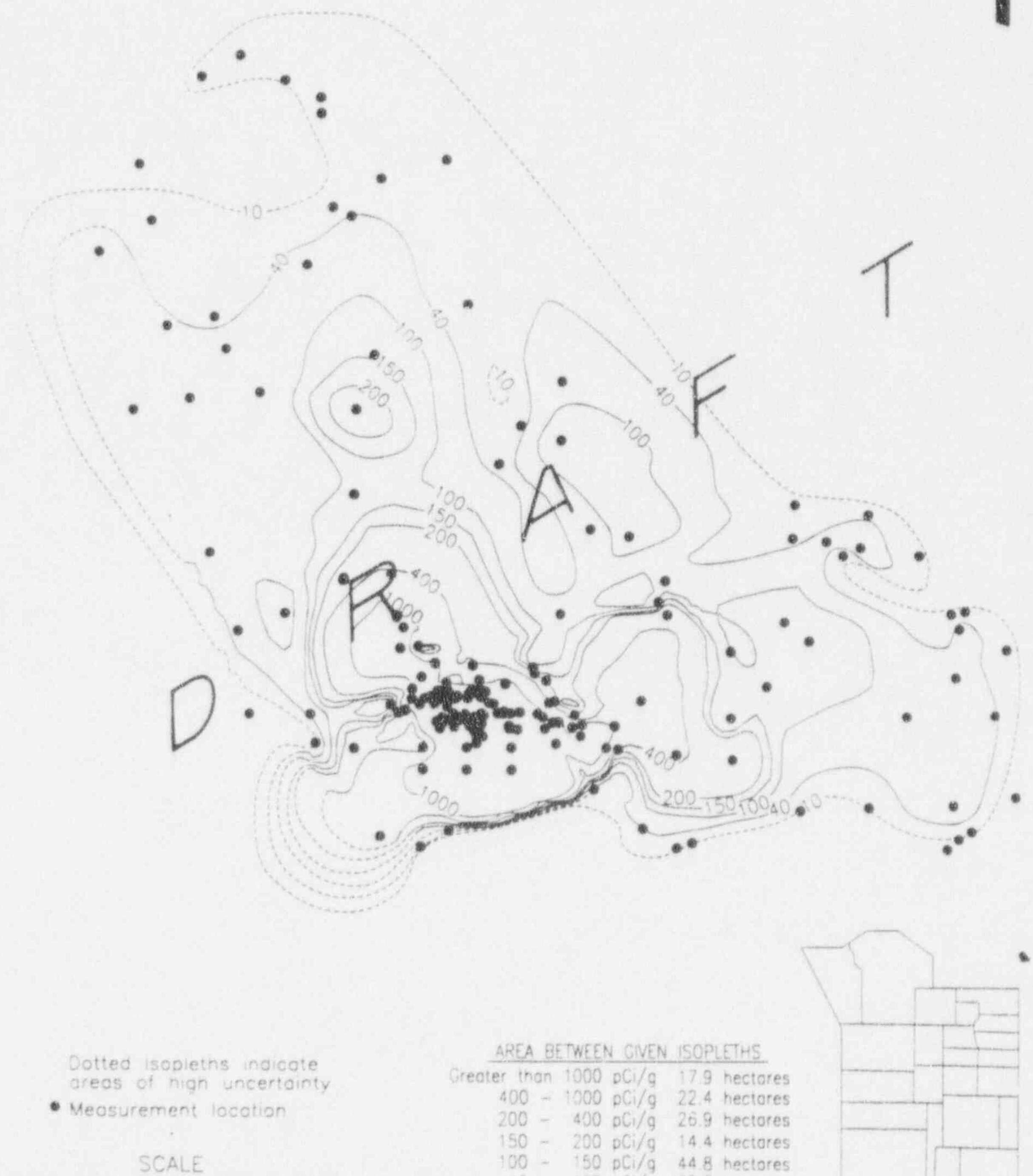
2.6 A Discussion of Contaminated Sites Near the NTS

The numbers in the last column of Table 2-3 are estimates of the 10 pCi/g area calculated by Gilbert and Simmons (1992) from in situ FIDLER measurements of Am made by the NAEG within fences around the ground zeros. The aerial surveys of the Clean Slate sites clearly show that contamination above 10 pCi/g extends beyond the fenced areas. Gilbert and

Simmons' estimates for Double Tracks and Area 13 agree well with the current estimates, which are based on direct measurements of soil Pu. However, this agreement may be an artifact: both sets of measurements (FIDLER and soil Pu) were limited to within the same fence at each site. Neither study measured Pu in soils outside the fenced area. Aerial surveys of these two sites might well show the 10 pCi/g area to extend beyond the fences and to be much larger than estimated.

Figure 2-17
Approximate Areas of Plutonium Contamination

Area 13



AREA BETWEEN GIVEN ISOPLETHS

Greater than 1000 pCi/g	17.9 hectares
400 - 1000 pCi/g	22.4 hectares
200 - 400 pCi/g	26.9 hectares
150 - 200 pCi/g	14.4 hectares
100 - 150 pCi/g	44.8 hectares
40 - 100 pCi/g	128.7 hectares
10 - 40 pCi/g	117.4 hectares

Table 2-3

Estimated Sizes of Areas Exceeding Certain Concentrations of Plutonium near the NTS

	Area (hectares) exceeding X pCi/g of Pu							
Site X =	1000	400	200	150	100	40	10	10*
Clean Slate 1	0	0	6	8	15	81	690	14
Clean Slate 2	4	17	26	39	77	170	280	45
Clean Slate 3	4	17	49	57	79	180	470	173
Double Tracks	1	1	3	4	7	8	11	10
Area 13	18	40	67	82	130	260	370	380
Smallboy Plume	12	130	400	670	940	2,100	6,200	—
Total	39	200	550	860	1,200	2,800	8,000	

*Estimates from Gilbert and Simmons (1992)

The estimated areas for the off-site regions are probably less precise than the estimates for the on-site regions. Although the Pu data used for Double Tracks and Area 13 may be more accurate than the in situ measurements from the NTS because no assumptions need to be made about relaxation depths, Pu/Am ratios, and other parameters, the Pu concentrations in small soil samples are often highly variable, especially near ground zero. The in situ system measures the activity over a wider field of view, giving less variable and more representative results. In addition, the NAEG soil samples were collected at random locations with the objective of estimating the Pu inventory, not determining the spatial distribution. As a result, there are large areas where no data are available. These data gaps, combined with the large variability in concentrations near the ground zeros, make drawing smooth isopleths extremely difficult in many cases.

No specific information is available concerning uncertainties in the aerial survey results. In general, the field of view of an airborne system is typically several hectares, much larger than that of a ground-based system, so aerial measurements often underestimate the intensity of localized high concentrations of radiation. Aerial systems are also sensitive to airborne radiation sources such as radon gas and to cosmic rays; however contributions from these sources are generally measured or estimated and extracted from the results. Additionally, as with other in situ systems, the estimated Pu concentrations depend on an assumed depth distribution and Pu/Am ratio.

Finally, the aerial system only measured concentrations above approximately 25 pCi/g. Estimates of the areas exceeding 10 pCi/g are based upon best professional judgment.

Adding the estimated areas for all the contaminated sites on and near the NTS gives the following areas exceeding the stated Pu activity:

1000 pCi/g	180 hectares	0.7 sq. mi.
400 pCi/g	600 hectares	2.3 sq. mi.
200 pCi/g	1,300 hectares	5.0 sq. mi.
150 pCi/g	2,000 hectares	7.7 sq. mi.
100 pCi/g	3,400 hectares	13.0 sq. mi.
40 pCi/g	12,000 hectares	46.0 sq. mi.
10 pCi/g	37,000 hectares	143.0 sq. mi.

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These estimates are believed to be accurate within a factor of two except in the case of the 10 pCi/g area. The available data are not adequate to accurately determine a 10 pCi/g isopleth at any of the sites under investigation. The error in our estimate of the total area exceeding 10 pCi/g could exceed a factor of four.

2.7 Depth of Plutonium Contamination

Data available for estimating the depth to which Pu is found in the soil are sparse. Although the total number of soil profiles collected and analyzed from the contaminated sites seems relatively large (about 275 from the NTS and 55 from the off-site safety shots), the sampling locations are widely scattered. Few sites have more than 10 sets of profile data available. Furthermore, the profiles from any one site are seldom entirely consistent.

It has been reported by various authors that at least 95 percent of the Pu occurs in the top 1 to 5 cm of soil (Shinn et al., 1992; Friesen, 1992). While many profiles do show this pattern, there are enough exceptions to argue against making generalizations. As was the case with the 10 pCi/g isopleth, the available data are not adequate to characterize the depth of Pu penetration at any of the contaminated sites. Assumptions about depth distributions are consistent with the data that exist, but the uncertainty is very high.

2.8 Volume of Contaminated Soil

The volumes of contaminated soil at each site have been calculated for three scenarios, called realistic, optimistic, and pessimistic. Each scenario entails different assumptions regarding the area and depth of Pu contamination.

Area: The realistic areas are the ones calculated by the methods previously described. Subjective optimistic and pessimistic estimates of area were produced by multiplying the realistic areas by the factor listed below:

	pCi/g Range	Optimistic	Pessimistic
NTS sites	>40	0.5	2
	10-40	0.5	5
Clean Slates	>40	0.5	2
	10-40	0.3	10
Double Tracks,	>40	0.3	3
Area 13	10-40	0.3	20
Smallboy Plume	>1,000	0.3	3
	400-1,000	0.4	2.5
	100-400	0.3	3
	40-100	0.4	2.5
	10-40	0.3	20

These multipliers represent a probable error of a factor of two unless the uncertainty is thought to be greater, as is the case with all the 10 to 40 pCi/g isopleths. As indicated, most of the uncertainty in the area of the 10 to 40 pCi/g isopleths is in the upper bound: the area cannot be less than 0, but could be very large. It should be emphasized that there are no data supporting the estimates of the 10 to 40 pCi/g areas at the Clean Slate sites and the Smallboy plume, and no data were taken outside the fences at Double Tracks and Area 13.

The cumulative areas calculated under these three scenarios for each site are given in Tables A-1 through A-15 in the Appendix.

Depth: The top 5 cm of soil probably contains most of the Pu at the majority of sites both on and off the NTS. Depending upon the surface concentration and the mobility of Pu within the soil column, it is possible that removing only the top 5 cm of soil in all areas would be sufficient to meet cleanup goals. It is also unlikely that considering the uneven terrain, currently available excavation equipment could remove less than 5 cm of surface soil. The optimistic case for volume thus assumes that regardless of the Pu surface concentration, removal of 5 cm of soil will be sufficient to meet the selected cleanup standard. Conversely, the pessimistic case assumes that Pu will have migrated to 25 cm within the soil profile and to meet cleanup requirements, the top 25 cm of soil will be removed from all areas, regardless of the chosen cleanup goal.

The realistic case attempts to take into account both the effect that surface concentration may have on the depth of Pu migration and the effect that the selected remediation level will have on the volume of soil excavated. If the regulatory cleanup level is less than 100 pCi/g the following excavation strategy would be followed:

- 5 cm in areas where surface Pu is less than 100 pCi/g
- 15 cm in areas where surface Pu is between 100 and 400 pCi/g
- 25 cm in areas where surface Pu exceeds 400 pCi/g.

For Pu cleanup levels set at 100 pCi/g, 150 pCi/g and 200 pCi/g, the depth of remediation would be 15 cm for the entire area exceeding that level. This should approximate the distribution of those concentration isopleths with depth. For cleanup levels greater than 400 pCi/g, it is assumed that the entire area exceeding that level will be removed to a depth of 10 cm. The estimated volumes under the three scenarios are given in Tables A-1 through A-15 in the Appendix. The total surface areas and volumes exceeding the various levels are summarized below in Table 2-4.

Log-log plots of the three sets of area estimates from Table 2-4 against the Pu concentration are approximately linear (Figure 2-18). The equations of the least squares regression lines are as follows:

Optimistic:	log Area = 5.51 - 1.18 (log Pu)
Realistic:	log Area = 5.85 - 1.18 (log Pu)
Pessimistic:	log Area = 6.64 - 1.35 (log Pu)

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The portions of the lines that extend below 40 pCi/g are shown as dotted on Figure 2-18 to emphasize that the estimates in this region are not well supported by data.

Table 2-4

Estimated Amounts of Soil Exceeding Certain Concentrations of Plutonium

	Area (hectares)			Volume (m^3 x 1,000)		
Pu (pCi/g)	Opt.	Real.	Pess.	Opt.	Real.	Pess.
1,000	83	180	390	42	180	970
400	280	600	1,300	140	600	3,300
200	580	1,300	3,100	290	2,000	7,600
150	850	2,000	4,600	420	3,000	12,000
100	1,500	3,400	7,800	750	5,100	20,000
40	5,600	12,000	26,000	2,800	9,400	64,000
10	17,000	37,000	220,000	8,500	22,000	540,000

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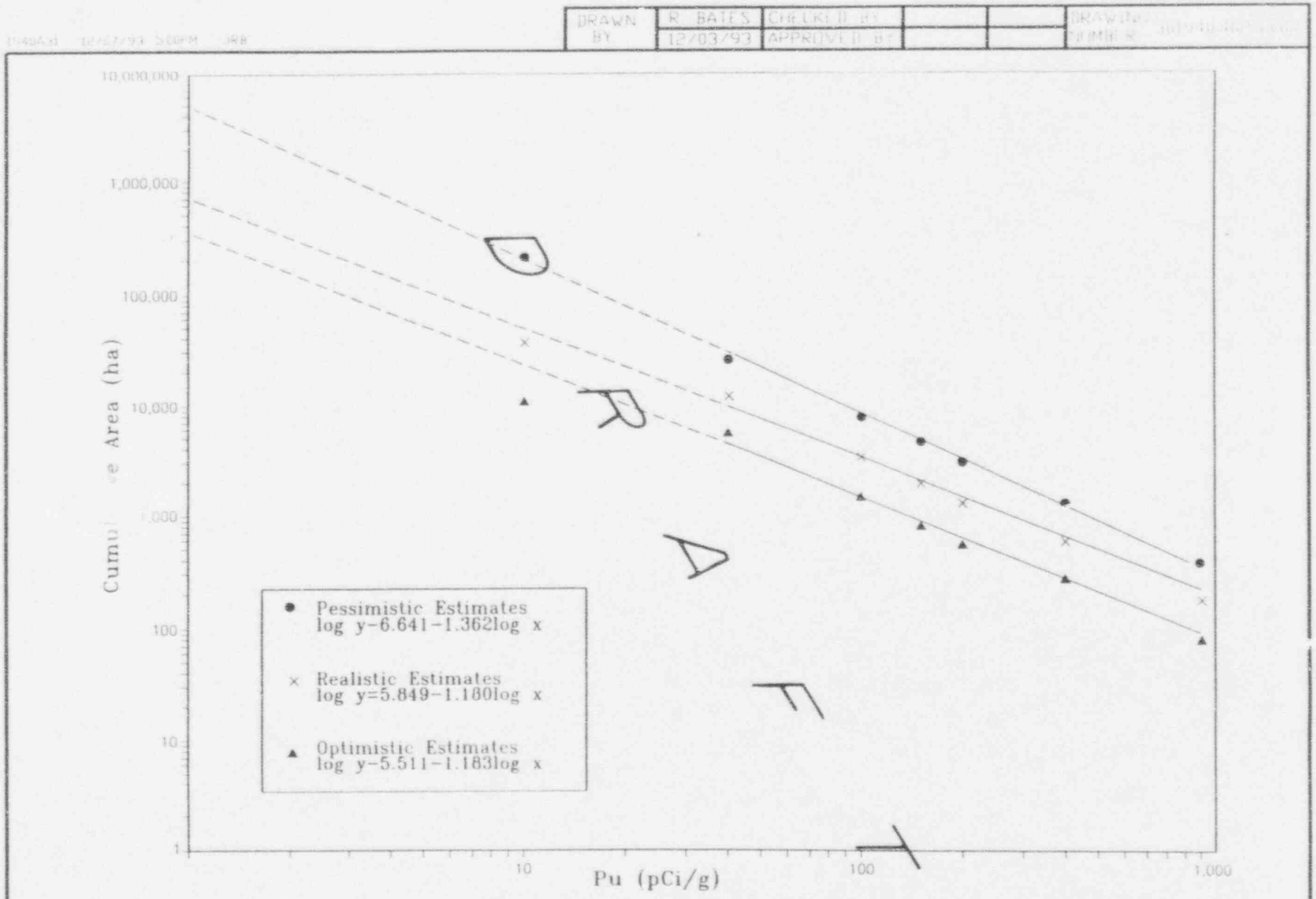

FIGURE 2-18

OBSERVED RELATIONSHIP BETWEEN TOTAL CONTAMINATED AREA AND PU CONCENTRATION

3.0 Cost Estimates

This section and its appendices provide cost estimates for the excavation, disposal (treatment and disposal), and reclamation of areas on the NTS which are contaminated with Pu from nuclear testing. Development of appropriate treatment technologies, excavation methods, and reclamation methods is under study and evaluation at this time. Therefore, estimates have been made using best available data; technological improvements and cost escalation, for example, could clearly affect overall costs.

3.1 Remediation Strategy

The following simplifying assumptions concerning the chosen remediation strategy were made for the purposes of estimating costs.

- Areas to be remediated are excavated with one or more pavement trimmers (e.g., Rotomills) or other similar equipment. Work on selection of an excavation technology to be employed is ongoing. Other technologies or mixes of technologies might eventually be chosen.

- At all stages, it is assumed that trucks transport the excavated soil to the next stage of processing. If volume reduction is employed, excavated soil is transported to the site where volume reduction is carried out; if not, excavated soil is transported directly to the disposal site. All transportation is assumed to occur on existing roads that are either public access or are controlled by DOE (Air Force controlled roads are not used).

- Volume reduction, if employed, will separate the soil into contaminated and uncontaminated portions. Here, the word "contaminated" means "having a Pu concentration large enough to be of regulatory interest"; similarly, "uncontaminated" means "having a Pu concentration small enough to be of no regulatory interest," as returned to its original site and spread evenly over the remediated area. The contaminated portion will be disposed of as waste.

- Disposal of contaminated soil will occur on the NTS. Contaminated soil is assumed disposed of as unpackaged waste. If the contaminated soil is packaged, the added cost, both in manpower and material, is considerable. Waste can either be disposed of in the

Radioactive Waste Management Sites (RWMS) or in craters, which could be capped when filled. The average crater volume is large (approximately 200,000 m^3 per crater) and 300 to 400 craters are potentially available for use. If a disposal site were opened on the TTR, the variable cost of remediating sites on the TTR would decrease, however considerable fixed costs would ensue.

- Environmental restoration, including revegetation, will occur on remediated sites. Excavated sites will be subject to short-term stabilization immediately after excavation. Long-term stabilization might involve seeding, transplanting, mulching, and irrigation.

- Certification through recharacterization is required. Areas to be remediated are surveyed for purposes of certification. Some areas adjacent to the surveyed area are also surveyed, to confirm that no additional remediation is required.

3.1.1 Cost Model

The method by which total cost is expressed depends on whether volume reduction is employed. The cost for remediating a region is the sum of fixed, area-driven, and volume-driven costs. Fixed costs include the cost of Rotomills, permitting costs, costs of mobile processing centers (if volume reduction is employed), and costs of building roads from the TTR to the NTS.

The area-driven cost for one hectare of excavated soil, regardless of the decision made concerning volume reduction, is

$$C_a = E + R + C + N$$

where

C_a = Cost of remediating one hectare,
E = Excavation cost,
R = Rehabilitation cost,
C = Radiation certification cost,
N = Soil nutrient addition cost.

If volume reduction is employed, the volume-driven cost of one cubic meter of excavated soil is

$$C_v \;=\; T + D + V + S$$

where

C_v = Cost of remediating one cubic meter,

T = Transport cost,

D = Disposal cost,

V = Volume reduction cost,

S = Soil spreading cost.

This model accounts only for economic costs, and not for such difficult-to-quantify costs as environmental damage from remediation and injury/health risk to workers. These types of social costs are discussed in other sections of this report. Difficult-to-quantify benefits, such as advances in volume reduction technology that might result, are also ignored here.

If volume reduction was not performed due to either economic or technological reasons, the cost of remediating one cubic meter would be

$$C_v \;=\; T + D$$

where the variables are defined as above.

3.1.2 Assumptions

The cost of remediation depends on many variables, few of which have exact known values. Costs are given as "realistic" (best estimate, based on current information), "optimistic" (estimate which results in the smallest cost), and "pessimistic" (estimate which results in the largest cost). Estimated costs are given to the nearest dollar, so costs can be summed and then rounded, rather than the less-accurate rounding and then summing. Unrealistic precision should not be inferred from this practice.

The cost of remediating Pu-contaminated areas on the NTS and TTR depends on the chosen remediation strategy. As many strategies are possible, the simplifying assumptions are made that remediation will proceed by excavation and that waste materials will be disposed of on the NTS.

Costs can be separated into area-driven costs (e.g., revegetation) and volume-driven costs (e.g., transportation). Area-driven costs depend only on the area remediated, volume-driven costs depend on both the area remediated and the depth of excavation. As this depth probably will not be constant, area and volume are not simple functions of one another. Accordingly, area-driven and volume-driven costs are calculated separately.

Volume-driven costs are estimated under four scenarios: disposal of excavated soil without volume reduction from sites on the NTS, disposal of excavated soil with volume reduction from sites on the NTS, disposal of excavated soil with volume reduction at the TTR, and disposal of excavated soil without volume reduction at the TTR. For these scenarios, realistic volume-driven costs and upper and lower bounds are given in Table 3-1.

Only variable costs (costs that change with volume or area remediated), and not fixed costs (one-time costs independent of volume remediated, such as those associated with starting or ending remediation), are accounted for in the preceding. As an example of a fixed cost, suppose 1,000 hectares were to be excavated with a Rotomill. At 23.2 hours per hectare excavated (the realistic estimate), 40 hours per work week, and 52 weeks per year, remediation of 1,000 hectares would require more than 11 years. To complete the task sooner, more Rotomills would have to be purchased. The purchase price of these Rotomills would be a fixed cost.

3.2 Estimation of Characterization Costs

Additional characterization sots may be required to clarify the distribution of Pu concentration levels prior to beginning soil remediation. Such costs are not included in the totals generated in this section, however, characterization costs were estimated to permit including such costs in the integration analysis of Section 5.0. The characterization cost estimates are summarized here.

Costs to obtain measurements of Pu contaminated soils depend on the level of contamination and the accuracy required. Although relatively low cost conventional aerial measurements may be adequate for the purpose of delineating areas with concentrations above approximately

35 pCi/g, more expensive ground-based or in situ techniques will be required if cleanup to lower levels is required. Figure 3-1 summarizes the measurement technology assumed and the corresponding range in characterization costs per unit area as a function of the clean-up level. Costs are site specific and highly variable depending upon measurement criteria. The best judgement of characterization costs for each clean-up level is the geometric mean of the limits specified by the ranges shown in the figure.

3.3 Estimation of Soil Excavation Costs

The Rotomill, a pavement trimmer, with a cutting width of 2.35 m, excavates a linear 366 m per hour, for an area of 0.086 hectares per hour, using a 60-minute efficiency hour. Ignoring difficulties that might arise from uneven terrain, the Rotomill will require approximately 11.6 hours to process 1 hectare of soil. The industry-standard efficiency hour is 50 minutes; the presence of contaminated soil would require at a minimum Level C Personal Protection Equipment (PPE), which would markedly reduce the efficiency hour below this. Further, the Rotomill would not operate at all times, as considerable time could be spent waiting for trucks to be properly positioned to receive excavated soil. An optimistic assessment of the work time factor would be 0.67, corresponding to a 40-minute efficiency hour. The realistic and pessimistic estimates are obtained by adjusting the work time factor; a realistic estimate of a 30-minute efficiency hour (work time factor 0.50) and a pessimistic estimate of a 20-minute efficiency hour (work time factor 0.33) result in optimistic, realistic, and pessimistic estimates of, respectively, 17.3, 23.2 and 35.1 hours to excavate one hectare of soil.

Table 3-1
Volume and Area Driven Costs

Scenario	Optimistic	Realistic	Pessimistic
No volume reduction, NTS ($\$/m^3$)	220	430	1,600
Volume reduction, NTS ($\$/m^3$)	160	350	1,100
No volume reduction, TTR ($\$/m^3$)	260	490	1,700
Volume reduction, TTR ($\$/m^3$)	160	360	1,200
Area cost ($1000s / hectare remediated)	15	29	73

Bulldozers operated at the NTS cost $210 per 10 hour workday, or $21 per hour (Hoar, 1993). The cost of operating a Rotomill is assumed equal to the cost of operating a bulldozer. The loaded rate for heavy equipment operators is approximately $60 per hour. In addition to the operator, support personnel and radsafe workers would be required; a loaded hourly rate of $55 per hour per worker is used here. An optimistic cost per hour is calculated as cost of the Rotomill plus cost of operator plus cost of two additional workers ($21 per hour + $60 per hour + $110 per hour), or $191 per hour. A realistic hourly cost is calculated by adding two additional workers, for a total of $301 per hour. A pessimistic hourly cost is calculated by adding two more workers, for a cost of $411 per hour.

Optimistic, realistic, and pessimistic estimates of excavation cost per hectare remediated are obtained by multiplying the appropriate hourly costs times the corresponding estimates of the numbers of hours required. This results in an optimistic, realistic, and pessimistic cost of, respectively, $3,304, $6,983, and $14,426 per hectare remediated.

Some areas might have to be excavated more than once. If this occurs, the cost of additional excavation is not reflected here.

3.4 Estimation of Environmental Rehabilitation Costs

If volume reduction is not employed, no soil will be replaced. The exposed subsoil may lack the nutrients and microflora to support plant growth. If volume reduction is employed, the native seedbank, plant nutrients, and microflora beneficial to higher plant growth may be destroyed.

Natural revegetation would be very slow due to the loss of viable topsoil. Revegetation by seeding or transplanting will be necessary to restore a stable plant community and provide long-term stabilization. Revegetation has had mixed success in arid environments, but has succeeded in the Mojave Desert (Graves et al., 1987; Kay, 1979), and, in particular, on the NTS (Wallace, 1980; Romney et al., 1987).

Revegetation costs vary with location and vegetation type and with the speed with which revegetation is expected to be accomplished, with faster results costing more. In view of the large uncertainty associated with revegetation costs, specifying separate revegetation costs for separate areas was not thought to be worthwhile. Low-level revegetation might consist of stabilization immediately following excavation, seeding a mix of native species, and mulching with straw, at a cost of as little as $9,000 per hectare. Seeding and mulching might have to be repeated several times if precipitation is inadequate. An intermediate alternative might be to combine a low level of revegetation with a 2 cm layer of gravel, to protect the site until vegetation can become established, at a cost of $15,000 per hectare. Higher level treatments might consist of manipulating the soil surface to form water harvesting catchments to collect rain water, using a combination of seeding and transplantation, and irrigation during the first year, at a cost of as much as $40,000 per hectare. Soil treatment expenses include the addition of gypsum, fertilizer, and microorganisms to replace removed materials. The three levels of treatment are estimated to cost $1,750, $2,000, and $3,000 for the optimistic, realistic, and pessimistic cases.

3.5 Estimation of Radiological Survey/Cleanup Certification Costs

Following excavation of contaminated soil, it will be necessary to collect radiological data over the remaining soil to assure the completeness of the cleanup, i.e., if the contamination has been reduced to the clean-up criteria. There are various methods of collecting this data.

The area surveyed must be larger than the area remediated; how much larger will depend on individual site. Optimistic, realistic, and pessimistic figures of hectares surveyed per hectare remediated are, respectively, 1.05, 1.10, and 1.25.

Cost per hectare surveyed depends on the type of survey conducted. An airborne survey, usable in delineating areas with concentrations exceeding approximately 25 pCi/g, is the least expensive (Rogers, 1993) (Figure 3-1). A survey with truck-mounted detectors, usable down to approximately 10 pCi/g, is more expensive. Hand-carried and positioned tripod-mounted stationary detectors, requiring minutes to hours of counting to survey a square meter of soil, would be impractical and extremely expensive, and are not considered.

For the optimistic figure, the cost of a low-cost airborne survey, $1,235 per hectare surveyed, is used. For the realistic estimate, the cost of a truck-mounted survey, using technology currently in development, or $4,942 per hectare surveyed is used (Rogers, 1993). For the pessimistic estimate, the cost of a truck-mounted survey using current technology, or $12,355 per hectare surveyed, is used (Rogers, 1993).

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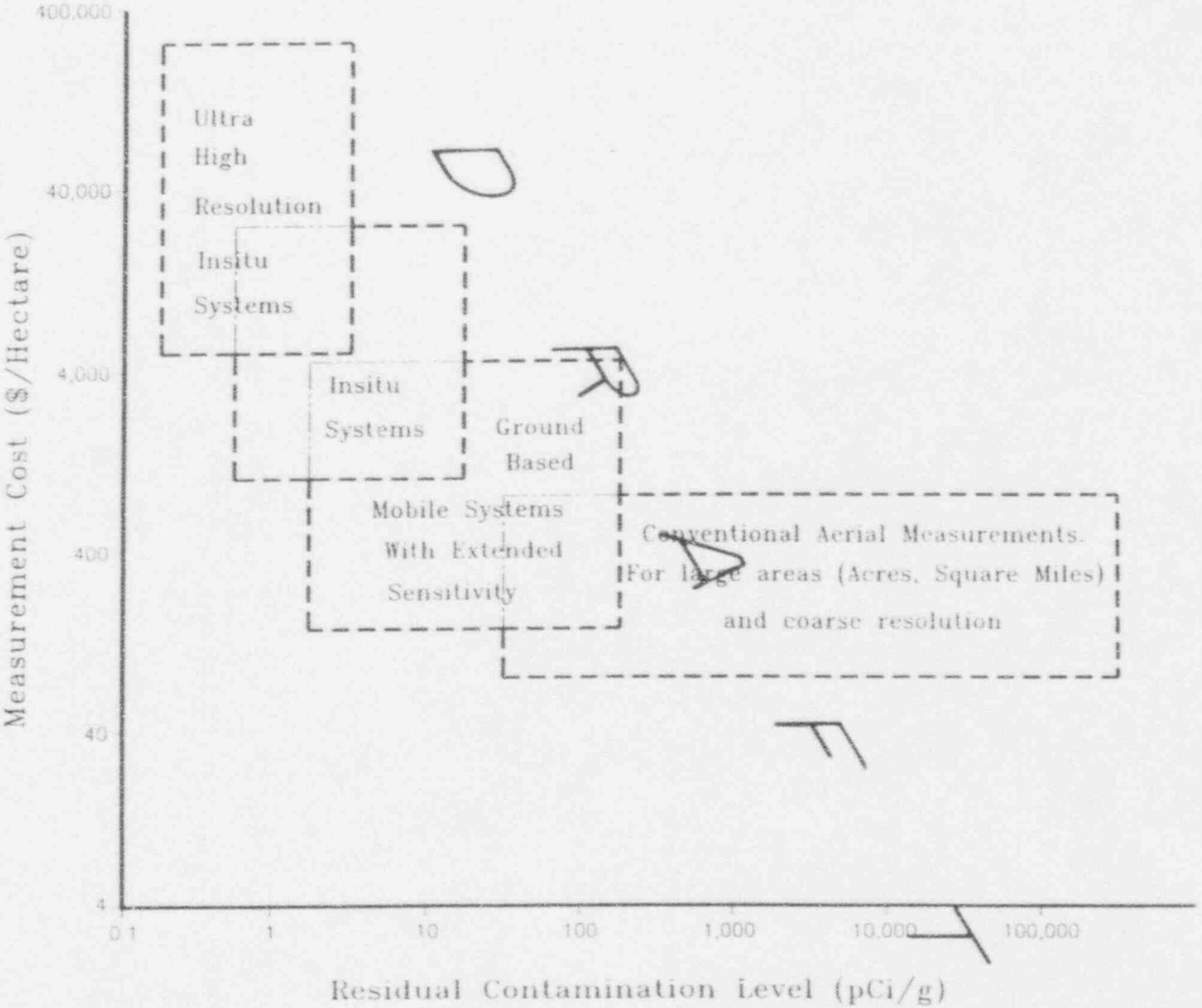

FIGURE 3-1
AREA DRIVEN CHARACTERIZATION COSTS

Adapted from Rogers, 1993

Multiplying these figures by the corresponding estimates for hectares surveyed/hectare remediated, we obtain optimistic, realistic, and pessimistic costs of, respectively, $1,297, $5,436, and $15,444 per hectare remediated.

3.6 Estimation of Transportation Costs

Transportation distances, and therefore costs, vary with location being remediated (requirements are greater for more remote sites) and with the decision made concerning volume reduction. If volume reduction is employed, soil will be transported from the point of excavation to the point of processing; uncontaminated soil will be returned to its original location, while contaminated soil will be transported to the disposal site. If volume reduction is not employed, soil will be transported directly to the disposal site.

The most likely earth-mover to be used is the 22-cubic yard truck; the struck (or level) capacity of such trucks is approximately 17 cubic meters. Using the trucks heaped, rather than struck, capacity would decrease the number of truckloads required and thereby reduce cost. As this would risk spreading contaminated soil, this option is not considered.

The time required for a large earth-moving truck, loaded, to travel one kilometer is 0.8 minute (optimistic), 1.1 minutes (realistic), and 1.3 minute (pessimistic) (Caterpillar Tractor, 1979). The time required for the return trip, unloaded, per kilometer is 0.7 minutes (optimistic), 0.9 minutes (realistic), and 1.1 minutes (pessimistic) (Caterpillar Tractor, 1979). Adjusting for a 50-minute efficiency hour, these times become: 1.0 minute (optimistic loaded), 1.3 minutes (realistic loaded), 1.6 minutes (pessimistic loaded), 0.8 minutes (optimistic unloaded), 1.1 minutes (realistic unloaded), and 1.3 minutes (pessimistic unloaded). A constant 50-minute efficiency hour is used here rather than the variable figure used for the Rotomill's operation. This is justified by the lower levels of environmental stress (e.g., temperature, wind) that the truck drivers would experience.

Distances which soil must be transported to disposal differ at sites on the NTS and TTR, with greater distances, and therefore costs, associated with sites on the TTR. The distance could be considerably reduced by creating a disposal site on the TTR. The distance could be somewhat reduced if permission could be obtained to use roads that cross Air Force land and these roads were suitably improved and maintained. This option, which might or might not be feasible, would entail considerable fixed cost, as described in Section 3.9. Transportation costs from the TTR were calculated under the assumption that no new roads would be constructed.

If volume reduction is employed, mobile processing centers will be set up approximately 2 kilometers from the point of excavation. The distance from the point of processing (if volume reduction is employed) or the point of excavation (if volume reduction is not employed) to the point of disposal is approximately 60 kilometers from sites on the NTS; distance varies from roughly 40 to 80 kilometers, with 60 being a rough average. From remediation sites on the TTR, the distance to the RWMS is approximately 400 kilometer via existing public roads.

3.6.1 Transportation Without Volume Reduction

If volume reduction is not employed, all excavated soil would be transported to the disposal site. For sites on the NTS, the distance to the disposal site is assumed to be 60 kilometers. Allowing five minutes for the truck to dump its load, the time required for traveling, loaded, to the disposal site, dumping, and returning unloaded is 1.9 hours (60 kilometers x {1.0 minutes per kilometer + 0.8 minutes per kilometer} + 5 minutes). The realistic and pessimistic estimates, calculated in the same manner, are, respectively, 2.5 hours and 3.0 hours.

The cost of operating a truck at the NTS is $130 per 10 hour workday, or $13 per hour. Allowing a loaded rate of $55 per hour for the driver, the total rate is $68 per hour. Hence, the optimistic, realistic, and pessimistic transportation costs are, respectively, $129, $170, and $204 per truckload. At 17 cubic meters per truckload, this translates to $7.59, $10.00, and $12.00 per cubic meter.

For sites on the TTR, the distance to the disposal site is 400 kilometers. Allowing five minutes for the truck to dump its load, the time (optimistic) required for traveling, loaded, to the disposal site, dumping, and returning unloaded is 12.1 hour (400 kilometers x {1.0 minutes per kilometer + 0.8 minutes per kilometer} + 5 minutes). The realistic and pessimistic estimates, calculated in the same manner, are, respectively, 16.1 hours and 19.4 hours per truckload. At $68 per hour and 17 cubic meter per truckload, this translates to respective optimistic, realistic, and pessimistic estimates of $48.40, $64.40, and $77.60 per cubic meter.

3.6.2 Transportation with Volume Reduction

Optimistically, the greatest truck speeds and the most favorable volume reduction achievable are assumed. At a rate of 1.0 minutes per kilometer (loaded), a rate of 0.8 minutes per kilometer (unloaded), and 5 minutes for dumping the soil, transportation of soil to the treatment point would require 9 minutes per truckload. At a rate of $68 per hour and 17 cubic meters per truckload, this translates to $0.60 per cubic meter.

For optimistic case calculations, 90 percent volume reduction is assumed. For each cubic meter of soil excavated, 0.1 cubic meters of contaminated soil would be transported to the disposal site, 60 kilometers away (for sites on the NTS), and 0.9 cubic meters of uncontaminated soil would be returned to the site of excavation, at a distance of 2 kilometers. Allowing five minutes for dumping soil, each truckload of soil returned to the site of excavation would require 9 minutes and each truckload of soil taken to the disposal site would require 1.9 hours. Accordingly, the cost of returning the uncontaminated portion of the soil would be $0.54 for each cubic meter of excavated soil, and the cost of transporting the contaminated portion would be $0.76 per cubic meter (1.9 hours per truckload x $68 per hour x 0.1 per 17 cubic meters per truckload) for each cubic meter of excavated soil. The total optimistic transportation cost for sites on the NTS would be ($0.60 + $0.54 + $0.76) per cubic meters excavated, which equals $1.90 per cubic meters.

Optimistic costs of transporting soil to and from the point of treatment do not change at the TTR; they are, respectively, $0.60 and $0.54 per cubic meter. The cost of transporting contaminated soil to the disposal site changes due to the greater distance. At a rate of 1.0 minutes per kilometer (loaded) and 0.8 minutes per kilometer (unloaded), with five minutes for dumping, the time required for disposal of a truckload is 12.1 hours (400 kilometers x {1.0 minutes per kilometer + 0.8 minutes per kilometer} + 5 minutes). This translates to a cost of $4.84 per cubic meter (12.1 hours per truckload x $68 per hour x 0.1 per 17 cubic meters per truckload). The total optimistic transportation cost for the TTR would be ($0.60 + $0.54 + $4.84) per cubic meter, which equals $5.98 per cubic meter.

For realistic values, assume moderate speeds and achievable volume reduction. At a rate of 1.3 minutes per kilometer (loaded), a rate of 1.1 minutes per kilometer (unloaded) and 5 minutes for dumping the soil, transportation of soil to the treatment point would require 10 minutes per truckload. At a rate of $68 per hour and 17 cubic meters per truckload, this translates to $0.67 per cubic meter.

For realistic calculations, 80 percent volume reduction is assumed. For each cubic meter of soil excavated, 0.2 cubic meters of contaminated soil would be transported to the disposal site, 60 kilometers away (for sites on the NTS), and 0.8 cubic meters of uncontaminated soil would be returned to the site of excavation, at a distance of 2 kilometers. Allowing five minutes for dumping soil, each truckload of soil returned to the site of excavation would require 10 minutes, and each truckload of soil taken to the disposal site would require 2.5 hours. Accordingly, the cost of returning the uncontaminated portion of the soil would be $0.53 for each cubic meter of excavated soil, and the cost of transporting the contaminated portion would be $2.00 per cubic meter (2.5 hours per truckload x $68 per hour x 0.2 per 17 cubic meters per truckload) for each cubic meter of excavated soil. The total realistic transportation cost for sites on the NTS would be ($0.67 + $.053 + $2.00) per cubic meter excavated, which equals $3.20 per cubic meter.

Realistic costs of transporting soil to and from the point of treatment do not change at the TTR; they are, respectively, $0.67 and $0.53 per cubic meter. The cost of transporting contaminated soil to the disposal site changes due to the greater distance. At a rate of 1.3 minutes per kilometer (loaded) and 1.1 minutes per kilometer (unloaded), with five minutes for dumping, the time required for disposal of a truckload is 16.1 hours (400 kilometers x {1.3 minutes per kilometer + 1.1 minutes per kilometer} + 5 minutes). This translates to a cost of $12.88 per cubic meter (16.1 hours per truckload x $68 per hour x 0.2 per 17 cubic meters per truckload). The total realistic transportation cost for the TTR would be ($0.67 + $0.53 + $12.88) per cubic meter, which equals $14.08 per cubic meter.

For pessimistic case values, we assume the slowest truck speeds and the least favorable volume reduction. At a rate of 1.6 minutes per kilometer (loaded), a rate of 1.3 minutes per kilometer (unloaded) and 5 minutes for dumping the soil, transportation of soil to the treatment point would require 11 minutes per truckload. At a rate of $68 per hour and 17 cubic meters per truckload, this translates to $0.73 per cubic meter.

For pessimistic calculations, 70 percent volume reduction is assumed. For each cubic meter of soil excavated, 0.3 cubic meters of contaminated soil would be transported to the disposal site, 60 kilometers away (for sites on the NTS), and 0.7 cubic meters of uncontaminated soil would be returned to the site of excavation, at a distance of 2 kilometers. Allowing five minutes for dumping soil, each truckload of soil returned to the site of excavation would require 11 minutes, and each truckload of soil taken to the disposal site would require 3.0 hours. Accordingly, the cost of returning the uncontaminated portion of the soil would be $0.51 for each cubic meter of excavated soil, and the cost of transporting the contaminated portion would be $3.60 per cubic meter (3.0 hours per truckload x $68 per hour x 0.3 per 17 cubic meters per truckload) for each cubic meter of excavated soil. The total realistic transportation cost for sites on the NTS would be ($0.73 + $0.51 + $3.60) per cubic meter excavated, which equals $4.84 per cubic meter.

Pessimistic costs of transporting soil to and from the point of treatment do not change at the TTR; they are, respectively, $0.73 and $0.51 per cubic meter. The cost of transporting contaminated soil to the disposal site changes due to the greater distance. At a rate of 1.6 minutes per kilometer (loaded) and 1.3 minutes per kilometer (unloaded), with five minutes for dumping, the time required for disposal of a truckload is 19.4 hours (400 kilometers x {1.6 minutes per kilometer + 1.3 minutes per kilometer} + 5 minutes). This translates to a cost of $23.28 per cubic meter (19.4 hours per truckload x $68 per hour x 0.3 per 17 cubic meter per truckload). The total pessimistic transportation cost for TTR would be ($0.73 + $0.51 + $23.28) per cubic meter, which equals $24.52 per cubic meter.

Additional transportation expenses not accounted for here include decontamination of trucks and PPE for operators. These expenses are expected to be small, compared to other costs, but still might sum to a considerable expense.

There is also the operational problem of transporting the contaminated material via public roads, as assumed here. The alternative of a government-owned road is mentioned above with associated fixed-cost estimates. Portage in covered vans would be difficult to justify both for operations and radiation safety. Portage in barrels as low-specific-activity waste is feasible but very expensive because of the quantities involved and its associated handling. Should containerization be necessary for transportation, the cost of a mil-van or transportainer will add about $40 per cubic meter to the cost. This expense may also be a requirement for disposal.

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3.7 Estimation of Volume Reduction Costs

As volume reduction comparable to what would be required for remediating contaminated areas on and around the NTS has not been previously attempted, cost estimates are highly speculative. Others' efforts at separation of uranium from soil, by both mechanical and chemical means, have, with economics of scale, resulted in costs as low as $100 per cubic yard, with costs of $200 per cubic yard being more typical and ranging up to $500 per cubic yard (Bliss, 1993). Here, the first figure is used as an optimistic estimate, the second as a realistic estimate, the third as a pessimistic estimate. Converting English units to metric yields optimistic, realistic, and pessimistic estimates of $131, $262, and $655 per cubic meter.

If volume reduction is employed, soil will be separated into contaminated and uncontaminated portions. The uncontaminated portion will be spread smoothly over the region from which the soil was removed. A skilled operator could do this with a bulldozer. The time required for this depends on the unknown cohesiveness of the uncontaminated soil resulting from volume reduction. Estimates of the time required to replace a cubic meter of soil (Haecker, 1993) range from 0.8 minutes (optimistic), to 0.9 minutes (realistic), to 1.1 minutes (pessimistic). Allowing $21 per hour for the equipment, $60 per hour loaded rate for the operator, and $55 per hour loaded rate for support personnel ($136 per hour total), the estimated costs for replacing a cubic meter of soil are $1.81 (optimistic), $2.04 (realistic), and $2.27 (pessimistic). Adjusting for volume of soil after volume reduction, this becomes $1.00 (optimistic), $2.00 (realistic), and $3.00 (pessimistic).

If volume reduction were not employed, no soil would be returned to be spread. Hence, the cost would be $0.

3.8 Estimation of Disposal Costs

Disposal cost depends on the achievable volume reduction; the greater the achievable volume reduction, the smaller the disposal cost. Similarly, disposal cost depends on the decision reached concerning volume reduction, as not using volume reduction is equivalent to an achievable volume reduction of zero.

The flat-fee cost for disposing of low-level waste on the NTS is currently $10 per cubic foot. This cost is scheduled to increase, at a rate of approximately $1 per cubic foot per year. As remediation would not take place immediately, the realistic cost estimate is $12 per cubic foot (projected rate for 1995). As remediation might begin later than 1995 and the most pessimistic case would have the waste disposed of in a commercial waste disposal site, the pessimistic cost estimate is $40 per cubic foot. Considering the escalation one might expect between now and the actual time of disposal, this figure could be 25 percent low.

The cost of placing waste in containers for disposal may range from $40 per cubic meter upward. Drums would require massive handling procedures to provide a production rate sufficient to handle the very large volumes anticipated. There would be proportional health and safety issues, increased volume for disposal (void space between stacked drums), and so on. The cost of drums is about four times the cost of transportainers per unit volume.

Alternately, it might be possible to dump waste in craters that would later be capped. Barker (1993) estimated the lifetime cost of operating the landfill in Crater UC-10 at the NTS at $6.00 per cubic foot. Disposal of waste from remediation is not identical to disposal of sanitary waste; for example, fewer tests are required for monitoring, although monitoring must continue longer. However, $6 per cubic foot can be used as an approximate optimistic cost.

Disposal costs are estimated under the conditions "volume reduction employed" and "volume reduction not employed." If volume reduction is employed, optimistic, realistic, and pessimistic estimates of cost are matched with corresponding estimates of achievable volume reduction.

If volume reduction is not employed, the cost of disposal is the volume excavated times the cost per unit volume. The optimistic, realistic, and pessimistic estimates for this cost are, respectively, $212 per cubic meter, $424 per cubic meter, and $1,589 per cubic meter.

If volume reduction is employed, the cost of disposal is the volume excavated times the cost per volume times (1 - achievable volume reduction). Using the per volume costs quoted above and the optimistic, realistic, and pessimistic achievable volume reductions of 0.90, 0.80, and 0.70, disposal costs can be calculated. The estimated optimistic cost is $21 per cubic meter. The realistic estimated cost is $85 per cubic meter. The estimated pessimistic cost is $477 per cubic meter.

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Note that disposing of the resulting large volume of waste, particularly if volume reduction is not employed, would require permitting new waste disposal facilities. This fixed cost, not considered here, could be large.

3.9 Estimation of Labor Required for Remediation

In the course of remediation, workers will be at risk from industrial accidents and be exposed to radioactive materials. The cost associated with these risks is best studied through the man-hours required to complete certain tasks. Required man-hours for excavation (per hectare excavated), transportation, and spreading of uncontaminated soil (per cubic meter excavated) can be derived from the estimates provided above. For convenience, these values are provided in Table 3-2.

Table 3-2
Estimated Man-hours Required for Remediation

Task	Man-hours (optimistic)	Man-hours (realistic)	Man-hours (pessimistic)
Excavation	51.9/ha	116.0/ha	245.7/ha
Transportation (No volume reduction, NTS)	0.11/m³	0.15/m³	0.18/m³
Transportation (Volume reduction, NTS)	0.03/m³	0.05/m³	0.07/m³
Transportation (No volume reduction, TTR)	0.72/m³	0.95/m³	1.14/m³
Transportation (Volume reduction, TTR)	0.09/m³	0.21/m³	0.36/m³
Soil Spreading	0.03/m³	0.03/m³	0.03/m³

Reliable figures for man-hours required for revegetation/environmental restoration, survey/certification, and, if employed, processing for volume reduction were not obtained, although they would not be negligible, and should be accounted for.

Estimates of the number of man-hours required for waste disposal depend on the decision made concerning volume reduction and the method by which wastes are processed. If wastes are processed by usual NTS waste-disposal procedures, approximately 1 man-hour is required for each 18 cubic meters of waste (Becker, 1993); this translates to 0.055 manhours per cubic meter. Using this figure, the following man-hours would be required for each cubic meter of excavated soil:

Scenario	Optimistic	Realistic	Pessimistic
No volume reduction	0.055	0.055	0.055
Volume reduction	0.005	0.011	0.016

If waste is disposed of by dumping in craters, the man-hours required for processing a cubic meter of waste would be approximately 0.0049. Using this figure, the following man-hours would be required for each cubic meter of excavated soil:

Scenario	Optimistic	Realistic	Pessimistic
No volume reduction	0.005	0.005	0.005
Volume reduction	0.000	0.001	0.001

The estimates of labor required are made under the assumption waste is unpackaged. Were this assumption not to hold, the labor required for packaging waste would be quite large. The labor required for waste disposal would increase by a factor of three to five.

A summary of volume and area dependent costs is presented in Table 3-3. The volume and area dependent costs are further subdivided into no volume reduction and volume reduction options.

TABLE 3-3

Estimated Costs For Soil Remediation on the NTS, NAFR, and TTR

	No Volume Reduction					
	Volume Costs on NTS ($M³)			Volume Costs on TTR ($/M³)		
Item	Optimistic	Realistic	Pessimistic	Optimistic	Realistic	Pessimistic
Transportation	8	10	12	48	64	78
Disposal	212	424	1,589	212	424	1,589
Total	220	434	1,601	260	488	1,667
	Volume Reduction					
Transportation	2	3	5	6	14	25
Volume Reduction	131	262	655	131	262	655
Soil Spreading	1	2	3	1	2	3
Disposal	21	85	477	21	85	477
Total	155	352	1,140	159	363	1,159
	Area Costs for NTS and TTR					
Excavation	3,304	6,983	14,426			
Certification	1,297	5,436	15,444			
Rehabilitation	9,000	15,000	40,000			
Soil Treatment	1,750	2,000	3,000			
Total	15,351	29,419	72,870			

3.10 Estimation of Fixed Costs

Estimating fixed costs requires even more assumptions than estimating variable costs. Even more than the variable costs, fixed costs are scenario-driven. Possible scenarios include volume reduction employed with only public roads used; volume reduction employed with new roads built; no volume reduction employed with only public roads used; and no volume reduction employed with new roads built. Table 3-4 summarizes rough cost estimates. Discussion of the individual cost components is provided below.

Table 3-4
Fixed Costs

Fixed Cost	Optimistic ($1000s)	Realistic ($1000s)	Pessimistic ($1000s)
Volume reduction employed, public roads only used	4,255	11,025	38,550
Volume reduction employed, new roads built	8,373	10,225	43,020
No volume reduction employed, public roads only used	1,825	4,425	10,050
No volume reduction employed, new roads built	5,973	8,725	21,420

3.10.1 Fixed Costs for All Scenarios

3.10.1.1 Cost of Rotomills

Clearly, a single Rotomill (or whatever device is used) will not be sufficient for the required excavation. The number of additional Rotomills that would have to be acquired depends on the area to be remediated and the time in which remediation is expected to be completed. The estimated number of Rotomills, at $450,000 each, which would have to be acquired is 4 (optimistic), 9 (realistic), and 19 (pessimistic). Hence, the optimistic, realistic, and pessimistic costs for acquiring Rotomills are, respectively, $1,800,000, $4,050,000, and $8,550,000.

3.10.1.2 Permitting for Disposing of Waste in Craters

Disposing of waste in craters would require permitting. Whether each crater would have to be permitted separately or a single permit could cover all craters is unclear. Permitting costs for waste disposal typically run $25,000 per permit (ECO Northwest, 1986). Optimistically, one permit would be required for the entire NTS. Pessimistically, as many as 300 permits (approximately one per crater) might be required. Realistically, permits might be obtained for groups of craters, requiring perhaps 15 permits. Accordingly, the permitting costs are $25,000 (optimistic), $375,000 (realistic), and $7,500,000 (pessimistic).

3.10.2 Fixed Costs Associated with Volume Reduction

If volume reduction is employed, mobile processing centers would be set up approximately 3 kilometers from excavation sites. The number of processing centers required might be as few as 12 (optimistic), as many as 15 (realistic), or as many as 30 (pessimistic). The cost of setting up and dismantling each center might be as little as $200,000 (optimistic) or as great as $750,000 (pessimistic). A realistic figure of $500,000 is used. Hence, the optimistic, realistic, and pessimistic figures for these centers are, respectively, $2,400,000, $7,500,000, and $22,500,000.

3.10.3 Fixed Costs Associated with Building Roads from TTR to NTS

3.10.3.1 Road Construction and Upgrade

To connect the TTR and NTS Area 12, approximately 60 km of road would have to be built, at a cost of $65,000 per km, or a total cost of $3,900,000. Additional roads would have to be upgraded, at a cost of approximately $6,200 (optimistic), $10,000 (realistic), or $21,000 (pessimistic) per km. The amount of road to be upgraded is 10 km (pessimistic), 40 km (realistic), and 70 km (pessimistic). Hence, the total cost for road construction and upgrade is $4,148,000 (optimistic), $4,300,000 (realistic), and $5,370,000 (pessimistic).

3.10.3.2 Transportation Costs from TTR

Transportation costs from the TTR were calculated under that assumption that no new roads would be constructed. If new roads are constructed, the TTR scenario should probably be discarded, both for cost and for man-hours. Note that road construction assumes that it is possible to obtain both permission for building roads across Air Force controlled land and truck drivers with proper clearances to operate on Air Force property.

3.11 Estimate of Total Costs

Estimates of the total variable costs incurred for remediation of the described areas on the NTS, NAFR and TTR for the optimistic, realistic, and pessimistic scenarios are shown in Table 3-5. The cases described involve no volume reduction and do not include estimates of fixed costs. Results indicate that if the chosen remediation level is 10 pCi/g, costs to remediate contaminated areas could range between $2.3 billion and $890 billion (Figure 3-2). Since this range was calculated by setting every uncertainty at its optimistic or pessimistic value, it is representative of a much wider than 90 percent confidence interval. Section 5.0 provides an uncertainty analysis for cost that more appropriately accounts for uncertainties.

The realistic costs represent the current best estimates for all parameters and produce a range of values from approximately $82 million (>1000 pCi/g) to $11 billion (10 pCi/g). The costs are lower than anticipated at the 10 and 40 pCi/g level (Figure 3-2) primarily because the excavation depth was chosen to be 5 cm rather than 15 or 25 cm which were used at higher activities. This reduces the soil volume and because the costs are primarily determined by volume, there is a significantly lower cost than a straight line projection would estimate. An approximate cost of $11 billion could be larger in the realistic case if plutonium is below 5 cm in the soil column.

A summary of the fixed costs as a function of cleanup level for each of the three scenarios is presented in Table 3-6. An estimate of the total costs (fixed plus variable) are contained in Table 3-7.

Table 3-5

Variable Costs as a Function of Plutonium Activity

	Pu Activity (pCi/g)						
	>1000	400-1000	200-400	150-200	100-150	40-100	10-40
Optimistic Scenario In Millions of Dollars (No Volume Reduction)							
Cost for Area	1	4	9	13	22	84	250
Cost for Volume	9	22	34	30	72	460	1,300
Total Cost	10	26	43	43	94	544	1,550
Cumulative Cost	10	36	79	122	216	760	2,310
Realistic Scenario In Millions of Dollars (No Volume Reduction)							
Cost for Area	5	17	38	57	99	350	1,100
Cost for Volume	77	180	470	420	930	1,800	5,400
Total Cost	82	197	508	477	1,029	2,150	6,500
Cumulative Cost	82	279	920	1,357	2,426	4,576	11,076
Pessimistic Scenario In Millions of Dollars (No Volume Reduction)							
Cost for Area	28	96	220	340	570	1,900	16,000
Cost for volume	1,600	3,700	7,000	6,400	13,000	71,000	770,000
Total Cost	1,628	3,796	7,220	6,740	13,570	72,900	786,000
Cumulative Cost	1,628	5,424	12,644	19,384	32,954	105,854	891,854

Note: Optimistic and pessimistic entries in this table represent bounds more extreme than a 90 percent confidence interval.

Table 3-6
Fixed Costs as a Function of Plutonium Activity for No Volume Reduction

	Pu Activity (pCi/g)						
	>1000	400-1000	200-400	150-200	100-150	40-100	10-40
Optimistic Scenario							
Fixed Cost ($ Million)	1.8	1.8	4.4	4.4	4.4	10.0	10.0
Realistic Scenario							
Fixed Cost ($ Million)	5.9	5.9	8.7	8.7	8.7	21.4	21.4
Pessimistic Scenario							
Fixed Cost ($ Million)	8.4	8.4	16.2	16.2	16.2	43.0	43.0

Note: Optimistic and pessimistic entries in this table represent bounds more extreme than a 90 percent confidence interval.

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Table 3-7
Total Costs as a Function of Plutonium Activity

	Pu Activity (pCi/g)						
	>1000	400-1000	200-400	150-200	100-150	40-100	10-40
Optimistic Scenario In Millions of Dollars (No Volume Reduction)							
Variable Cost	10	26	43	43	94	544	1,550
Fixed Cost	1.8	1.8	4.4	4.4	4.4	10.0	10.0
Total Cost	12	28	47	47	98	554	1,560
Cumulative Cost	12	38	83	126	220	770	2,320
Realistic Scenario In Millions of Dollars (No Volume Reduction)							
Variable Cost	82	197	508	477	1,029	2,150	6,500
Fixed Cost	5.9	5.9	8.7	8.7	8.7	21.4	21.4
Total Cost	88	203	517	486	1,038	2,171	6,521
Cumulative Cost	88	285	929	1,366	2,435	4,597	11,097
Pessimistic Scenario In Millions of Dollars (No Volume Reduction)							
Variable Cost	1,628	3,796	7,220	6,740	13,570	72,900	786,000
Fixed Cost	8.4	8.4	16.2	16.2	16.2	43.0	43.0
Total Cost	1,636	3,804	7,236	6,756	13,586	72,943	786,043
Cumulative Cost	1,636	5,432	12,660	19,400	32,970	105,897	891,897

Note: Optimistic and pessimistic entries in this table represent bounds more extreme than a 90 percent confidence interval.

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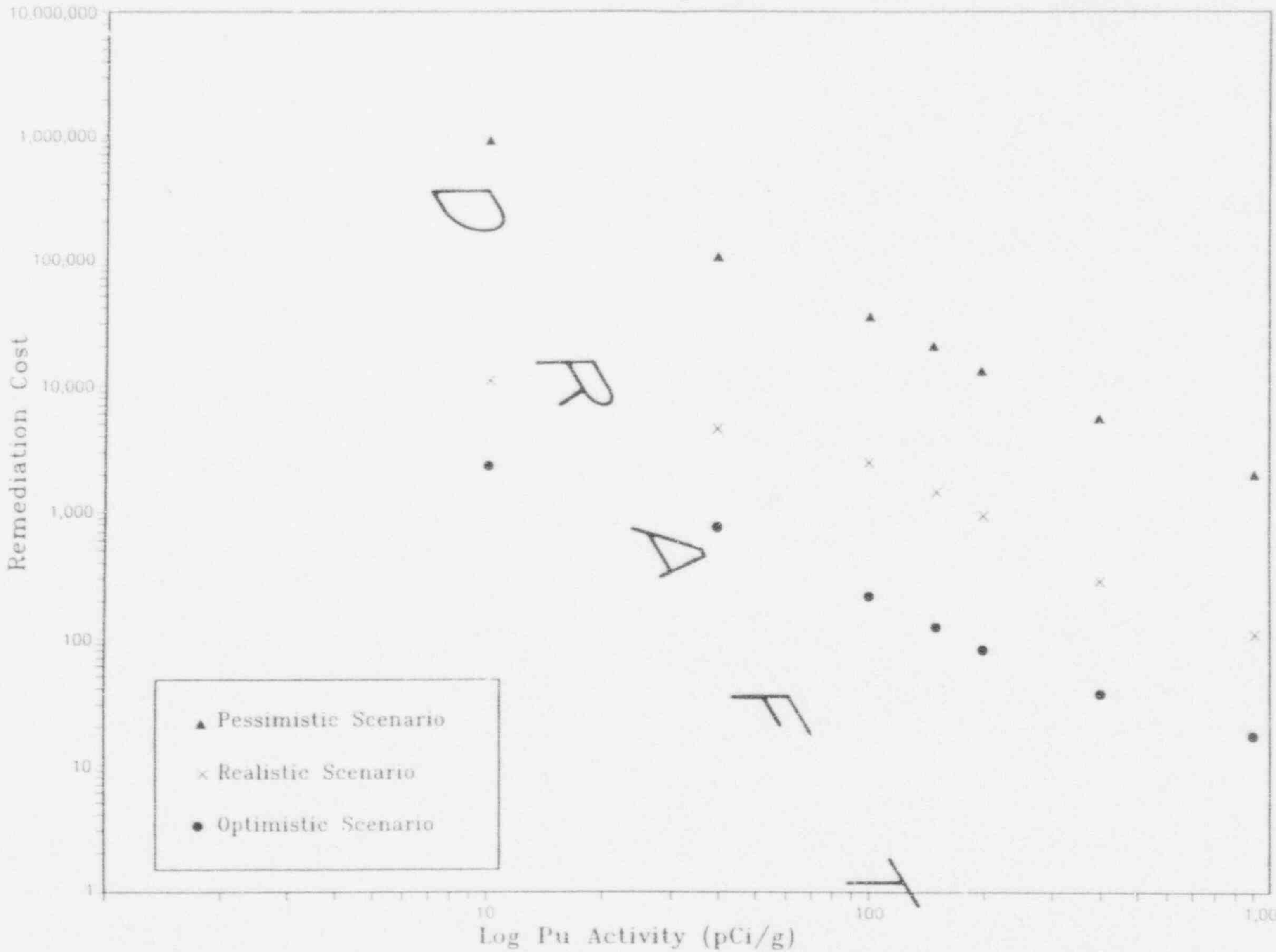

FIGURE 3-2

PLUTONIUM ACTIVITY CLEAN-UP STANDARDS VS. TOTAL REMEDIATION COST FOR THREE DIFFERENT SCENARIOS

4.0 Public and Occupational Health Risks

Residual Pu in surface soils at the NTS and adjoining areas may pose a long-term public health risk to future populations if they inhabit those contaminated lands after an assumed loss of institutional control. Health risks resulting from exposures to contaminated soils can be managed by developing suitable cleanup limits (i.e., concentration of Pu in soil) and then treating or removing soils that exceed the prescribed limits. However, attempts to remediate Pu-contaminated sites will also pose risks to worker health and safety that must be balanced against the public health risks that would be averted by soil-remediation programs. The principal goals of this section are to provide estimates of the impacts to public and worker health that would occur under various cleanup levels and to indicate the uncertainties inherent in these estimates.

4.1 Public Health Risks

The principal health hazard associated with the habitation of a site where Pu is present in soil is the induction of cancer resulting from the inhalation of airborne Pu derived from the resuspension of contaminated soils. Ingestion of Pu in soils and homegrown produce and meat contributes little to internal doses (see Kercher and Anspaugh, 1991), and therefore this route of exposure can be neglected in estimating cancer risk.

4.1.1 Methodology

The risk-assessment methodology for estimating population risks resulting from soil-based exposures to Pu consists of three basic components: (1) determination of the time-dependent changes in the levels of airborne Pu at a contaminated area, (2) characterization of all pertinent exposure-related characteristics of the population(s) at risk, and (3) specification of the relationship between inhalation exposure and cancer risk. Because the half-life of ^{239}Pu is 24,110 years, unremediated soils will represent a health risk for thousands of years. However, the quantification of that risk is difficult because it requires a series of assumptions regarding the timing and duration of future land-use changes, the type of land uses (e.g., residential, commercial, or ranching), and the size(s) of resident populations. As a means of simplifying this analysis, a population is assumed to inhabit the site at a point 100 years from the present. The density of this population is assumed to stay constant over time. The size of the population is determined by the population density and the areal extent of contamination. Population risk is expressed as the cumulative number of excess cancer deaths in the exposed population over time.

The baseline population risk for Pu-contaminated lands is calculated as

$$R_{pop} = RF \times B_r \times PD \times \sum_{i=1}^{n} A_i TIC_i \ , \tag{4-1}$$

where

R_{pop}	=	Population risk, number of fatal cancers,
RF	=	Cancer-risk factor, probability of cancer per pCi of Pu inhaled,
B_r	=	Annual inhalation rate of Pu-contaminated air (m^3/y),
PD	=	Constant population density (persons/ha),
A_i	=	Surface area of *i*th contaminated area (ha),
TIC_i	=	Time-integrated concentration of Pu in air at the *i*th area of contamination (pCi-y/m^3).

4.1.2 Concentrations of Pu in Air

Plutonium-contaminated soil particles are suspended into air by wind moving over the land surface. The relationship between the concentrations of a contaminant in air and soil at a given location is a complex function of soil, land cover, and contaminant properties as well as local meteorology. One proven method of determining the concentration of a soil contaminant in air at a given location is termed the mass-loading approach (see Anspaugh et al., 1975; Shinn, 1992). With this method, the airborne concentration of a contaminant is calculated as the product of the mass loading of particles in air, the concentration of the contaminant in soil, and an enhancement factor, that is,

$$C_a = TSP \times C_s \times E_f \ , \tag{4-2}$$

where

C_a	=	Concentration of Pu in air (pCi/m^3),
TSP	=	Particulate mass loading in air (g/m^3),
C_s	=	Concentration of Pu in soil (pCi/g),
E_f	=	Enhancement factor (unitless).

The mass loading of particulate matter in rural areas like the NTS is in the range of (2 to 4) x 10^{-5} g/m^3. Shah et al. (1986) gave TSP values for 20 rural sites in the U.S., and the geometric mean of those data was 2.8 x 10^{-5} g/m^3, with a geometric standard deviation (GSD) of 1.6. These lognormal statistics are used to represent the variability in TSP levels at the Pu-contaminated sites. The enhancement factor is equal to the concentration of a contaminant in airborne particles divided by its concentration in soil. Large differences have been observed between the enhancement factors for Pu at nuclear and nonnuclear sites. Shinn et al. (1986) reported E_f values of 0.0019 to 0.015 for two nuclear tests, compared with values of 0.87 and 1.04 at two nonnuclear tests. The lower values for nuclear shots are attributed to the incorporation of Pu in amorphous glass created during the nuclear blasts. The resulting matrix evidently reduces the suspendability of Pu in soils at those sites. However, the E_f values for the nuclear tests were based on measurements that were made relatively close to the ground-zero locations of the tests, and therefore, it is likely that the E_f values will increase with distance from ground zero. Unfortunately, no experimental measurements are available to define the relationship between distance (or concentration) and E_f at the nuclear test sites. For the purposes of this assessment, it is assumed that E_f equals 1 for all of the nonnuclear tests and at nuclear-test locations where the concentration of Pu in soil less than or equal to about 100 pCi/g. At locations with higher concentrations of Pu at the nuclear shots, the E_f is assumed to equal 0.01. In addition, it is assumed that after remediation soils are allowed to weather so that their erodability is the same as before remediation (i.e., enhanced resuspension does not occur after sites are populated).

The time-dependent decrease of Pu in soil is mainly a function of its radioactive decay and the rate that it is lost via resuspension to the atmosphere. Downward leaching into soil is assumed to be small compared to those removal processes. The mathematical explanation for this process is found in Appendix B.

The resuspension rates reported by Shinn et al. (1986) for two nuclear and two nonnuclear sites ranged over four orders of magnitude (i.e., 2.1×10^{-7} to 2.1×10^{-3} per year). However, when these rates are normalized by dividing them by the site-specific E_f values the range decreases two orders of magnitude, with a geometric mean of 2.4×10^{-4} 1/y and a GSD of 5.6. The resuspension rates for the two types of test sites are therefore estimated to be the products of the appropriate E_f values and the normalized resuspension rate.

4.1.3 Characterization of Exposure Scenarios

The most important exposure-related factors needed to describe future populations at risk are breathing rate, fraction of time that individuals spend breathing Pu-contaminated air, and population density. Layton (1993) estimated that the lifetime-average breathing rates for males and females are 14 and 10 m^3 per day, respectively, with an average of 12 m^3 per day for both sexes. These breathing rates are based on the oxygen requirements for metabolizing fat, protein, and carbohydrate in the average U.S. diet. The portion of the daily volume of air inhaled by individuals that is contaminated with Pu depends on the amount of time the individuals spend at a contaminated location. For residential land uses, the fraction of time at a contaminated site is represented by the fraction of time spent at home. Activity surveys conducted for children and adults in California indicate that people spend an average of nearly 70 percent of their time at home (Wiley, 1991; Wiley et al., 1991). However, for a commercial facility where individuals spend 8 to 9 hours at work, the fraction of a year spent at a fixed work location is only about 25 percent. For the purposes of this analysis, it is assumed that the average land-use mix is 90 percent residential and 10 percent commercial, and therefore the weighted-average percent of time at a given location is 66 percent. The annual volume of contaminated air that is inhaled is then approximately 2,900 m^3.

Future population densities across the contaminated lands will be a complex function of the kinds of land uses that emerge and whether those land uses are sustainable (e.g., there should be enough groundwater to support the needs of the resident populations and businesses). The population density of Nevada is currently about 0.046 persons per hectare compared with 0.12 persons per hectare for the western U.S., 0.386 for the South, and 1.2 for the Northeast (Bureau of the Census, 1992). For the lower-bound estimate of population density, the value of 0.00386 persons/ha for Nye County, Nevada, is used. This lower-bound estimate represents the situation in which the government maintains institutional control over the NTS, and essentially no population growth occurs in the future. A population denstiy of 0.0386 persons/ha, which is the statewide average, is used as the nominal population density. The upper-bound estimate is taken as 0.386 persons/ha, which is approximately the population density of Nevada's most populated county (i.e., Clark County). For low population densities, there is unlikely to be any significant alteration in the land surface that would affect the resuspension of plutonium. However, as population density increases with the attendant expansion of roads, buildings, and other ground-covering structures and materials, there could be an associated decrease in resuspension. This has not been accounted for in this analysis.

4.1.3.1 Cancer Risk Factor

The principal organs at risk following inhalation exposure to airborne Pu are the lung, bone surface, and liver (NAS, 1988). The probability of incurring cancer in one of these organs is a function of the cumulative radiation dose received by the organ and the relationship between dose and cancer risk. An inhalation risk factor that reflects the total risk of cancer at all sites can be developed from

$$RF = \sum_{j=1}^{3} D_j \times R_j \ , \qquad (4\text{-}3)$$

where

RF	=	Risk factor, lifetime probability of cancer per pCi of Pu inhaled,
D_j	=	Dose factor for the *j*th organ, rad of cumulative dose (to age 70 y) per pCi of Pu inhaled,
R_j	=	Lifetime probability of incurring cancer in the *j*th organ per rad cumulative dose.

The value of D_j will change as a function of age because of age-dependent physiologic and biokinetic parameters. In addition, the cumulative dose will decrease as the age at exposure increases since the cumulative dose is to age 70 years.

EPA (1993) has published an inhalation RF of 3.8×10^{-8} per pCi for Pu, but did not provide any estimate of its uncertainty. In this study, an inhalation RF was derived independently using Equation 4-3 and dose/response analyses given in Layton et al. (1993) for the target organs. For a child ten years of age, the dose factors for the bone surface, liver, and lung are 1.1×10^{-4}, 3.7×10^{-5}, and 1×10^{-4} rads per pCi, respectively, and the associated cancer probabilities per unit dose are 9 x 10^{-5}, 2.8 x 10^{-4}, and 2.8 x 10^{-4} per rad. The resulting risk factor is 4.8 x 10^{-8} per pCi inhaled, which is only 1.26 times greater than the factor adopted by EPA. However, the same calculation for a 40-year-old individual shows that the risk factor is 1.28 times lower because the cumulative dose per unit of exposure is lower as the age at exposure increases. This is not accounted for in the EPA risk factor.

To obtain an estimate of the uncertainty in the risk factor, a Monte Carlo simulation was completed based on the use of a GSD of 2 to represent the uncertainties in each of the organ doses and cancer probabilities per unit dose. The variation in doses is assumed to be independent from the variation in the probabilities of cancer; however, the following correlation coefficients were used (for the log-transformed doses) to represent the dependencies between organ doses: lung-liver, 0.88; lung-bone, 0.77; and bone-liver, 0.82. The GSD of 2 for organ doses is based on burdens of Pu in autopsied organs, and for the organ-specific cancer probabilities on a dose-response analysis (Layton et al., 1993). The correlations between organ doses are derived from data on the burdens of Pu in autopsied organs (Popplewell et al., 1985) . The resulting GSD of the composite risk factor is 1.9. Because the risk factor derived herein is in close agreement with the one presented by EPA, EPA's value of 3.8 x 10^{-8} per pCi is used.

4.1.3.2 Population Risks

The population risk measures for the contaminated test sites were calculated by using Equation 4-1 along with the results of the source-term analysis given in Section 2.0. The geometric means of the upper and lower limits of the concentration isopleths were used to represent the Pu concentrations needed to estimate the population exposures associated with each of the contaminated areas. The total numbers of cancer fatalities were then computed as the sum of the products of the individual areas and time-integrated concentrations times the cancer-risk factor, breathing rate, and population density. The mean numbers of cancers estimated for the baseline case of no remediation and the three source-term estimates (i.e., optimistic, realistic, and pessimistic) were 7.5, 17, and 62 (for the upper-bound population density of 0.386 persons per hectare). The corresponding values for the nominal and lower-bound estimates of population density are obtained by dividing these results by factors of 10 and 100, respectively. Estimates for the numbers of cancers averted for various target cleanup levels were also determined for various cleanup levels and the results are presented in Table 4-1. The lowest level gives the largest number of averted cancers; however, sequentially higher levels do not provide proportionately higher reductions in cancers. This is due to the nonlinear relationship between the areal extents of contamination and the levels of Pu contamination in those areas (see Section 5). A Monte Carlo simulation of the predicted numbers of cancers gave a coefficient of variation of 1.3, which corresponds to a GSD of 2.7.

Table 4-1
Estimates of Cancer Fatalities Averted by Remediating Pu Contaminated Soils to Alternative Cleanup Levels[a]

	Estimates of Contaminated Areas		
Cleanup Limits pCi/g	Optimistic	Realistic Cancer Fatalities Averted[b]	Pessimistic
10	6.2	14	45
40	3.9	9.5	22
100	2.7	6.6	16
150	2.5	6.2	15
200	2.4	6.1	15
400	2.3	5.7	14
1,000	2.1	5.4	13

[a]For the upper-bound population density of 0.386 persons per hectare.
[b]Mean cancer fatalities averted, based on 6000 Monte Carlo simulations. The coefficient of variation is approximately 1.3 and the associated geometric standard deviation is 2.7.

4.2 Worker Risks

Occupational risks associated with remediation activities are discussed in this subsection. Some of the general assumptions used in this analysis are:

- Dust suppression measures are taken at the excavation sites.

- Workers at the excavation sites wear sufficient respiratory protection to keep the inhalation doses below regulatory limits by an as low as reasonably achievable (ALARA) factor typical for DOE installations and their operations.

- Account is taken of the fact that the DOE will not permit operations under standard operating procedures (SOPs) that lead to risk levels higher than those normally achieved by ALARA or ALARA-type measures in similar DOE installations.

- Trucks are not completely filled (only just below struck volume), and are covered in order to keep the surface of the soil pile out of the slipstream.

- Each soil pile at the treatment plant is covered by a warehouse-type structure to suppress wind erosion; one structure for the plant input and one structure each for the plant output of the contaminated and uncontaminated potions of the soil.

- Drivers either wear respiratory protection or work in positive overpressure.

- Workers in the treatment plant are protected by sufficient workspace ventilation and/or by wearing respiratory protection as needed.

Additional assumptions are discussed in the introductions to the various scenarios.

The principal risks faced by workers are fatal and nonfatal accidents and excess cancers associated with occupational exposures to Pu and other radionuclides. Worker risk estimates are developed separately for various distinct activities that workers would be engaged in. Operational safety risks in many industries are known and can be obtained in the form of accident statistics from the U.S. Department of Labor and other sources (U.S. Dept. of Labor, 1986 and 1990). The unit risks are usually expressed in terms of occurrence per man-year of labor, and the risk models are constructed using the assumption that there is a linear relationship between the total effort in man-years and the risk. The work time of all workers in remediation activities and in the treatment plants is included in the analysis; so are the efforts of workers who construct the treatment plant, perform routine decontamination activities in the plant, and carry out the decontamination and disposal during final decommissioning (DOE, 1985). The worker risks in the treatment plant are evaluated separately.

The occupational fatalities are separated into events involving heavy equipment such as trucks, Rotomills, and graders, events in the treatment plant involving forklifts, and accidents not involving forklifts. The magnitude of the forklift risk is dependent on the packaging requirements. This separation is indicated because heavy equipment and forklift accidents rank among the more severe accidents, and different options are likely to require different efforts in heavy equipment and forklift operations. The total occupational risk is then the sum of these three complementary but mutually exclusive risk components, the transportation risk, and the cancer risk.

Cancer risks occur because workers are exposed directly to penetrating X and gamma radiation associated with weapons grade Pu. In addition, they are exposed by inhalation to airborne Pu due to soil erosion by wind and remedial activities. The risk models used in the analysis are based on DOE experience, resulting in an experimental ALARA factor, and doses per man-year of effort. The work time of all workers in remediation activities and in the treatment plants is included; so are the efforts of workers who do routine decontamination in the plant and the decontamination during final decommissioning (DOE, 1985; Rao and Gobel, 1993).

All of these component risks are proportional to the volume of earth excavated, transported, and treated. To facilitate the integration analysis in which costs and benefits are compared (see Section 5.0), occupational risks are expressed in the form of risk densities, i.e., as risks per unit soil volume.

The risk densities were evaluated for two different options for remediation:

- A remediation plan consisting of excavation, transport, and disposal. No soil treatment is included in this version of site remediation.
- A site remediation plan that adds a soil treatment plant to the plan adopted in the first option. Transportation mileages are adapted to the new requirements.

4.2.1 Data Used and Results

Estimates of fatality rates per unit volume of soil remediated were derived from fatality rates per man-year of work for the various work activities and the results of Section 3.0 which provide estimates of volumes for various remediation scenarios. Tables 4-2 and 4-3 summarize the results. Appendix C provides the details of the analyses including the

Table 4-2

Risk Density to Occupational Receptors during Remediation of Pu Contaminated Soils Involving No Volume Reduction at NTS (m^{-3})

Fatal Occupational Remediation Risks	Value ± Standard Error (m^{-3})	ε	x_g	σ_g
Fatalities Involving Heavy Equipment	$(2.03 \pm 1.47) \cdot 10^{-8}$	$5.59 \cdot 10^{-1}$	$2.18 \cdot 10^{-8}$	1.88
Treatment Plant Operational Accidents	n/a	n/a	n/a	n/a
Treatment Plant Forklift Accidents	n/a	n/a	n/a	n/a
Traffic Accident Fatalities	$(8.49 \pm 3.37) \cdot 10^{-7}$	$3.97 \cdot 10^{-1}$	$7.79 \cdot 10^{-7}$	1.52
Total Occupational Accident Fatalities	$(8.75 \pm 3.37) \cdot 10^{-7}$	$3.85 \cdot 10^{-1}$	$8.07 \cdot 10^{-7}$	1.50
Radiation Cancer Fatalities due to Routine Exposures	$(1.91 \pm 1.01) \cdot 10^{-9}$	$5.30 \cdot 10^{-1}$	$1.62 \cdot 10^{-9}$	1.81

Table 4-3
Risk Density to Occupational Receptors during Remediation of Pu Contaminated Soils Involving 80 Percent Volume Reduction at NTS (m^{-3})

Fatal Occupational Remediation Risks	Value ± Standard Error (m^{-3})	ε	x_g	σ_g
Fatalities Involving Heavy Equipment	$(2.63 \pm 1.47) \cdot 10^{-8}$	$5.59 \cdot 10^{-1}$	$2.18 \cdot 10^{-8}$	1.88
Treatment Plant Operational Fatalities	$(1.14 \pm 0.37) \cdot 10^{-8}$	$3.22 \cdot 10^{-1}$	$1.08 \cdot 10^{-8}$	1.40
Treatment Plant Forklift Fatalities	$(1.14 \pm 0.49) \cdot 10^{-8}$	$4.30 \cdot 10^{-1}$	$1.02 \cdot 10^{-8}$	1.58
Traffic Accident Fatalities	$(2.02 \pm 1.01) \cdot 10^{-7}$	$5.01 \cdot 10^{-1}$	$1.75 \cdot 10^{-7}$	1.74
Total Occupational Accident Fatalities	$(2.51 \pm 0.82) \cdot 10^{-7}$	$3.25 \cdot 10^{-1}$	$2.38 \cdot 10^{-7}$	1.40
Radiation Cancer Fatalities due to Routine Exposures	$(3.81 \pm 1.93) \cdot 10^{-9}$	$5.07 \cdot 10^{-1}$	$3.28 \cdot 10^{-9}$	1.75

derivation of the relative errors ε of the means, the geometric means x_g and the geometric standard deviations σ_g. Assumptions made for the evaluation in addition to those at the beginning of the section are:

- A volume reduction factor of about 80 percent is assumed for the soil fraction that is enriched in Pu.

- The mileage for NTS contaminated sites is 2 km to the treatment plant and 60 km further to the disposal site. For contaminated sites located on TTR, it is assumed that the distance to the treatment site is 2 km, and the distance from there to the disposal site is an additional 400 km.

- Soil processing man-years per cubic meter are equivalent to man-years per cubic meter required for spreading, excavating, and waste disposal.

The data for the various estimates are provided in the following subsections. The tables provide the values and the references for the parameters used in the remediation and occupational risk equations given in Appendix C.

4.2.1.1 Handling

Table 4-4 provides the data used to calculate the estimated fatality rate per cubic meter of soil excavated in all activities involving the operation of heavy earthmoving equipment. Operations in the treatment plant not involving forklift operations are covered by the data in Table 4-5. The fatality rate per cubic meter of activities involving forklift accidents is calculated from the data in Table 4-6. Note that this fatality rate per cubic meter is somewhat smaller than that for heavy equipment operation. The numerical results of the calculation are listed in Tables 4-2 and 4-3 for the non-treatment and treatment options, respectively.

4.2.1.2 Transportation Risks

The transportation risk densities and corresponding data are listed in Table 4-7 for the non-treatment option, and in Table 4-8 for the treatment option. Note that the fatality rates are given per cubic meter of soil excavated, which are also the rates per cubic meter transported and treated. The numerical values for the non-treatment and treatment options are listed in Tables 4-2 and 4-3.

Table 4-4

Occupational Fatalities in Accidents Operating Heavy Equipment

Symbol	Description (unit)	Value	Reference
p_1	Fatality Rate per man-year in operations with heavy equipment (yr^{-1})	$(3.7 \pm 1.9) \cdot 10^{-4}$	Clough, 1986
n_{1i}	Man-years of work per m^3 of soil excavated in option i ($yr\ m^{-3}$)	$(7.1 \pm 1.4) \cdot 10^{-5}$	Barker, 1993 Assumes excavation and waste disposal (same value when spreading is included, i.e., volume reduction).

Table 4-5

Occupational Fatalities in Accidents in Treatment Plant Operations Without Forklift Use

Symbol	Description (unit)	Value	Reference
p_2	Fatality Rate per man-year in treatment plant operations (yr^{-1})	$(1.6 \pm 0.4) \cdot 10^{-4}$	Department of Labor, 1990
n_{2i}	Man-years of work per m^3 of soil processed in option i ($yr\ m^{-3}$)	$(7.1 \pm 1.4) \cdot 10^{-5}$	Barker, 1993 This value is 0 if no processing is involved.

Table 4-6

Occupational Fatalities in Treatment Plant Accidents Involving Forklifts

Symbol	Description (unit)	Value	Reference
p_3	Fatality Rate per man-year for forklifts in accidents (yr^{-1})	$(1.6 \pm 0.6) \cdot 10^{-4}$	Department of Labor, 1986
n_{2i}	Man-years of work in plant required per m^3 of soil processed in option i ($yr\ m^{-3}$)	$(7.1 \pm 1.4) \cdot 10^{-5}$	Barker, 1993 This value is 0 if no processing is involved.

Table 4-7
Fatal Occupational Traffic Accidents (no treatment)

Symbol	Description (unit)	Value	Reference
p_7	Linear Probability Density for Occupational Traffic Fatalities (m^{-1})	$(6.77 \pm 2.60) \cdot 10^{-11}$	National Transportation Statistics, 1986
f_{qi}	Fraction of volume at set of sites q in option i	(0.9 ± 0.015) NTS (0.1 ± 0.015) TTR	Merkhofer and Voth, 1993
V_i	Volume of Soil Transported on one truck (struck volume) (m^3)	15 ± 1	Barker, 1993
L_{1i}	Distance Traveled to soil treatment plant location in option i (m)	0	Barker, 1993 (no treatment)
L_{2i}	Distance Traveled as treated high activity soil in option i (m)	$8.0 \cdot 10^5$ TTR $1.2 \cdot 10^5$ NTS	Barker, 1993 (assumes round-trip)
L_{3i}	Distance Traveled as treated low activity soil in option i (m)	0	All soil is disposed of and assumed to be high activity.
F_{vi}	Fraction of soil of high activity after treatment in option i	1 ± 0	No treatment employed - disposal only.

Table 4-8

Fatal Occupational Traffic Accidents (assume treatment/volume reduction)

Symbol	Description (unit)	Value	Reference
p_7	Linear Probability Density for Occupational Traffic Fatalities (m^{-1})	$(6.77 \pm 2.60) \cdot 10^{-11}$	National Transportation Statistics, 1986
f_{qi}	Fraction of volume at set of sites q in option i	(0.9 ± 0.015) NTS (0.1 ± 0.015) TTR	Merkhofer and Voth, 1993
V_t	Volume of Soil Transported on one truck (struck volume) (m^3)	15 ± 1	Barker, 1993
L_{1i}	Distance Traveled to soil treatment plant location in option i (m)	$4.0 \cdot 10^3$	Barker, 1993 (assumes round-trip)
L_{2i}	Distance Traveled as treated high activity soil in option i (m)	8.0 • 105 TTR $1.2 \cdot 10^5$ NTS	Barker, 1993 (assumes round-trip)
L_{3i}	Distance Traveled as treated low activity soil in option i (m)	$4.0 \cdot 10^3$	Barker, 1993 (returned to site of excavation)
F_{vi}	Fraction of soil of high activity after treatment in option i	0.2 ± 0.07	Barker, 1993 80 percent volume reduction

4.2.1.3 Combined Occupational Accident Fatalities

The combined fatality risk rates per cubic meter of soil excavated are given by the sum of the handling and the transportation risk. The numerical values for the combined risk densities per cubic meter are listed separately in Table 4-2 for the non-treatment option, and in Table 4-3 for the treatment option.

4.2.1.4 Occupational Cancer Fatalities

Per cubic meter of soil excavated, transported, treated and handled, the fatality rate is given by the data in Table 4-9. The resulting numerical values are listed in Table 4-2 for the option without soil treatment, and in Table 4-3 for the option with soil treatment.

4.2.2 Results of the Calculations

The arithmetic results in Tables 4-2 and 4-3 and their standard errors are given to about three digits, not because these digits are all meaningful but in order to avoid the propagation of rounding errors in further calculations involving these data. Clearly, the risk densities are dominated by the traffic fatalities for both options; the radiation cancer risk densities are three orders of magnitude lower. The relative standard errors ε vary between 30 and 60 percent. As approximations to an equivalent lognormal distribution are needed for the integration analysis in Section 5.0, the geometric mean of the lognormal distribution and its geometric standard deviation are listed in the last two columns. The geometric standard deviations vary between 1.4 and 1.9, yielding 95 percent confidence intervals that span a factor of about 2 to almost 4 above or below the geometric mean.

Table 4-9
Radiation Cancer Risk from Routine Operations

Symbol	Description (unit)	Value	Reference
n_{1i}	Man-years of work required per m^3 of soil excavated (yr m^{-3})	$(7.1 \pm 1.4) \cdot 10^{-5}$	Barker, 1993 Assumes excavation and waste disposal (same value when spreading is included).
n_{2i}	Man-years of work per m^3 of soil processed in option i (yr m^{-3})	$(7.1 \pm 1.4) \cdot 10^{-5}$	Barker, 1993 This value is 0 if no processing is involved.
D_{eff}	Annual dose equivalent per man-year in DOE installations (Sv yr^{-1})	$(6.7 \pm 1.6) \cdot 10^{-4}$	Rao and Gobel, 1993
a_{rc}	Risk coefficient for radiation cancer, corrected for exposure at low dose rates (Sv^{-1})	$(4.0 \pm 1.6) \cdot 10^{-2}$	ICRP, 1990

5.0 Integration Analysis

The work described in the previous sections of this report provides a basis for estimating and comparing the costs and benefits of alternative Pu concentration cleanup levels for the NTS and related sites. This section of the report describes the integration analysis used for the evaluation and presents conclusions regarding the comparison of costs and benefits.

5.1 Integration Approach

Three principles guided the design of the integration analysis. First, it was deemed desirable to avoid a form of analysis that would require a specific value assumption regarding how much society should spend to protect public health. Some cost-benefit analyses convert estimated reductions in risk (e.g., fatalities averted) into equivalent dollar benefits and emphasize only the bottom line comparisons of total dollar benefits with total dollar costs. While useful in some contexts, this approach can detract from the analysis by pinning conclusions on some specific, and potentially controversial, value tradeoff (e.g., a specified dollar value per fatality averted). An alternative approach, used here, is to present comparisons in their natural units, for example, reporting the estimated numbers of cancer fatalities averted as a result of adopting a particular cleanup level and comparing that number with the estimated dollar costs of achieving that level. This approach treats key value tradeoffs as variables in the analysis. The tradeoffs necessary to justify various cleanup levels can be computed and compared with the value tradeoffs inherent in other policy decisions.

The second principle guiding the design of an integration approach was that the method of integration should permit easy evaluation of the impacts of changes in technical assumptions. The short time frame for this analysis and the limits of available data necessarily required many estimates to be based on unvalidated, best professional judgment. Other parties may disagree with some or all of the specific numerical assumptions adopted here and may wish to investigate whether the conclusions of the analysis would be altered if different assumptions were adopted. To enable results to be easily adjusted to reflect alternative assumptions, the integration analysis was implemented in computer code. The model can be reevaluated to investigate the sensitivity of conclusions to alternative assumptions.

The third basic principle guiding the design was that the uncertainties surrounding the analysis should be estimated quantitatively. Nearly every critique of cost-risk-benefit analysis methodology argues for the importance of estimating uncertainties. Analyses that report only single values for risks, costs, and benefits ignore the range of possibilities and convey a false sense of precision. Also, risk estimates based on point estimates of uncertain quantities can be very much in error. The reason for this is that the most relevant point estimate of risk for decision making, according to decision theory, is an expected value. However, the expected value of a function of uncertain variables is not generally equal to the function of the expected values of the variables. Finally, estimating uncertainties is useful in that it can provide guidance regarding where efforts to reduce remaining uncertainties are most needed.

Uncertainty analysis can be conducted using a fully probabilistic approach, wherein uncertainties in costs, risks, and benefits are described by probability distributions, or using a simpler error analysis, wherein uncertainties are described by error bands generated using some approximate technique (e.g., as in Appendix C). With a fully probabilistic analysis, probability distributions describing key variables are generated and then propagated through an integration model to derive probability distributions for key model outputs. A probabilistic approach was selected because a simpler error analysis would ignore three important considerations. First, many uncertainties are highly skewed, with more potential for values to be much higher than expected as compared to much lower than expected. Second, many uncertainties are dependent, or correlated, so that if one uncertain quantity turns out to be higher than expected, others are more likely to as well. Third, as noted above, failure to treat uncertainties correctly often produces errors in estimates of expected value. Although error propagation techniques exist for overcoming these problems, the resulting analysis can easily become as complicated as a fully probabilistic analysis. In addition to eliminating biases that would be introduced by simpler methods, the selected approach has the advantage of remaining useful for future analyses which may incorporate more accurate measures of the quantities required as inputs for cost-benefit analysis.

Although a fully probabilistic approach was selected for the integration analysis, it should be recognized that the time frame for the analysis did not permit application of formal methods (e.g., Merkhofer, 1987) for developing probability distributions for key input variables. Thus, the accuracy of final results is limited by the accuracy of input estimates.

5.2 The Integration Model

The integration model consists of two components, (1) a fully probabilistic model for estimating the health and cost impacts of alternative cleanup levels and (2) a multiattribute utility function for comparing and combining the various health and cost impacts based on fundamental value judgments.

As noted above, a modeling approach was required that accounts for correlations among variables. For this reason, influence diagrams (Oliver and Smith, 1990) were used. Influence diagrams are graphic representations of probabilistic models that can be easily understood by non-experts. Automated algorithms exist for converting influence diagrams into computational models.

The probability distributions describing the uncertain variables in the influence diagrams were developed by fitting shifted lognormal distributions (lognormal distributions shifted along the x-axis) to the optimistic, best judgment (or realistic), and pessimistic values estimated for the variables as described in the previous sections of this report. Most uncertainties were judged to be highly skewed, with lower bounds and long "tails" representing the possibility of low probability extreme values. Therefore, lognormal distributions were regarded as generally well-suited to the representation of uncertainties. The various committees which developed the estimates provided in the previous sections were instructed to define best-judgement, optimistic, and pessimistic values as medians and 5 and 95 percent fractiles, respectively, and the fitting of distributions was conducted accordingly. For reference, the assessed fractiles and parameters for each probability distribution in the model are provided in Appendix D.

The influence diagrams were analyzed using the software package DPL (Call and Miller, 1990), with continuous distributions represented by six-level discrete approximations that preserve the lower moments of the distributions (Miller and Rice, 1983). Probability distributions generated by processing discrete approximations were smoothed by fitting, in most cases, shifted lognormal distributions. The details of the analysis are discussed below according to the major submodels and the corresponding impacts that were estimated.

5.2.1 Public Health Risk Submodel

Figure 5-1 shows the influence diagram model for estimating public risk. The nomenclature for this and other influence diagrams used in this report is as follows. A rectangular node with rounded corners represents an output of the model. As shown in Figure 5-1, the two outputs for the public risk submodel are (1) no-action, baseline risk (i.e., the number of discounted excess public cancer fatalities that would occur under a no-cleanup scenario) and (2) post-remediation risk (i.e., the number of discounted excess cancer fatalities that would

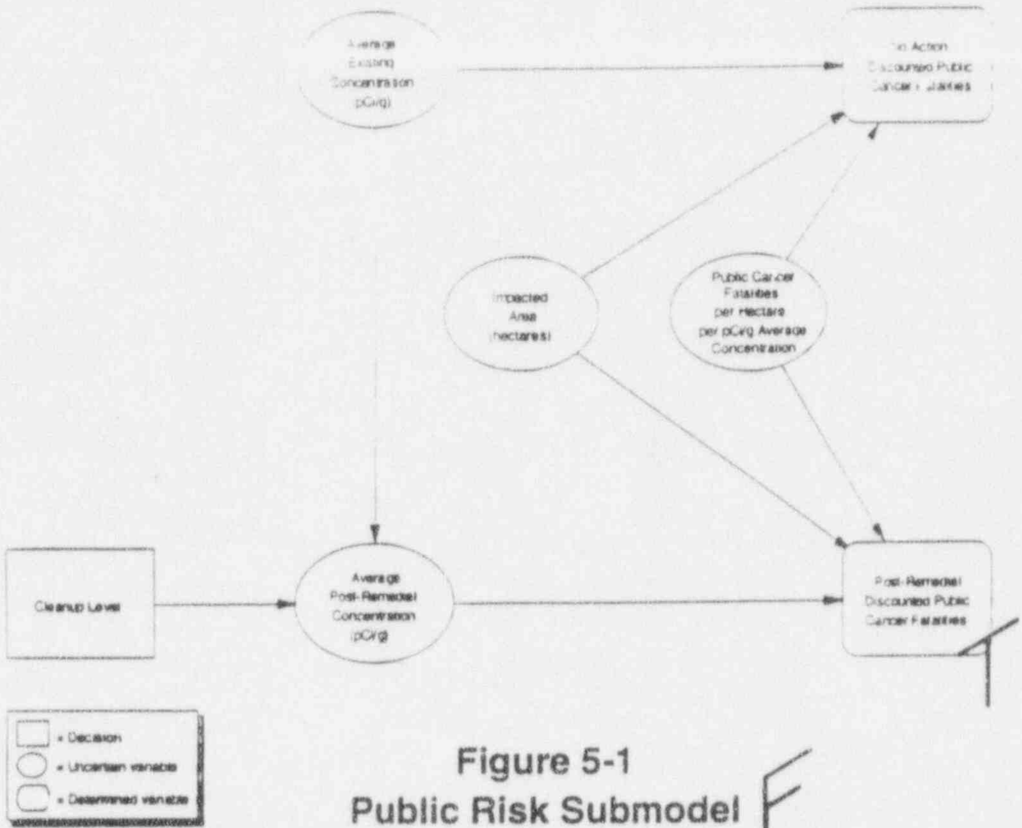

Figure 5-1
Public Risk Submodel

occur given cleanup to a specified concentration level). Note that discounted rather than total fatalities are estimated to account for the long time period over which health effects are accumulated (beyond 100,000 years) and the general preference people have to avert near-term fatalities over long-term fatalities. Since the model permits computing results with a discount rate equal to zero, no discounting is a special case which can easily be estimated using the model.

A node in the shape of an ellipse represents an influencing uncertainty (a random variable for the probabilistic model). Four influencing uncertainties are represented in the public risk submodel: (1) average existing soil concentrations, (2) average post-remediation soil concentrations, (3) the size of the impacted area, and (4) an aggregate risk factor expressed as the total number of excess public cancer fatalities resulting per unit area and per unit concentration of Pu in soil. Because the concentration variables represent averages across the impacted area, the model ignores spatial variability. As will be clarified below, this introduces no significant error since the dose-response model is linear in exposure, and future populations are assumed to be uniformly distributed across the impacted area. The rectangular node with right-angled corners represents the selection of a cleanup level.

An arrow from one node to another indicates that the first node influences the value of the second (i.e., a mathematical dependency exists). For example, the influence diagram for the public risk submodel shows that the number of discounted no-action (baseline) cancer fatalities depends on the average existing site concentration (expressed in pCi/g within the impacted area), the size of the impacted area (expressed in hectares), and the overall risk factor (expressed in discounted fatalities per hectare per pCi/g). Specifically, the number of discounted baseline excess cancer fatalities is the product of these three quantities. The number of discounted cancer fatalities given remediation is computed in an analogous fashion. If no arrows are shown between two variables in an influence diagram, then those variables are (conditionally) independent of one another.

The other important influence represented in the public risk submodel, as illustrated by connecting arrows in Figure 5-1, is the dependency of post-remedial site concentrations on existing site concentrations and the cleanup level. Figure 5-2 illustrates the functional form of the assumed relationship. The plot shows that an approximate linear relationship exists between the logarithm of existing soil concentrations and the logarithm of total area contaminated at that level or higher. Cleanup to a specified level will have the effect of truncating the plot; that is, lopping off all concentrations higher than the specified cleanup level, as illustrated in the figure. Note that integrating the area-concentration relationship in its truncated or non-truncated form and dividing by the impacted area gives the average concentration under the baseline or post-remedial scenarios, respectively. Appendix E provides the detailed calculations.

The Figure 5-1 influence diagram shows that the average concentration within the impacted area is assumed to be independent of the size of the impacted area (i.e., no arrow is drawn from the node representing impacted area to the node representing average concentration). This is justified as follows. First, for the purposes of this analysis, the impacted area is arbitrarily defined to be the area contaminated at or above 1 pCi/g. The impacted area defines the geographic boundary for the population considered to be potentially at risk. As described in Section 4.1.3.1, a linear relationship is assumed between risk and concentration, so that even very low concentrations are presumed to contribute to total population risk.

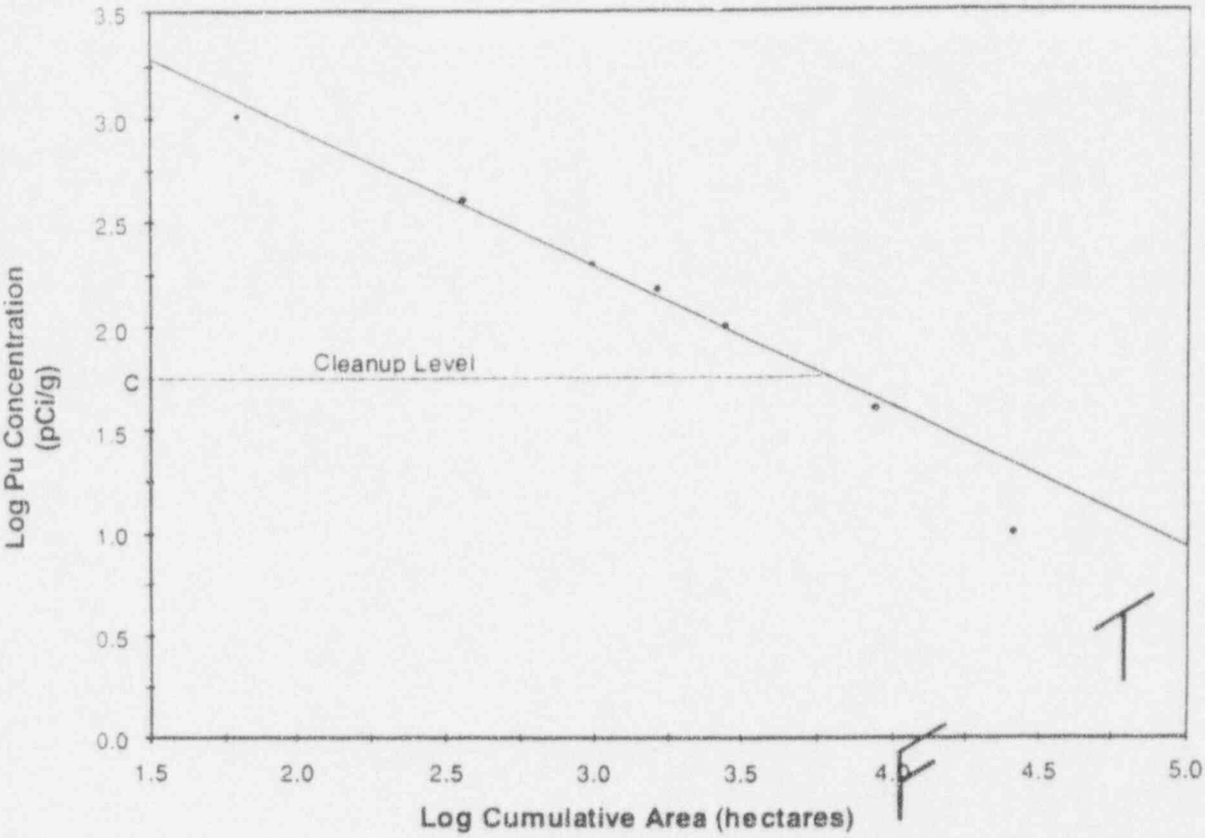

Figure 5-2
Relationship Between Pu Concentration and Area Contaminated at or Above that Level

Ignoring risks to populations exposed at below 1 pCi/g produces only an insignificant error in baseline risk estimates. Second, uncertainty regarding the relationship between concentration and area (Figure 5-2) is dominated by uncertainty over the y-intercept. The reason for this is the judgment that, while pockets of contamination at various levels may have been over- or under-estimated, such errors are not expected to significantly alter the estimated distribution of concentration levels. Thus, the straight line relationship may be shifted up or down, but the slope is not expected to significantly change. The result is that the average concentration within the impacted area is not affected by uncertainty in the relationship of Figure 5-2, provided that the impacted area is defined to be that area contaminated at or above some specified amount.

Note also that the aggregate risk factor is assumed to be independent of cleanup level. In reality, some dependency does exist which is ignored by the probabilistic model. For example, as discussed in Section 4, the ratio of Pu concentration in air to that in soil depends on physical properties of plutonium particles, with some contaminating material (that produced primarily by the safety tests) being more easily suspendable in air. This difference is quantified in Section 4.1.2 through the assignment of different enhancement factors to sites with different contamination levels. The distributions of contaminants having different enhancement factors are not exactly identical (i.e., the contaminants having different physical properties would be described by slightly different straight-line fits similar to that shown in Figure 5-2). As a consequence, the average ratio of Pu concentration in air to that in soil varies slightly across different cleanup levels because the average enhancement factor for the of concentration levels. Thus, the straight line relationship shown in Figure 5-2 may be shifted up or down, but the slope is not expected to significantly change. The result is that the average concentration within the impacted area is not affected by uncertainty in the remaining material varies. A sensitivity analysis was conducted to verify that this effect is minor and can be ignored.[1]

Another ignored dependency between cleanup level and aggregate risk factor relates to the assumption that future populations are uniformly distributed across the impacted area. Cleanup to lower concentrations reduces the geographic variability of concentrations, thus reducing the likelihood that some occupants might build homes on or near areas with much higher than average concentrations. For this reason, the probability distributions describing the aggregate risk factor should have greater variance under the no-cleanup alternative and under the alternatives where cleanup is conducted only to high concentrations. Ignoring this dependency is likely to cause public health risks and risk reductions achievable through cleanup to be underestimated. More generally, the accuracy of risk estimates could be improved through improved modeling of the possibilities and uncertainties regarding future land use and the resulting exposures to populations.

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[1] A related consideration is that remediation is likely to produce a temporary increase in the ratio of Pu concentration in air to that in soil. The effect diminishes over time as disturbed soil weathers. Since this effects is of short duration (tens of years) compared to the time at which a population is assumed to become established on the impacted area (100 years), it is ignored in the analysis.

5.2.1.1 Estimates of Public Health Risk

The public risk submodel was used to provide probabilistic estimates of the numbers of health effects as follows. A probability distribution for the y-intercept in Figure 5-2 was obtained by fitting a shifted lognormal distribution to estimated best-judgment and 90 percent confidence limits for the uncertainty range of the concentration versus area relationship (Appendix D). Probability distributions for impacted area were then obtained by extrapolating the linear relationship to a concentration level of 1 pCi/g. Figure 5-3 shows the resulting probability distribution for the size of the impacted area. Figure 5-4 shows the average post-remedial concentration within the impacted area for the no-action case and for each cleanup level. The average concentration is not strongly affected by cleanup level because the average is determined mostly by the very large areas contaminated at between 1 and 10 pCi/g, which are not altered by any of the cleanup levels considered.

A lognormal probability distribution was assumed for the overall risk factor. The parameters of the distribution were derived from the results of the Monte Carlo analyses described in Section 4.1.3.2. As discussed, the analysis assumes that the impacted area is populated with a constant (over time) population density of between roughly 0.004 and 0.4 persons per hectare beginning 100 years in the future. To eliminate the small differences associated with the impact of the cleanup level on average enhancement factor, a least-squares line was fit to the various risk estimates and average Pu concentrations calculated from the disaggregated analysis described in Section 4.2. The result provided the geometric mean for the lognormal distribution. The geometric standard deviation of the Monte Carlo analysis was selected as the geometric standard deviation for the lognormal distribution. Figure 5-5 shows the resulting probability distribution for risk factor.

Probability distributions for public fatalities were obtained by multiplying the random variable for risk factor (Figure 5-5) times the random variable for impacted area (Figure 5-3) times the average concentration within the impacted area (Figure 5-4). Figure 5-6 shows the results. As expected, cleaning up to a lower concentration shifts the distribution to the left, towards lower numbers of health effects. However, the effect is small compared to the uncertainties involved. The major contribution to these uncertainties is uncertainty over the size of the impacted area and uncertainty over the population density within this area. The estimated total (undiscounted) numbers of cancer fatalities attributable to the contamination range from a low of less than 1 to a high of more than 50. The expected value for the no-action

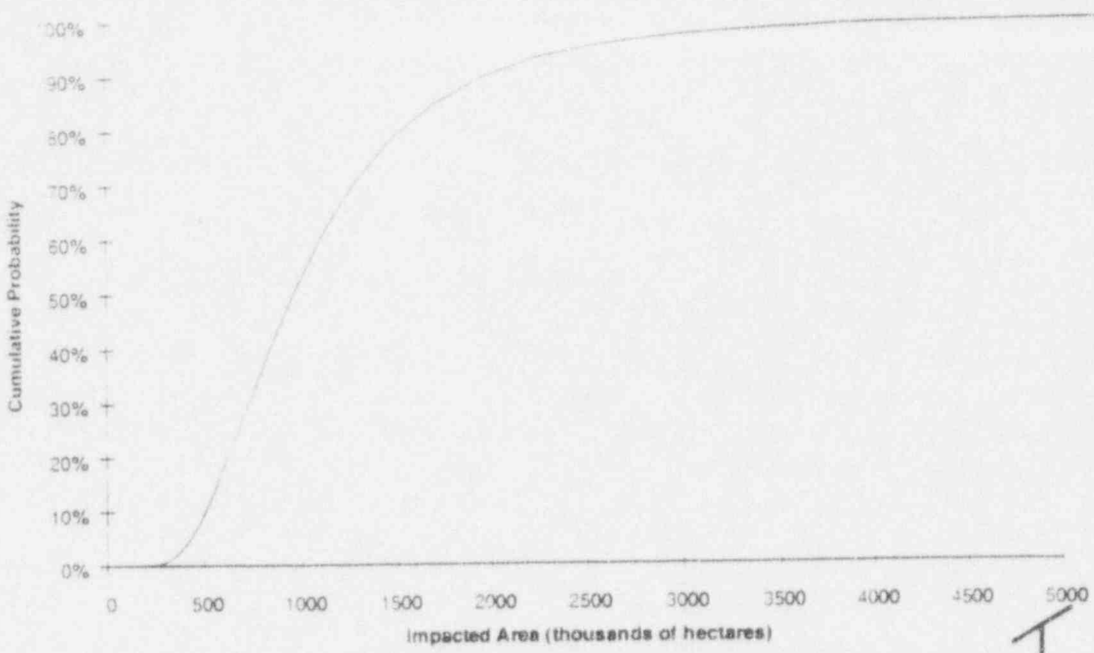

Figure 5-3
Probability Distribution for the Size of the Impacted Area

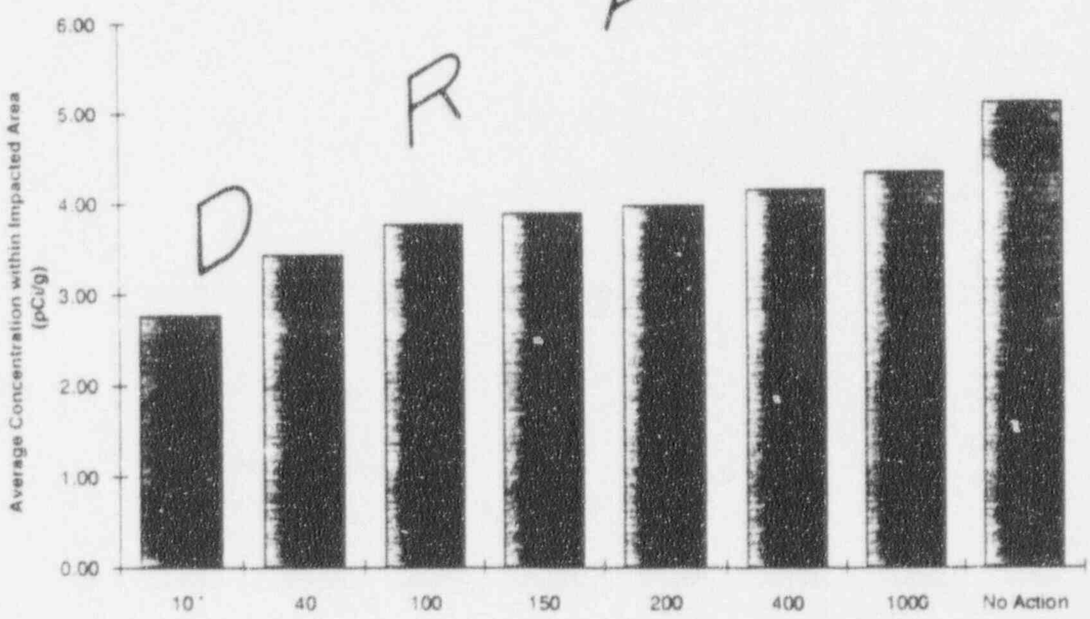

Figure 5-4
Average Post-Remedial Concentrations Within the Impacted Area as a Function of Cleanup Level

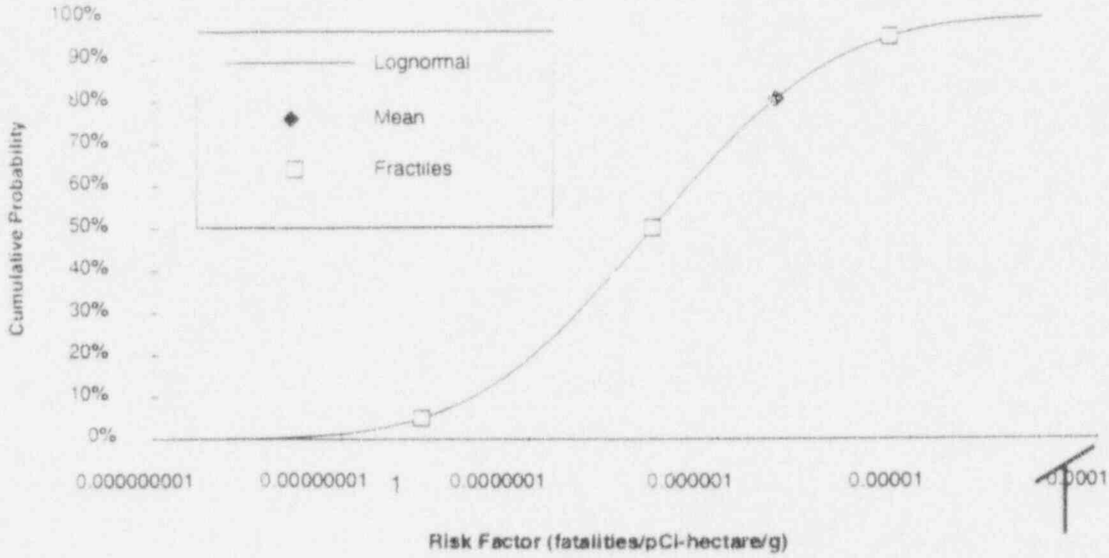

Figure 5-5
Probability Distribution Describing Numbers of Public Health Effects per Hectare per pCi/g

(baseline) case is 11. The expected value is relatively high compared to the 5 and 95 percent fractiles because the distribution is highly skewed.

The excess cancer fatalities resulting from Pu contamination are estimated to occur over a very long period of time due to the long half-life of the contaminant. Thus, an infinite time horizon was used in this analysis. The results in Figure 5-6 represent total fatalities summed over this infinite time horizon. The estimated annual rate of health effects is very small relative to the total number of health effects. Figure 5-7 plots expected annual fatalities as a function of time. As illustrated, the peak annual baseline population risk is expected to be roughly 0.003 fatalities per year (one every 330 years).

Since the method of analysis preserves the correlations among the uncertain variables, the probability distribution for the number of discounted cancer fatalities averted by the cleanup is that of the random variable defined as the difference between the random variable representing the discounted baseline health effects and the random variable describing

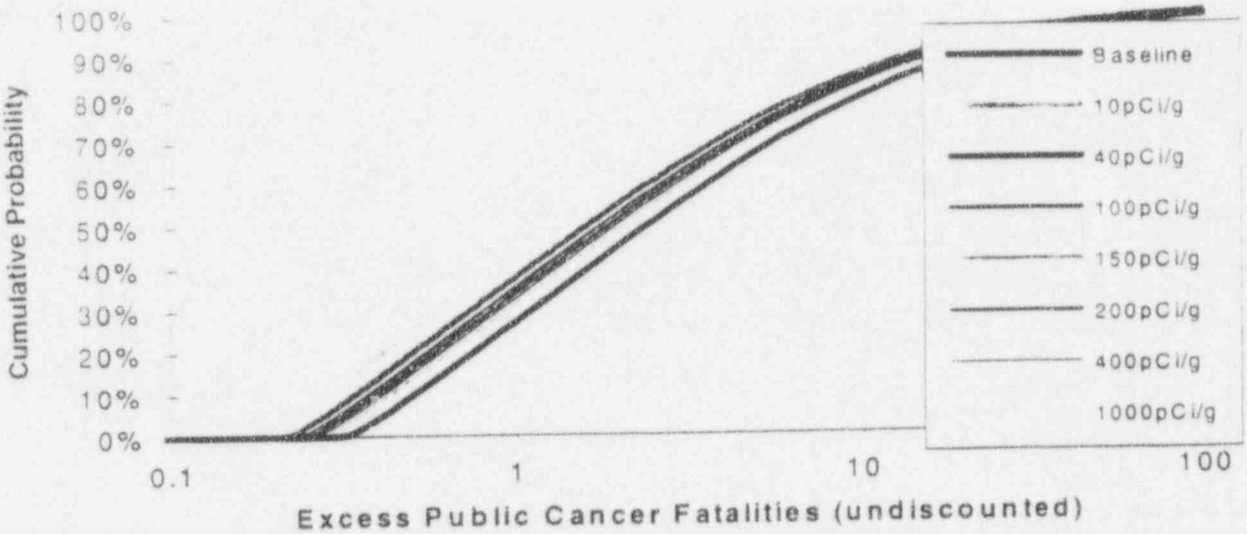

Figure 5-6
Probability Distributions Describing Numbers of Excess Public Cancer Fatalities Under Alternative Cleanup Levels

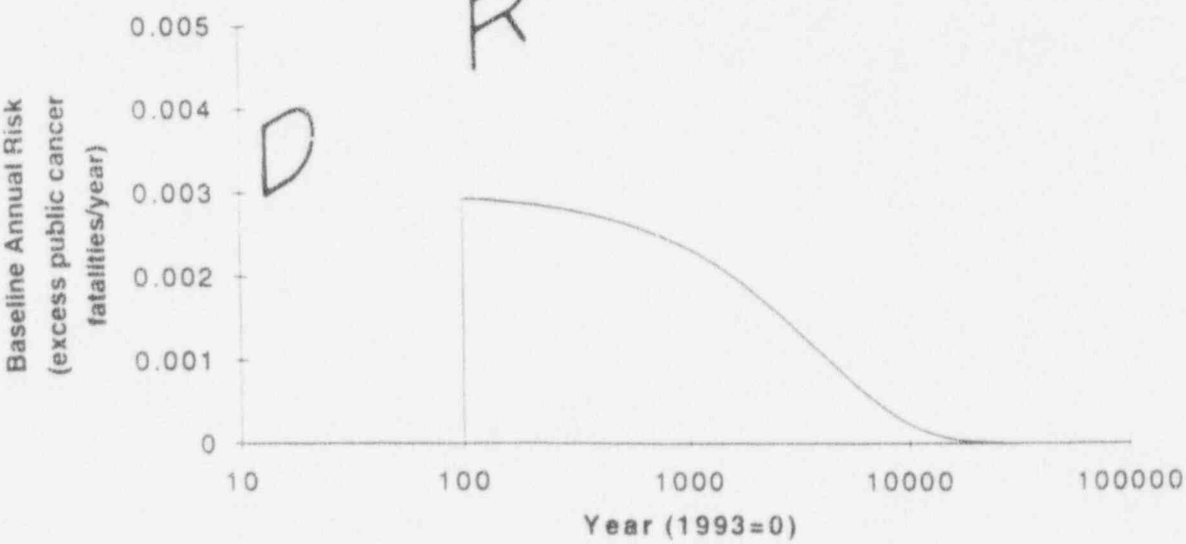

Figure 5-7
Time-Dependence of Baseline Public Risk

discounted post remedial health effects. Figure 5-8 shows the probability distribution describing uncertainty over health effects averted, assuming a discount rate of zero.

A comparison of Figure 5-8 with Table 4-1 in Section 4.0 shows good agreement at the low ends of the distribution, but the means and high values from Figure 5-8 are considerably higher than those estimated in Section 4.1.3.2. The main reason for this is that the current analysis provides a more accurate and comprehensive accounting of uncertainties. The number of cancer fatalities is essentially determined as the product of several uncertain quantities (i.e., the impacted area, the Pu concentrations in the impacted area, the risk factor, and the population). Higher than expected values affect multiplications more than lower than expected values, (e.g., $(2 \pm 1) \times (2 \pm 1) = 4^{+5}_{-3}$). Thus, a comprehensive analysis of uncertainty tends to show more potential for higher than anticipated health impacts than would a simpler approach. This illustrates the importance of conducting a comprehensive uncertainty analysis to avoid underestimating risk.

5.2.2 Cost Submodel

Figure 5-9 shows the influence diagram model for estimating costs. The output of the model is the total cost of cleanup to a specified level. As discussed in Section 3.1.2, costs may be separated into fixed costs and variable costs, with variable costs divided into those cost components that mainly depend on the area requiring remediation (e.g., characterization, reclamation, and excavation costs) and those costs that mainly depend on the volume of soil requiring remediation (e.g., treatment and disposal costs). As illustrated in the influence diagram, variable costs depend on four variables: (1) the total area requiring remediation, (2) the average cost per unit area remediated for those cost components that depend on area, (3) the total volume of soil requiring remediation, and (4) the average cost per unit volume for those cost components that depend on volume. Obviously, total variable cost is the sum of area-related cost per unit area times total area plus volume-related cost per unit volume times total volume.

As described in Section 3.0, costs depend on whether soil treatment for the purposes of volume reduction is undertaken. For the purposes of this analysis, the lowest cost approach is assumed to be selected. Given the fixed and variable cost estimates provided in Section 3.0, volume reduction is less costly provided that the volume of excavated soil is greater than about 40,000 m^3, which is well below the volumes likely to be generated under any of the cleanup levels considered.

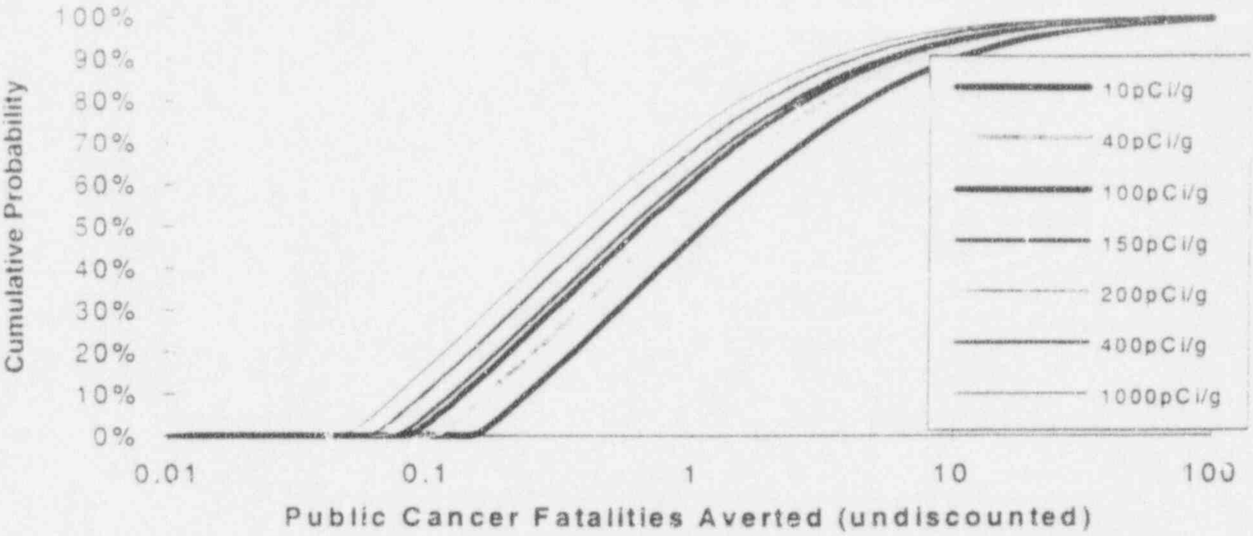

Figure 5-8
Probability Distributions Describing Numbers of Public Cancer Fatalities Averted Under Alternative Cleanup Levels

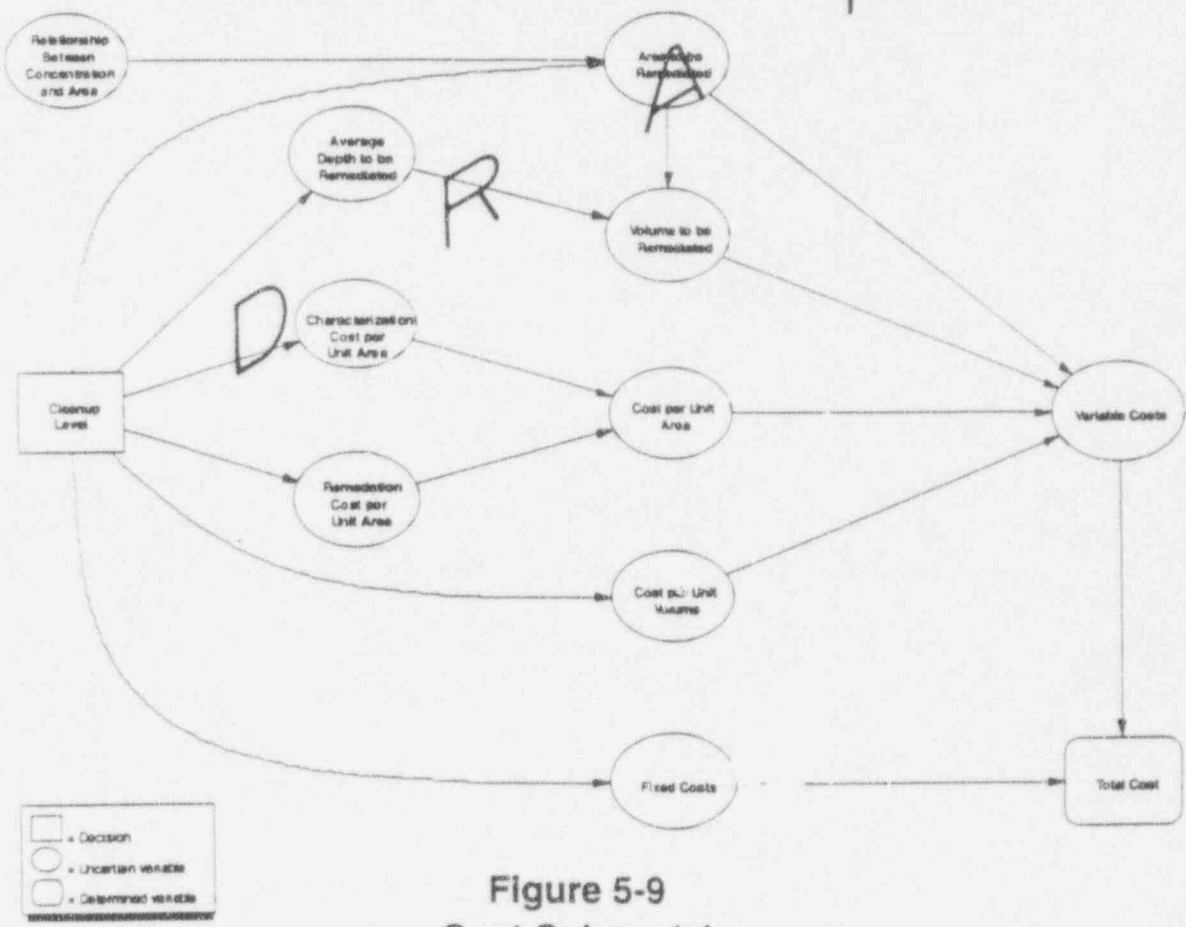

Figure 5-9
Cost Submodel

The influence diagram shows that fixed costs, cost per unit area, and cost per unit volume are all assumed to be independent of one another. Also, characterization costs per unit area and remediation costs per unit area are assumed independent. However, the influence diagram shows that the volume requiring remediation depends on (i.e., is the product of) the total area requiring remediation and the average remediation depth. Thus, although average depth to be remediated and area to be remediated are assumed to be independent, the model accounts for the probabilistic dependencies between area and volume.

5.2.2.1 Estimates of Total Cost

Probability distributions for area to be remediated as a function of cleanup level were obtained from the relationship between area and concentration in Figure 5-2, assuming uncertainty in the y-intercept as described previously. Probability distributions for average depth to be remediated were obtained by fitting shifted lognormal probability distributions to the realistic, optimistic, and pessimistic values described in Section 2.8.1. The probability distribution for volume to be remediated was obtained by multiplying the random variables for area and depth. Figure 5-10 and 5-11 show the probability distributions for area and volume to be remediated, respectively, as a function of cleanup level.

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The Figure 5-10 probability distributions for area agree well with those presented in Table 2-4 in Section 2.0, with the optimistic and pessimistic values interpreted as 5 percent and 95 percent fractile values. The Figure 5-11 probability distributions for volume have been shifted upwards and are somewhat more narrow than those suggested by the entries in Table 2-4. There are several reasons for this. First, the current analysis accounts for the upwards shift caused by multiplication (described above). Second, the optimistic and pessimistic values for volume in Table 2-4 are more extreme than 5 and 95 percent fractiles because of the way they were calculated. Finally, a shifted lognormal distribution (which was fit to smooth out discretizing errors) preserves moments but in this case ignores the tail of the distribution that allows for some low probability that costs may be lower than the shifted origin. For example, the greatest error from this effect occurs for the risk curve shown in Figure 5-11 for the 10pCi/g cleanup level. Although the curve shows no chance of a volume less than about 30 million cubic meters, the non-smoothed discrete result estimates a probability of about 5 percent that volume would be below 30 million and about 1 percent that volume would be below 10 million. In reality, however, it seems likely that an absolute minimum volume exists for a specified cleanup level because a minimum operating depth

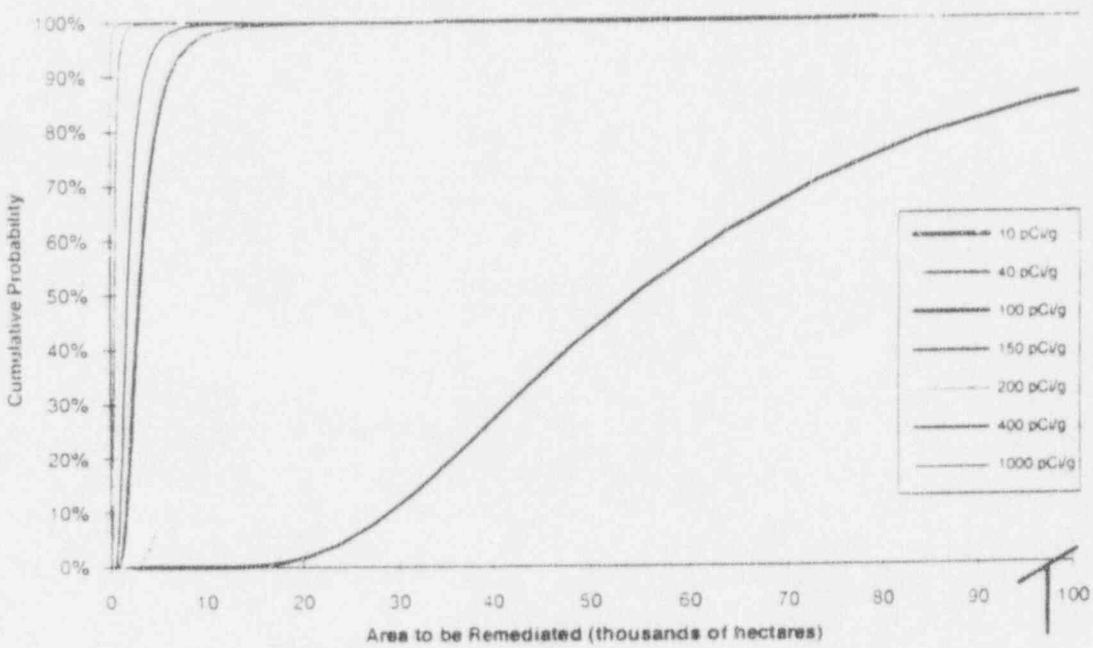

Figure 5-10
Probability Distributions Describing Area Requiring Remediation

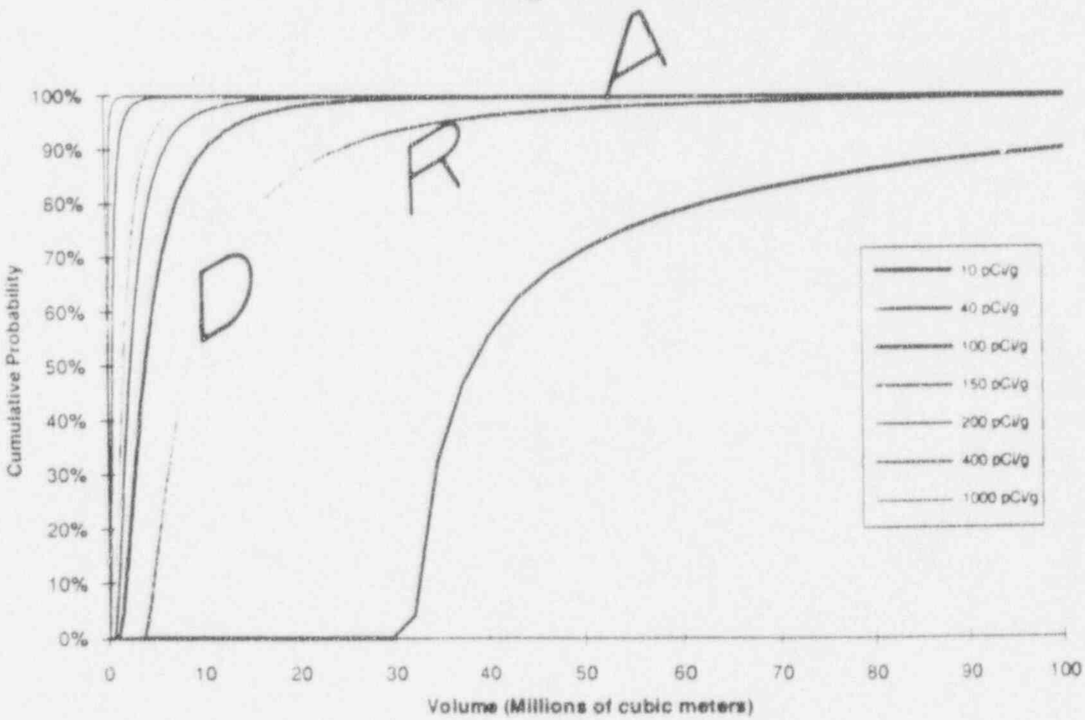

Figure 5-11
Probability Distributions Describing Soil Volume Requiring Remediation

likely exists excavation machinery (e.g., Rotomill) and because some minimum area will require remediation for any given cleanup level.

The probability distribution for fixed costs, costs per unit volume, characterization costs per unit area, and remediation costs per unit area were each obtained by fitting shifted lognormal distributions to the realistic, optimistic, and pessimistic values provided in the various subsections of Section 3.

Probability distributions for cost per unit area were obtained by summing the random variables for characterization costs and remediation costs per unit area.

The probability distributions for area-related costs were obtained by multiplying the cost per unit area and area random variables. The probability distributions for volume-related costs were obtained by multiplying the cost per unit volume and volume random variables. Finally, the probability distributions for total cost were obtained by adding the random variables for the fixed cost component to those for the volume and area-related components. Figure 5-12 shows the resulting total cost uncertainties.

5.2.3 Worker Risk Submodel

Figure 5-13 shows the influence diagram model for estimating worker safety risk. The output of the submodel is the total number of worker fatalities due to accidents. As described in Section 4.2, worker fatalities will be approximately a linear function of the volume of soil remediated. Thus, as illustrated in the influence diagram, the number of worker fatalities depends on the volume to be remediated and the average number of fatalities per unit volume.

5.2.3.1 Estimates of Worker Fatalities

Probability distributions for average number of worker fatalities per unit volume of soil remediated were obtained by fitting lognormal probability distributions to the mean and standard deviation estimated in Tables 4-2 and 4-3 and Section 4.2.1. Separate distributions were fit assuming volume reduction and assuming no value reduction, so that the worker fatalities per unit volume variable is conditional on volume. The probability distribution for volume to be remediated was obtained as described above for the cost submodel. The probability distributions for total number of worker fatalities were obtained by multiplying the random variables for fatalities per unit volume and volume. Figure 5-14 shows the resulting worker fatalities distributions.

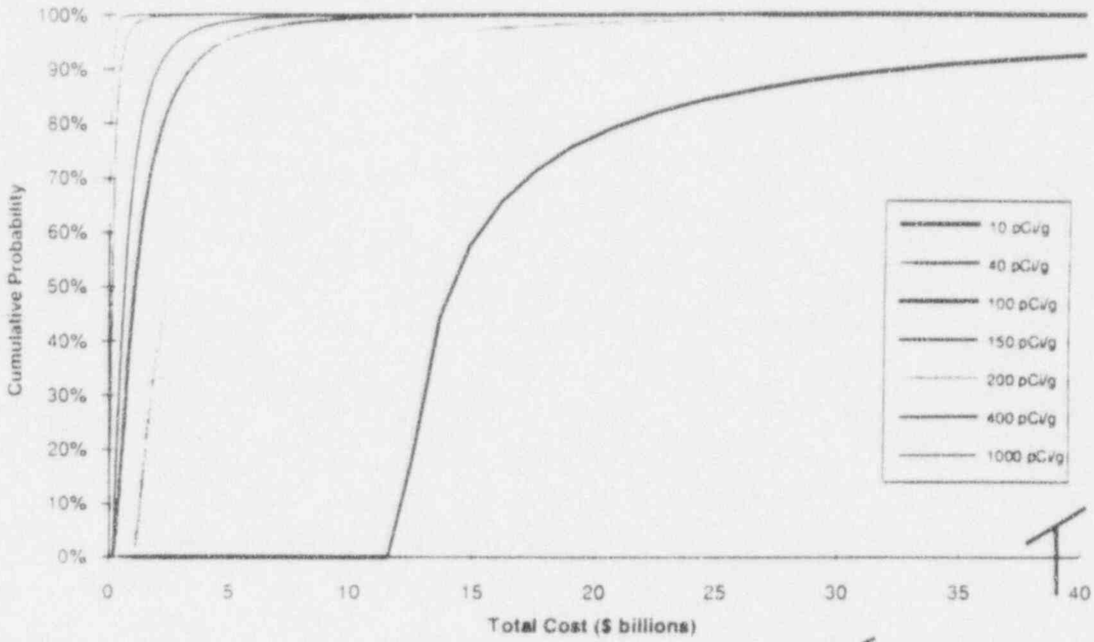

Figure 5-12
Probability Distributions Describing Total Costs of Achieving Alternative Cleanup Levels

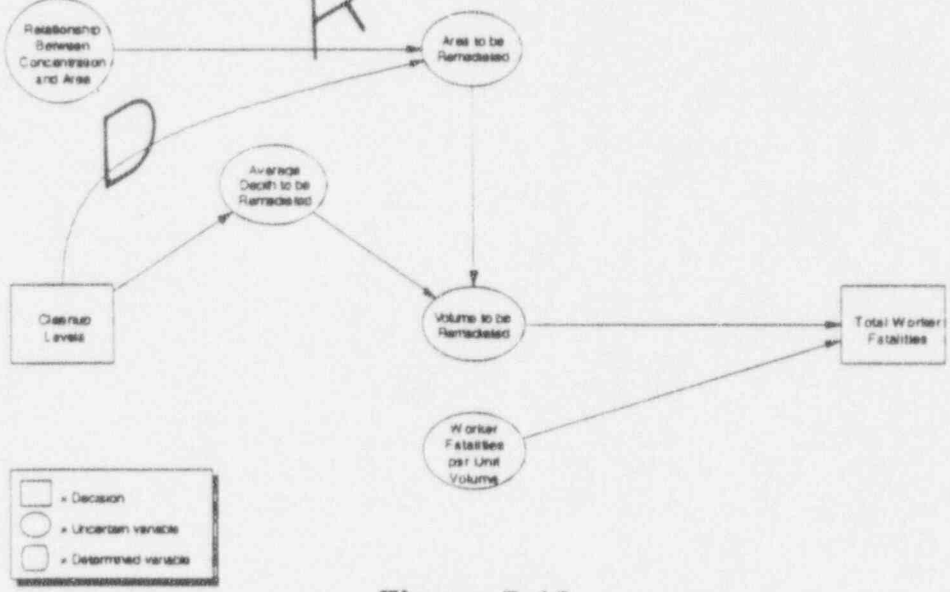

Figure 5-13
Worker Risk Submodel

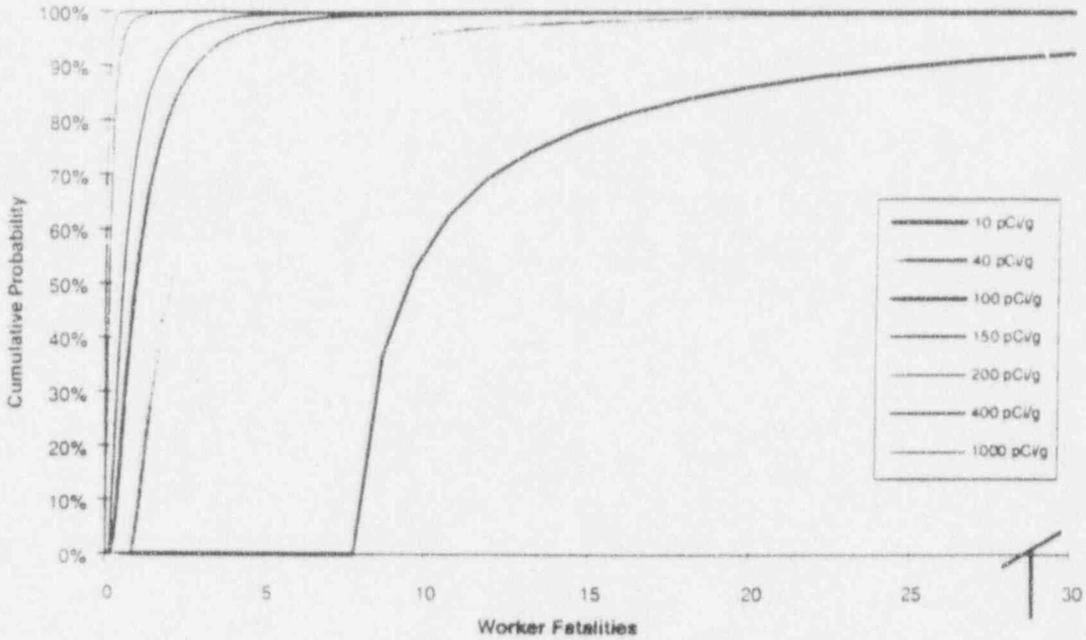

Figure 5-14
Probability Distributions Describing Worker Fatalities Resulting Under Alternative Cleanup Levels

5.3 Integrated Model

Figure 5-15 shows the complete cost-benefit model. It is composed of the three submodels described above plus an overall measure of net benefit that accounts for the three types of estimated impacts: (1) public fatalities averted by the cleanup, (2) economic costs to achieve the cleanup level, and (3) worker fatalities resulting from the cleanup.

To facilitate the description of the integrated model, let the triplet defining the estimated impacts be denoted (x_1, x_2, x_3). The variables x_1, x_2, and x_3 may be thought of as defining the relevant attributes for characterizing the consequences of selecting a specified cleanup level. The integrated model produces a joint probability distribution, denoted $P(x_1, x_2, x_3; c_i)$, describing the uncertainties over x_1, x_2, and x_3, for each cleanup level $c_i = c_1, c_2, \ldots, c_n$. Note that each joint probability distribution can be thought of as defining a lottery $L_i = L(c_i)$ that assigns a probability to each possible combination, (x_1, x_2, x_3), of public fatalities averted, worker fatalities, and economic costs that might occur as a result of clearing up to the specified level c_i.

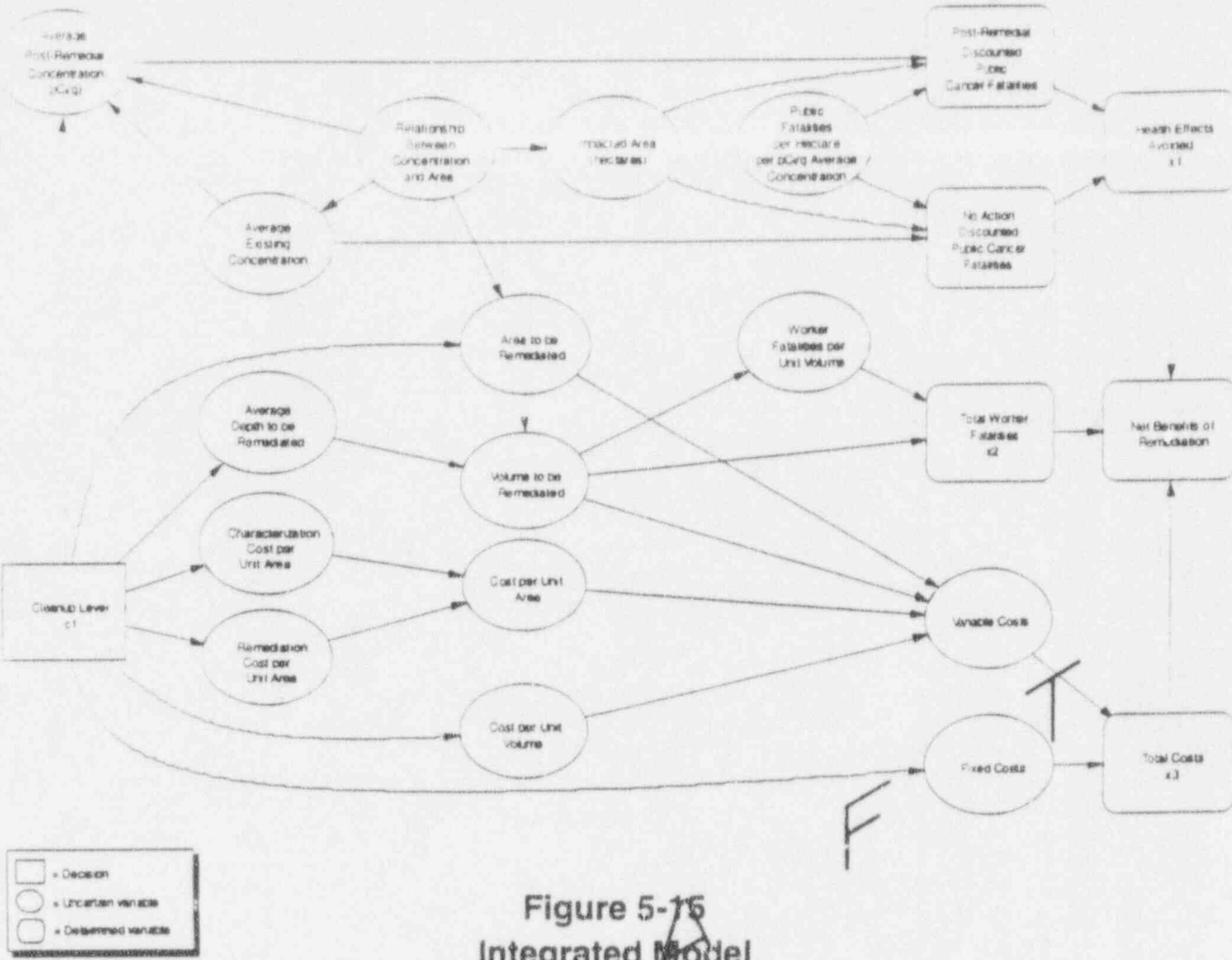

Figure 5-15
Integrated Model

5.3.1 Multiattribute Utility Function

The overall measure of net benefit is derived using a multiattribute utility function. The utility function, denoted U, assigns a number $U(x_1,x_2,x_3)$ to each triplet of impacts (x_1,x_2,x_3) such that the lottery L_1 should be preferred to a lottery L_2 if and only if the expected utility of the lottery L_1 is greater than the expected utility of the lottery L_2. The proof that the utility function exists and has the property that greater utility implies greater preference follows from a set of fundamental axioms (von Neumann and Morgenstern, 1947; Savage, 1954; Pratt, Raiffa, and Schlaifer, 1964).

A key result of utility theory is that the multiattribute utility function $U(x_1,x_2,x_3)$ will have an additive form:

$$U(x_1,x_2,x_3) = k_1u_1(x_1) + k_2u_2(x_2) + k_3u_3(x_3), \tag{5-1}$$

if and only if the attributes x_1, x_2, and x_3 satisfy a condition known as additive independence (Fishburn, 1965). The u_i are called single attribute utility functions and the k_i are called scaling coefficients or weights. Determining whether or not the condition of additive independence exists requires presenting hypothetical lotteries over the attributes to the responsible policymakers and asking those policymakers to express their preferences for those lotteries (detailed discussions of the approach may be found in Keeney and Raiffa, 1976, and von Winterfeldt and Edwards, 1986). It is important to conduct independence tests, since additive independence does not exist for many attributes that might be defined to characterize a decision's consequences.

Previous studies have explored whether additive independence and related types of independence conditions hold, from the perspective of various DOE policymakers, for public fatalities, worker fatalities, and costs (for detailed descriptions of the independence tests as applied in two studies, see Appendix G of DOE, 1986, and Section 5-1 of SNL, 1991). These studies concluded that the additive form is appropriate. In addition, these previous studies determined that each of the single attribute utility functions in the above equation is linear (e.g., Merkhofer and Keeney, 1987). Since the utility function can be arbitrarily scaled, it can be expressed as:

$$U(x_1,x_2,x_3) = w_1x_1 - w_2x_2 - x_3, \qquad (5\text{-}2)$$

where w_1 and w_2 are tradeoff weights expressing policymaker willingness to spend dollars to avoid public and worker fatalities, respectively. These weights are sometimes referred to as measures of value of life because they express a policy judgment about what maximum amount society should be willing to spend to avoid a fatality occurring to some randomly selected individual as a result of the hazard under study. The negative signs precede the terms w_2x_2 and x_3 because workers fatalities (x_2) and costs (x_3) are undesirable, whereas averting public fatalities (x_1) is desirable.

5.3.2 Combined Results

Previous figures have displayed the marginal probability distributions describing key outputs of the integrated models the numbers of public fatalities averted (x_1), the numbers of worker fatalities (x_2), and costs (x_3). Figures 5-16 through 5-18 provide examples of one of the many types of conditional probability distributions that can be generated by the model. These figures show the probability distributions for cancer fatalities averted, worker fatalities, and costs for the 40 pCi/g cleanup level conditioned on a pessimistic view (95 percent fractile value) of the size of the impacted area (area contaminated at or above 1 pCi/g). These figures may be interpreted as describing the uncertainty in cancer fatalities averted, worker fatalities, and costs if it turned out that existing Pu concentrations were higher than expected, but within the range of current uncertainties. As can be seen by comparing Figures 5-16 through 5-18 with Figures 5-6, 5-12, and 5-14, the effect of learning that concentrations are higher than anticipated would be to shift estimates of health effects averted, worker fatalities, and costs upward.

Figures 5-19, 5-20, and 5-21 show the estimated expected values and uncertainties in the number of public cancer fatalities averted, total costs, and worker fatalities as a function of cleanup level. These figures represent the main results of the integration analysis. The solid lines show expected values and the dashed lines show the 90 percent confidence regions for the respective variables. As illustrated, the level of uncertainties that exist is considerable. However, the figures clearly show that as the cleanup level concentration is lowered, dramatic increases in costs and worker fatalities are expected compared with more modest increases in expected public fatalities averted. Figure 5-22 compares the expected cancer fatilities averted with expected worker facilities. As shown, for cleanup to low levels, the estimated number of fatalities saved is comparable to the number of fatalities likely to result from accidents during cleanup. Cleanup to 10 pCi/g is estimated to produce even more fatalities that are saved.

5.3.3 Policy Judgments Required to Justify Alternative Cleanup Levels

Since the implementation of any cleanup level will result in some level of public cancer fatalities averted, some level of worker fatalities, and some economic loss, the choice of a cleanup level for the NTS requires making value tradeoffs among these consequences. The tradeoffs are the weights w_1, w_2, and w_3 in Equation 5-2, and one can ask what weights would be required to justify various cleanup levels. Mathematically, the weights that just justify a cleanup level are those that would make the utility of consequences under the cleanup level equal the utility of the consequences assuming no cleanup.

Figure 5-23 shows the value of public life (weight w_1) that would be required to justify each cleanup level as a function of several different judgments for the value of worker life (values of w_2 between 0 and $10 million), according to the results of the analysis. The results in the figure assume no discounting of future health effects. As illustrated, the weight placed on worker fatalities has virtually no influence. The reason for this is that worker fatalities are relatively small compared to the very large economic costs estimated. Figure 5-24 shows the

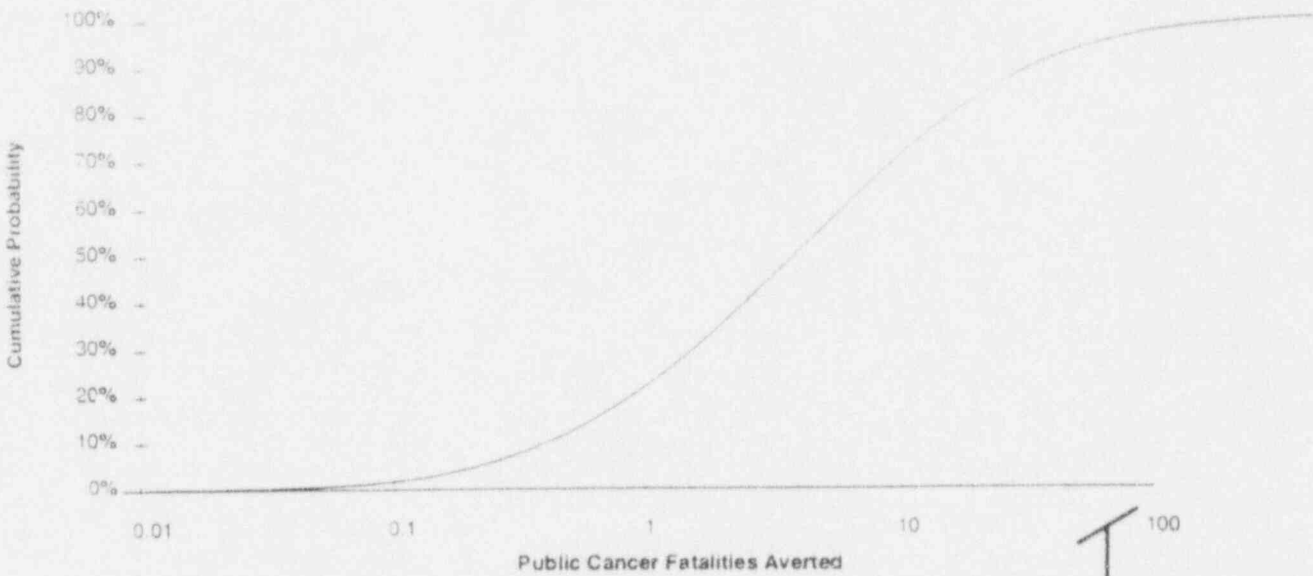

Figure 5-16
Conditional Probability Distribution for Public Health Effects Averted Assuming Impacted Area is Larger than Anticipated

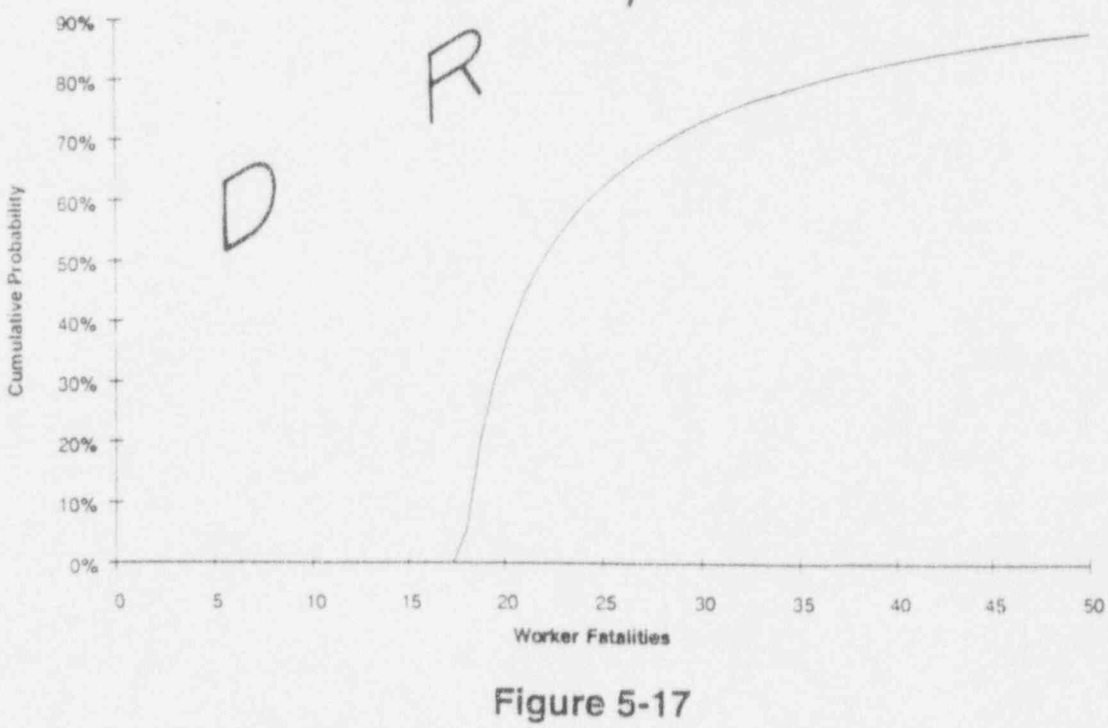

Figure 5-17
Conditional Probability Distribution for Worker Fatalities Assuming Impacted Area is Larger than Anticipated

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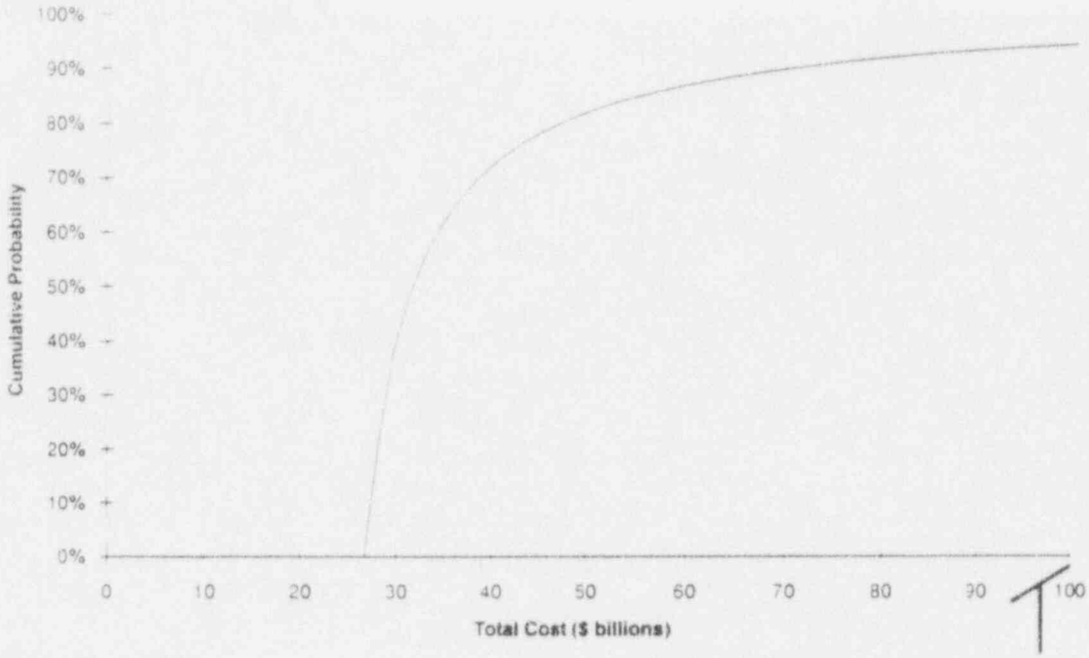

Figure 5-18
Conditional Probability Distribution for Total Costs Assuming Impacted Area is Larger than Anticipated

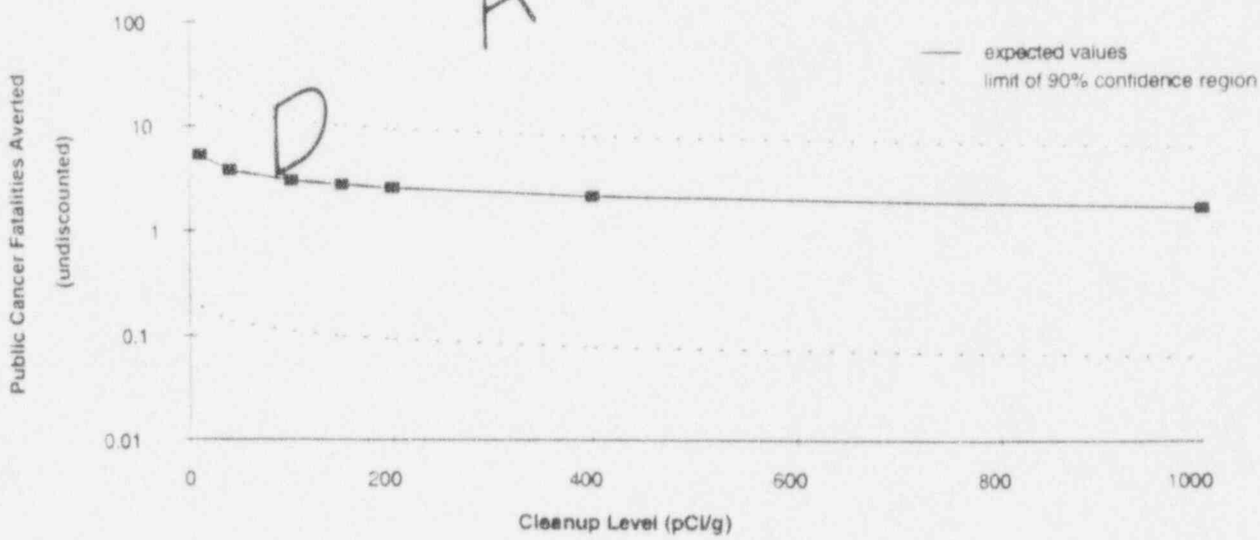

Figure 5-19
Expected Public Cancer Fatalities Averted and Uncertainty as a Function of Cleanup Level

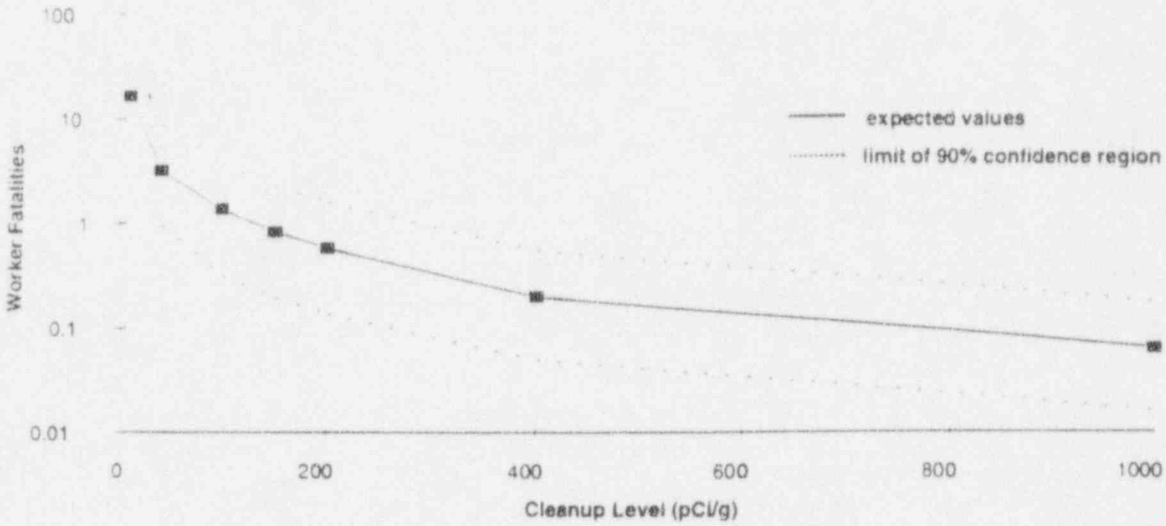

Figure 5-20
Expected Worker Fatalities and Uncertainties as a Function of Cleanup Level

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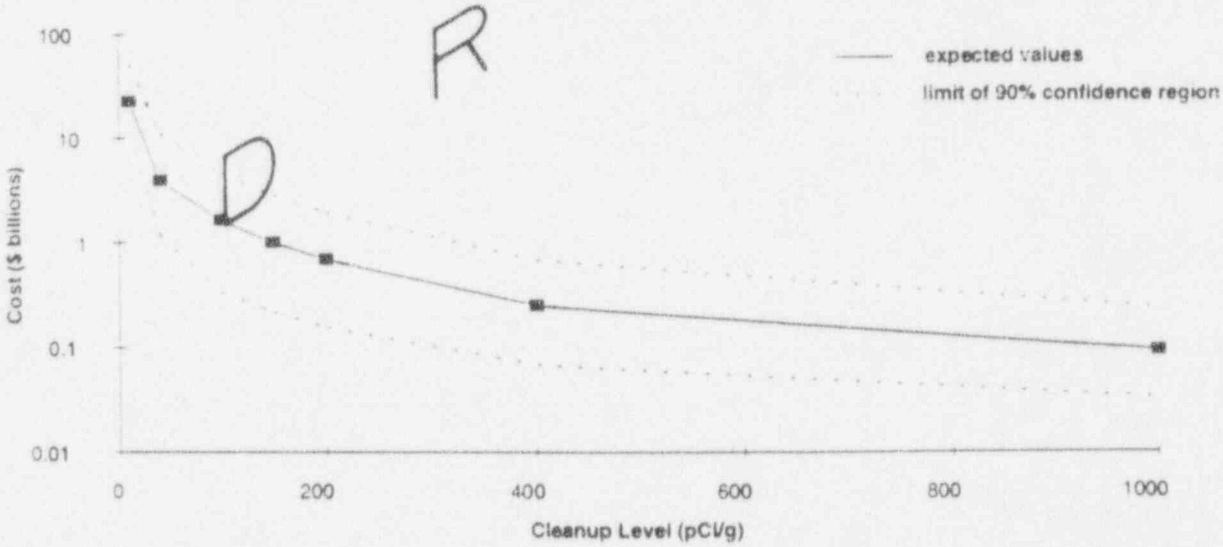

Figure 5-21
Expected Total Costs and Uncertainties as a Function of Cleanup Level

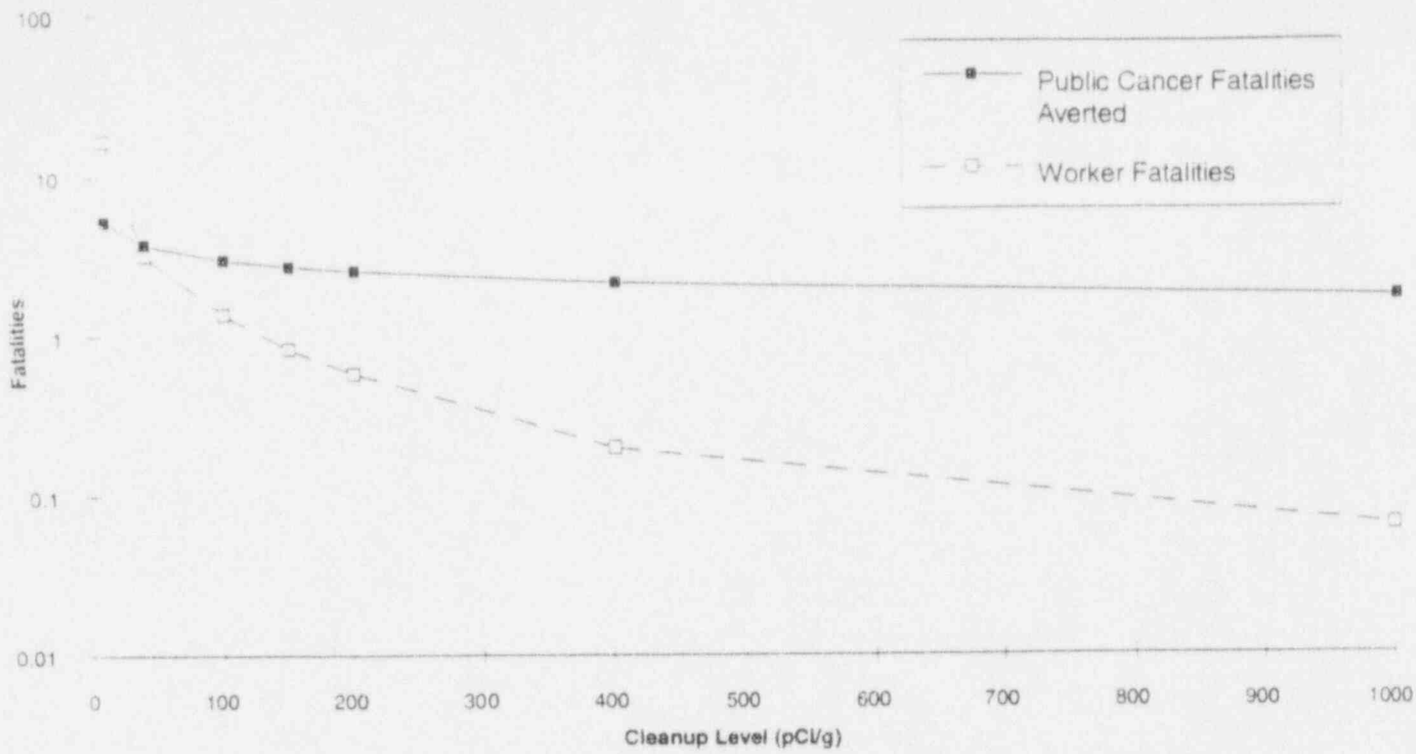

Figure 5-22
A Comparison of Estimates Expected Public Cancer Fatalities Averted with Estimates Expected Workers Fatalities as a Function of Cleanup Level

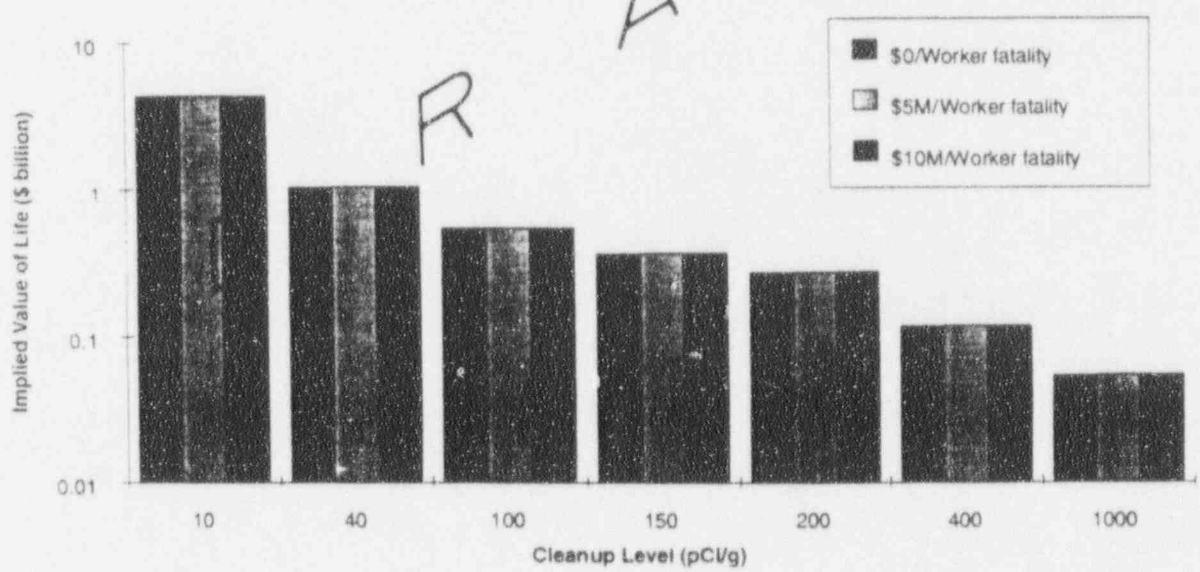

Figure 5-23
Value of Statistical Public Fatality Averted Required to Justify Alternative Cleanup Levels Under Various Assumptions for the Value of Avoiding a Worker Fatality and Assuming No Discounting

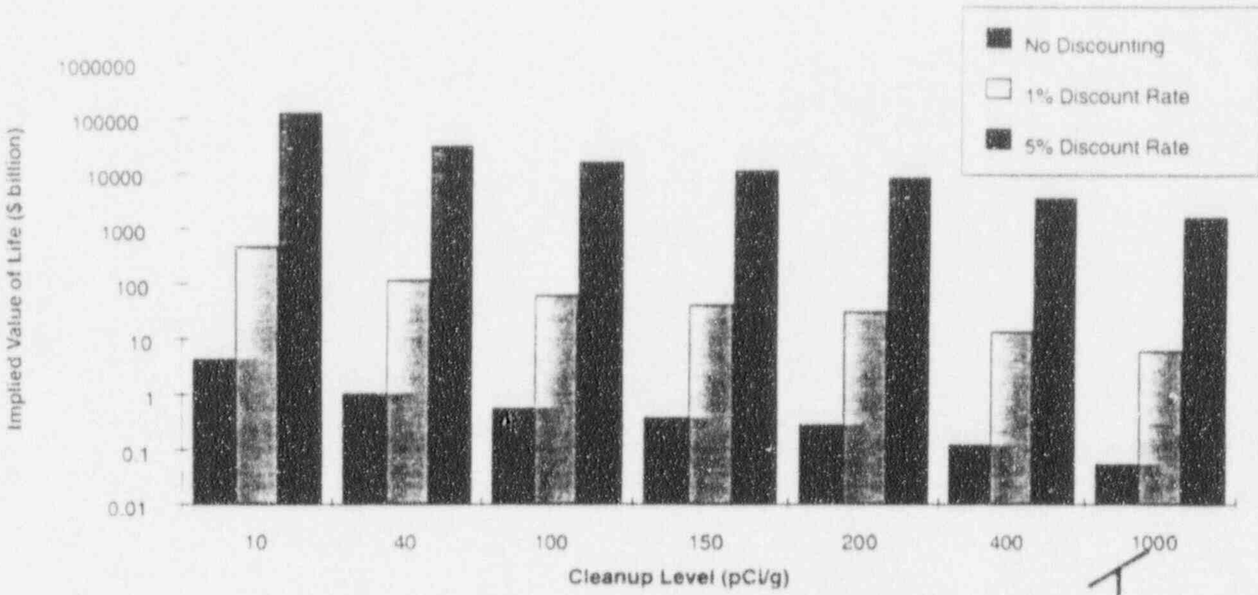

Figure 5-24
Value of Statistical Public Fatality Averted Required to Justify Alternative Cleanup Levels Under Various Assumptions for Discount Rate

values of public life that would be required assuming different values for the discount rate: 0, 1, and 5 percent. The values range from just over $10 million for the 1,000 pCi/g level with no discounting to nearly $50 trillion for 10 pCi/g with a 5 percent discount rate. For comparison, surveys indicate that the values used in other government decision making contexts typically range from several tens of thousands of dollars to about ten million dollars (e.g., Graham and Vaupel, 1981).

The results may be interpreted as implying that if cleanup levels at the 10 pCi/g level or lower are being seriously considered for the NTS, then there is very high value to postponing implementation of the cleanup and collecting additional information on existing uncertainties. This is especially the case for improved characterization information (worth up to almost $1 billion) and improved remediative cost information (worth up to nearly $5 billion).

5.4 Value of Resolving Remaining Uncertainties

As stated earlier, an advantage of an analysis that quantifies uncertainties with probability distributions is the opportunity to conduct value of information analyses. Value of information analyses provide an estimate of what it is worth to resolve each of the uncertainties represented in the analysis (Howard, 1968; Demski, 1972; Merkhofer, 1977).

Figure 5-25 illustrates how the value of information can be calculated by revising the influence diagram. As can be seen by comparing Figure 5-25 with 5-15, the influence diagram has been altered to include an arrow from one of the influencing uncertainties, the overall risk factor (the number of public fatalities per pCi/g average site concentration), to the decision node representing the choice of a cleanup level. According to influence diagram notation, an arrow from an uncertain variable to a decision means that the value of the uncertain variable is known prior to making the decision. If the cost per unit volume were known prior to selecting a cleanup level for the NTS, then the choice of cleanup level could, in theory at least, be adjusted depending on the risk—no cleanup or cleanup to less stringent levels would be optimal if the risk factor was very low, while cleanup to more stringent levels would be optimal if the risk factor was very high. Altering the model in this way will increase the decision utility, as computed using Equation 5-2. The difference between the expected utility calculated with revised model of Figure 5-25 and the original model of Figure 5-15 is the value of completely eliminating uncertainty on the risk factor. The value of eliminating each of the other uncertainties represented in the model can similarly be computed, as can the value of simultaneously eliminating several uncertainties. Since any real information-gathering effort will produce less than perfect information, the values computed in this way serve as upper bounds for what it might be worth to collect information addressing each uncertainty.

The computed value of information will, of course, depend on the value of public and worker life (i.e., the weights assigned to w_1 and w_2). The analysis was conducted with two sets of weights. First, the value of information was computed using values of public and worker life similar to those used other major DOE analyses (e.g., DOE, 1986; SNL, 1991, Applied Decision Analysis, 1992). Specifically, for the first calculation w_1 was assumed to be \$5 million per statistical public fatality averted and w_2 was assumed to be \$2 million per statistical worker fatality averted. Then, the analysis was repeated using value of life judgments that make cleanup to a 10 pCi/g level just justifiable at the NTS with no discounting, roughly \$5 billion. To simplify the analysis, the choice of a cleanup level was restricted to two options: 10 pCi/g versus no action. Ignoring the options of other cleanup levels causes the value of information to be underestimated slightly.

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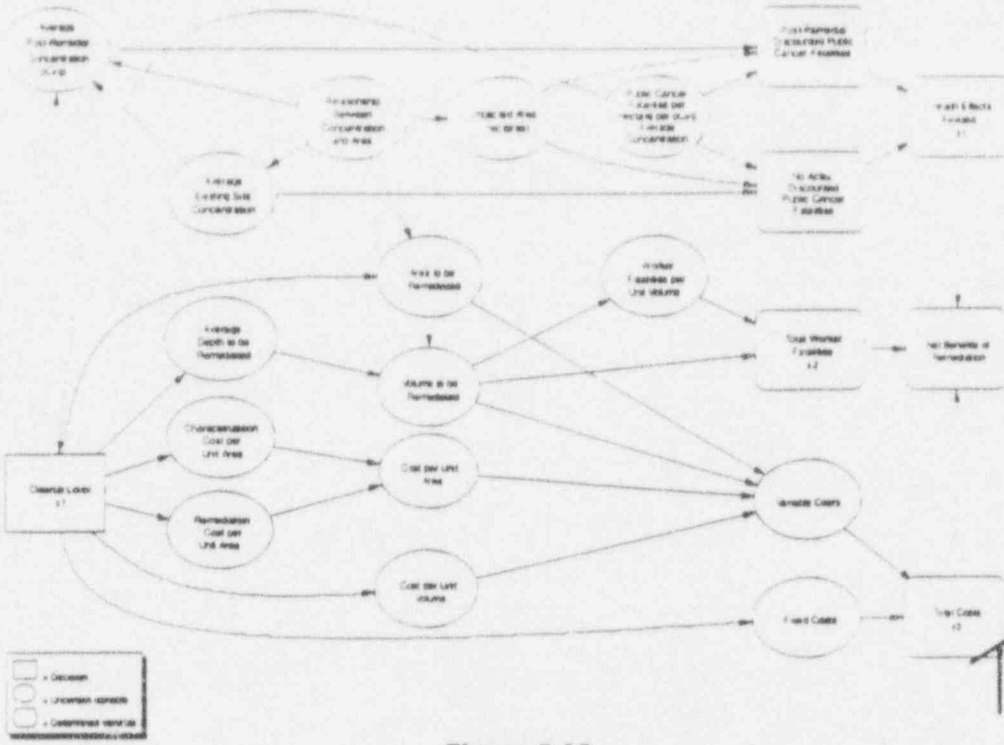

Figure 5-25
To Calculate the Value of Perfect Information on the Overall Risk Factor, the Influence Diagram is Modified by Drawing an Arrow from the Node Representing the Risk Factor to the Node Representing Cleanup Level

Using weights reflecting typical values of public and worker life, the value of information was estimated to approximately zero. The reason for this is that estimated costs are so high that it is virtually impossible, according to the estimated uncertainties, for additional information to change the conclusion that costs of cleanup outweigh benefits. However, when the higher weights are used, very high values of resolving several uncertainties were estimated, as summarized in Figure 5-27. Note that the estimated values indicate what it is worth to resolve uncertainties for the purpose of selecting a cleanup level only. Thus, the value of eliminating uncertainty over the size of the impacted area is zero. As described in the discussion of Figures 5-16 through 5-18, learning that the impacted area is larger than anticipated results in both costs and risks being larger than anticipated. Therefore, the ratio of benefits to costs resulting from cleanup do not change by much so the decision of what level to clean to is not impacted. Although the value of information regarding contaminated area is zero for the purpose of selecting a standard, the value of such information is obviously quite high for the purpose of learning exactly what locations require cleanup. Thus, the actual value of obtaining the information identified in Figure 5-26 will be higher to the extent that such information is useful for other decisions beyond selecting a cleanup level.

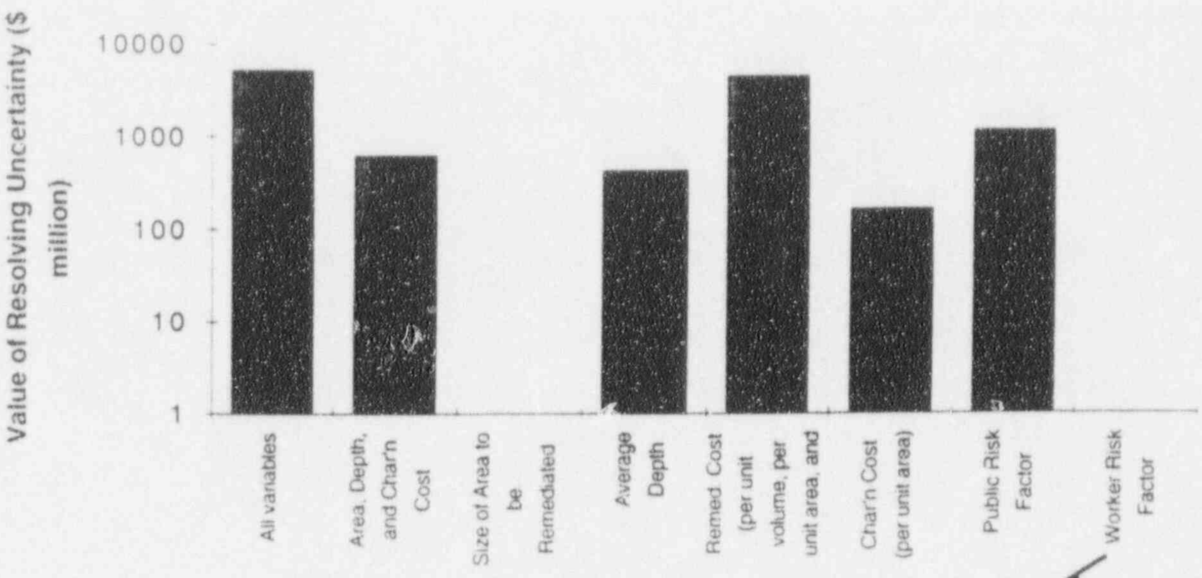

Figure 5-26
Value of Eliminating Various Uncertainties Assuming Weight w_1 Just Sufficient to Justify Cleanup to 10 pCi/g

5.5 Limitations of the Analysis

The main limitation of the integration analysis is the limited accuracy of the input assumptions. Key results, such as the expected public health risk and expected cleanup costs, depend not only on the best-judgment values assumed for the various quantities discussed in previous sections, but on the pessimistic and optimistic values as well. These estimates, especially the optimistic and pessimistic estimates, were generated very quickly and without opportunity for review by knowledgeable individuals other than those who participated directly in this study. Furthermore, it is likely that existing uncertainties have been underestimated. Underestimating uncertainties causes the estimates of the value of collecting information to be underestimated and may result in risks being underestimated. For example, as noted previously, estimating risks using average concentrations and population densities ignores the possibility that future populations may, by chance, locate on or near small areas with much higher than average concentrations. Thus, the analysis underestimates the uncertainty in the aggregate risk factor and, in turn, underestimates public cancer fatalities and the expected numbers of cancers averted by cleanup. Also, if uncertainties in future population densities over the impacted area are underestimated, such that it is likely that densities greater than 0.4 people/hectare (100 people/square mile) will occur sometime within the next 10,000 years, then risks and risk reductions could be significantly higher. Obviously, future population densities depend primarily on land use policies. This illustrates that the decision to cleanup the NTS and related sites is, in reality, not so much a decision about risk as it is a decision about how much society should spend to provide flexibility for future land use.

Cost uncertainties are also not fully addressed in the integration analysis. As noted in Appendix D, the pessimistic estimates for cost per unit volume were revised upwards at a point in the analysis too late to be reflected in the integration analysis. Fixed cost estimates have similarly been revised and, contrary to the integration model, fixed costs are likely to depend on volume (since, for example, the assumptions that greater volumes would simply require the cleanup to take longer is unlikely to hold in practice). Estimates of characterization costs account for the costs of improved understanding of surface concentrations, but do not account for the additional tests that would be required to clarify concentration-depth relationships. Also, costs estimates used in the integration analysis assume that contaminated soil can be treated so as to reduce the volume of material requiring disposal. High disposal costs make treatment economically preferable for most volume scenarios, and it is for this reason that 80 percent of soil reduction is generally assumed. However, significant technical uncertainties exist such that the feasibility of obtaining 80 percent volume reduction is questionable. It is for this reason that the no-volume-reduction case is highlighted in Section 3. Also, there are significant uncertainties regarding what the actual costs of onsite disposal of soil might be. For example, if the permitting costs associated with disposal could be significantly reduced, no treatment might be much more competitive. Finally, there are several additional costs associated with cleanup that were not estimated because they were assumed to be small relative to those cost components that were estimated. The aggregate impact of such oversimplifications may be significant.

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Several other considerations which may or may not be important are ignored in the analysis. For example, the public health risks associated with other radionuclides and other contaminants are not addressed, nor are the risks to the public that might result from remedial actions (e.g., due to increased Pu suspension resulting from disturbing the contaminated soil). Also omitted are impacts on the natural environment. For example, removing and/or treating the topsoil covering large areas would destroy plants and most animal life. Although the cost estimates used in this analysis assume reseeding and other efforts to minimize long-term adverse environmental impacts, the disbenefits associated with the environmental damage that would occur have not been accounted for in the analysis. Similarly, socioeconomic impacts including public concern, impacts on property values, and other effects on local communities are not addressed.

5.6 Summary and Conclusions

Despite its limitations, the results of the analysis provide a strong argument against cleanup of the NTS and related sites to soil concentrations below 1000 pCi/g at this time. To do so would imply a willingness to spend vast economic resources to achieve a very small reduction in the expected incidence of cancer fatalities to future populations who might potentially live on contaminated areas. The estimated public cancer fatalities that would be averted is of the same magnitude as the number of worker fatalities expected to result from the cleanup effort. Adoption of such cleanup levels for the NTS would be dramatically inconsistent with the value tradeoff judgments implied by other decisions regarding the investment of limited resources to reduce public health risks.

The analysis suggests that a rational approach would be to delay implementation of a low cleanup level pending the outcome of additional information gathering activities. If cleanup levels as low as 10 pCi/g are under serious consideration for the NTS, then the analysis shows that resolving current uncertainties regarding existing Pu concentrations and remediation costs prior to selecting a specific cleanup level may be worth up to several billion dollars.

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Appendix A
Estimated Extent of Plutonium Contamination by Site

Table A-1
Yucca Flat

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m³) Optimistic	Realistic	Pessimistic
1000	36.3	72.6	145.2	18,150	72,600	363,000
400	116.8	233.5	467.0	58,375	233,500	1,167,500
200	236.5	472.9	945.8	118,225	709,350	2,364,500
150	364.1	728.0	1,456.0	182,000	1,092,000	3,640,000
100	786.9	1,573.5	3,147.0	393,752	2,360,250	7,867,500
40	3,917.2	7,834.1	15,668.2	1,958,525	5,724,050	39,170,500
10	13,156.4	26,312.4	108,059.7	6,578,100	14,963,200	270,149,250

Table A-2
Schooner Area 20

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m³) Optimistic	Realistic	Pessimistic
1000	0.0	0.0	0.0	0	0	0
400	0.0	0.0	0.0	0	0	0
200	0.0	0.0	0.0	0	0	0
150	4.0	8.0	16.0	2,000	12,000	40,000
100	17.5	34.8	69.8	8,700	52,200	174,000
40	38.7	77.1	154.6	19,275	73,432	385,500
10	117.2	234.3	939.6	58,575	152,044	2,350,500

Table A-3
Cabriolet

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	9.0	18.0	36.0	4,500	18,000	90,000
400	15.2	30.3	60.6	7,575	30,300	151,500
200	34.3	68.4	136.8	17,100	102,600	342,000
150	41.4	82.6	165.2	20,650	123,900	413,000
100	57.6	115.0	230.0	28,750	172,500	575,000
40	122.3	224.3	488.6	61,075	267,450	1,221,500
10	292.3	584.0	2,188.6	146,075	437,450	5,471,500

Table A-4
Little Feller I & II

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	14.2	28.4	56.8	7,100	28,400	142,000
400	38.5	77.0	154.0	19,250	77,000	385,000
200	59.0	118.0	236.0	29,550	177,000	590,000
150	69.3	138.6	272.2	34,650	207,900	693,000
100	86.4	172.8	345.6	43,200	259,200	864,000
40	142.1	284.2	568.4	71,050	391,900	1,421,000
10	241.0	481.9	1,556.9	120,475	490,750	3,892,250

Table A-5
Danny Boy

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	1.1	2.2	4.4	550	2,200	11,000
400	2.6	5.2	10.4	1,300	5,200	26,000
200	5.2	10.4	20.8	2,600	15,600	52,000
150	6.6	13.2	26.4	3,300	19,800	66,000
100	8.7	17.4	34.8	4,350	26,100	87,000
40	14.4	28.7	57.6	7,175	37,028	143,500
10	25.8	51.4	170.9	12,850	48,359	427,250

Table A-6
Buggy

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	2.3	4.6	9.2	1,150	4,600	23,000
400	6.9	13.8	27.6	3,450	15,800	69,000
200	9.7	19.3	38.6	4,825	28,950	96,500
150	10.9	21.6	43.2	5,400	32,400	108,000
100	12.8	25.3	50.6	6,325	37,950	126,500
40	17.5	34.6	69.2	8,650	56,435	173,000
10	25.7	50.9	150.7	12,725	64,590	376,750

Table A-7
Plutonium Valley

Remediation Level (pCi/g)	Cumulative Area (hectares)			Cumulative Volume (m^3)		
	Optimistic	Realistic	Pessimistic	Optimistic	Realistic	Pessimistic
1000	6.7	13.3	26.6	3,325	13,300	66,500
400	13.9	27.7	55.4	6,925	27,700	138,500
200	36.4	72.6	145.2	18,150	108,900	363,000
150	56.5	112.8	225.6	28,200	169,200	564,000
100	103.2	206.1	412.2	51,525	309,150	1,030,500
40	290.9	581.4	1,162.8	145,350	524,606	2,907,000
10	409.2	818.0	2,345.8	204,500	642,918	5,864,500

Table A-8
GMX

Remediation Level (pCi/g)	Cumulative Area (hectares)			Cumulative Volume (m^3)		
	Optimistic	Realistic	Pessimistic	Optimistic	Realistic	Pessimistic
1000	0.5	1.0	2.0	250	1,000	5,000
400	1.1	2.2	4.4	550	2,200	11,000
200	1.6	3.1	6.2	775	4,650	15,500
150	1.9	3.6	7.2	900	5,400	18,000
100	3.3	6.3	12.6	1,575	9,450	31,500
40	8.3	16.3	32.6	4,075	16,611	81,500
10	41.3	82.1	362.1	20,550	49,533	905,250

Table A-9
Frenchman Flat

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	0.0	0.0	0.0	0	0	0
400	0.0	0.0	0.0	0	0	0
200	0.3	0.6	1.2	150	900	3,000
150	0.7	1.3	2.6	350	1,950	6,500
100	1.4	2.8	5.4	700	4,200	13,500
40	7.9	15.7	31.2	3,950	10,628	78,000
10	45.6	91.1	408.2	22,800	48,305	1,020,500

Table A-10
Clean Slate 1

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	0.0	0.0	0.0	0	0	0
400	0.0	0.0	0.0	0	0	0
200	2.9	5.7	11.4	1,425	8,550	28,500
150	4.1	8.1	16.2	2,025	12,150	40,500
100	7.6	15.0	30.0	3,750	22,500	75,000
40	40.6	81.0	162.0	20,250	55,504	405,000
10	222.9	688.5	6,237.0	111,375	359,025	15,592,500

Table A-11
Clean Slate 2

Remediation Level (pCi/g)	Cumulative Area (hectares)			Cumulative Volume (m^3)		
	Optimistic	Realistic	Pessimistic	Optimistic	Realistic	Pessimistic
1000	2.0	3.9	7.8	975	3,900	19,500
400	8.6	17.1	34.2	4,275	17,100	85,500
200	13.3	26.4	52.8	6,600	39,600	132,000
150	19.6	39.0	78.0	9,750	58,500	195,000
100	38.7	77.1	154.2	19,275	115,650	385,500
40	83.9	167.4	334.8	41,850	177,661	837,000
10	117.9	280.8	1,468.8	58,860	234,318	3,672,000

Table A-12
Clean Slate 3

Remediation Level (pCi/g)	Cumulative Area (hectares)			Cumulative Volume (m^3)		
	Optimistic	Realistic	Pessimistic	Optimistic	Realistic	Pessimistic
1000	2.0	3.9	7.8	975	3,900	19,500
400	8.6	17.1	34.2	4,275	17,100	85,500
200	24.6	49.0	98.0	12,250	73,500	245,000
150	28.7	57.1	114.2	14,275	85,650	285,000
100	39.7	79.0	158.0	19,750	118,500	395,000
40	87.7	175.0	350.0	43,750	183,347	875,000
10	176.4	470.7	3,307.0	88,105	331,060	8,267,500

Table A-13
Double Tracks

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	0.2	0.6	1.8	90	600	4,500
400	0.5	1.5	4.5	1,035	1,500	11,250
200	1.0	3.0	9.0	1,260	4,500	22,500
150	1.2	3.7	11.1	1,365	5,550	27,750
100	2.1	6.8	20.4	1,830	10,200	51,000
40	2.6	8.3	24.9	2,055	12,344	62,250
10	3.6	11.5	88.9	2,535	13,943	222,250

Table A-14
Area 13

Remediation Level (pCi/g)	Cumulative Area (hectares) Optimistic	Realistic	Pessimistic	Cumulative Volume (m^3) Optimistic	Realistic	Pessimistic
1000	5.4	17.9	53.7	2,685	17,900	134,250
400	12.1	40.3	120.9	6,045	40,300	302,250
200	20.2	67.2	201.6	10,080	100,800	504,000
150	24.5	81.6	244.8	12,240	122,400	612,000
100	37.9	126.4	379.2	18,960	189,600	948,000
40	76.5	255.1	765.6	38,280	294,153	1,914,000
10	11.8	372.5	3,115.6	55,905	352,854	7,789,000

Table A-15
Smallboy Plume

Remediation Level (pCi/g)	Cumulative Area (hectares)			Cumulative Volume (m³)		
	Optimistic	Realistic	Pessimistic	Optimistic	Realistic	Pessimistic
1000	3.6	12.1	36.3	1,815	12,100	90,750
400	52.2	133.5	339.8	26,095	133,500	849,500
200	133.1	403.0	1,148.3	66,520	604,500	2,870,750
150	214.0	672.5	1,956.8	106,945	1,008,750	4,892,000
100	294.9	942.0	2,765.3	147,370	1,413,000	6,913,250
40	764.3	2,115.6	5,699.0	382,090	2,133,550	14,248,250
10	1,978.4	6,162.5	86,637.3	989,125	4,157,022	216,593,250

Appendix B

Time Dependent Decrease of Pu in Soil

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B.1 Time Dependent Decrease of Pu in Soil

The time-dependent decrease of Pu in soil is mainly a function of its radioactive decay and the rate that it is lost via resuspension to the atmosphere. Downward leaching into soil is assumed to be small compared to those removal processes. Expressed mathematically (Layton et al., 1993),

$$C_s(t) = C_s(0) \ x \ \exp[-(\lambda_{dr} + \lambda_{rr})t], \qquad \text{(B-1)}$$

where

$C_s(0)$	=	concentration of Pu in soil at time zero (pCi/g),
λ_{dr}	=	rate of radioactive decay for Pu (2.8×10^{-5} 1/y),
λ_{rr}	=	resuspension rate (1/y).

The time-integrated concentration of Pu (denoted TIC_a) of Pu in air can be computed by substituting Equation B-1 into Equation 4-2 (see Chapter 4.0) and integrating to obtain

$$TIC_a = \int_0^\infty C_s(0) \ x \ \exp[-(\lambda_{dr} + \lambda_{rr})t] \ x \ TSP \ x \ E_f \ dt, \qquad \text{(B-2)}$$

where

TSP	=	Particulate mass loading in air (g/m^3),
C_s	=	Concentration of Pu in soil (pCi/g),
E_f	=	Enhancement factor (unitless).

This reduces to

$$TIC_a = \frac{C_s(0) \ x \ TSP \ x \ E_f}{(\lambda_{dr} + \lambda_{rr})}. \qquad \text{(B-3)}$$

Appendix C
Worker Risk Analysis

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C.1 Uncertainty Analysis

As in any evaluation, risk estimates need to be given together with their uncertainties. Here, the fact is used that risks are usually products of a number of factors, some of which may be sums. When transformed into logarithmic space, the product becomes the sum of the logarithms of the factors. For many factors, the *Central Limit Theorem* (Korn and Korn, 1968) states that the sum will be asymptotically normally distributed, regardless of the distributions of the logarithmic terms. If the factors themselves are already lognormally distributed, i.e., if the logarithmic terms are normally distributed, then the sum is exactly normal, regardless of the number of terms. Consequently, if the factors in the product are approximately lognormally distributed, then the convergence to a normal distribution requires but a few terms.

Due to these facts, it is convenient to assume that the factors in the product forming the risk are approximately lognormally distributed, and can thus be approximated by a lognormal random variable. A product of lognormally distributed random variables is again lognormal. The geometric standard deviation of the product is best calculated in logarithmic space from the standard errors of the factors by the usual error propagation formulae (Brandt, 1976; Bevington, 1969; Seiler, 1987). In this particular case, the Gaussian approximation for small relative errors of the parameters is exact, that is, it is valid regardless of the size of the input errors. The definitions

$$y(x) \equiv ln(x) \;, \qquad \text{(C-1)}$$

and

$$S(x) \equiv ln\left(\sigma_g(x)\right) \;. \qquad \text{(C-2)}$$

will be needed in the following.

C.2 Normal and Lognormal Distributions in the Uncertainty Analysis

In many cases, it will be necessary to convert a normal distribution with the mean $\bar{x}$ and the standard error s into an equivalent lognormal distribution, defined by the geometric mean $\bar{x}_g$ and the geometric standard deviation σ_g. Equivalence will be chosen here to require the two distributions to have the same 68 percent confidence interval. This leads to the equations for the geometric mean, and

$$\bar{x}_g = \sqrt{(\bar{x} + s)(\bar{x} - s)} \qquad \text{(C-3)}$$

$$\sigma_g = \sqrt{\frac{\bar{x} + s}{\bar{x} - s}} \ , \qquad \text{(C-4)}$$

or

$$S(x) = \frac{1}{2}\, ln\left(\frac{\bar{x} + s}{\bar{x} - s}\right) \equiv \frac{1}{2}\, ln\left(\frac{1 + \varepsilon}{1 - \varepsilon}\right) , \qquad \text{(C-5)}$$

where the quantity ε is the relative error of the mean $\bar{x}$. These approximations are valid for small relative errors ε only. For larger values of ε, the approximation

$$\sigma_g(x) \approx 1 + \varepsilon \ , \qquad \text{(C-6)}$$

or

$$S(x) \approx ln(1 + \varepsilon) \ , \qquad \text{(C-7)}$$

can be used. For ε larger than about 0.8, no suitable approximation is possible as the mean is then no longer different from zero, a value for which the probability density function of a lognormal distribution is zero.

Conversely, if the characteristics of a lognormal distribution are known and the equivalent normal distribution is needed, the equations are

$$\bar{x} = \frac{1}{2}\, \bar{x}_g \left(\sigma_g + \frac{1}{\sigma_g}\right) , \qquad \text{(C-8)}$$

and

$$\Delta \overline{x} = \frac{1}{2} \overline{x_g} \left(\sigma_g - \frac{1}{\sigma_g} \right) . \qquad \text{(C-9)}$$

Here, there are no problems connected with the value x = 0 because the condition $\sigma_g \geq 1$ leads to a bracket in Equation C-3 which is positive semidefinite, that is, zero or positive.

C.3 Systematic and Random Errors

One of the many fruitful distinctions between different types of uncertainties is the classification of errors into random and systematic errors. Random errors of a stochastic variable are caused by a few or many different sources of variability, the sign of the deviation cannot be predicted, but the error can be reduced by obtaining more information, such as more measurements. Systematic errors, on the other hand, have mostly one or only a few causes, affect the variable in a mostly predictable way, and their magnitude cannot be reduced by obtaining more measurements affected by the same error. A typical example of a variable with a random error is the number of gamma rays emitted by a radioactive source in a given time; typical examples of variables with a systematic error are the mass of a body weighed by a scale which systematically indicates low masses, and the concentration of an aerosol predicted by an atmospheric dispersion model that neglects sedimentation and thus always overestimates the concentration.

Here, the two types of error are treated separately, and are only combined at the end of the calculation. The influence of random errors of model parameters is evaluated using the methods of analytical error propagation where possible, and Monte Carlo methods where appropriate (Cox and Baybutt, 1981). The influence of systematic errors is evaluated roughly by giving pessimistic, optimistic, and realistic estimates for the variables deemed most susceptible to systematic errors.

C.4 Analytical Error Propagation

Analytical error propagation is based on a multi-dimensional Taylor series expansion of the model function $f(\mathbf{x}) = f(x_1, x_2, ..., x_n)$ around the point $\mathbf{x} = \mathbf{x}_0$. A termination of the series after the first term results in the so-called Gaussian approximation (Brandt, 1976; Bevington, 1969; Seiler, 1987) where the quantities σ_{kk} are the diagonal elements of the

$$\left(\Delta f(x)\right)^2 = \sum_{i=1}^{n} \left[\frac{\partial f(x)}{\partial x_i}\right]^2_{x=x_o} \sigma^2_{ii}$$

$$+ 2 \sum_{i=1}^{n} \sum_{j=i+1}^{n} \left[\frac{\partial f(x)}{\partial x_i}\right]_{x=x_o} \left[\frac{\partial f(x)}{\partial x_j}\right]_{x=x_o} \sigma^2_{ij} \, , \qquad \text{(C-10)}$$

covariance matrix and the squares of the standard errors Δx_k, and the quantities σ_{ij} are the off-diagonal elements of the covariance matrix which are zero only if the quantities x_i and x_j are uncorrelated. For uncorrelated parameters x_i and x_j, the cross-terms are then zero, and Equation C-5 reduces to the first sum

$$\left(\Delta f(x)\right)^2 = \sum_{i=1}^{n} \left[\frac{\partial f(x)}{\partial x_i}\right]^2_{x=x_o} \left(\Delta x_i\right)^2 \, . \qquad \text{(C-11)}$$

This is the form generally used. Often, however, some of the parameters in a function are correlated and then the more general Equation C-5 has to be used. If existing correlations are ignored, the errors calculated by Equation C-6 may be considerably too large or too small (Smith et al., 1992). The Gaussian approximation in Equation C-5 is only valid for small relative errors $\Delta x_i / x_i$; for larger relative errors, more terms are needed in the Taylor series. It is, however, often surprising to see as a function of increasing relative errors just how far the Gaussian terms yield acceptable estimates (Seiler, 1987).

C.5 Occupational Fatalities in the Operation of Heavy Equipment

Estimates of fatalities from occupational accidents are based on the number of man-years at work for the given activity, for example, operating heavy construction equipment. All workers engaged in such work in the operational part of site remediation are included, except workers in the volume reduction plant. Estimates of man-years required for the various activities are provided in Section 2.0. Let R_m be the worker risk associated with the risk component. Then

$$R_m = r_m V_m , \tag{C-12}$$

where

r_m = Volume density of this risk,
V_m = Soil volume remediated in option m.

The logarithmic standard error is then given by

$$S^2(R_m) = S^2(r_m) + S^2(V_m), \tag{C-13}$$

the sum of the squares of the logarithmic standard errors of the two factors. Using the symbols

p_1 = Fatality rate per man-year in operations with heavy equipment (yr^{-1}),
n_{1i} = Man-years of work per m^3 of soil excavated in option i ($yr\ m^{-3}$),
r_{f1i} = Risk density for fatal occupational accidents in option i (m^{-3}),

the risk density for general occupational fatalities per m^3 of soil excavated is given by

$$r_{f1i} = p_1 n_{1i} , \tag{C-14}$$

with lognormally distributed factors. For the error propagation, arithmetic relative standard errors of the risks are used here:

$$\left(\frac{\Delta r_{f1i}}{r_{f1i}}\right)^2 = \left(\frac{\Delta p_1}{p_1}\right)^2 + \left(\frac{\Delta n_{1i}}{n_{1i}}\right)^2 + \left(\frac{\Delta p_1}{p_1}\right)^2 \left(\frac{\Delta n_{1i}}{n_{1i}}\right)^2 \tag{C-15}$$

Although the Gaussian approximation is valid for quite large relative errors (Seiler, 1987), one higher order term is added here to make the equation exact.

C.6 Occupational Fatalities in Treatment Plant Operations

Fatality estimates for these occupational accidents are similarly derived from the number of man-years at work. All workers occupied in the treatment plant are included in the calculation of the man-years needed. Using the symbols

p_2	=	Fatality rate per man-year of treatment plant operations (yr^{-1}),
n_{2i}	=	Man-years of work per m^3 of soil processed in option i ($yr\ m^{-3}$),
r_{f2i}	=	Total risk density for fatal accidents in plant for option i,

the risk density per m^3 of soil for general occupational fatalities in the treatment plant is given by

$$r_{f2i} = p_2 \; n_{2i} \; , \tag{C-16}$$

and its relative standard error by

$$\left(\frac{\Delta r_{f2i}}{r_{f2i}}\right)^2 = \left(\frac{\Delta p_2}{p_2}\right)^2 + \left(\frac{\Delta n_{2i}}{n_{2i}}\right)^2 + \left(\frac{\Delta p_2}{p_2}\right)^2 \left(\frac{\Delta n_{2i}}{n_{2i}}\right)^2 . \tag{C-17}$$

Due to the added term, this approximation is again exact and holds regardless of the size of the relative errors.

C.7 Fatalities in Treatment Plant Operations Involving Forklifts

The model for fatal forklift accidents also estimates fatalities from the number of man-years at work (DOL, 1986). Again, all workers occupied in the treatment plant are included in the calculation of this part of the total work effort. Using the symbols

p_3	=	Fatality rate from forklift accidents per man-year (yr^{-1}),
n_{2i}	=	Man-years of total work in plant required per m^3 processed ($yr\ m^{-3}$),
R_{f3i}	=	Risk density for fatal accidents in option i (m^{-3}),

the risk density for occupational fatalities per m^3 of soil treated in the treatment plant involving forklift accidents is given by

$$r_{f3i} = p_3 \, n_{2i} , \tag{C-18}$$

and its relative standard error by

$$\left(\frac{\Delta r_{f3i}}{r_{f3i}} \right)^2 = \left(\frac{\Delta p_3}{p_3} \right)^2 + \left(\frac{\Delta n_{2i}}{n_{2i}} \right)^2 + \left(\frac{\Delta p_3}{p_3} \right)^2 \left(\frac{\Delta n_{2i}}{n_{2i}} \right)^2 . \tag{C-19}$$

This approximation is again exact, regardless of the magnitude of the relative errors. Note that this risk density and its error depend on n_{2i} in the same manner as r_{f2i}.

C.8 Occupational Traffic Accidents

These accident risks involve only fatalities and injuries among the soil transport crews due to trauma incurred in one-vehicle accidents and two-vehicle collisions (Madsen et al., 1986). The risk of occupational fatalities due to traffic accidents involving the soil transport crews depends on the distances traveled with treated and untreated soils, and on the volume reduction for strongly contaminated soils due to soil treatment. In this first approximation, the set of contaminated sites will be split into two sets of sites: those on the NTS (q = 1) and those on the TTR and NAFR (q = 2). The same power law connecting average contamination and contaminated area is used for both sets, with fractions determined from the raw data. Using the following symbols

p_7	=	Linear probability density for occupational traffic fatalities (m^{-1}),
f_{qi}	=	Fraction of volume at set of sites q in option i,
V_t	=	Volume of soil transported on one truck (m^3),
L_{1iq}	=	Distance traveled with untreated soil in option i (m),
L_{2iq}	=	Distance traveled with treated contaminated soil in option i (m),
L_{3iq}	=	Distance traveled with treated uncontaminated soil in option i (m),
F_{vi}	=	Fraction of soil of high activity after treatment in option i,
r_{f7i}	=	Risk density for occupational traffic fatalities option i (m^{-3}),

where the distances $L_{\mu i q}$ for μ = 1, 2, and 3 are assumed to be nonstochastic in character. The traffic fatality risk density f[illegible]he transport crew per m^3 of soil transported is

$$r_{f7i} = \frac{p_7}{V_1} \sum_{q=1}^{2} f_{qi} \left[L_{1iq} + F_{vi} \, L_{2iq} + \left(1 - F_{vi}\right) L_{3iq} \right] \qquad \text{(C-20)}$$

$$\equiv \frac{p_7}{V_1} \, E_i \; ,$$

where the second part of the equation defines the auxiliary quantity E_i

$$E_i \equiv \sum_{q=1}^{2} f_{qi} \left[L_{1iq} + F_{vi} \, L_{2iq} + \left(1 - F_{vi}\right) L_{3iq} \right] . \qquad \text{(C-21)}$$

The standard error of the risk density is given by

$$\left(\frac{\Delta r_{f7i}}{r_{f7i}}\right)^2 = \left(\frac{\Delta p_7}{p_7}\right)^2 + \left(\frac{\Delta V_1}{V_1}\right)^2 + \left(\frac{\Delta E_i}{E_i}\right)^2 \qquad \text{(C-22)}$$

$$+ \left(\frac{\Delta p_7}{p_7}\right)^2 \left(\frac{\Delta V_1}{V_1}\right)^2 + \left(\frac{\Delta p_7}{p_7}\right)^2 \left(\frac{\Delta E_i}{E_i}\right)^2$$

where the error term ΔE_i can be estimated from

$$\left(\Delta E_i\right)^2 = \sum_{q=1}^{2} \left[L_{1iq} + F_{vi} \, L_{2iq} + \left(1 - F_{vi}\right) L_{3iq} \right]^2 \left(\Delta f_{qi}\right)^2 \qquad \text{(C-23)}$$

$$+ \left[\sum_{q=1}^{2} f_{qi} \left(L_{2iq} - L_{3iq}\right) \right]^2 \left(\Delta F_{vi}\right)^2 .$$

Equation C-23 is not exact, but it contains sufficient higher order terms to be an appropriate approximation even for relatively large relative errors.

C.9 Total Occupational Accident Fatalities

The sum of all occupational accident fatalities from accidents involving heavy equipment operations, treatment plant operations, and traffic accidents is

$$
\begin{aligned}
r_{fi} &= r_{f1i} + r_{f2i} + r_{f3i} + r_{f7i} \\
&= p_1 n_{1i} + \left(p_2 + p_3\right) n_{2i} + \frac{p_7}{V_1} E_i .
\end{aligned}
\qquad \text{(C-24)}
$$

The relative standard deviation is given by the expression

$$
\begin{aligned}
\left(\Delta r_{fi}\right)^2 = {} & r_{f1i}^2 \left(\frac{\Delta r_{f1i}}{r_{f1i}}\right)^2 + r_{f7i}^2 \left(\frac{\Delta r_{f7i}}{r_{f7}}\right)^2 \\
& + \left(p_2 + p_3\right)^2 n_{2i}^2 \left[\frac{\left(\Delta p_2\right)^2 + \left(\Delta p_3\right)^2}{\left(p_2 + p_3\right)^2}\right. \\
& \left. + \left(\frac{\Delta n_{2i}}{n_{2i}}\right)^2 + \frac{\left(\Delta p_2\right)^2 + \left(\Delta p_3\right)^2}{\left(p_2 + p_3\right)^2} \left(\frac{\Delta n_{2i}}{n_{2i}}\right)^2\right] .
\end{aligned}
\qquad \text{(C-25)}
$$

The third term here accounts for the sum in Equation C-24 as a factor in both r_{f2i} and r_{f3i}. It is this dependence which gives Equation C-25 its peculiar form. The geometric mean and standard deviation needed in Equations C-12 and C-13 can be derived from Equations C-3 to C-8.

C.10 Occupational Risks of Radiation Cancer

The model for occupational cancer estimates the corresponding risk from the number of persons exposed and the average dose for DOE workers employed in similar installations. All workers in the operational part of the remedial action are included here, including the workers in the treatment plant. Using the symbols

n_{1i} = Man-years of work required per m^3 of soil excavated ($yr\ m^{-3}$),
n_{2i} = Man-years of work required per m^3 of soil processed ($yr\ m^{-3}$),
D_{eff} = Annual dose equivalent per man-year in DOE installations ($Sv\ yr^{-1}$),
a_{rc} = Risk coefficient for radiation cancer at high dose rates (Sv^{-1}),
ϕ_{rc} = Dose rate effectiveness factor for carcinogenesis at low dose rates.
r_{c9i} = Lifetime risk density for radiation cancer per m^3 handled (m^{-3}),

the risk density per m^3 of soil for occupational radiation cancers is given by

$$r_{c9i} = \left(n_{1i} + n_{2i}\right) D_{eff} \frac{a_{rc}}{\phi_{rc}} . \tag{C-26}$$

The relative standard deviation is given by the expression

$$\left(\frac{\Delta r_{c9i}}{r_{c9i}}\right)^2 = \frac{\left(\Delta n_{1i}\right)^2 + \left(\Delta n_{2i}\right)^2}{\left(n_{1i} + n_{2i}\right)^2} + \left(\frac{\Delta D_{eff}}{D_{eff}}\right)^2 + \left(\frac{\Delta a_{rc}}{a_{rc}}\right)^2$$

$$+ \left(\frac{\Delta \phi_{rc}}{\phi_{rc}}\right)^2 + \frac{\left(\Delta n_{1i}\right)^2 + \left(\Delta n_{2i}\right)^2}{\left(n_{1i} + n_{2i}\right)^2} \left[\left(\frac{\Delta D_{eff}}{D_{eff}}\right)^2 + \left(\frac{\Delta a_{rc}}{a_{rc}}\right)^2 + \left(\frac{\Delta \phi_{rc}}{\phi_{rc}}\right)^2 \right] + \left(\frac{\Delta D_{eff}}{r_{f1i}}\right)^2$$

$$\left[\left(\frac{\Delta a_{rc}}{a_{rc}}\right)^2 + \left(\frac{\Delta \phi_{rc}}{\phi_{rc}}\right)^2 \right]$$

$$+ \left(\frac{\Delta a_{rc}}{a_{rc}}\right)^2 \left(\frac{\Delta \phi_{rc}}{\phi_{rc}}\right)^2 . \tag{C-27}$$

The first term here accounts for the sum in Equation C-26 as a factor in the risk density. These two equations quantify the only contribution of occupational risks to the total cancer risk, and the total cancer risk is therefore

$$r_{ci} = r_{c9i} , \tag{C-28}$$

as well as

$$\Delta r_{ci} = \Delta r_{c9i} . \tag{C-29}$$

Note that when this contribution is in some way combined with the contribution of Equation C-18, the quantities n_{1i} and n_{2i} occur in both values making them dependent on each other. Again, the mean and standard error in the linear space of Equations C-22 and C-23 need to be transformed into the logarithmic space of Equations C-6 and C-7 using Equations C-3 to C-7.

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Appendix D
Description of Probability Distribution Inputs

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APPENDIX D
DESCRIPTION OF PROBABILITY DISTRIBUTION INPUTS

The following table provides the assessed fractiles and the parameters of the fit distribution for each uncertain input to the probabilistic model.

Variable	Units	Assessed Fractiles			Mean	Distribution Parameters*		
		5%	50%	95%		λ	σ	δ
Alpha**	ln(hectares)	12.97	13.77	14.71	13.79	1.60	0.11	8.84
Public Risk Factor	fatalities/pCi-hectare/g	2.65×10^{-8}	1.95×10^{-6}	7.53×10^{-6}	7.32×10^{-6}	-14.62	1.72	0
Avg. Depth (10 pCi/g)	cm	5	6.1	25	10.14	0.16	1.73	4.93
Avg. Depth (40 pCi/g)	cm	5	8.4	25	10.93	1.45	0.96	4.12
Avg. Depth (100, 150, 200 pCi/g)	cm	5	15	25	14.60	2.56	0.49	0
Avg. Depth (400, 1000 pCi/g)	cm	5	10	25	11.87	2.01	0.66	2.5
Worker Risk Factor (No Volume Reduction)	fatalities/m^3	1.58×10^{-7}	8.07×10^{-7}	4.13×10^{-6}	1.32×10^{-6}	-14.03	0.41	0
Worker Risk Factor (Volume Reduction)	fatalities/m^3	1.37×10^{-7}	2.38×10^{-7}	4.14×10^{-7}	2.52×10^{-7}	-15.25	0.34	0
Fixed Cost (No Volume Reduction)	dollars	$1.83\times10^{+06}$	$6.58\times10^{+06}$	2.1[illegible]$\times10^{+07}$	$8.70\times10^{+06}$	15.70	0.75	0
Fixed Cost (Volume Reduction)	dollars	$4.26\times10^{+06}$	$1.36\times10^{+07}$	$4.40\times10^{+07}$	$1.75\times10^{+07}$	16.43	0.71	0
Cost per Unit Area	dollars/hectare	9.90x10[illegible]	$1.58\times10^{+04}$	$5.37\times10^{+04}$	$2.21\times10^{+04}$	8.85	1.13	$8.83\times10^{+03}$
Cost per Unit Volume (No Volume	dollars/m^3	222	437	545***	405	5.97	0.27	0
Cost per Unit Volume (Volume Reduction)	dollars/m^3	101	244	549***	278	5.50	0.51	0
Measurement Cost (10 pCi/g)	dollars/hectare	$8.20\times10^{+02}$	$1.19\times10^{+04}$	$1.74\times10^{+05}$	$4.49\times10^{+04}$	9.39	1.63	0
Measurement Cost (50, 100, 150 pCi/g)	dollars/hectare	$4.61\times10^{+02}$	$3.77\times10^{+03}$	$3.09\times10^{+04}$	$8.54\times10^{+03}$	8.24	1.28	0
Measurement Cost (400, 1000 pCi/g)	dollars/hectare	$4.61\times10^{+02}$	$1.59\times10^{+03}$	$5.49\times10^{+03}$	$2.11\times10^{+03}$	7.37	0.75	0

* Either a shifted lognormal or a lognormal distribution is fit to all variables. The parameters λ and σ are the mean and standard deviation respectively of the underlying normal distribution, while the parameter δ is the displacement or shift of the distribution.

** Alpha is the intercept of the ln(Area) - ln(Concentration) relationship; that is, the natural log of the area contaminated at or above 1pCi/g.

*** These entries differ from those contained in Section 4.0 due to revisions made following the initiation of the integration analysis.

Appendix E
Relationships Among Cleanup Level, Area, and Average Concentration

E.1 Relationship Among Cleanup Level, Area, and Average Concentration

The integration analysis relies on an empirically derived model relating concentration level to the area of land contaminated at or above that level. Specifically, the model involves a linear relationship between the log of concentration and the log of area contaminated at or above that concentration. This model is summarized in the equation:

$$\ln(a) = \alpha + \beta \ln(c) \qquad \text{(E-1)}$$

where:	c	=	concentration level
	a	=	area contaminated at or above that concentration level

This model provides a basis for deriving three key relationships needed for the evaluation:

$$A_r = f(C_s, \alpha, \beta, C_l) \qquad \text{(E-2)}$$

$$C_{pre} = g(\alpha, \beta, C_l) \qquad \text{(E-3)}$$

$$C_{post} = h(C_s, \alpha, \beta, C_l) \qquad \text{(E-4)}$$

where:	A_r	=	area requiring remediation
	C_l	=	minimum concentration level for which health effects should be calculated (assumed 0.01 pCi/g)
	C_s	=	cleanup level
	C_{pre}	=	pre-remediation average concentration
	C_{post}	=	post-remediation average concentration
	α	=	intercept parameter for Equation E-1
	β	=	slope parameter for Equation E-1

This appendix derives closed form expressions for the relationships summarized in Equations E-2, E-3, and E-4 above. For the uncertainty analysis, the uncertainties in α and β are propagated through these expressions to give the uncertainties in area requiring remediation, pre-remediation average concentration, and post-remediation average concentration, respectively.

E.2 Area to be Remediated

The model for area to be remediated is derived very simply from Equation E-1 above. It is assumed that the area requiring remediation is exactly that area that is contaminated at concentration levels above the cleanup level. Solving Equation E-1 for a gives:

$$a(c) = e^{\alpha} \cdot c^{\beta} \tag{E-5}$$

Solving Equation E-5 for A_r gives:

$$A_r = e^{\alpha} \cdot C_s^{\beta} \tag{E-6}$$

E.3 Pre-remedial Average Concentration

The equation for pre-remedial average concentration is also derived simply from Equation E-1 above. First note that the first derivative of the cumulative area function in Equation E-5 gives the incremental area associated with an infinitesimal decrement in concentration. The product of concentration and incremental area can be integrated over the range of concentrations and divided by total area to give average concentration:

$$C_{pre} = \lim_{C_0 \to \infty} \frac{1}{A_1} \int_{c=C_0}^{C_1} \beta \cdot e^{\alpha} \cdot c^{\beta} \cdot dc \tag{E-7}$$

which can be simplified to:

$$C_{pre} = \lim_{C_0 \to \infty} \frac{1}{A_1} \cdot \frac{e^{\alpha} \cdot \beta}{\beta + 1} \cdot [C_1^{\beta+1} - C_0^{\beta+1}] \tag{E-8}$$

Taking the limit, and assuming that β is less than -1 (which is necessary for the average concentration to be finite) produces the closed-form equation:

where:

$$C_{pre} = \frac{1}{A_1} \cdot \frac{e^{\alpha} \cdot \beta}{\beta + 1} \cdot C_1^{\beta+1} \tag{E-9}$$

$$A_1 = e^{\alpha} . C_1^{\beta} \tag{E-10}$$

E.4 Post-remedial Average Concentration

Post-remedial average concentration is derived similarly to pre-remedial average concentration. The additional assumption that is needed to derive this relationship is that, as a result of remediation, all areas with pre-remedial concentrations above the standard will have their concentrations reduced to the standard, while all areas with concentrations equal to or less than the standard will not be affected. Thus, the expression for post-remedial average concentration is broken into two parts, one representing the area weighted concentration for those areas currently at or below the standard, and one representing the area weighted post-remedial concentration for those areas that will be remediated:

$$C_{post} = \frac{1}{A_1}\left[e^{\alpha} \cdot C_s^{\beta+1} + \int_{c=C_s}^{C_1} \beta \cdot e^{\alpha} \cdot c^{\beta} \cdot dc\right] \tag{E-11}$$

which can be written in closed-form as:

$$C_{post} = \frac{1}{A_1} \cdot \left[e^{\alpha} \cdot C_s^{\beta+1} + \frac{e^{\alpha} \cdot \beta}{\beta+1} \cdot \left(C_1^{\beta+1} - C_s^{\beta+1}\right)\right] \tag{E-12}$$

The relationships derived in the equations above are depicted graphically for various levels of concentration using the best-judgment estimates of α and β.

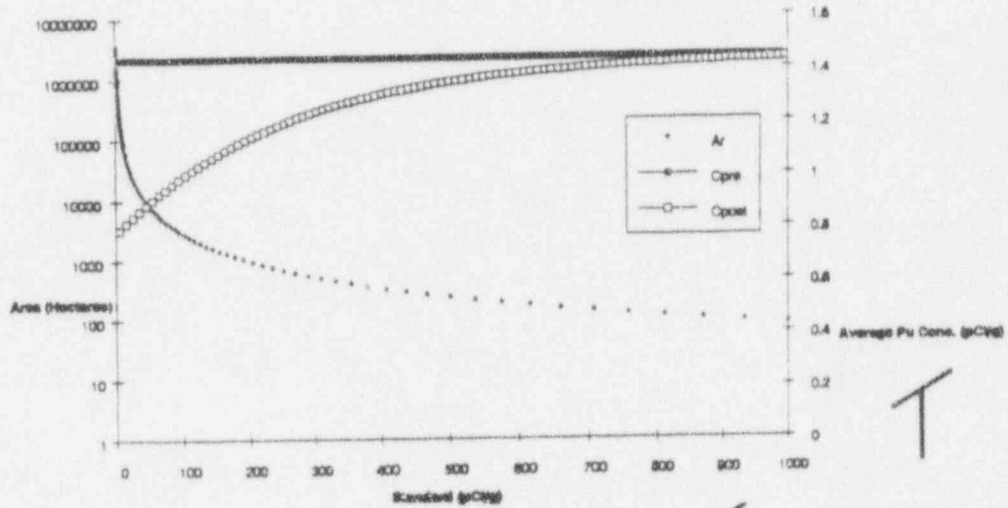

Figure E.1. Relationships Among Variables for Various Cleanup Levels Assuming Best-Judgment Values for α and β.