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A comparative study of ^{239,240}Pu in soil near the former Rocky Flats Nuclear Weapons Facility, Golden, CO

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Abstract

The Rocky Flats Nuclear Weapons Plant near Golden, CO released plutonium into the environment during almost 40 years of operation. Continuing concern over possible health impacts of these releases has been heightened by lack of public disclosure of the US Department of Energy (DOE) activities. A dose reconstruction study for the Rocky Flats facilities, begun in 1990, provided a unique opportunity for concerned citizens to design and implement field studies without participation of the DOE, its contractors, or other government agencies. The Citizens Environmental Sampling Committee was formed in late 1992 and conducted a field sampling program in 1994. Over 60 soil samples, including both surface and core samples, were collected from 28 locations where past human activities would have minimal influence on contaminant distributions in soil. Cesium-137 activity was used as a means to assess whether samples were collected in undisturbed locations. The distribution of plutonium (as ^{239,240}Pu) in soil was consistent with past sampling conducted by DOE, the Colorado Department of Public Health and Environment, and others. Elevated levels of ^{239,240}Pu were found immediately east of the Rocky Flats Plant, with concentrations falling

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rapidly with distance from the plant to levels consistent with background from fallout. Samples collected in areas south, west, and north of the plant were generally consistent with background from fallout. No biases in past sampling due to choice of sampling locations or sampling methodology were evident. The study shows that local citizens, when provided sufficient resources, can design and implement technical studies that directly address community concerns where trust in the regulated community and/or regulators is low.

Keywords: Plutonium; Cesium; Rocky Flats Plant; Historical releases; Distribution in soil; Public consultation

1. Introduction

The Rocky Flats Environmental Technology Site, formerly known as the Rocky Flats Nuclear Weapons Plant, released plutonium as well as other radionuclides and hazardous chemicals into the environment near Golden, CO, during its years of operation, 1952–1989. Long-standing community concern over possible health impacts of these releases led to a nine-year dose reconstruction study (Radiological Assessments Corporation (RAC), 1999). The Health Advisory Panel (HAP) that oversaw these studies recognized that the public considered past soil sampling studies conducted near the Rocky Flats Plant to be inadequate because (1) many studies had been conducted by the US Department of Energy (DOE), rather than an independent group or agency, and (2) prior sampling locations and techniques did not address all public concerns about past releases. The HAP created the Citizens Environmental Sampling Committee (CESC) in 1992 to provide the public with a means to address these concerns. Soil samples were collected in 1994, and a comprehensive technical report was published by the Colorado Department of Public Health and Environment (CESC, 1996). Lockhart et al. (1998) described the advantages and disadvantages of having this investigation directed by citizens. This paper focuses on ^{239,240}Pu concentrations observed in soil samples.

Soil sampling was conducted to address three questions concerning past soil sampling near the Rocky Flats Plant. First, were past sampling studies biased by the methodologies used to collect, prepare, and analyze soil samples? Second, did selection of sample locations take into account disturbances in the top several centimeters of soil? Since plutonium deposited onto soil surfaces tends to remain in the upper most soil layers unless disturbed, sampling in undisturbed soils is necessary to accurately reflect residual ^{239,240}Pu contamination from past deposition. Third, have variations in wind patterns, resuspension and deposition, and/or other factors led to deposition of significant amounts of ^{239,240}Pu in areas around the Rocky Flats Plant that have not been characterized in the past?

2. Rocky Flats Plant history

From 1952 to 1989, Rocky Flats' workers used plutonium to build nuclear weapons triggers called "pits". Weapons grade plutonium (Pu) was (mainly

^{239,240}Pu) used in these triggers remains in the environment for thousands of years after release. Workplace accidents, spills, fires, emissions, leaking storage containers, and day-to-day operations allowed plutonium and many chemicals to be released from the plant site. Two major events caused the largest releases of plutonium outside the Rocky Flats Plant boundaries. These events included a fire that occurred in the plutonium processing building in 1957, and wind-blown releases, mainly during 1968 and 1969, from an outdoor waste storage area called the 903 Area, located directly east of the main buildings at the Rocky Flats Plant.

The 903 Area contained about 5000 30- and 50-gallon steel barrels filled with waste oil and solvents that were contaminated with plutonium and uranium. Acids created in these waste barrels caused extensive corrosion. An estimated 5000 gallons of plutonium-contaminated waste oil leaked from the corroded drums onto the soil. The leaking barrels were moved in 1967 and 1968; however, contaminated soil was disturbed during the clean-up effort and left exposed for months. Researchers estimated that between 20 and 200 g (or 1.4 and 14 curie (Ci) of ^{239,240}Pu) had leaked onto the 903 Area soil. When the Rocky Flats Plant staff monitored and mapped the area in July 1968, they found soil contamination covering 22,500 m^2 (261,000 square feet, 6 acres), with the highest plutonium concentrations in the top inch of soil (Meyer et al., 1996). Windstorms in late 1968 and early 1969 blew plutonium-contaminated soil particles on- and off-site, affecting a much larger area. Subsequent soil sampling east of the 903 Area indicated that this wind-blown soil was a major contributor to off-site contamination. The amount of ^{239,240}Pu estimated to have been released to the off-site environment from the 903 Area was between 25 and 200 g (or 1.8 and 14 Ci of ^{239,240}Pu), with a median value of 52 g (or 3.7 Ci). An asphalt covering (commonly called the 903 Pad) was placed over part of the 903 Area in mid-1969 to control wind-blown contamination. However, winds continued to transport smaller quantities of plutonium not covered by asphalt. Gravel was later placed in the 903 Area east to the interior fence line to reduce subsequent wind-driven suspension of plutonium dust.

3. Methods

3.1. Sampling procedures

The CESC chose sampling locations by consensus. By means of a questionnaire containing a map of the area surrounding the Rocky Flats Plant, each committee member submitted three sampling locations. Final selection of locations included at least one from each member and took into consideration the region's history of contaminant deposition and the unique local meteorology and topography. Further details of this unique citizen-directed process are provided in Lockhart et al. (1998) and CESC (1996). A total of 28 locations were chosen for soil sampling, 16 of which were outside the area commonly sampled by other investigators. Euclidean coordinates (degrees, distance in km), with the 903 Area of the Rocky Flats

Plant as the origin, were used as site identification numbers for these sample locations (Fig. 1).

To educate themselves about specific soil sampling protocol, the CESC invited two teams of investigators, one from Colorado State University (CSU) and one from Edgerton, Germeshausen and Grier (EG&G), the plant operator at the time, to demonstrate their sampling techniques. The two methods were chosen as current examples of soil sampling employed in environmental investigations at the Rocky Flats Plant.

The CSU team collected surface samples to a depth of 3 cm at each location. The EG&G team collected several soil cores to a depth of 5 cm and combined them into a single composite soil sample, following the Rocky Flats sampling protocol (Litaor et al., 1995). Soil samples were collected by the two teams within 15 m of each other at three different sites near the Rocky Flats Plant: on the south shore of Standley Lake (309,6.4), at an area south of the Rocky Flats Plant near Leyden Reservoir (351,4.9), and in Jefferson County Open Space near the south shore of Great Western Reservoir (278,2.2). Each of the six soil samples was sieved, ground, and divided equally into three split samples by the CSU team. Each of these three replicate sets was analyzed by a different laboratory.

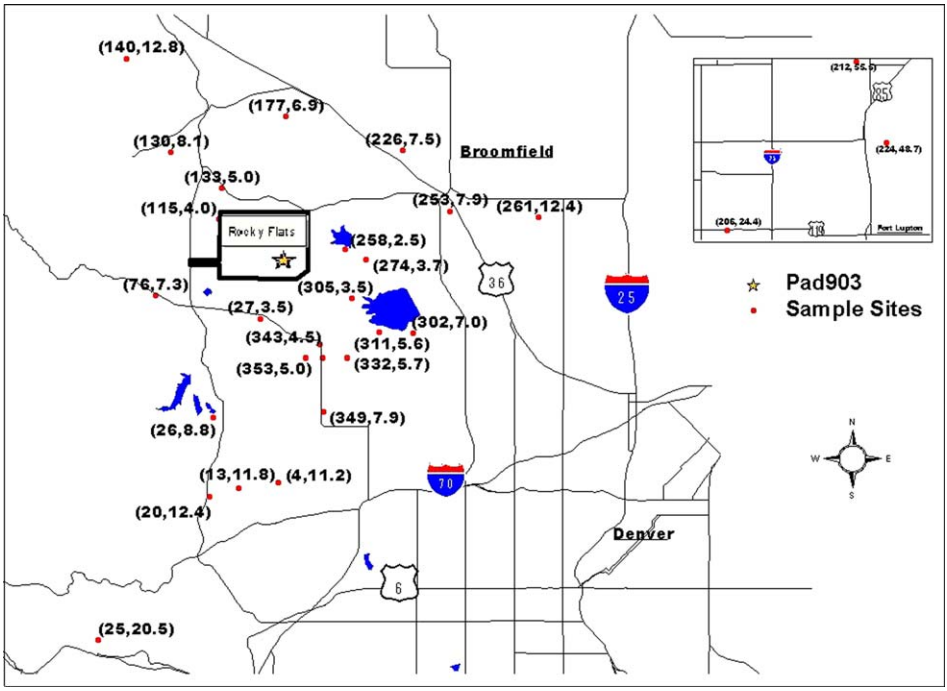

Fig. 1. Locations of CESC soil samples. Inset includes areas 45–50 km north northeast of the Rocky Flats Plant. Location identifiers include angle (Euclidean coordinates) and distance in km from the center of the plant.

The CESC and the EG&G team used different commercial laboratories, while the CSU team analyzed their set at their own university laboratory.

Based on the Committee members' observations of these sampling demonstrations, the CESC decided on a modified sampling procedure adopted from those used by previous investigators, particularly those developed by the CSU team (Ibrahim et al., 1997; Webb et al., 1997). The CESC sampling procedure was selected to allow comparisons with other studies in which surface samples were collected from the upper 3 cm, and to assess radioactivity in the soil profile (0–21 cm). The intent of the sampling was to provide a measure of ^{239,240}Pu activity in surface soils in locations where plutonium released from the plant may have deposited. Both ^{239,249}Pu and ^{137}Cs activities in surface and core samples were measured and used to assess whether sampling locations could be considered undisturbed. A brief discussion of the soil sampling procedures is presented below.

At each soil sampling location, a 25 cm × 25 cm wooden frame was placed on the ground. All vegetation was removed from within the wooden frame. A trench was then excavated to provide access to the soil to be sampled.

A 7 cm × 7 cm × 21 cm core soil sample ("B") was collected first from the front vertical wall within the framed area exposed by the access trench (Fig. 2). The "A" surface soil sample measuring 18 cm × 25 cm × 3 cm was removed from the remaining undisturbed portion of the sampling area. Co-located field duplicates were collected at three locations. A surface sample designated "C" was the co-located duplicate of an "A" sample and a core sample designated "D" was the co-located duplicate of a "B" sample.

3.2. Laboratory procedures

A commercial laboratory located in Fort Collins, Colorado, analyzed all CESC soil samples for ^{239,240}Pu and ^{137}Cs (Table 1). All samples were also analyzed for ^{238}Pu, ^{235}U, ^{238}U, and ^{241}Am, and six samples for ^{90}Sr (CESC, 1996). In addition, five standard reference material (SRM) samples, Rocky Flats Soil Number 1 (NIST, 1981), provided by CSU, were analyzed for ^{238}Pu and ^{239,240}Pu (CESC, 1996).

3.3. Quality control

Chain of custody and decontamination of all sampling equipment followed standard procedures. Since analysis involved sample destruction, analytical precision was assessed by comparing values from co-located field duplicates. Analytical accuracy was assessed by inclusion of SRM Rocky Flats soil samples.

3.4. Upper tolerance level

Measurements of global fallout concentrations of individual radionuclides in the Colorado environment give a range of values and differ by as much as an order of magnitude from sample to sample (Webb et al., 1997; Litaor, 1995; Litaor et al., 1995). These differences in part reflect the inherent non-uniform distribution of some radionuclides. Webb et al. (1997) reported background levels of ^{239,240}Pu

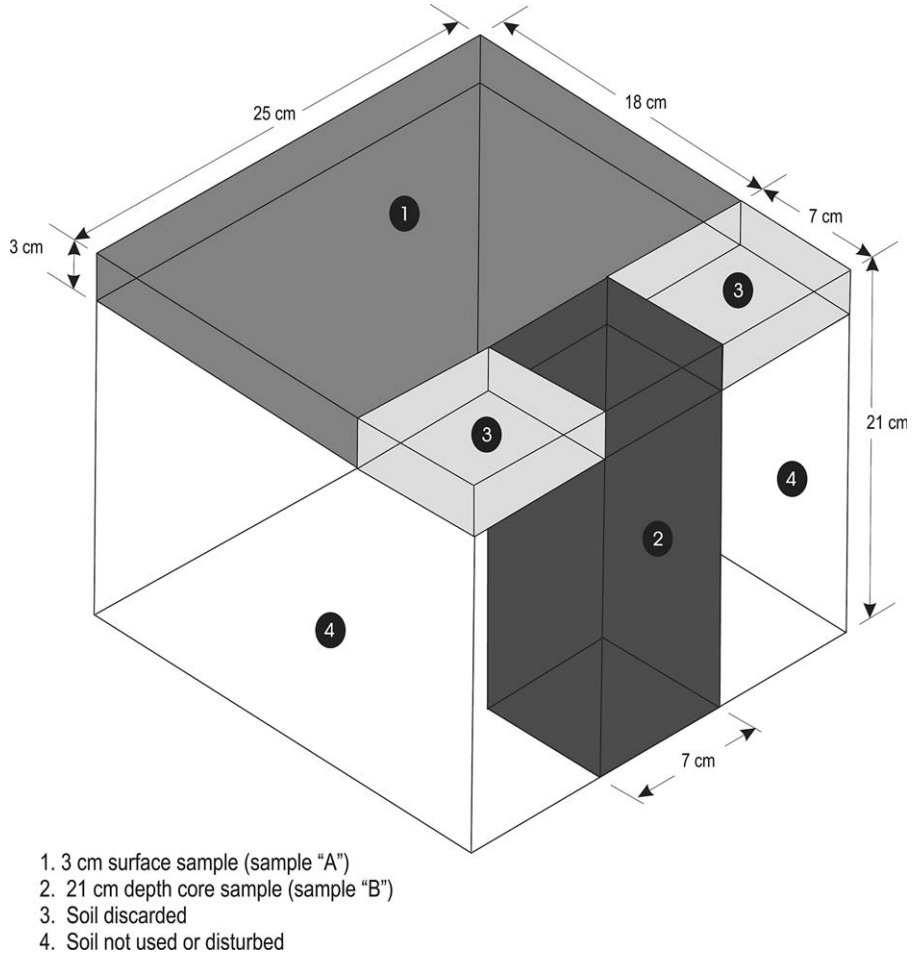

Fig. 2. Schematic of soil sampling method.

from 10 locations along the Colorado Front Range to range from 1.1 to 4.6 Bq/kg with a mean of 2.1 Bq/kg. EG&G (1995) reported background levels of ^{239,240}Pu from 50 locations along the Colorado Front Range to range from 0.63 to 2.66

Table 1
Analytical methods for CESC samples

Analyte	Minimum detectable activity (MDA)	Method
^{239,240}Pu	0.7 Bq/kg per 2 g sample	Total dissolution, ion exchange separation, micro precipitation, and alpha spectrometry (EPA, 1980)
^{137}Cs	1.5 Bq/kg per 500 g sample	Direct assay using gamma spectrometer in a calibrated geometry (EPA, 1980)

Bq/kg with a mean of 1.4 Bq/kg. Whether a soil sample with a level of ^{239,240}Pu contamination above the average but within the range is really above background is difficult to judge. In this paper, results are compared to the upper tolerance level (UTL), a statistic calculated to determine the 99% upper bound of all values within a normal distribution. The UTL for background ^{239,240}Pu reported by EG&G (1995) is 3.1 Bq/kg.

4. Results and discussion

4.1. Data quality

Accuracy of ^{239,240}Pu analysis was assessed by inclusion of SRM samples (Table 2). NIST (1981) has established standard values in Rocky Flats soil of 8.1 Bq/kg for ^{239,240}Pu for the SRM. Although two of the six SRM analyses were higher than the NIST standard value for ^{239,240}Pu (20 and 27 Bq/kg), the high values are possibly due to the inclusion of a hot particle in the sample (Litaor et al., 1995).

Precision of ^{239,240}Pu measurements was assessed by two data sets. First, results from the three replicate sets of split samples of soil collected by CSU and EG&G were in good agreement (Table 3). Second, results from the three co-located field duplicate paired samples were within reasonable limits (Table 4). Paired duplicates at sites 224,48.6 and 349,7.9 were either below detection limits or below the UTL. Paired duplicates at site 258,2.5 yielded values of 54 and 166 Bq/kg for ^{239,240}Pu. Differences of threefold are not unexpected for radiochemical analysis for low-level plutonium in adjacent samples (Webb et al., 1997; Litaor et al., 1995).

4.2. Sampling depth

Different sampling depths used by CSU and EG&G at paired sites 15 m apart gave consistent differences in ^{239,240}Pu results (Table 3). The CSU method of sampling to a 3-cm depth yielded higher ^{239,240}Pu concentrations than the EG&G method of sampling to a 5-cm depth for all paired samples, a finding significant at the ($p < 0.01$) level using a simple sign test. This trend, however, should be interpreted with caution. The difference is consistent with the observation that ^{239,240}Pu concentrations drop rapidly with depth at undisturbed locations (Litaor

Table 2
Standard reference material[a]

Sample	^{239,240}Pu (Bq/kg)
SRM 50	20
SRM 50 (duplicate)	7.8
SRM 51	6.1
SRM 52	5.7
SRM 53	27
SRM 54	10

[a] Rocky Flats Soil #1, NIST (1981) standard value = 8.1 Bq/kg.

Table 3
^{239,240}Pu activity in soil samples collected by EG&G and CSU (± value)

Location	EG&G samples			CSU samples		
	EG&G[a]	CSU[b]	CESC[a]	EG&G[a]	CSU[b]	CESC[a]
309,6.4	2.2 (0.44)	1.6 (0.23)	3.3 (0.42)	7.8 (1.1)	6.4 (0.28)	9.6 (0.87)
351,4.9	0.32 (0.15)	0.34 (0.05)	0.33 (0.13)	0.89 (0.28)	0.92 (0.08)	0.85 (0.26)
278,2.2	40 (5.4)	44 (2.6)	56 (3.9)	60 (7.4)	81 (5.4)	89 (5.7)

All activities in Bq/kg and uncertainties are ±1 sigma.
[a] EG&G and the CESC submitted soil samples to commercial laboratories for analysis.
[b] The CSU team analyzed soil samples in their own laboratories.

et al., 1994; Hulse et al., 1999), but the small differences seen (less than a factor of 6, and generally within a factor of 3), are within the range of those expected for samples collected close together at the same sampling depth (Webb et al., 1997). These results could also be due to variation in ^{239,240}Pu deposition at closely spaced locations and that the CSU and EG&G results are comparable. Thus, our results do not indicate that a substantial bias was introduced in past studies due to differences in collections depths (3 vs. 5 cm) even when the 5-cm samples were composited.

4.3. Soil disturbance: surface vs. core samples

Careful selection of sampling sites and collection of both surface and core samples at each location allowed the CESC to explore the issue of soil disturbance in a

Table 4
Probability estimates for ^{239,240}Pu concentrations at CESC sampling locations

Soil sample	^{239,240}Pu activity	Probability[a]	Soil sample	^{239,240}Pu activity	Probability[a]
258,2.5 C	166.5	0.01	25,20.5	1.2	BB
258,2.5 A	54.5	0.24	343,4.5	1.1	BB
274,3.7	11.8	0.5	302,7.0	1.1	BB
305,3.5	3.7	0.7	4,11.2	1.0	BB
133,5.0	3.3	0.36	26,8.8	0.9	BB
115,4.0	3.3	0.36	311,5.6	0.7	BB
13,11.8	3.2	NC	20,12.4	0.7	BB
177,6.9	2.7	NC	212,55	0.7	BB
76,7.2	2.3	NC	332,5.7	0.5	BB
253,7.9	2.3	0.07	353,5.0	0.5	BB
130,8.1	2.0	NC	224,48.6	0.5	BB
140,12.8	1.9	NC	261,12.4	0.5	BB
27,3.5	1.5	0.8	349,7.9	0.4	BB
345,5.2	1.4	BB	206,24.4	0.3	BB
226,7.5	1.4	BB			

All activities as Bq/kg. NC, not calculated, sampling location was outside of the modeling domain. BB, not calculated, analytical result equal to or below average background from fallout.
[a] Probability of observing a concentration as high or higher than that reported. Probabilities based on indicator Kriging model from Litaor (1995).

more rigorous manner than published studies at the time of sampling. Sampling of soil to detect residuals from air-borne releases of plutonium that occurred several decades previous is subject to considerable uncertainty. In particular, ^{239,240}Pu deposited on soil surfaces is stable in the first several centimeters of soil and theoretically should reflect past deposition (Litaor et al., 1994; Hulse et al., 1999). However, ^{239,240}Pu in surface soils may become a poor indicator of past releases if soils are disturbed through wind or water erosion, agricultural practices, construction, or other activities.

Sampling in the current study was designed to address these issues in three ways. First, general soil sampling locations were identified in areas believed to have been unaffected by human activities since the 1960s, based on historical land use and observations of long-time residents. Second, specific sampling locations were chosen in areas with significant native vegetative cover and away from obvious surface erosion features. Finally, sampling and analysis of soil included both near surface (to 3 cm) and deeper or core (to 21 cm) samples. The 3-cm sample would reflect past surface ^{239,240}Pu deposition at an undisturbed site. The 21-cm sample was intended to provide a total soil inventory. Large amounts of ^{239,240}Pu activity in deeper soils are unlikely to be due to percolation and would suggest some natural disturbance of upper soil layers by biological translocation mechanisms such as decayed root channels or earthworm activity (Litaor et al., 1994).

Activity of ^{137}Cs in surface and core samples can be used in much the same manner to assess possible past disturbance since ^{137}Cs and ^{239,240}Pu have virtually identical depth profiles in soil at undisturbed locations (Hulse et al., 1999). Cesium-137 concentrations averaged 44 Bq/kg with the five highest activities ranging from 88 to 109 Bq/kg (CESC, 1996), slightly above the UTL of 83 Bq/kg reported by EG&G (1995). However, these results are likely not different from fallout background in light of recent studies that yielded an average of 120 Bq/kg from 20 background locations from 50 km south to 50 km north of Rocky Flats along the Colorado Front Range (Hulse et al., 1999).

Concentrations of ^{239,240}Pu found in core samples (21 cm depth) were almost always less than those found in surface samples (3 cm) (Fig. 3). Ratios obtained by dividing surface results by core results fell mostly above a value of two, with many values in the range of 3 and higher. In all but two cases, surface-to-core ratios for ^{239,240}Pu and ^{137}Cs were similar. One high value (20) was observed for ^{239,240}Pu in sample 258,2.5 C and D, and a similar high value (19) was observed for ^{137}Cs in sample 177,6.9.

If all ^{239,240}Pu or ^{137}Cs at a single location is present in the upper 3 cm of soil, the ratio of surface-to-core would be 21 divided by 3 or 7, assuming that soil density was consistent throughout the upper 21 cm of soil. Actually, this ideal is not realized because (1) some plutonium and cesium will percolate into soils deeper than 3 cm and (2) small rocks encountered in core samples were discarded (Webb et al., 1997). For this analysis, a ratio of 2 was considered indicative of an intact profile. If soil density were constant, this ratio would mean that about one-third of the total activity of ^{239,240}Pu or ^{137}Cs is found in the upper 14% of the soil core.

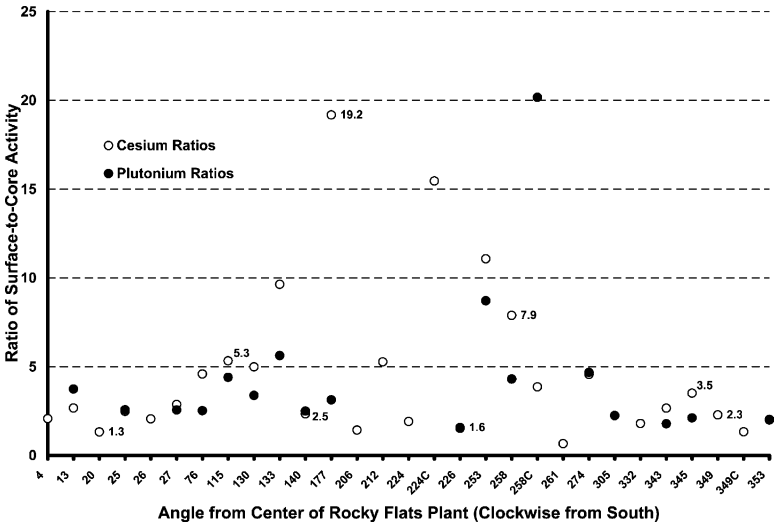

Fig. 3. Surface-to-core ratios for samples collected by the CESC. The *X*-axis includes only angle identifiers since all these identifiers are unique and sufficient to fully identify sampling location.

Surface-to-core ratios for ^{239,240}Pu and ^{137}Cs (Fig. 3) are almost all higher than one (45 out of 46 results), and most fall in the range between >1 and approximately 7 (39 of 46 results). In particular, all ratios for samples with ^{239,240}Pu activity above average background of 1.4 Bq/kg (EG&G, 1995) were 2.2 or higher. Most soil sample results thus indicate that a high percentage of total ^{239,240}Pu and ^{137}Cs activity was present in the upper 3 cm of soil. This finding is consistent with soil that has been undisturbed since the early 1960s and thus a possible bias in previous studies caused by sampling in "disturbed" areas is not reflected in our results.

4.4. Plutonium deposition patterns

The third question for the CESC was whether variations in wind patterns, resuspension and deposition, and/or other factors might have led to deposition of significant amounts of ^{239,240}Pu in areas around the Rocky Flats Plant that had not been previously characterized. This possibility was addressed by selecting a variety of sampling locations both east of the plant and in other areas generally not sampled in the past. Samples collected east of the plant would allow comparison of the current sampling results with those of past studies. Other samples would provide some information on the possibility that ^{239,240}Pu in surface soils might be found at elevated levels in areas south, west, and north of the plant. Finding substantial ^{239,240}Pu in these areas would be contrary to the prevailing theory that Rocky Flats-related plutonium can only be detected above background from fallout in a plume extending generally east of the Rocky Flats Plant.

Using a soil sampling method adapted from that used by CSU, soil samples were collected from 28 locations and analyzed for ^{239,240}Pu and ^{137}Cs (Table 4). Most of the sampling results were in the range consistent with background from fallout from atmospheric nuclear testing. Seven values for ^{239,240}Pu activity in surface samples exceeded the UTL of 3.1 Bq/kg (EG&G, 1995).

Contours for estimated ^{239,240}Pu activity around the former Rocky Flats Plant based on previous work are illustrated in Fig. 4. Litaor (1995) calculated these estimates using indicator kriging for a comprehensive dataset. Using the same kriging analysis, separate estimates of probability of detecting a concentration as high or higher than those found in the CESC's soil samples are provided in Table 4. For these analyses, a probability of 0.5 would indicate that the observed value matches the value expected based on Litaor's model. Likewise, probabilities of 0.1 and 0.9 would indicate that the observed values were higher and lower than expected, respectively. Two samples located near Great Western Reservoir (258,2.5 and 253,7.9) appear to be outliers, in that these results are only expected in their locations with low probability. That is, these values appear to be higher than expected based on historical data. Note that contours west of the 903 Pad become increas-

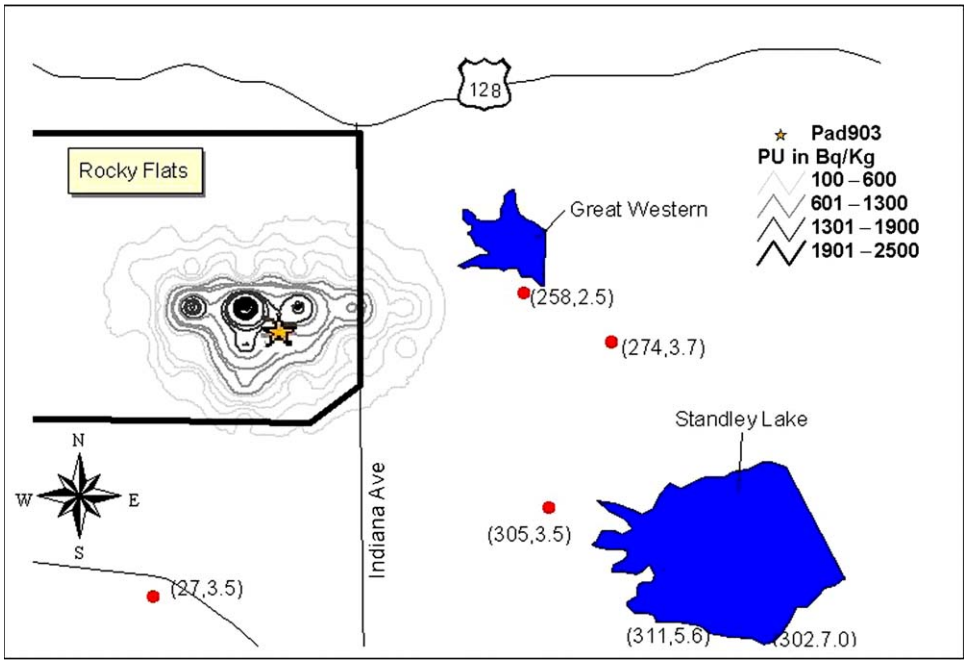

Fig. 4. Comparison of estimates from Litaor et al. (1995) and results from surface samples collected by the CESC. Isopleths represent the 50% probability contours for given ^{239,240}Pu concentrations (recalculated from Litaor, 1995). Overlain on the contours are locations for CESC soil samples collected within Litaor's modeling domain. Contours to the west of Pad 903 uncertain due to the paucity of soil data available for locations west of the Rocky Flats Plant.

ingly uncertain due to relative paucity of historical data collected to the west of the Pad. This analysis considers only contours to the east of the Pad.

The sample at 258,2.5 C was collected at a location within 0.5 m from sample 258,2.5 A. Activity of ^{239,240}Pu at 258,2.5 C (166 Bq/kg) was about 3 times that in the sample from 258,2.5 A (54 Bq/kg). The difference could be explained by a "hot particle", a soil particle with unusually high ^{239,240}Pu content, in the sample collected at 258,2.5 C. As observed in the SRM samples (Table 2) obtained from Rocky Flats, a small percentage of aliquots of soil can show unusually high activity (McDowell and Whicker, 1978; NIST, 1981), which is apparently due to such particles.

This explanation is consistent with the high surface-to-core Pu ratio for sample 258,2.5 C (~20). If a hot particle occurred in the upper 3 cm of soil, such a high ratio would be expected. The high ^{239,240}Pu ratio does not seem to be associated with unusual soil disturbance, since the surface-to-core ratio for ^{137}Cs (3.9) was in the same range as most other samples.

The ^{239,240}Pu activity observed in sample 253,7.9 is difficult to interpret. Litaor's model loses sensitivity with distance from the Rocky Flats Plant, because soil concentrations drop to levels consistent with background from fallout within a few km of the eastern edge of the plant. The kriging algorithms used by Litaor are based on relationships of ^{239,240}Pu activities at one point with others at various distances from that point. When activities in an area vary about a mean background level, spatial discrimination in the model is reduced. The activity at site 253,7.9 (2.3 Bq/kg) is within the range of background reported by EG&G (1995), 0.63–2.66 Bq/kg, and confidence that the model can accurately predict the probability of exceeding a given value in the background range is low.

The highest result from among CESC samples that is not subject to a concern of a hot particle is that for sample location 258,2.5 A (54.5 Bq/kg). Surface-to-core ratios for both ^{239,240}Pu and ^{137}Cs are similar and in the range observed in other samples (Fig. 3). Contours representing the probability to exceed the cutoff ^{239,240}Pu level of 54.5 Bq/kg are illustrated in Fig. 5. Probability values represent the spatial uncertainty involved in the indicator Kriging model (Litaor et al., 1995). The value of 54.5 Bq/kg is expected at its location near the south shore of Great Western Reservoir with a probability of greater than 20%. This result is somewhat unusual, but not statistically significant.

Other results from a nearby location, 278,2.2, are provided in Table 3. The average ^{239,240}Pu activities in these samples were 47 and 76 Bq/kg for samples collected by EG&G and CSU, respectively. These activities are expected with probabilities somewhat greater than and somewhat less than 20%, respectively. Samples taken at and near location 258,2.5 therefore present a consistent picture of ^{239,240}Pu contamination, although both activities reported may be somewhat higher than expected according to Litaor's model.

Samples collected outside of Litaor's modeling domain are all consistent with background from atmospheric testing of nuclear weapons in the early 1960s. In fact, all of these samples showed ^{239,240}Pu activity below the UTL for background plutonium of 3.1 Bq/kg estimated by EG&G (1995). It should be noted that these

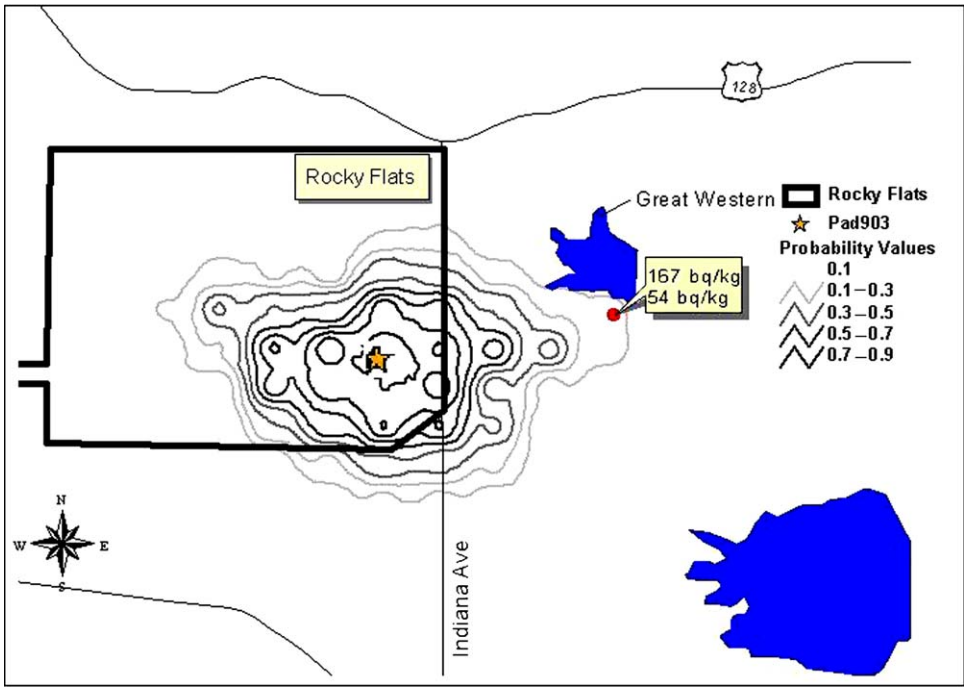

Fig. 5. Probability plot for ^{239,240}Pu concentration of 54.5 Bq/kg. Isopleths connect locations of equal probability of observing an activity of 54.5 Bq/kg or higher, based on Litaor et al. (1995).

low results do not prove that Rocky Flats related plutonium has not migrated outside of Litaor's modeling domain. ^{240}Pu:^{239}Pu isotopic ratio data, which distinguish Rocky Flats plutonium from fallout plutonium (Krey, 1976; Litaor, 1999), have shown Rocky Flats-related plutonium to migrate as far as 19 km east of the plant (Ibrahim et al., 1997).

One hypothesis advanced by a member of the CESC was that night-time air flows north along the South Platte River valley might have carried ^{239,240}Pu particles many kilometers to areas where the valley widens and wind velocities drop. At this point, small particles might have deposited onto soil. The two samples collected at the first significant widening in the valley (224,48.6 and 212,55.0) show no evidence that this mechanism was important in distributing ^{239,240}Pu from Rocky Flats.

4.5. Other radionuclides

Soil samples collected by the CESC were also analyzed for ^{238}Pu, ^{235}U, ^{238}U, ^{241}Am, and ^{90}Sr. None of the results yielded high enough soil concentrations of these isotopes to suggest that further investigation was necessary. Complete results from analyses of these isotopes as well as for ^{239,240}Pu and ^{137}Cs are available in CESC (1996).

5. Conclusions

The findings of this work answered the three questions posed at the beginning of this paper.

1. Our results do not demonstrate a substantial bias in past sampling studies at Rocky Flats due to differences in methods of collection (such as sample depth), preparation, or analysis of soil samples for ^{239,240}Pu. Samples collected to a depth of 5 cm could, however, yield results somewhat lower than those collected to 3 cm in undisturbed locations.
2. A bias in previous studies caused by sampling in "disturbed" areas is also not reflected in our results. The current sample locations are reasonably characterized as undisturbed and present a picture of distribution of contamination similar to that shown by the comprehensive data set used to build Litaor's model. No trend toward higher or lower values is evident in the CESC's results compared to those of previous investigations.
3. Results in this paper correlate well with concentrations and distribution of ^{239,240}Pu reported by previous investigators and summarized and analyzed by Litaor et al. (1995). Overall, data collected in this study were consistent with prior results in areas known to have been affected by past releases. Activity of ^{239,240}Pu in soil close to the eastern edge of the Rocky Flats Plant boundary was 10–100 times higher than average background from fallout. Farther from the Rocky Flats Plant to the east, and at locations south, west, and north, concentrations of ^{239,240}Pu were much lower, and generally within the range of background from fallout. Samples from the 16 locations not previously sampled yielded results that matched expected patterns of environmental distribution of ^{239,240}Pu. Still, areas immediately south and southwest (2–10 km) of the Rocky Flats Plant have only been sparsely sampled, compared to areas east of the plant, by this and previous studies.

This study demonstrates that a committee of interested citizens, with sufficient technical support and funding, can design and carry out a field sampling study that provides useful data on environmental contamination. Citizen involvement bridges a common gap that exists between a wary public, which at times sees itself as a victim of environmental mismanagement, and agencies of government which have the power to affect the condition of that environment. The results of the present study increase the confidence that the public can place in sampling results presented by both the DOE and regulatory agencies for the area surrounding the Rocky Flats Plant.

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