DP-MS-75-30
IAEA-SM-199/85
Conf-751105--13

RELATIONSHIPS AMONG PLUTONIUM CONTENTS OF SOIL, VEGETATION, AND ANIMALS COLLECTED ON AND ADJACENT TO AN INTEGRATED NUCLEAR COMPLEX IN THE HUMID SOUTHEASTERN UNITED STATES

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A Paper for Presentation at the
Symposium on Transuranium Nuclides in the Environment
to be held in San Francisco, California on
November 17-21, 1975 and for publication
in the *Proceedings*.

This paper was prepared in connection with work under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.

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ABSTRACT

RELATIONSHIPS AMONG PLUTONIUM CONTENTS OF SOIL, VEGETATION, AND ANIMALS COLLECTED ON AND ADJACENT TO AN INTEGRATED NUCLEAR COMPLEX IN THE HUMID SOUTHEASTERN UNITED STATES

Twenty-three representative sampling locations on and adjacent to the Savannah River Plant (SRP) site were selected to obtain information on plutonium movement in the food chain under southeastern U. S. environmental conditions. Soil, a resuspendible fraction of the soil, honeysuckle *(Lonicera japonica)*, and camphor weed *(Heterotheca subaxillaris)* were collected at each location. Grasshoppers and cotton rats *(Sigmodon hispidus)* were collected at some locations. The plutonium concentrations in soil at the selected locations ranged from 1.5 fCi/g to 171 fCi/g, and alpha percentages of ^{238}Pu ranged from 2 to 66. The concentration of plutonium in the vegetation and on the leaves ranged from 0.17 to 76.1 fCi/g, and the alpha percentages of ^{238}Pu, from 3 to 61. The concentration of plutonium in cotton rats and grasshoppers ranged from 0.07 to 3.58 fCi/g, and the alpha percentages of ^{238}Pu ranged from 22 to 80.

The average ratio of plutonium concentration of vegetation to that of the surrounding soil was 10^{-1}; the corresponding ratio for cotton rats and soil was 10^{-2}. These ratios appear to be independent of the plutonium concentration in the soil. Deposition on the surfaces of leaves and stems was the principal mechanism of plutonium contamination of vegetation. Comparisons among the plutonium values of the vegetation, soil, and resuspendible fraction suggest the use of a proposed resuspendible measurement technique as a monitoring method to indicate subtle changes in the plutonium concentration of the soil surface that are not detectable by routine soil sampling. Although the ^{238}Pu data in the various ecosystem components were not conclusive, they do support evidence presented in other studies that there is an apparent increase in the biological availability of ^{238}Pu relative to that of ^{239,240}Pu in the environment. The plutonium concentrations of all ecosystem components decreased as the distance from the reprocessing plants increased.

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INTRODUCTION

Plutonium behavior in terrestrial ecosystems in the United States has been studied principally in arid areas using plutonium from weapons tests [1,2]. Results of those studies are not directly applicable to the humid, heavily vegetated climates of the southeastern United States and to plutonium from an operating nuclear fuel reprocessing plant.

The Savannah River Plant (SRP) provides a unique opportunity within the humid southeastern United States to study the behavior of plutonium in the environment. SRP is on a reservation of 77,830 hectares. Public access to the reservation is controlled. The reservation consists of fresh-water streams, old fields, and forests. Wildlife, including a deer herd of 6,000, abounds. For over 20 years this integrated nuclear complex has included nuclear reactors (three of original five are operating at present), two nuclear fuel reprocessing plants, a fuel fabrication facility, a heavy water production unit, and a nuclear research laboratory. The reprocessing plants, along with global fallout, are the sources of the plutonium that enters SRP environs. Each source releases plutonium of unique isotopic composition: 95 and 25 α% ^{238}Pu* from reprocessing plants, compared with 10 α% ^{238}Pu from global fallout. These isotopic differences provide a convenient basis for studying the origin and transport of plutonium that is found in the SRP ecosystem.

An extensive environmental monitoring program at SRP has provided information on the plutonium content of soil [3]. This monitoring program was used to establish a background concentration of plutonium in SRP soil of approximately 2 mCi/km^2. This concentration is well within the range reported for the southeastern United States [4]. Results of the monitoring program were used to construct idealized isopleths showing plutonium deposition starting at the nuclear fuel reprocessing areas and decreasing toward the plant perimeter (Figure 1). These isopleths represent plutonium concentrations that range from a background level of approximately 9 fCi/g to a high of 2740 fCi/g adjacent to one of the nuclear fuel reprocessing facilities.

The objective of the study discussed in this paper was to establish relationships among the plutonium contents of soil, vegetation, and animals. To obtain food chain information, sampling locations were selected by utilizing

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* $$\alpha\ \%\ ^{238}\mathrm{Pu} = \frac{^{238}\mathrm{Pu\ alpha\ activity}}{\mathrm{Total\ Pu\ alpha\ activity}} \times 100$$

the established isopleths. At each location, samples of soil and two types of vegetation (camphor weed and honeysuckle) were taken. At selected locations, grasshoppers and cotton rats were also collected.

METHODS AND MATERIALS

Characteristics of Sampling Locations

Twenty-three sampling locations were selected: 5 within the 3-mCi/km^2 soil isopleth, 8 within the 2-mCi/km^2 isopleth, and 10 at a 40-km radius surrounding SRP (Fig. 2 and 3). Each sampling location was chosen on the basis of its vegetation and animal habitat. The location criteria required a non-forested, undisturbed area with a good vegetation cover. Locations were selected with sufficient distances between them that cotton rat populations would not overlap.

Sampling Methods and Preparation

Soil

Composite soil samples of ten cores were taken at each of the 23 sampling locations according to the procedures described by McLendon [3].

Resuspendible material was collected at the surface of each location with a special sampler. These samples represent the material on the soil surface that could be dispersed in the atmosphere. The sampler had a 232-cm^2 head attached to a small, portable vacuum cleaner that produced an average wind speed of 6 m/sec. The resuspendible material was oven-dried, ashed, and analyzed for plutonium according to previously developed procedures [5,6,7].

Vegetation

Honeysuckle *(Lonicera japonica)* and camphor weed *(Heterotheca subaxillaris)* were collected in July 1975, in the vicinity of the soil sampling locations to determine plutonium content of vegetation. Honeysuckle was chosen because of its acknowledged dietary preference by deer during the summer months. Camphor weed was used as the second type of vegetation because of its abundance and because it has been shown to be extensively grazed by numerous insects [8]. Approximately 200 to 300 grams of dry weight for each species were taken by clipping the vegetation at ground level. Each sample was oven-dried, ashed, and analyzed for plutonium by the same method as used for the resuspendible material.

Insects and Animals

Grasshopper samples (approximately 30 g dry weight) were collected in late August 1975 when the grasshopper population had peaked because sufficient samples for analysis could not be obtained earlier. Because of the limited time remaining for analysis, only three samples were collected. Two were from the areas immediately surrounding the nuclear fuel reprocessing areas, and one was at a distant location to serve as a control. Approximately 100 to 150 grams of grasshoppers were collected from each area. Each sample was oven-dried, ashed, and analyzed by the same method as was used for analyzing the resuspendible material.

Cotton rats *(Sigmodon hispidus)* were sampled at 9 locations. Distances between these locations were sufficient to ensure that they represented distinct populations with a negligible chance of animal movement from one location to another. Approximately 10 to 20 cotton rats were collected from each location and divided into juvenile (<40 g dry weight) [9], immatures (40 to 90 g dry weight), and adults (>90 g dry weight). Plutonium concentrations of rats from each area were determined if sufficient sample was available. Cotton rats were frozen upon capture and later thawed, dipped in paraffin to reduce mobility of surface-deposited plutonium, and skinned. The gastrointestinal tract was removed from the remaining carcass. Tissues around any wound were also excised. Plutonium concentrations of the rat carcasses (skin and gastrointestinal tract removed) were determined by the same technique as was used for analyzing the resuspendible material. Measured plutonium concentrations should represent both uptake and lung contamination.

RESULTS

Soil

The plutonium concentrations of the soil core samples (0-15 cm depth) varied widely and generally reflected the sampling distance from plutonium sources at SRP. The concentrations range from offplant lows of 0.2 fCi ^{238}Pu/g* and 1.3 fCi ^{239}Pu/g** to onplant highs of 46.4 fCi ^{238}Pu/g and 163.8 fCi ^{239}Pu/g (Table I).

The plutonium concentrations of the resuspendible materials showed the same variation with distance from the sources (Table I) as the soil core samples. However, the concentrations on a per gram basis were generally higher than those of soil core samples.

The offplant concentrations are consistent with concentrations for fallout plutonium reported for this latitude band (30° to 40°) [4].

Vegetation

The plutonium concentrations of honeysuckle and camphor weed samples decreased with increasing distance from the SRP sources (Table II). The concentrations for honeysuckle ranged from 0.03 fCi ^{238}Pu/g and 0.27 fCi ^{239}Pu/g

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* All samples weights were dry weights.
** All ^{239}Pu analyses include ^{240}Pu also.

offplant to 10.9 fCi $^{238}Pu/g$ and 15.1 fCi $^{239}Pu/g$ onplant. The concentrations for camphor weed ranged from 0.01 fCi $^{238}Pu/g$ and 0.16 fCi $^{239}Pu/g$ offplant to 18.5 fCi $^{238}Pu/g$ and 74.9 fCi $^{239}Pu/g$ onplant. Both species showed a wide range in α% ^{238}Pu reflecting the existence of one or more plutonium sources in conjunction with global fallout.

Insects and Animals

The two grasshopper samples collected near nuclear fuel reprocessing plants contained detectable plutonium concentrations (Table III), but the plutonium concentration of the control sample was less than the analytical detection limit (1 fCi per sample).

The plutonium concentrations of the adult rat samples ranged from less than detectable ^{238}Pu* and 0.05 fCi $^{239}Pu/g$ to 0.69 fCi $^{238}Pu/g$ and 0.96 fCi $^{239}Pu/g$. Generally, the plutonium contents of the juvenile and immature samples were similar to those of adult samples, and the α % ^{238}Pu of all age classes were similar. However, samples of all age classes were available from only four sampling locations.

DISCUSSION

Plant-Soil Relationships

Numerous studies on the relationship between the plutonium contents of vegetation and soil have been reported. Most of the studies were conducted in the laboratory and showed uptake factors** ranging from 10^{-6} to 10^{-4} [1,10,11,12]. Romney [13] and Buchholz [14] reported that the uptake factor increases with time when Ladino clover is repeatedly harvested from the same soil; however, similar cropping studies with alfalfa showed no obvious trends. A few studies have been concerned with the relationship between the plutonium content of the vegetation and the soil under field conditions. Hakonson, et al. [15] reported plutonium concentration ratios (vegetation-to-soil) of 10^{-2} and 10^{-1} for plants grown on plutonium-containing sediments under field conditions. Johnson, et al. [16] reported similar plant/sediment plutonium concentration ratios for plants grown in aquatic environments at Rocky Flats. From the data available for the vegetation and soil, a concentration ratio of 10^{-1} can be determined for the present study (Table V). This ratio is not significantly affected by distance from the reprocessing plants.

An examination of α% ^{238}Pu data (Tables I and II) indicates that deposition on the surfaces of vegetation is the principal mechanism contributing to the

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* Analytical detection limit = 1 fCi/sample.

** $$\text{Uptake Factor} = \frac{\text{Pu concentration in vegetation, Ci/g of dry vegetation}}{\text{Pu concentration in soil, Ci/g of dry soil}}$$

plutonium content. For example, at Sample Location 1 (0.5 km from source), values of α% ^{238}Pu were 57% in soil, 55% in resuspendible material, and 20% in vegetation. Because the nearest SRP source for that area has an α% ^{238}Pu value of 25%, the vegetation, the youngest component of the sampling area, shows the deposition of plutonium from the nearest SRP source along with fallout, and the soil and resuspendible material show the influence of earlier releases. That deposition is the principal mechanism of plutonium entry into vegetation is further established with the information obtained from Sample Location 3 (1.3 km from source). The soil in this area has an α% ^{238}Pu of 21%; the resuspendible material, 66%; and vegetation, 60%. The source affecting this area is approximately 95% ^{238}Pu. Atmospheric particulates in this area, collected on tacky paper, show an α% ^{238}Pu of 59 ±19% indicating a dilution of plutonium from the SRP source with global fallout [17]. Vegetation and resuspendible material for this area reflect the deposition of this fallout, and the soil shows the accumulation of years of plutonium input from the source and global fallout. If uptake were a principal mechanism, the α% ^{238}Pu determined for vegetation would reflect the plutonium composition of the soil.

Although at greater distances the advantages provided by the differences in α% ^{238}Pu are no longer present, similar concentration ratios are calculated. This observation supports the conclusion that surface deposition on vegetation is the principal mechanism leading to the observed plutonium values.

Animal-Soil Relationships

Numerous investigators report the toxicity and behavior of plutonium in laboratory animals [2], and a few report plutonium content in field animals [10]. However, little information is available for determining relative plutonium contents of animals and soil. From the plutonium analyses available for the three grasshopper samples and the eight adult rat samples, a concentration ratio of animal plutonium to soil plutonium of about 10^{-2} can be calculated (Table VI). That ratio appears to be independent of the amount of plutonium in soil and could therefore provide an approximation of the plutonium content in animals where soil concentrations of plutonium are known.

Resuspendible Material

Analysis of resuspendible material is rapidly and easily conducted. The α% ^{238}Pu varies more in resuspendible material than in any other ecosystem component analyzed. This variation suggests the utilization of plutonium analyses of resuspendibles as a monitoring method to detect small changes in the plutonium concentration of surface soils not detectable by sampling soil cores or vegetation.

Biological Availability of ^{238}Pu

Comparison of the α% ^{238}Pu values for rat carcasses, soil, vegetation, and resuspendible material suggests an apparent increase in the biological availability of ^{238}Pu relative to ^{239}Pu in the environment (Table VII). Although these data are not statistically conclusive, they support evidence presented in other studies. Hanson [18] postulated several theories to explain the apparent increased availability of ^{238}Pu. In his theory development, he used the data of Hakonson and Johnson [19], who have reported $^{238}Pu/^{239}Pu$ ratios of 0.05 in soils, 0.10 in vegetation, and 1.0 in animal components of the Trinity Site ecosystem. At this time, further study of natural systems is needed to provide a firmer statistical base for Hanson's hypothesis.

Plutonium Distribution With Distance From the Reprocessing Plant

Because the plutonium concentrations of camphor weed, honeysuckle, soil, and resuspendibles are all higher near sources and decrease as the distance from the source increases, regression equations of the following form were fitted to the data as shown in Fig. 4 through 7, and the line is described by the equation

$$\ln Y = b_0 + b_1 \ln d$$

where Y = total plutonium concentration in soil, resuspendible material or vegetation; b_0 = concentration of plutonium at 1 km from the source; b_1 = slope of linear relationship between ln Y and ln d; and d = distance from the nearest source. These equations permit one to estimate the plutonium concentration of the various ecosystem components out to 10 km with a high degree of confidence. Total plutonium concentrations of samples from the 40-km radius are not related to distance from the SRP sources.

None of the slopes of the regression equations in Fig. 4 through 7 are significantly different from -1 (t test of slopes where $P > 0.05$ [20]), indicating that concentrations are approximately proportional to 1/d. A consideration of simple diffusion processes from a single point source suggests that concentrations should be proportional to $1/d^2$. The reason for this difference is not known at the present time.

Adult cotton rats that were collected from eight onplant study locations also show a decrease in plutonium content as distance from the source increases. The regression equation describing this distribution has the coefficients $\hat{b}_0 = -0.72$ and $\hat{b}_1 = -0.78$ ($r^2 = 0.761$; df = 6; $P < 0.01$), where $\hat{b}_0$ and $\hat{b}_1$ are the least squares estimators of b_0 and b_1. The $\hat{b}_1$ estimate is not significantly different from -1, indicating that the decrease in the plutonium concentration observed for the cotton rats is similar to that observed for vegetation, resuspendible material, and soil.

The estimates of $\hat{b}_1$ for the regression equations in Fig. 4 are not significantly different from each other (Test of Homogeneity of Regression Coefficients: $F = 0.84$, df = 3.32, and $P > 0.05$ [20]). Since $\hat{b}_1 = -1$, then a general equation can be written for each ecosystem component i, as follows:

$$\ln \mathrm{Conc}(i) = a(i) + (-1) \ln d,$$

where a(i) changes for different ecosystem components. For any two components i and j

$\ln \mathrm{Conc}(i) - \ln \mathrm{Conc}(j) = [a(i) - \ln d] - [a(j) - \ln d]$, which may be simplified to

$$\ln (\mathrm{Conc}(i) - \ln \mathrm{Conc}(j) = a(i) - a(j)$$

Since $a(i) - a(j) = \mathrm{Constant} - k$

$$\frac{\mathrm{Conc}(i)}{\mathrm{Conc}(j)} = e^k$$

This relationship is specific for the choice of i and j component. Thus, the similarity of the $\hat{b}_1$ values implies that the plutonium concentration ratios between ecosystem components are nearly equal throughout the areas influenced by SRP sources. This finding is unexpected because the two reprocessing plants at SRP release plutonium of different isotopic composition. The similarity of concentration ratios between ecosystem components indicates that plutonium from the various sources behaves in a similar fashion and that plutonium concentration ratios calculated from the data are of wide applicability in the Southeast.

IMPLICATIONS FOR FUTURE STUDIES

If knowledge of the fallout and resuspension at each sampling location or an equation relating fallout and resuspension to distance from the source were available, it would be possible to develop a simple model for predicting plutonium concentrations of ecosystem components. Because the geography, soil types, and species sampled are typical of the southeastern United States, this model would be of general applicability to the Southeast. Work currently under way at Savannah River should produce the necessary information for such a model.

ACKNOWLEDGEMENT

The information contained in this article was developed during the course of work under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.

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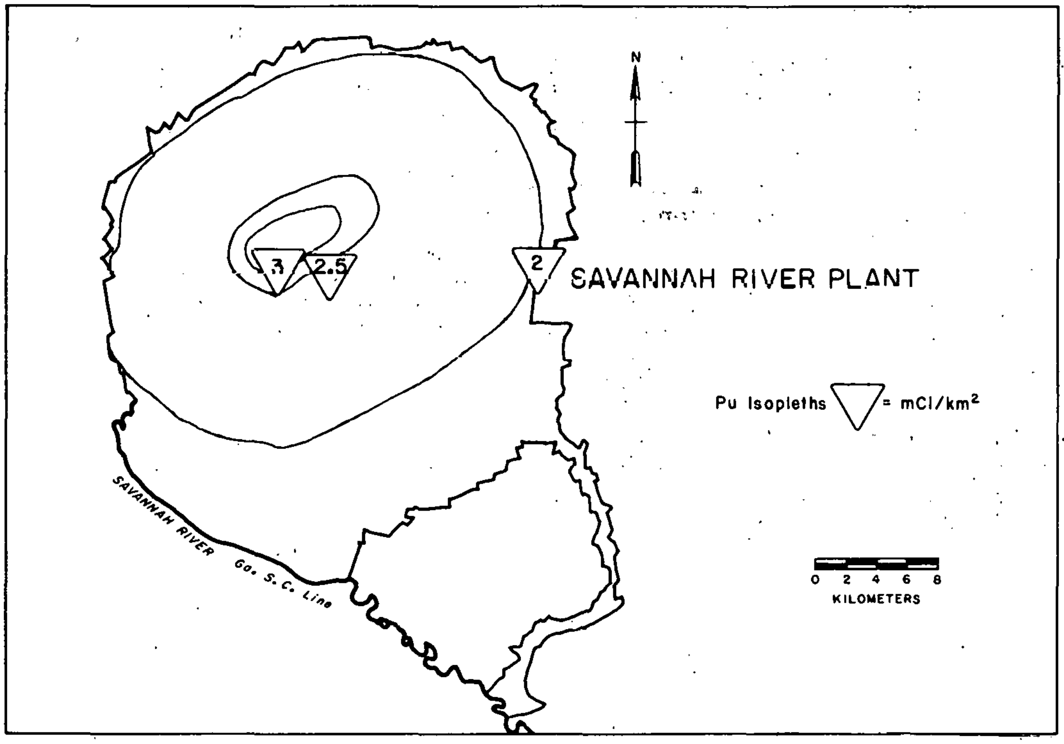

FIG. 1. PLUTONIUM DEPOSITION ON THE SAVANNAH RIVER PLANT

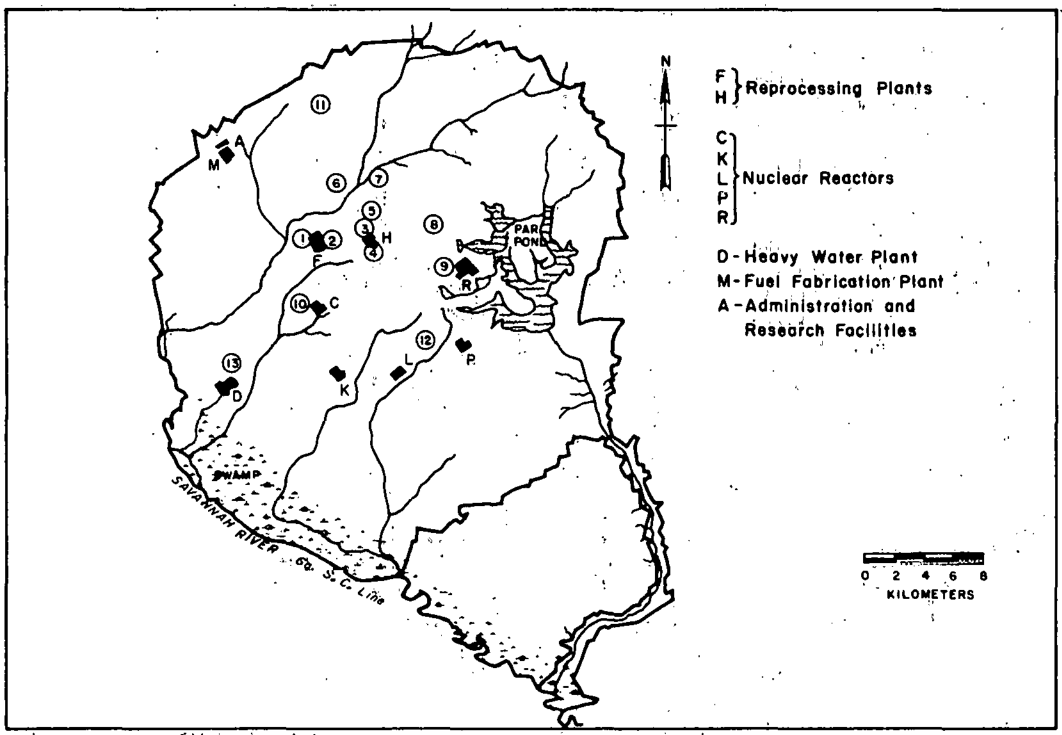

FIG. 2. ONPLANT SAMPLING LOCATIONS

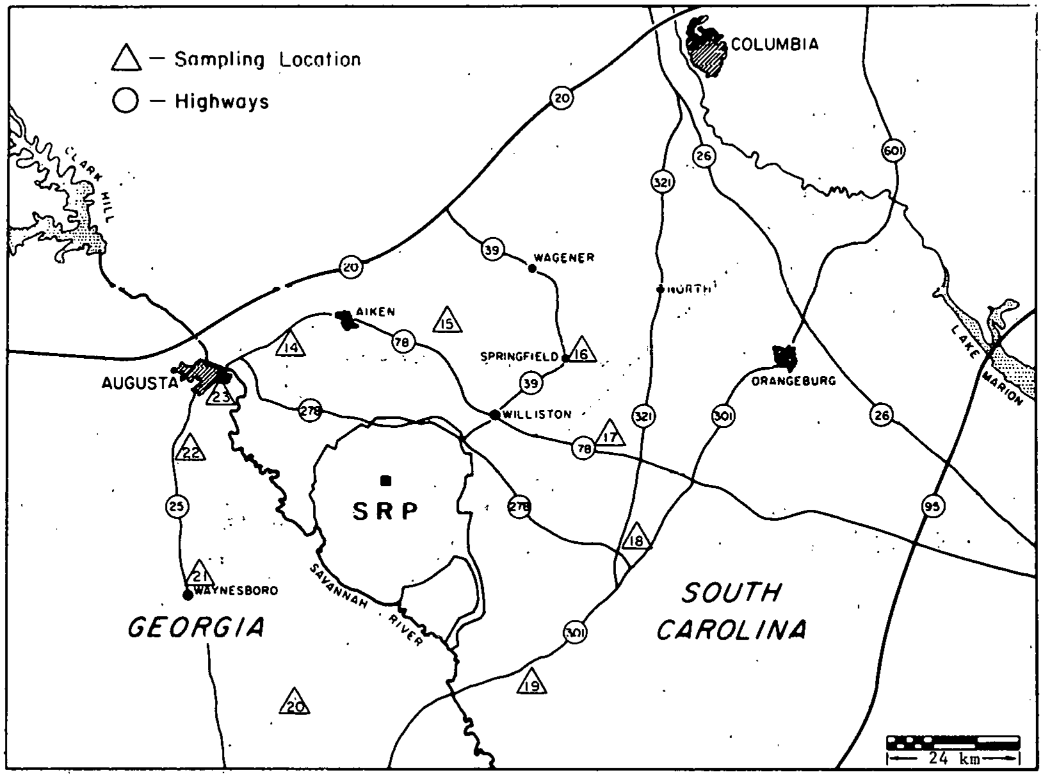

FIG. 3. OFFPLANT SAMPLING LOCATIONS

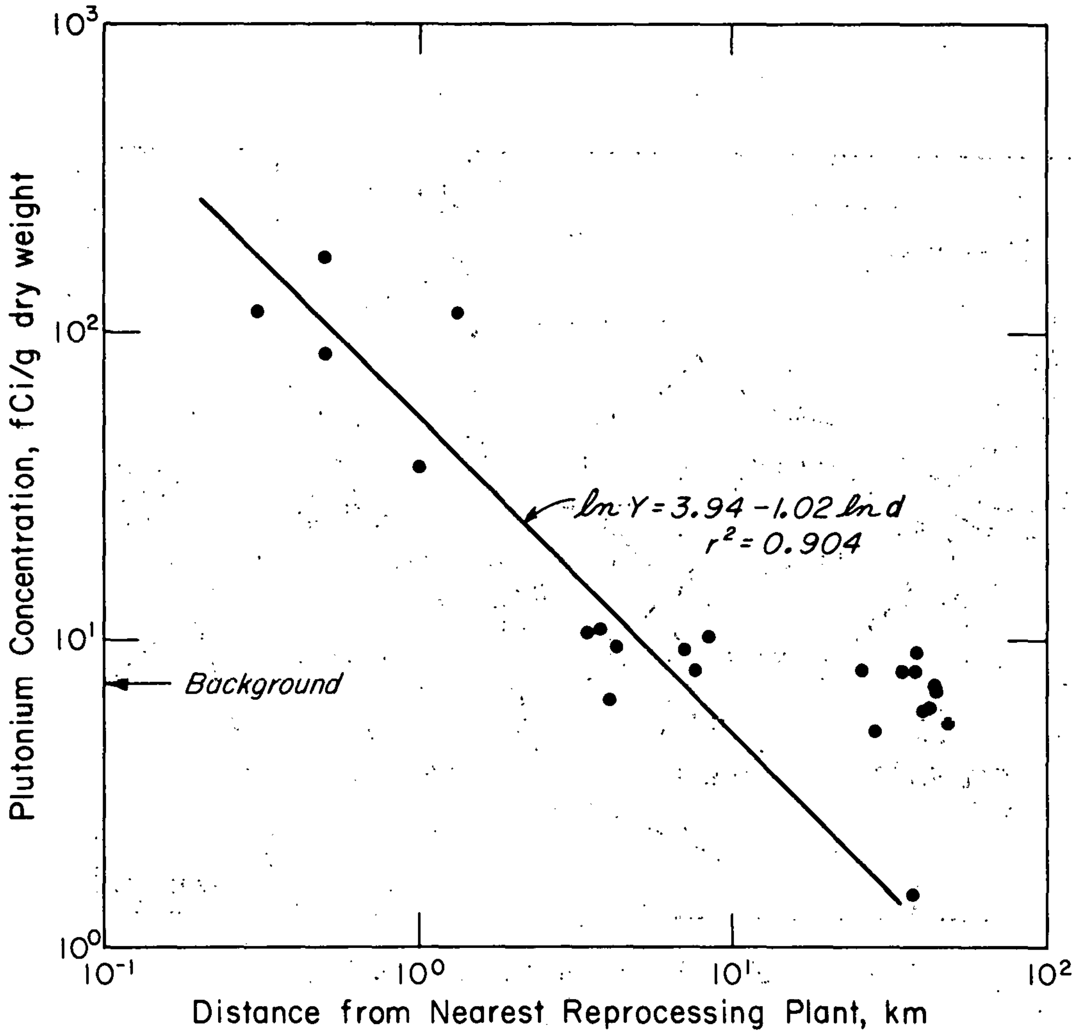

FIG. 4. RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF SOIL AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

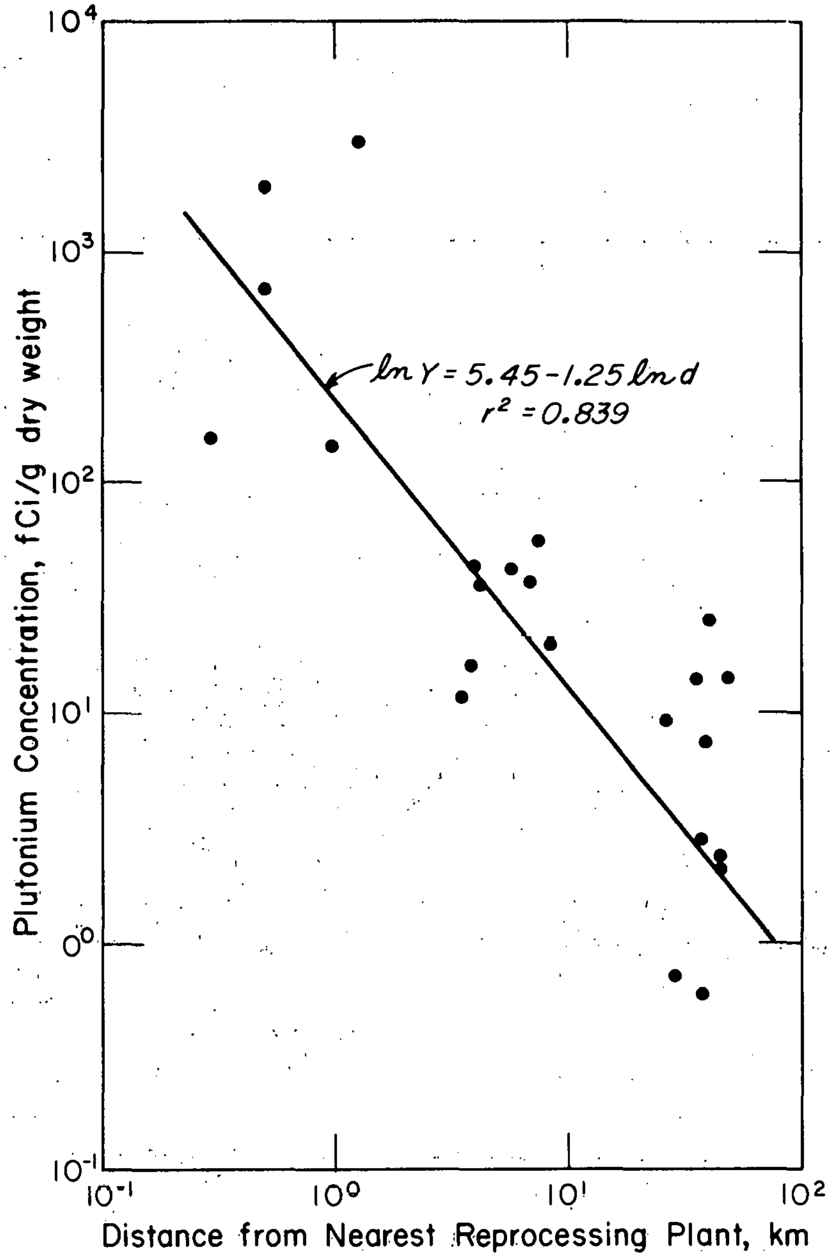

FIG. 5 RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF RESUSPENDIBLE MATERIALS AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

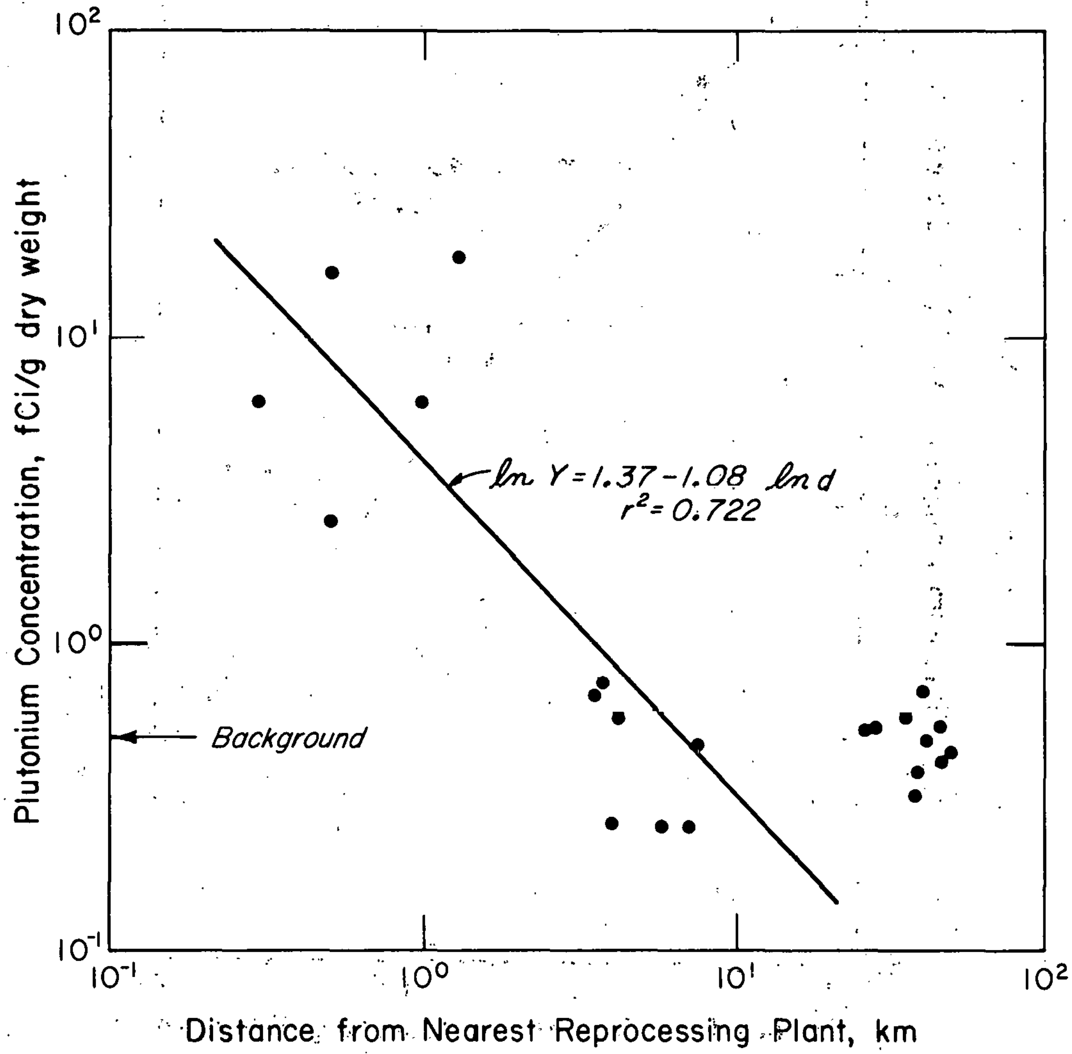

FIG. 6 RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF HONEYSUCKLE AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

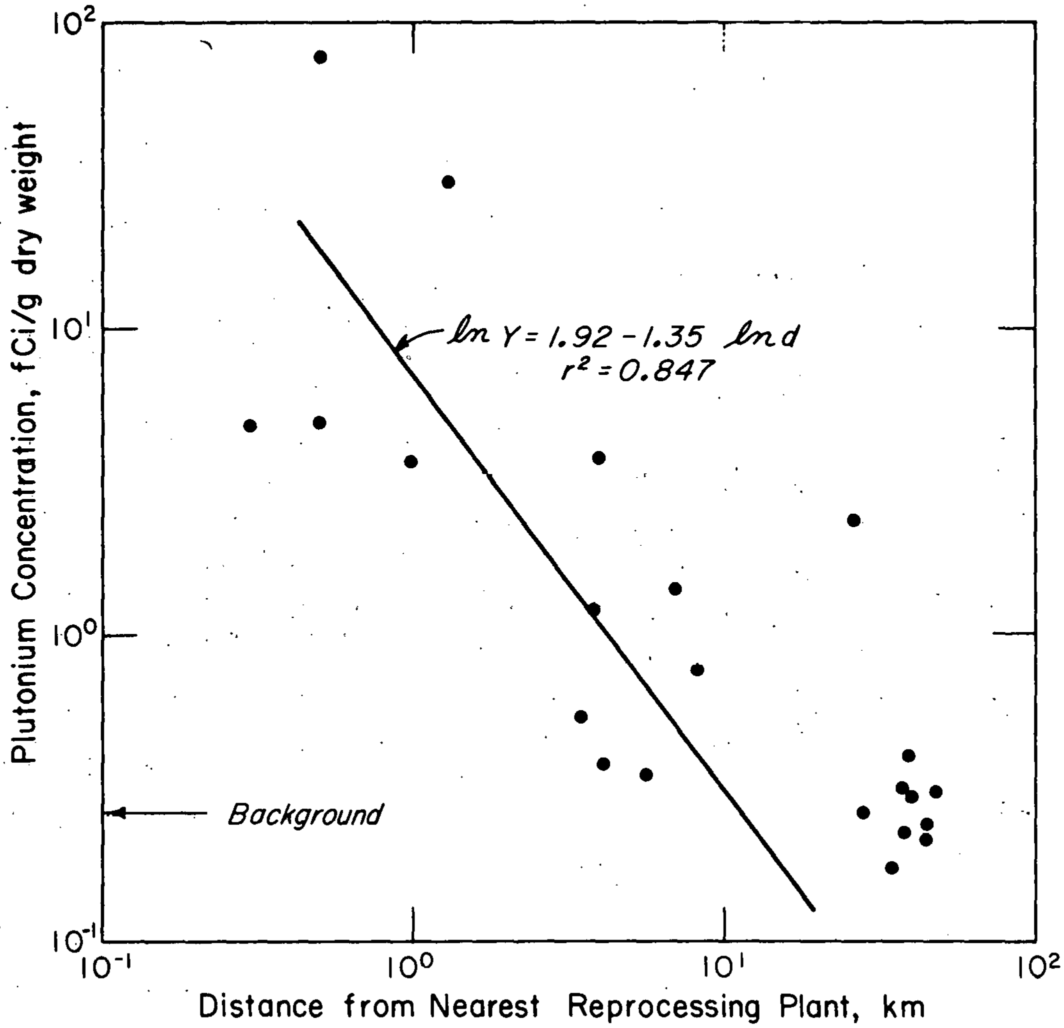

FIG. 7 RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF CAMPHOR WEED AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

TABLE I. PLUTONIUM CONCENTRATIONS OF SOIL CORES AND RESUSPENDIBLE MATERIAL

Sample Location[a]	Distance from SRP Source,[b] km	*Soil Cores (0-15 cm depth)* ^{238}Pu,[c] fCi/g	^{239}Pu,[d] fCi/g [c]	α% ^{238}Pu	*Resuspendible Material (0-0.1 cm)* ^{238}Pu, fCi/g[c]	^{239}Pu,[d] fCi/g [c]	α% ^{238}Pu
Onplant							
Inside 3 mCi/km² isopleth							
1	0.5	46.4 ±7.9	37.0 ± 6.8	56 ±12	387.9 ±12.4	311.8 ±11.1	55 ± 2
2	0.5	7.2 ±5.0	163.8 ±21.8	4 ± 3	118.1 ± 7.2	1805.7 ±28.0	2 ± 0
3	1.3	23.4 ±2.8	89.9 ± 5.8	21 ± 3	1931.1 ±32.2	996.8 ±23.2	66 ± 1
4	0.3	13.4 ±4.7	101.2 ±12.1	12 ± 4	50.9 ± 3.2	106. ± 5.	32 ± 2
5	1.0	2.9 ±1.9	33.6 ± 6.0	8 ± 5	45.9 ± 2.6	100. ± 4.	31 ± 2
Inside 2 mCi/km² isopleth							
6	3.8	4.0 ±1.8	6.9 ±2.3	37 ±19	1.9 ±0.6	14.2 ± 1.6	12 ± 4
7	8.4	0.8 ±0.8	9.5 ±1.8	8 ± 8	2.9 ±0.4	17.1 ± 1.0	14 ± 2
8	7.0	1.2 ±1.4	8.2 ±2.6	13 ±15	7.0 ±0.9	30.8 ± 2.0	18 ± 3
9	7.5	0.7 ±0.4	7.1 ±1.1	9 ± 5	7.6 ±0.8	49.8 ± 2.1	13 ± 2
10	4.0	0.5 ±0.4	5.8 ±1.1	3 ± 6	7.2 ±0.7	37.4 ± 1.5	16 ± 2
11	5.7	0.6 ±0.9	7.0 ±2.2	3 ±12	3.8 ±0.8	40.0 ± 2.6	9 ± 2
12	4.2	0.8 ±1.1	9.1 ±3.5	3 ±12	1.8 ±0.4	33.9 ± 1.9	5 ± 1
13	3.5	0.8 ±1.2	9.7 ±2.7	3 ±12	1.7 ±0.3	10.2 ± 0.7	14 ± 3
Offplant							
At 40 km radius							
14	28	0.6 ±0.5	4.4 ±1.4	12 ±10	0.4 ±0.2	0.3 ±0.2	57 ±36
15	26	0.5 ±0.3	7.3 ±0.9	5 ± 4	0.6 ±0.3	9.1 ±1.3	6 ± 3
16	38	0.2 ±0.2	1.3 ±0.4	14 ±11	0.2 ±0.09	0.5 ±0.16	21 ±14
17	38	0.8 ±0.8	7.1 ±1.7	10 ±10	0.8 ±0.2	2.0 ±0.4	29 ± 9
18	45	0.4 ±0.2	6.2 ±0.8	6 ± 3	0.2 ±0.09	1.8 ±0.27	10 ± 5
19	49	0.2 ±0.2	5.1 ±0.8	4 ± 4	1.8 ±0.4	12.5 ±1.2	12 ± 3
20	41	0.4 ±0.4	5.5 ±1.0	7 ± 7	2.3 ±0.6	23.8 ±2.0	9 ± 2
21	45	0.3 ±0.2	6.5 ±0.8	4 ± 3	0.7 ±0.2	1.7 ±0.3	28 ± 9
22	40	0.5 ±0.4	8.6 ±1.2	6 ± 4	2.1 ±0.4	5.5 ±0.6	28 ± 5
23	35	0.7 ±0.4	7.4 ±0.9	9 ± 5	4.8 ±0.6	9.2 ±0.9	34 ± 5

a. See Figures 2 and 3.
b. Fuel reprocessing plant.
c. Dry weight.
d. Includes ^{240}Pu also.

TABLE II. PLUTONIUM CONCENTRATIONS OF HONEYSUCKLE AND CAMPHOR WEED

Sample Location[a]	*Honeysuckle* ^{238}Pu, fCi/g[b]	*Honeysuckle* ^{239}Pu,[c] fCi/g[b]	*Honeysuckle* α% ^{238}Pu	*Camphor Weed* ^{238}Pu, fCi/g[b]	*Camphor Weed* ^{239}Pu,[c] fCi/g[b]	*Camphor Weed* α% ^{238}Pu
Onplant						
1	0.4 ±0.1	2.1 ±0.1	17 ±2	1.2 ±0.2	3.7 ±0.3	25 ±4
2	1.2 ±0.1	15.1 ±0.4	7 ±1	1.6 ±0.2	74.9 ±1.3	3 ±0.3
3	10.9 ±0.3	7.2 ±0.3	60 ±2	18.5 ±0.7	11.7 ±0.5	61 ±3
4	2.7 ±0.1	3.5 ±0.2	43 ±2	2.6 ±0.2	2.2 ±0.2	54 ±5
5	2.8 ±0.2	3.1 ±0.2	47 ±4	1.1 ±0.2	2.6 ±0.2	30 ±5
6	0.23 ±0.04	0.53 ±0.06	30 ±5	0.3 ±1	0.9 ±1	26 ±7
7	0.69 ±0.05	1.05 ±0.06	40 ±3	0.29 ±0.04	0.49 ±0.06	37 ±7
8	0.09 ±0.02	0.16 ±0.03	37 ±10	0.18 ±0.03	1.2 ±0.1	12 ±2
9	0.03 ±0.02	0.43 ±0.06	7 ±3	0.11 ±0.04	0.30 ±0.06	27 ±1
10	0.08 ±0.02	0.17 ±0.03	31 ±9	0.07 ±0.1	3.1 ±0.2	19 ±2
11	0.17 ±0.03	0.8 ±0.1	16 ±3	0.04 ±0.02	0.30 ±0.05	11 ±5
12	0.07 ±0.02	0.50 ±0.04	12 ±3	0.07 ±0.02	0.29 ±0.04	19 ±5
13	0.07 ±0.03	0.6 ±0.1	11 ±5	0.04 ±0.03	0.5 ±0.1	7 ±5
Offplant						
14	0.07 ±0.02	0.45 ±0.05	13 ±4	0.032±0.014	0.23 ±0.04	12 ±6
15	0.06 ±0.01	0.54 ±0.03	10 ±2	0.14 ±0.03	2.27 ±0.13	6 ±1
16	0.03 ±0.01	0.34 ±0.04	8 ±3	0.15 ±0.008	0.17 ±0.03	8 ±4
17	0.04 ±0.01	0.27 ±0.04	12 ±5	0.013±0.009	0.22 ±0.04	6 ±4
18	0.064±0.015	0.47 ±0.04	12 ±3	0.025±0.010	0.22 ±0.03	10 ±4
19	0.04 ±0.01	0.39 ±0.04	10 ±4	0.006±0.006	0.31 ±0.04	2 ±2
20	0.10 ±0.02	0.38 ±0.03	22 ±4	0.03 ±0.01	0.27 ±0.04	9 ±5
21	0.04 ±0.01	0.37 ±0.03	9 ±3	0.028±0.011	0.18 ±0.03	13 ±6
22	0.14 ±0.04	0.58 ±0.09	19 ±6	0.04 ±0.01	0.36 ±0.04	10 ±4
23	0.05 ±0.01	0.52 ±0.05	9 ±3	0.01 ±0.01	0.16 ±0.03	7 ±4

a. See Figures 2 and 3 and Table I.
b. Dry weight.
c. Includes ^{240}Pu also.

TABLE III. PLUTONIUM CONCENTRATIONS OF GRASSHOPPERS

Sample Location[a]	^{238}Pu, *fCi/g*[b]	^{239}Pu,[c] *fCi/g*[b]	α% ^{238}Pu
1	0.38 ±0.10	1.18 ±0.16	25 ±7
3	1.36 ±0.13	1.38 ±0.13	50 ±6
13 (Control)	<0.03	<0.03	-

a. See Figure 2 and Table I.
b. Dry weight.
c. Includes ^{240}Pu also.

TABLE IV. PLUTONIUM CONCENTRATIONS OF COTTON RATS[a]

Sample Location[b]	*Juveniles*[c] ^{238}Pu, fCi/g[f]	^{239}Pu,[g] fCi/g[f]	α% ^{238}Pu	*Immatures*[d] ^{238}Pu, fCi/g[f]	^{239}Pu,[g] fCi/g[f]	α% ^{238}Pu	*Adults*[e] ^{238}Pu, fCi/g[f]	^{239}Pu,[g] fCi/g[f]	α% ^{238}Pu
1	-	-	-	0.44 ±0.07	0.45 ±0.07	49 ±10	-	-	-
2	0.20 ±0.06	0.41 ±0.09	33 ±12	-	-	-	0.22 ±0.08	0.61 ±0.13	27 ±11
3	1.62 ±0.15	1.96 ±0.17	45 ± 5	0.64 ±0.12	1.04 ±0.15	39 ± 8	0.69 ±0.10	0.96 ±0.12	42 ± 7
4	0.26 ±0.08	*h*	-	0.16 ±0.04	0.15 ±0.04	51 ±15	0.11 ±0.08	0.39 ±0.15	22 ±17
5	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	0.06 ±0.03	0.01 ±0.01	80 ±54
7	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	*h*	0.08 ±0.04	-
10	-	-	-	-	-	-	0.15 ±0.07	0.12 ±0.06	56 ±36
11	0.54 ±0.15	0.17 ±0.08	76 ±28	-	0.13 ±0.05	-	0.08 ±0.03	0.05 ±0.02	58 ±28
12	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	0.08 ±0.04	0.05 ±0.03	62 ±36

a. Skinned and gastrointestinal tract removed.
b. See Figure 2 and Table I.
c. <40 g dry weight.
d. 40 to 90 g dry weight.
e. >90 g dry weight
f. Dry weight
g. Includes ^{240}Pu also.
h. Less than 1 fCi/sample.

TABLE V. AVERAGE CONCENTRATION RATIOS[a] FOR CAMPHOR WEED AND HONEYSUCKLE

	Average Concentration Ratio	
	Onplant	*Offplant*
Camphor Weed/Soil	0.218	0.069
Honeysuckle/Soil	0.093	0.077

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a. $\frac{\text{pCi of plutonium/g dry weight}}{\text{pCi of plutonium/g dry weight}}$

TABLE VI. AVERAGE CONCENTRATION RATIOS[a] BETWEEN VARIOUS COMPONENTS OF THE ECYSYSTEM

Components of the Ecosystem	*Average Concentration Ratio*
Cotton Rats[b]/soil	0.014
Grasshoppers[c]/soil	0.022
Cotton Rats[b]/vegetation	0.14
Grasshoppers[c]/vegetation	0.28

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a. $\frac{\text{pCi of plutonium/g dry weight}}{\text{pCi of plutonium/g dry weight}}$

b. Skinned and gastrointestinal tract removed.

c. Whole

TABLE VII. PLUTONIUM CONCENTRATIONS AND ALPHA PERCENTAGES IN ECOSYSTEM COMPONENTS

Ecosystem Component	Onplant Locations					Offplant Locations				
	No. of Samples	Pu Concentration, fCi/g[a]		α% ^{238}Pu		No. of Samples	Pu Concentration, fCi/g[a]		α% ^{238}Pu	
		Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	Mean	Std. Dev.
Soil	13	45.5	55.8	14.8	15.0	10	6.40	2.16	7.8	3.3
Resuspendibles	13	295.4	561.7	22.2	19.3	10	8.03	8.21	23.4	15.3
Camphor Weed	13	9.9	21.5	25.6	17.3	10	0.44	0.70	8.4	3.4
Honeysuckle	13	4.2	6.1	27.6	17.2	10	0.49	0.12	12.3	4.6
Adult Cotton Rats	8	0.46	0.55	43.4	25.8					

a. Dry weight.

DP-MS-75-30
IAEA-SM-199/85

RELATIONSHIPS AMONG PLUTONIUM CONTENTS OF SOIL, VEGETATION, AND ANIMALS COLLECTED ON AND ADJACENT TO AN INTEGRATED NUCLEAR COMPLEX IN THE HUMID SOUTHEASTERN UNITED STATES

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A Paper for Presentation at the
Symposium on Transuranium Nuclides in the Environment
to be held in San Francisco, California, on
November 17-21, 1975
This symposium is sponsored by the International Atomic
Energy Agency (IAEA) assisted by the U. S. Energy
Research and Development Administration (ERDA)

This paper was prepared in connection with work under Contract No. AT(07-2)-1 with the U. S. Energy Research and Development Administration.

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INTRODUCTION

Plutonium behavior in terrestrial ecosystems in the United States has been studied principally in arid areas using plutonium from weapons tests [1,2]. Results of those studies are not directly applicable to the humid, heavily vegetated climates of the southeastern United States and to plutonium from an operating nuclear fuel reprocessing plant.

The Savannah River Plant (SRP) provides a unique opportunity within the humid southeastern United States to study the behavior of plutonium in the environment. SRP is on a reservation of 77,830 hectares. Public access to the reservation is controlled. The reservation consists of fresh-water streams, old fields, and forests. Wildlife, including a deer herd of 6,000, abound. For over 20 years this integrated nuclear complex has included nuclear reactors (three of original five are operating at present), two nuclear fuel reprocessing plants, a fuel fabrication facility, a heavy water production unit, and a nuclear research laboratory. The reprocessing plants, along with global fallout, are the sources of plutonium that enters SRP environs. Each source releases plutonium of unique isotopic composition: 95 and 25 α% ^{238}Pu* from reprocessing plants, compared with 10 α% ^{238}Pu from global fallout. These isotopic differences provide a convenient basis for studying the origin and transport of plutonium that is found in the SRP ecosystem.

An extensive environmental monitoring program at SRP has provided information on the plutonium content of soil [3]. The monitoring program was used to establish a background concentration of plutonium in SRP soil of approximately

$$* \ \alpha\% \ ^{238}\text{Pu} = \frac{^{238}\text{Pu alpha activity}}{\text{Total Pu alpha activity}} \times 100$$

2 mCi/km^2. This concentration is well within the range reported for the southeastern United States [4]. Results of this monitoring program were used to construct idealized isopleths showing plutonium deposition starting at the nuclear fuel reprocessing areas and decreasing toward the plant perimeter (Figure 1). These isopleths represent plutonium concentrations that range from the background level of approximately 9 fCi/g to a high of 2740 fCi/g adjacent to one of the nuclear fuel reprocessing facilities.

The objective of the study discussed in this paper was to establish relationships among the plutonium contents of soil, vegetation, and animals. To obtain food chain information, sampling locations were selected by utilizing the established isopleths. At each location, samples of soil and two types of vegetation (camphor weed and honeysuckle) were taken. At selected locations, grasshoppers and cotton rats were also collected.

METHODS AND MATERIALS

Characteristics of Sampling Locations

Twenty-three locations were selected using information from the soil monitoring program: 5 within the 3-mCi/km^2 isopleth, 8 within the 2-mCi/km^2 isopleth, and 10 at a 40-km radius surrounding SRP (Fig. 2 and 3). Each sampling location was chosen on the basis of its vegetation and animal habitat. The location criteria required a non-forested, undisturbed area with a good vegetation cover. Locations were selected with sufficient distances between them that cotton rat populations would not overlap.

Sampling Methods and Preparation

Soil

Composite soil samples of ten cores were taken at each of the 23 sampling locations according to the procedures described by McLendon (1975) [3].

Resuspendible material was collected at the surface of each location with a special sampler. These samples represent the material on the soil surface that could be dispersed in the atmosphere. The sampler had a 232-cm^2 head attached to a small, portable vacuum cleaner that produced an average wind speed of 6 m/sec. The resuspendible material was oven-dried, ashed, and analyzed for plutonium according to previously developed procedures [5,6,7].

Vegetation

Honeysuckle (*Lonicera japonica*) and camphor weed (*Heterotheca subaxillaris*) were collected in July 1975, in the vicinity of the soil sampling locations to determine plutonium content of vegetation. Honeysuckle was chosen because of its acknowledged dietary preference by deer during the summer months. Camphor weed was used as the second type of vegetation because of its abundance and because it has been shown to be extensively grazed by numerous insects [8]. Approximately 200 to 300 grams of dry weight for each species were taken by clipping the vegetation at ground level. Each sample was oven-dried, ashed, and analyzed for plutonium by the same method as used for the resuspendible material.

Insects and Animals

Grasshopper samples (approximately 30 g dry weight) were collected in late August 1975 when the grasshopper population had peaked because sufficient samples for analysis could not be obtained earlier. Because of the limited time remaining for analysis, only three samples were collected. Two were from the areas immediately surrounding the nuclear fuel reprocessing areas, and one was at a distant location to serve as a control. Approximately 100 to 150 grams of grasshoppers were collected from each area. Each sample was oven-dried, ashed, and analyzed by the same method as was used for analyzing the resuspendible material.

Cotton rats (*Sigmodon hispidus*) were sampled at 9 locations. Distances between these locations were sufficient to ensure that they represented distinct populations with a negligible chance of animal movement from one location to another. Approximately 10 to 20 cotton rats were collected from each location and divided into juvenile (<40 g dry weight) [9], immatures (40 to 90 g dry weight), and adults (>90 g dry weight). Plutonium concentrations of rats from each area were determined if sufficient sample was available. Cotton rats were frozen upon capture and later thawed, dipped in paraffin to reduce mobility of surface-deposited plutonium, and skinned. The gastrointenstinal tract was removed from the remaining carcass. Tissues around any wound were also excised. Plutonium concentrations of the rat carcasses (skin and gastrointestinal tract removed) were determined by the same technique as was used for analyzing the resuspendible material. Measured plutonium concentrations should represent both uptake and lung contamination.

RESULTS

Soil

The plutonium concentrations of the soil core samples (0-15 cm depth) varied widely and generally reflected the sampling distance from plutonium sources at SRP. The concentrations range from offplant lows of 0.2 fCi ^{238}Pu/g* and 1.3 fCi ^{239}Pu/g** to onplant highs of 46.4 fCi ^{238}Pu/g and 163.8 fCi ^{239}Pu/g (Table 1).

The plutonium concentrations of the resuspendible materials showed the same variation with distance from the sources (Table 1) as the soil core samples. However, the concentrations on a per gram basis were generally higher than those of soil core samples.

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* All samples weights were dry weights.

** All ^{239}Pu analyses include ^{240}Pu also.

The offplant concentrations are consistent with concentrations for fallout plutonium reported for this latitude band (30° to 40°) [4].

Vegetation

The plutonium concentrations of honeysuckle and camphor weed samples decreased with increasing distance from the SRP sources (Table II). The concentrations for honeysuckle ranged from 0.03 fCi ^{238}Pu/g and 0.27 fCi ^{239}Pu/g offplant to 10.9 fCi ^{238}Pu/g and 15.1 fCi ^{239}Pu/g onplant. The concentrations for camphor weed ranged from 0.01 fCi ^{238}Pu/g and 0.16 fCi ^{239}Pu/g offplant to 18.5 fCi ^{238}Pu/g and 74.9 fCi ^{239}Pu/g onplant. Both species showed a wide range in α% ^{238}Pu reflecting the existence of one or more plutonium sources in conjunction with global fallout.

Insects and Animals

The two grasshopper samples collected near nuclear fuel reprocessing plants contained detectable plutonium concentrations (Table III), but the plutonium concentration of the control sample was less than the analytical detection limit (1 fCi per sample).

The plutonium concentrations of the adult rat samples ranged from less than detectable ^{238}Pu* and 0.05 fCi ^{239}Pu/g to 0.69 fCi ^{238}Pu/g and 0.96 fCi ^{239}Pu/g. Generally, the plutonium contents of the juvenile and immature samples were similar to those of adult samples, and the α % ^{238}Pu of all age classes were similar. However, samples of all age classes were available from only four sampling locations.

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* Analytical detection limit = 1 fCi/sample.

DISCUSSION

Plant-Soil Relationships

Numerous studies on the relationship between the plutonium contents of vegetation and soil have been reported. Most of the studies were conducted in the laboratory and showed uptake factors* ranging from 10^{-6} to 10^{-4} [1,10,11,12]. Romney [13] and Buchholz [14] reported that the uptake factor increases with time when Ladino clover is repeatedly harvested from the same soil; however, similar cropping studies with alfalfa showed no obvious trends. A few studies have been concerned with the relationship between the plutonium content of the vegetation and the soil under field conditions. Hakonson, et al. [15] reported plutonium concentration ratios (vegetation-to-soil) of 10^{-2} and 10^{-1} for plants grown on plutonium-containing sediments under field conditions. Johnson, et al. [16] reported similar plant/sediment plutonium concentration ratios for plants grown in aquatic environments at Rocky Flats. From the data available for the vegetation and soil, a concentration ratio of 10^{-1} can be determined for the present study (Table V). This ratio is not significantly affected by distance from the reprocessing plants.

An examination of $\alpha\%$ ^{238}Pu data (Table I and II) indicates that deposition on the surfaces of vegetation is the principal mechanism contributing to the plutonium content. For example, at Sample Location 1 (0.5 km from source), values of $\alpha\%$ ^{238}Pu were 57% in soil, 55% in resuspendible material, and 20% in vegetation. Because the nearest SRP source for that area has an $\alpha\%$ ^{238}Pu value of 25%, the vegetation, the youngest component of the sampling area, shows the deposition of plutonium from the nearest SRP source along with fallout, and the soil and resuspendible material show the influence of earlier releases. That deposition

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$$\text{* Uptake Factor} = \frac{\text{Pu concentration in vegetation, Ci/g of dry vegetation}}{\text{Pu concentration in soil, Ci/g of dry soil}}$$

is the principal mechanism of plutonium entry into vegetation is further established with the information obtained from Sample Location 3 (1.3 km from source). The soil in this area has an α% ^{238}Pu of 21%; the resuspendible material, 66%; and vegetation, 60%. The source affecting this area is approximately 95% ^{238}Pu. Atmospheric particulates in this area, collected on tacky paper, show an α% ^{238}Pu of 59 ±19% indicating a dilution of plutonium from the SRP source with global fallout [17]. Vegetation and resuspendible material for this area reflect the deposition of this fallout, and the soil shows the accumulation of years of plutonium input from the source and global fallout. If uptake were a principal mechanism, the α% ^{238}Pu determined for vegetation would reflect the plutonium composition of the soil.

Although at greater distances the advantages provided by the differences in α% ^{238}Pu are no longer present, similar concentration ratios are calculated. This observation supports the conclusion that surface deposition on vegetation is the principal mechanism leading to the observed plutonium values.

Animal-Soil Relationships

Numerous investigators report the toxicity and behavior of plutonium in laboratory animals [2], and a few report plutonium content in field animals [10]. However, little information is available for determining relative plutonium contents of animals and soil. From the plutonium analyses available for the three grasshopper samples and the eight adult rat samples, a concentration ratio of animal plutonium to soil plutonium of about 10^{-2} can be calculated (Table VI). That ratio appears to be independent of the amount of plutonium in soil and could therefore provide an approximation of the plutonium content in animals where soil concentrations of plutonium are known.

Resuspendible Material

Analysis of resuspendible material is rapidly and easily conducted. The α% ^{238}Pu varies more in resuspendible material than in any other ecosystem component analyzed. This variation suggests the utilization of plutonium analyses of resuspendibles as a monitoring method to detect small changes in the plutonium concentration of surface soils not detectable by sampling soil cores or vegetation.

Biological Availability of ^{238}Pu

Comparison of the α% ^{238}Pu values for rat carcasses, soil, vegetation, and resuspendible material suggests an apparent increase in the biological availability of ^{238}Pu relative to ^{239}Pu in the environment (Table VII). Although these data are not statistically conclusive, they support evidence presented in other studies. Hanson [18] postulated several theories to explain the apparent increased availability of ^{238}Pu. In his theory development, he used the data of Hakonson and Johnson [19], who have reported $^{238}Pu/^{239}Pu$ ratios of 0.05 in soils, 0.10 in vegetation, and 1.0 in animal components of the Trinity Site ecosystem. At this time, further study of natural systems is needed to provide a firmer statistical base for Hanson's hypothesis.

Plutonium Distribution With Distance From the Reprocessing Plant

Because the plutonium concentrations of camphor weed, honeysuckle, soil, and resuspendibles are all higher near sources and decrease as the distance from the source increases, regression equations of the following form were fitted to the data as shown in Fig. 4 through 7, and the line is described by the equation

$$\ln Y = b_o + b_1 \ln d$$

where Y = total plutonium concentration in soil, resuspendible material or vegetation; b_o = concentration of plutonium at 1 km from the source; b_1 = slope of linear relationship between ln Y and ln d; and d = distance from the nearest source. These equations permit one to estimate the plutonium concentration of the various ecosystem components out to 10 km with a high degree of confidence. Total plutonium concentrations of samples from the 40-km radius are not related to distance from the SRP sources.

None of the slopes of the regression equations in Fig. 4 through 7 are significantly different from -1 (t test of slopes where $P > 0.05$ [20]), indicating that concentrations are approximately proportional to 1/d. A consideration of simple diffusion processes from a single point source suggests that concentrations should be proportional to $1/d^2$. The reason for this difference is not known at the present time.

Adult cotton rats that were collected from eight onplant study locations also show a decrease in plutonium content as distance from the source increases. The regression equation describing this distribution has the coefficients $\hat{b}_o = -0.72$ and $\hat{b}_1 = -0.78$ ($r^2 = 0.761$; df = 6; $P < 0.01$), where $\hat{b}_o$ and $\hat{b}_1$ are the least squares estimators of b_o and b_1. The $\hat{b}_1$ estimate is not significantly different from -1 indicating that the decrease in the plutonium concentrations observed for the cotton rats is similar to that observed for vegetation, resuspendible material, and soil.

The estimates of $\hat{b}_1$ for the regression equations in Fig. 4 are not significantly different from each other (Test of Homogeniety of Regression Coefficients; $F = 0.84$, df = 3,32, and $P > 0.05$; [20]). Since $\hat{b}_1 = -1$, then a general equation can be written for each ecosystem component i, as follows:

$$\ln \mathrm{Conc}(i) = a(i) + (-1) \ln d,$$

where a(i) changes for different ecosystem components. For any two components i and j

$$\ln \mathrm{Conc}(i) - \ln \mathrm{Conc}(j) = [a(i) - \ln d] - [a(j) - \ln d],$$ which may be simplified to

$$\ln \mathrm{Conc}(i) - \ln \mathrm{Conc}(j) = a(i) - a(j)$$

Since $a(i) - a(j) = \mathrm{Constant} = k$

$$\frac{\mathrm{Conc}(i)}{\mathrm{Conc}(j)} = e^k$$

This relationship is specific for the choice of i and j component. Thus, the similarity of the $\hat{b}_1$ values implies that the plutonium concentration ratios between ecosystem components are nearly equal throughout the areas influenced by SRP sources. This finding is unexpected because the two reprocessing plants at SRP release plutonium of different isotopic composition. The similarity of concentration ratios between ecosystem components indicates that plutonium from the various sources behaves in a similar fashion and that plutonium concentration ratios calculated from the data are of wide applicability in the Southeast.

IMPLICATIONS FOR FUTURE STUDIES

If knowledge of the fallout and resuspension at each sampling location or an equation relating fallout and resuspension to distance from the source were available, it would be possible to develop a simple model for predicting plutonium concentrations of ecosystem components. Because the geography, soil types, and species sampled are typical of the southeastern United States, this model would be of general applicability to the Southeast. Work currently under way at Savannah River should produce the necessary information for such a model.

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TABLE I. PLUTONIUM CONCENTRATIONS OF SOIL CORES AND RESUSPENDIBLE MATERIAL

Sample Location[a]	Distance from SRP Source,[b] km	Soil Cores (0-15 cm depth) ^{238}Pu,[c] fCi/g	^{239}Pu,[d] fCi/g [c]	α% ^{238}Pu	Resuspendible Material (0-0.1 cm) ^{238}Pu, fCi/g[c]	^{239}Pu,[d] fCi/g [c]	α% ^{238}Pu
Onplant							
Inside 3 mCi/km^2 isopleth							
1	0.5	46.4 ±7.9	37.0 ± 6.8	56 ±12	387.9 ±12.4	311.8 ±11.1	55 ± 2
2	0.5	7.2 ±5.0	163.8 ±21.8	4 ± 3	118.1 ± 7.2	1805.7 ±28.0	2 ± 0
3	1.3	23.4 ±2.8	89.9 ± 5.8	21 ± 3	1931.1 ±32.2	996.8 ±23.2	66 ± 1
4	0.3	13.4 ±4.7	101.2 ±12.1	12 ± 4	50.9 ± 3.2	106. ± 5.	32 ± 2
5	1.0	2.9 ±1.9	33.6 ± 6.0	8 ± 5	45.9 ± 2.6	100. ± 4.	31 ± 2
Inside 2 mCi/km^2 isopleth							
6	3.8	4.0 ±1.8	6.9 ±2.3	37 ±19	1.9 ±0.6	14.2 ± 1.6	12 ± 4
7	8.4	0.8 ±0.8	9.5 ±1.8	8 ± 8	2.9 ±0.4	17.1 ± 1.0	14 ± 2
8	7.0	1.2 ±1.4	8.2 ±2.6	13 ±15	7.0 ±0.9	30.8 ± 2.0	18 ± 3
9	7.5	0.7 ±0.4	7.1 ±1.1	9 ± 5	7.6 ±0.8	49.8 ± 2.1	13 ± 2
10	4.0	0.5 ±0.4	5.8 ±1.1	8 ± 6	7.2 ±0.7	37.4 ± 1.5	16 ± 2
11	5.7	0.6 ±0.9	7.0 ±2.2	8 ±12	3.8 ±0.8	40.0 ± 2.6	9 ± 2
12	4.2	0.8 ±1.1	9.1 ±3.5	3 ±12	1.8 ±0.4	33.9 ± 1.9	5 ± 1
13	3.5	0.8 ±1.2	9.7 ±2.7	8 ±12	1.7 ±0.3	10.2 ± 0.7	14 ± 3
Offplant							
At 40 km radius							
14	28	0.6 ±0.5	4.4 ±1.4	12 ±10	0.4 ±0.2	0.3 ±0.2	57 ±36
15	26	0.5 ±0.3	7.3 ±0.9	6 ± 4	0.6 ±0.3	9.1 ±1.3	6 ± 3
16	38	0.2 ±0.2	1.3 ±0.4	14 ±11	0.2 ±0.09	0.5 ±0.16	21 ±14
17	38	0.8 ±0.8	7.1 ±1.7	10 ±10	0.8 ±0.2	2.0 ±0.4	29 ± 9
18	45	0.4 ±0.2	6.2 ±0.8	6 ± 3	0.2 ±0.09	1.8 ±0.27	10 ± 5
19	49	0.2 ±0.2	5.1 ±0.8	4 ± 4	1.8 ±0.4	12.5 ±1.2	12 ± 3
20	41	0.4 ±0.4	5.5 ±1.0	7 ± 7	2.3 ±0.6	23.8 ±2.0	9 ± 2
21	45	0.3 ±0.2	6.5 ±0.8	4 ± 3	0.7 ±0.2	1.7 ±0.3	28 ± 9
22	40	0.5 ±0.4	8.6 ±1.2	6 ± 4	2.1 ±0.4	5.5 ±0.6	28 ± 5
23	35	0.7 ±0.4	7.4 ±0.9	9 ± 5	4.8 ±0.6	9.2 ±0.9	34 ± 5

a. See Figures 2 and 3.
b. Fuel reprocessing plant.
c. Dry weight.
d. Includes ^{240}Pu also.

TABLE II. PLUTONIUM CONCENTRATIONS OF HONEYSUCKLE AND CAMPHOR WEED

Sample Location[a]	*Honeysuckle* ^{238}Pu, *fCi/g*[b]		^{239}Pu,[c] *fCi/g*[b]		α% ^{238}Pu		*Camphor Weed* ^{238}Pu, *fCi/g*[b]		^{239}Pu,[c] *fCi/g*[b]		α% ^{238}Pu	
Onplant												
1	0.4	±0.1	2.1	±0.1	17	±2	1.2	±0.2	3.7	±0.3	25	±4
2	1.2	±0.1	15.1	±0.4	7	±1	1.6	±0.2	74.9	±1.3	3	±0.3
3	10.9	±0.3	7.2	±0.3	60	±2	18.5	±0.7	11.7	±0.5	61	±3
4	2.7	±0.1	3.5	±0.2	43	±2	2.6	±0.2	2.2	±0.2	54	±5
5	2.8	±0.2	3.1	±0.2	47	±4	1.1	±0.2	2.6	±0.2	30	±5
6	0.23	±0.04	0.53	±0.06	30	±5	0.3	±1	0.9	±1	26	±7
7	0.69	±0.05	1.05	±0.06	40	±3	0.29	±0.04	0.49	±0.06	37	±7
8	0.09	±0.02	0.16	±0.03	37	±10	0.18	±0.03	1.2	±0.1	12	±2
9	0.03	±0.02	0.43	±0.06	7	±3	0.11	±0.04	0.30	±0.06	27	±1
10	0.08	±0.02	0.17	±0.03	31	±9	0.07	±0.1	3.1	±0.2	19	±2
11	0.17	±0.03	0.8	±0.1	16	±3	0.04	±0.02	0.30	±0.05	11	±5
12	0.07	±0.02	0.50	±0.04	12	±3	0.07	±0.02	0.29	±0.04	19	±5
13	0.07	±0.03	0.6	±0.1	11	±5	0.04	±0.03	0.5	±0.1	7	±5
Offplant												
14	0.07	±0.02	0.45	±0.05	13	±4	0.032	±0.014	0.23	±0.04	12	±6
15	0.06	±0.01	0.54	±0.03	10	±2	0.14	±0.03	2.27	±0.13	6	±1
16	0.03	±0.01	0.34	±0.04	8	±3	0.15	±0.008	0.17	±0.03	8	±4
17	0.04	±0.01	0.27	±0.04	12	±5	0.013	±0.009	0.22	±0.04	6	±4
18	0.064	±0.015	0.47	±0.04	12	±3	0.025	±0.010	0.22	±0.03	10	±4
19	0.04	±0.01	0.39	±0.04	10	±4	0.006	±0.006	0.31	±0.04	2	±2
20	0.10	±0.02	0.38	±0.03	22	±4	0.03	±0.01	0.27	±0.04	9	±5
21	0.04	±0.01	0.37	±0.03	9	±3	0.028	±0.011	0.18	±0.03	13	±6
22	0.14	±0.04	0.58	±0.09	19	±6	0.04	±0.01	0.36	±0.04	10	±4
23	0.05	±0.01	0.52	±0.05	9	±3	0.01	±0.01	0.16	±0.03	7	±4

a. See Figures 2 and 3 and Table I.
b. Dry weight.
c. Includes ^{240}Pu also.

TABLE III. PLUTONIUM CONCENTRATIONS OF GRASSHOPPERS

Sample Location[a]	^{238}Pu, *fCi/g*[b]	^{239}Pu,[c] *fCi/g*[b]	α% ^{238}Pu
1	0.38 ±0.10	1.18 ±0.16	25 ±7
3	1.36 ±0.13	1.38 ±0.13	50 ±6
13 (Control)	<0.03	<0.03	-

a. See Figure 2 and Table I.
b. Dry weight.
c. Includes ^{240}Pu also.

ABLE IV. PLUTONIUM CONCENTRATIONS OF COTTON RATS[a]

	Juveniles[c]			*Immatures*[d]			*Adults*[e]		
ample Location[b]	^{238}Pu, *fCi/g*[f]	^{239}Pu,[g] *fCi/g*[f]	α% ^{238}Pu	^{238}Pu, *fCi/g*[f]	^{239}Pu,[g] *fCi/g*[f]	α% ^{238}Pu	^{238}Pu, *fCi/g*[f]	^{239}Pu,[g] *fCi/g*[f]	α% ^{236}Pu
1	-	-	-	0.44 ±0.07	0.45 ±0.07	49 ±10	-	-	-
2	0.20 ±0.06	0.41 ±0.09	33 ±12	-	-	-	0.22 ±0.03	0.61 ±0.13	27 ±11
3	1.62 ±0.15	1.96 ±0.17	45 ± 5	0.64 ±0.12	1.04 ±0.15	39 ± 8	0.69 ±0.10	0.96 ±0.12	42 ± 7
4	0.26 ±0.08	*h*	-	0.16 ±0.04	0.15 ±0.04	51 ±15	0.11 ±0.03	0.39 ±0.15	22 ±17
5	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	0.06 ±0.03	0.01 ±0.01	80 ±54
7	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	*h*	0.08 ±0.04	-
10	-	-	-	-	-	-	0.15 ±0.07	0.12 ±0.06	56 ±36
11	0.54 ±0.15	0.17 ±0.08	76 ±28	-	0.13 ±0.05	-	0.08 ±0.03	0.05 ±0.02	58 ±28
12	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	0.08 ±0.04	0.05 ±0.03	62 ±36

. Skinned and gastrointestinal tract removed.
. See Figure 2 and Table I.
. <40 g dry weight.
. 40 to 90 g dry weight.
. >90 g dry weight
. Dry weight
. Includes ^{240}Pu also.
. Less than 1 fCi/sample.

TABLE V. AVERAGE CONCENTRATION RATIOS[a] FOR CAMPHOR WEED AND HONEYSUCKLE

	Average Concentration Ratio	
	Onplant	*Offplant*
Camphor Weed/Soil	0.218	0.069
Honeysuckle/Soil	0.093	0.077

a. $\frac{\text{pCi of plutonium/g dry weight}}{\text{pCi of plutonium/g dry weight}}$

TABLE VI. AVERAGE CONCENTRATION RATIOS[a] BETWEEN VARIOUS COMPONENTS OF THE ECYSYSTEM

Components of the Ecosystem	*Average Concentration Ratio*
Cotton Rats[b]/soil	0.014
Grasshoppers[c]/soil	0.022
Cotton Rats[b]/vegetation	0.14
Grasshoppers[c]/vegetation	0.28

a. $\frac{\text{pCi of plutonium/g dry weight}}{\text{pCi of plutonium/g dry weight}}$

b. Skinned and gastrointestinal tract removed.

c. Whole

ABLE VII. PLUTONIUM CONCENTRATIONS AND ALPHA PERCENTAGES IN ECOSYSTEM COMPONENTS

cosystem omponent	Onplant Locations					Offplant Locations				
	No. of Samples	Pu Concentration, fCi/g[a]		α% ^{238}Pu		No. of Samples	Pu Concentration, fCi/g[a]		α% ^{238}Pu	
		Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	Mean	Std. De
cil	13	45.5	55.8	14.8	15.0	10	6.40	2.16	7.8	3.3
esuspendibles	13	295.4	561.7	22.2	19.3	10	8.03	8.21	23.4	15.3
amphor Weed	13	9.9	21.5	25.6	17.3	10	0.44	0.70	8.4	3.4
oneysuckle	13	4.2	6.1	27.6	17.2	10	0.49	0.12	12.3	4.6
dult Cotton Rats	8	0.46	0.55	43.4	25.8					

:. Dry weight.

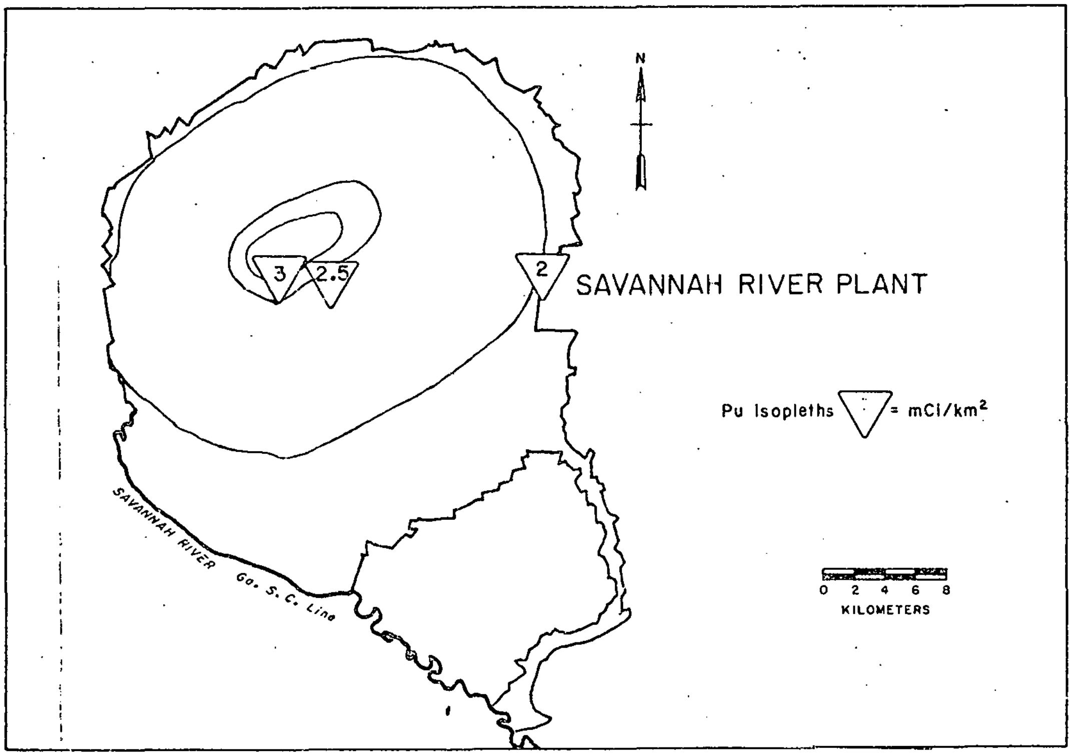

FIG. 1. PLUTONIUM DEPOSITION ON THE SAVANNAH RIVER PLANT

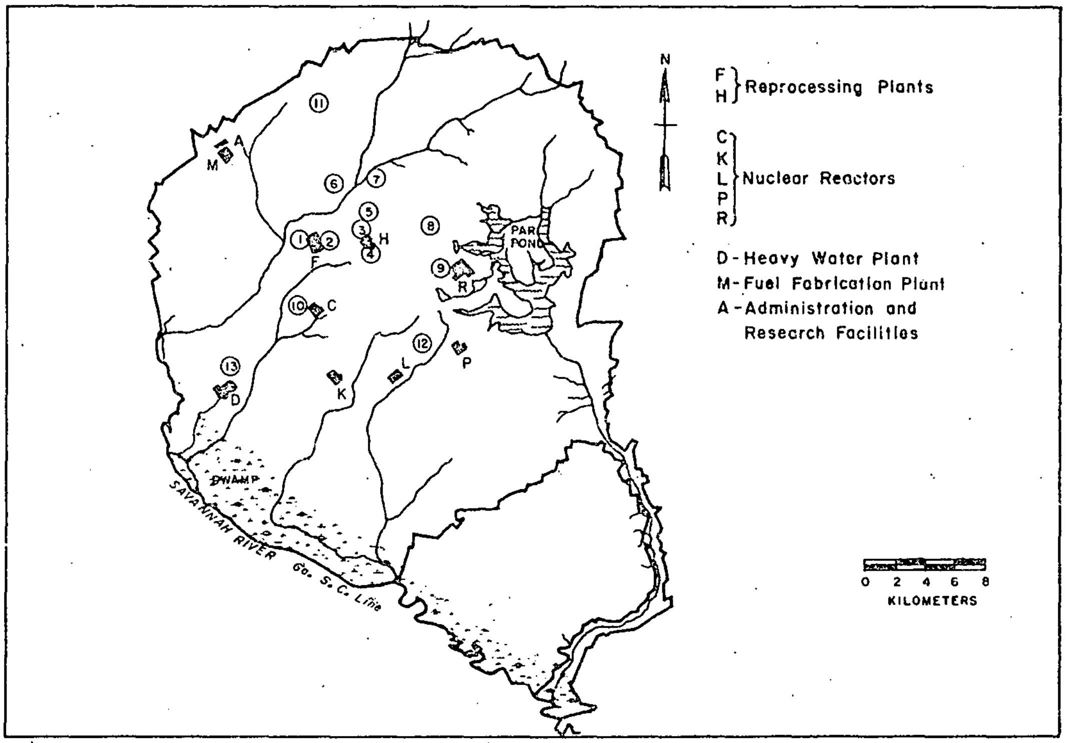

FIG. 2. ONPLANT SAMPLING LOCATIONS

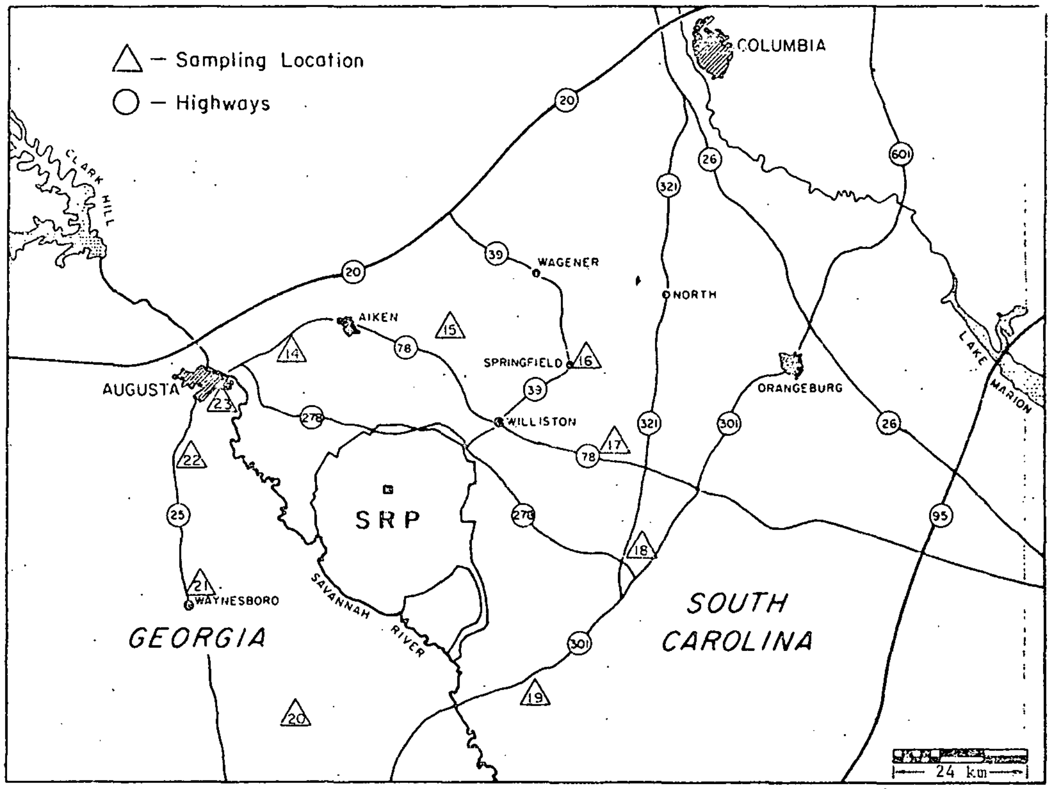

FIG. 3. OFFPLANT SAMPLING LOCATIONS

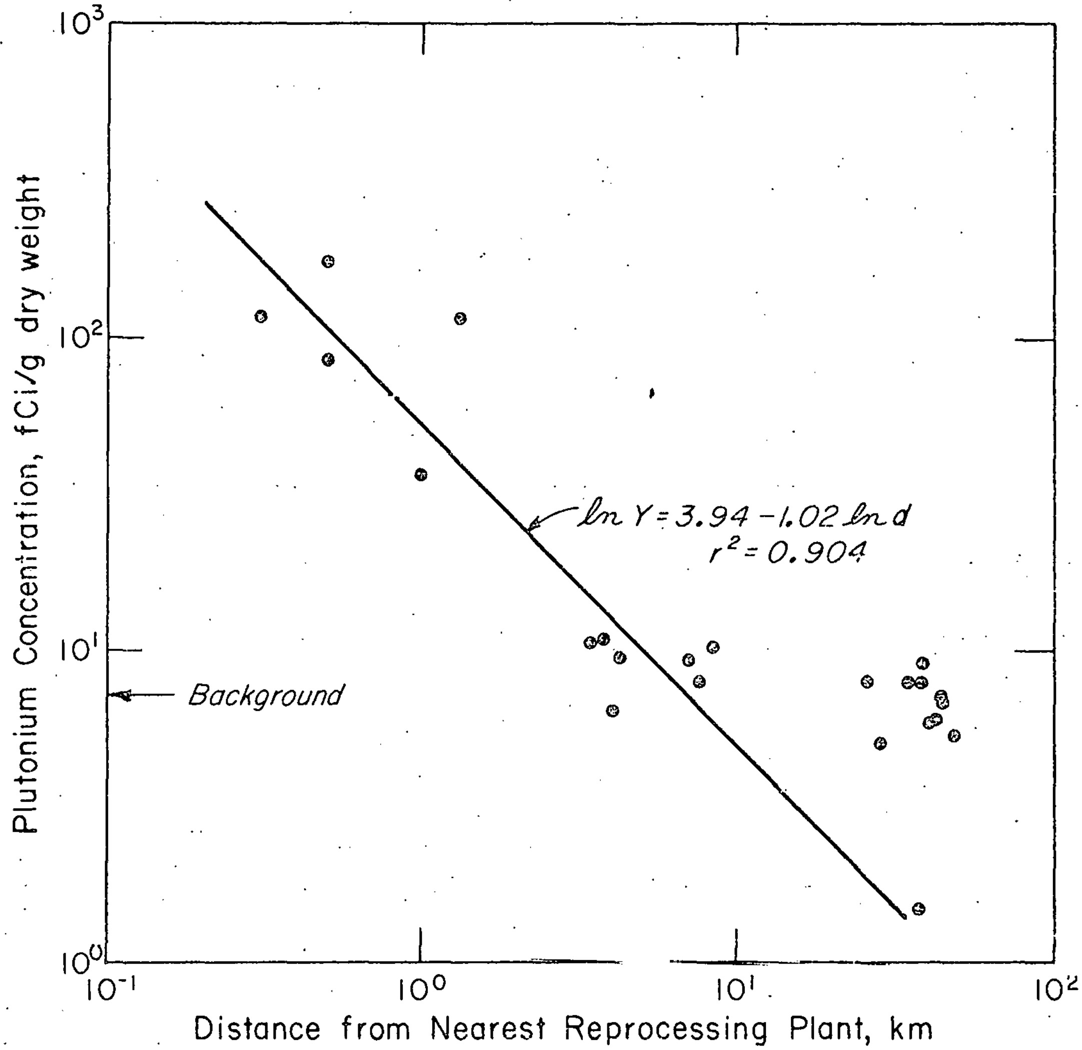

FIG. 4. RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF SOIL AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

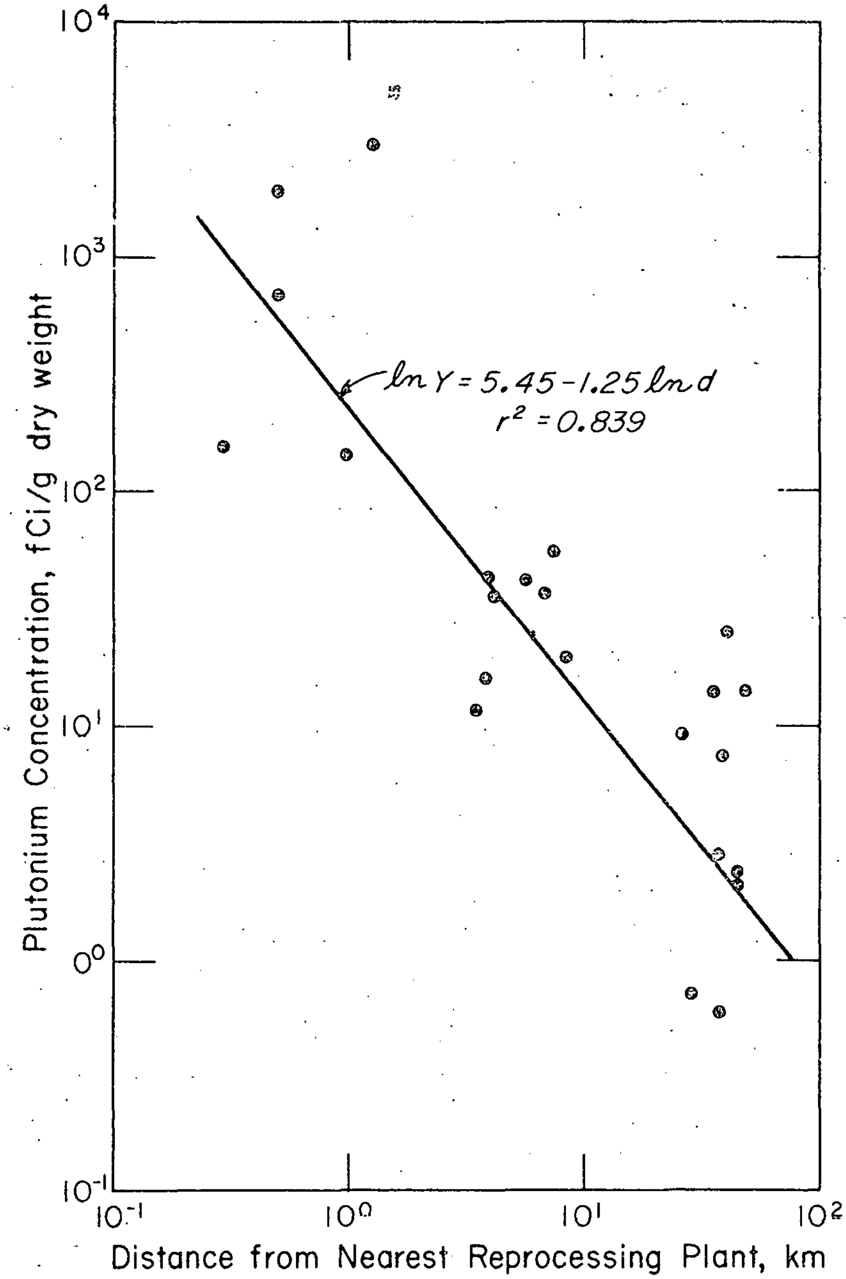

FIG. 5 RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF RESUSPENDIBLE MATERIALS AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

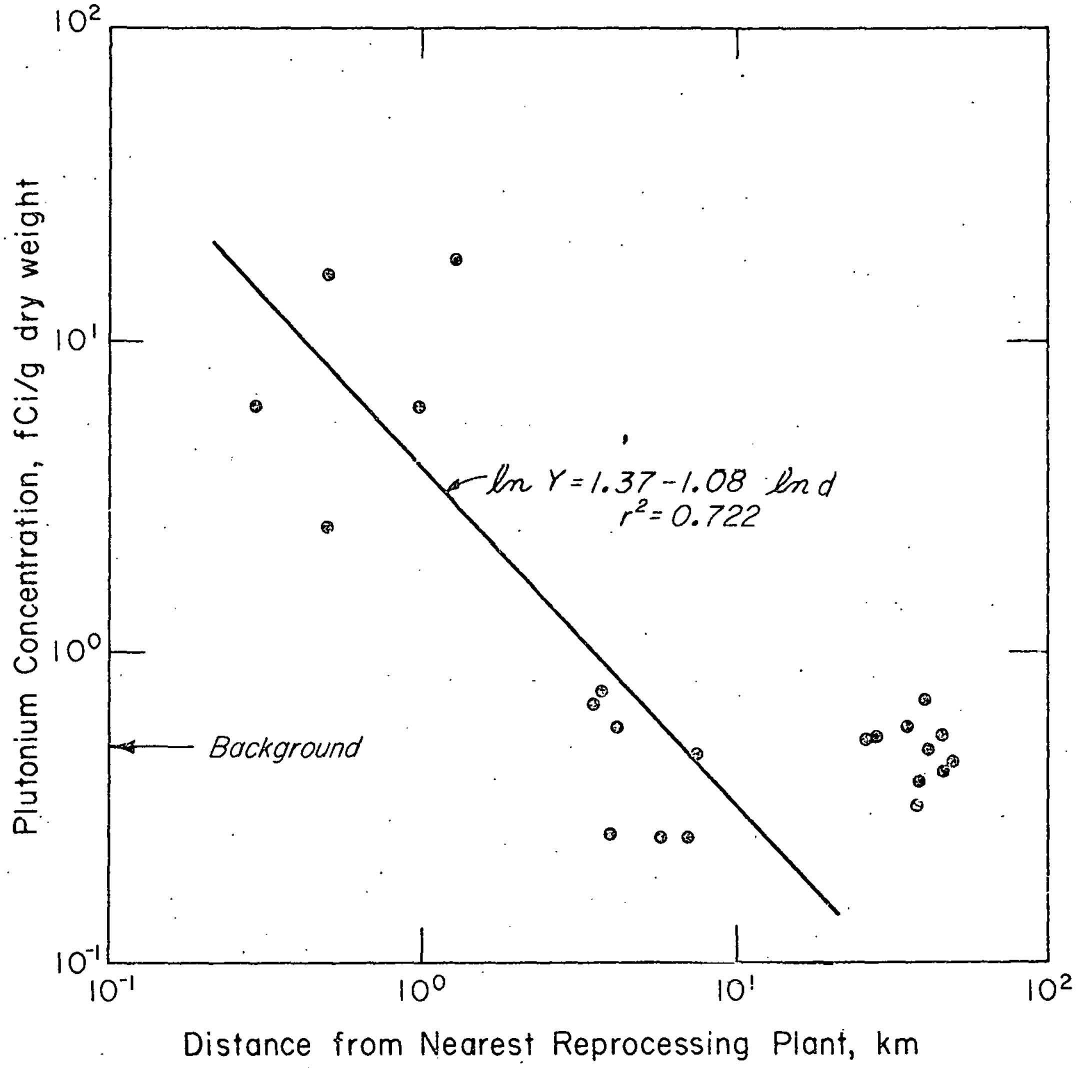

FIG. 6 RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF HONEYSUCKLE AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT

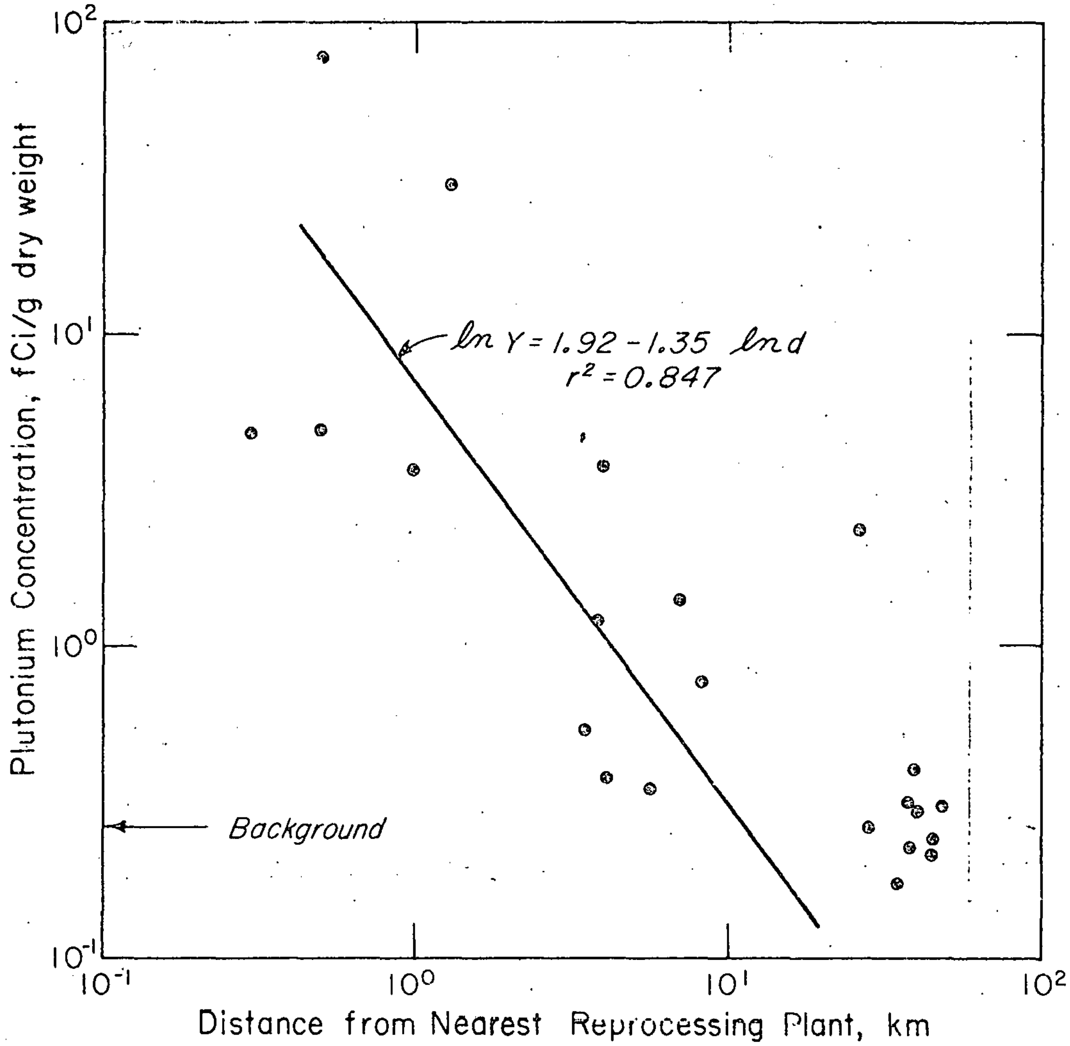

FIG. 7 RELATIONSHIP BETWEEN PLUTONIUM CONCENTRATION OF CAMPHOR WEED AND DISTANCE FROM NUCLEAR FUEL REPROCESSING PLANT