BEST
AVAILABLE
COPY

Plutonium in Rocky Flats Freshwater Systems

D. PAINE

This study was initiated to determine the behavior of plutonium in the freshwater aquatic environs at the Rocky Flats Dow Chemical plutonium fabrication plant, Golden, Colo. The principal study area included four holding ponds for waste solutions generated at the plant complex.

Samples of biotic and abiotic components were collected from the spring of 1971 through the summer of 1973. These components consisted of sediment, water, seston, zooplankton, fish, vegetation, and small mammals in close proximity to the aquatic systems. Laboratory experiments were performed to quantify field results. Owing to the high variability of plutonium concentrations in the environment, numerous samples were collected and analyzed by a modified solvent-extraction liquid-scintillation counting procedure.

Sediments were the major site of $^{239,240}Pu$ deposition. Coring analysis revealed the largest concentrations at subsurface-sediment depths, and thus depth-profile data were used in calculating total inventory. A retention function determined in the laboratory demonstrated a rapid transfer of plutonium from water to sediment. Pond reconstruction during the study period resulted in significant increases in mean-surface(top 5 cm)-sediment concentrations.

Seston contained 30 to 80% of the $^{239,240}Pu$ in an unfiltered water sample. Concentration ratios in seston, ranging from 10^4 to 10^5, were higher than those found in marine studies. No vertical distribution of $^{239,240}Pu$ was noted in pond water. Laboratory experiments suggested active uptake by algae rather than by simple surface adsorption. Zooplankton showed a discrimination against plutonium concentration along the simple phytoplankton-to-zooplankton food chain. Fish flesh and bone showed no levels above minimum detectable activity (MDA, 0.03 d/min per 10-g sample for a 100-min count). Vegetation associated with pond sediments contained higher concentration ratios from sediment to aerial portions of plants than previously observed, ranging from 10^{-2} to 10^{-1}.

Although plutonium in the biosphere presently exists at very low concentrations, trophic biomagnification and possible localized contamination may result in increased plutonium concentrations in organisms of higher trophic levels. Cycling processes and biological uptake of plutonium must be understood before environmental releases so that rational assessment of its potential hazard can be performed. The major concern with plutonium is its potential hazard to man. Plutonium could enter man either directly through inhalation of atmospherically suspended material or indirectly through incorporation into his food chain. The inhalation route is considered the most hazardous mode of entry to man (Taylor, 1973). However, the concentration of plutonium in sediments or in aquatic

ADMIN RECORD

SW-A-005956

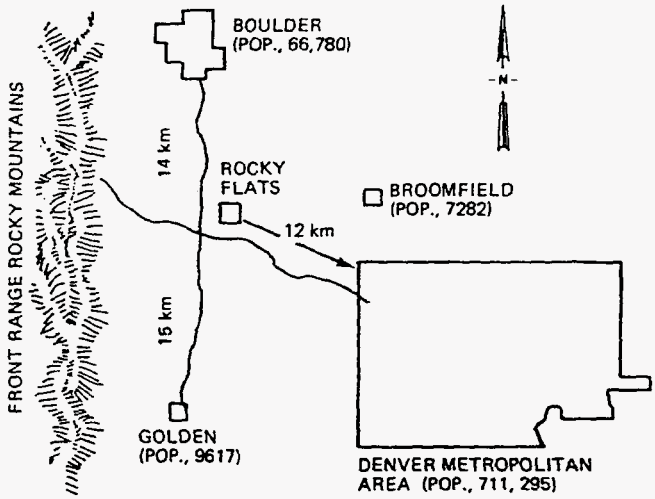


Fig. 1 Rocky Flats installation relative to nearby population centers.

organisms frequently exceeds concentrations in surrounding waters by orders of magnitude. This concentration process may pose unexpected hazards when considering food-chain transport.

Before this investigation little information concerning plutonium movement in aquatic systems was available (Stannard, 1973; Noshkin, 1972). Fallout and marine studies comprised the bulk of this environmental data, with average concentrations in the femtocurie range (Pillai, Smith, and Folsom, 1964; Aarkrog, 1971; Noshkin et al., 1971). In general, all freshwater studies have concurred that sediments appear to be the major reservoir for ultimate plutonium deposition and that relatively insignificant transport of plutonium through biotic systems to man exists (Emery and Klopfer, 1976; Hakonson, Nyham, and Purtymun, 1976).

The purpose of this investigation was to determine the behavior of plutonium in freshwater systems at the Rocky Flats Dow Chemical plutonium fabrication plant, Golden, Colo. The objectives were to (1) investigate the distribution patterns of plutonium in the biotic and abiotic components of the Rocky Flats freshwater systems, (2) determine any concentrating processes that were occurring, and (3) determine if any biological mobilization processes existed. It was the first attempt of its kind at delineating the cycling processes of plutonium using a holistic systems approach.

Methods and Materials

Figure 1 shows the location of the Rocky Flats area relative to the larger surrounding metropolitan areas. The plant site itself covers approximately 10 km^2.

Figure 2 shows the general sampling area at Rocky Flats. The principal study area included the four holding ponds (B-series ponds) for waste solutions generated at the plant complex. These ponds were drained by Walnut Creek, which flowed into Great Western reservoir, the City of Broomfield's municipal water supply. Great Western's water sources were provided by Walnut Creek (2%), Coal Creek (8%), and Clear Creek watershed (90%) (Hammond, 1971). The A-series and C_1 ponds were monitoring ponds that did not receive routine releases of plutonium waste. Pond A_1 had received low-level

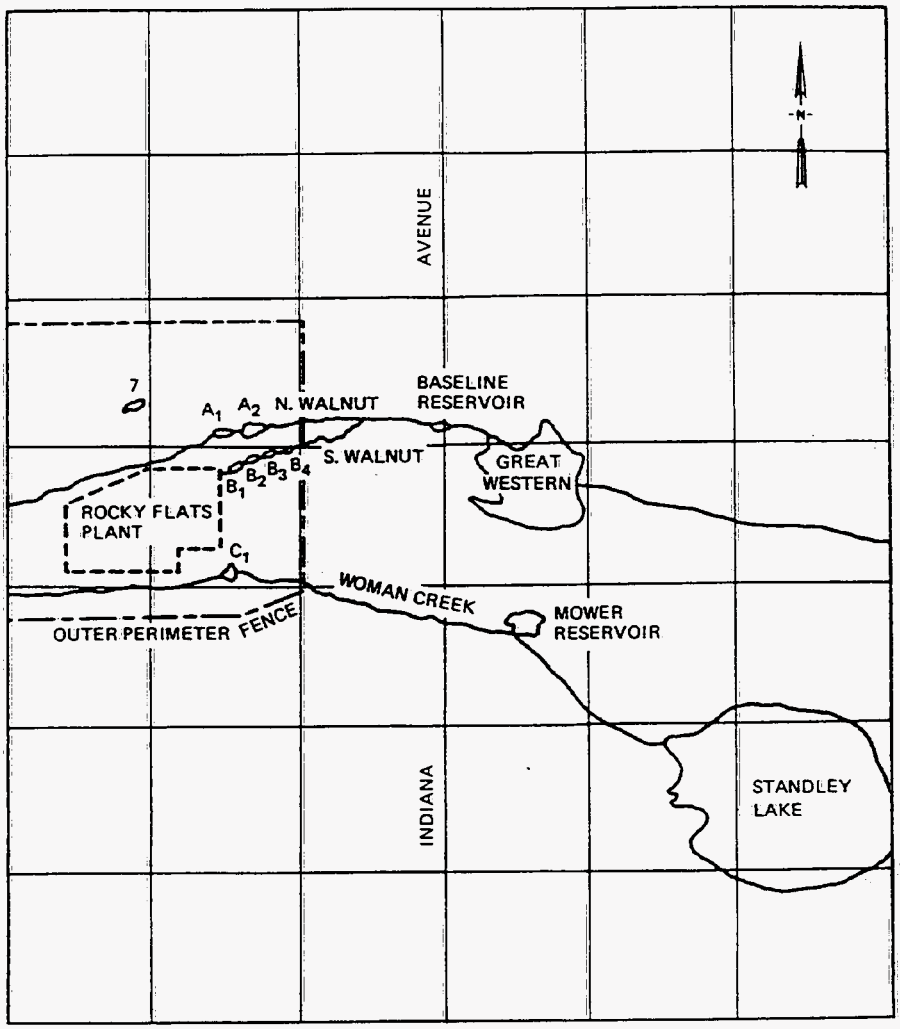


Fig. 2 Study area of Rocky Flats environs showing ponds, streams, and reservoirs. Flow on Woman and Walnut Creeks is from west to east.

plutonium contamination from past nonroutine releases. After the completion of this study, pond A_2 was constructed to handle excessive water runoff. This pond was not investigated in this study. Pond C_1 received runoff from the "pad" area located several hundred yards due northeast. This area was previously contaminated by plutonium from leaking 50-gal drums and was subsequently covered with an asphalt pad. The southernmost pond (pond C_1) drained into Woman Creek, which flowed into Standley Lake, an irrigation reservoir as well as the municipal water supply for Westminster, Colo. Pond 7, located several miles northeast of the study area, was used as a control pond for this study. Samples were periodically collected from pond 7 and used as background correction.

Primary plutonium waste discharged to the pond complex included laundry wastes and process waste solutions generated by various phases of the plant's operation. Owing

to the high variability of plutonium concentrations in the environment, numerous samples were collected and analyzed by a modified solvent-extraction liquid-scintillation counting procedure (Keough and Powers, 1970). Counting yield was 96%. Overall chemical recovery was 90%. The minimum detectable activity (MDA) was 0.30 d/min per sample for a 100-min count. Modifications and additional analysis information are presented in a report by Johnson, Svalberg, and Paine (1974). Unless otherwise stated, all references to plutonium in this chapter include both ^{239}Pu and ^{240}Pu plutonium isotopes because the analytical procedure did not discriminate between plutonium isotopes.

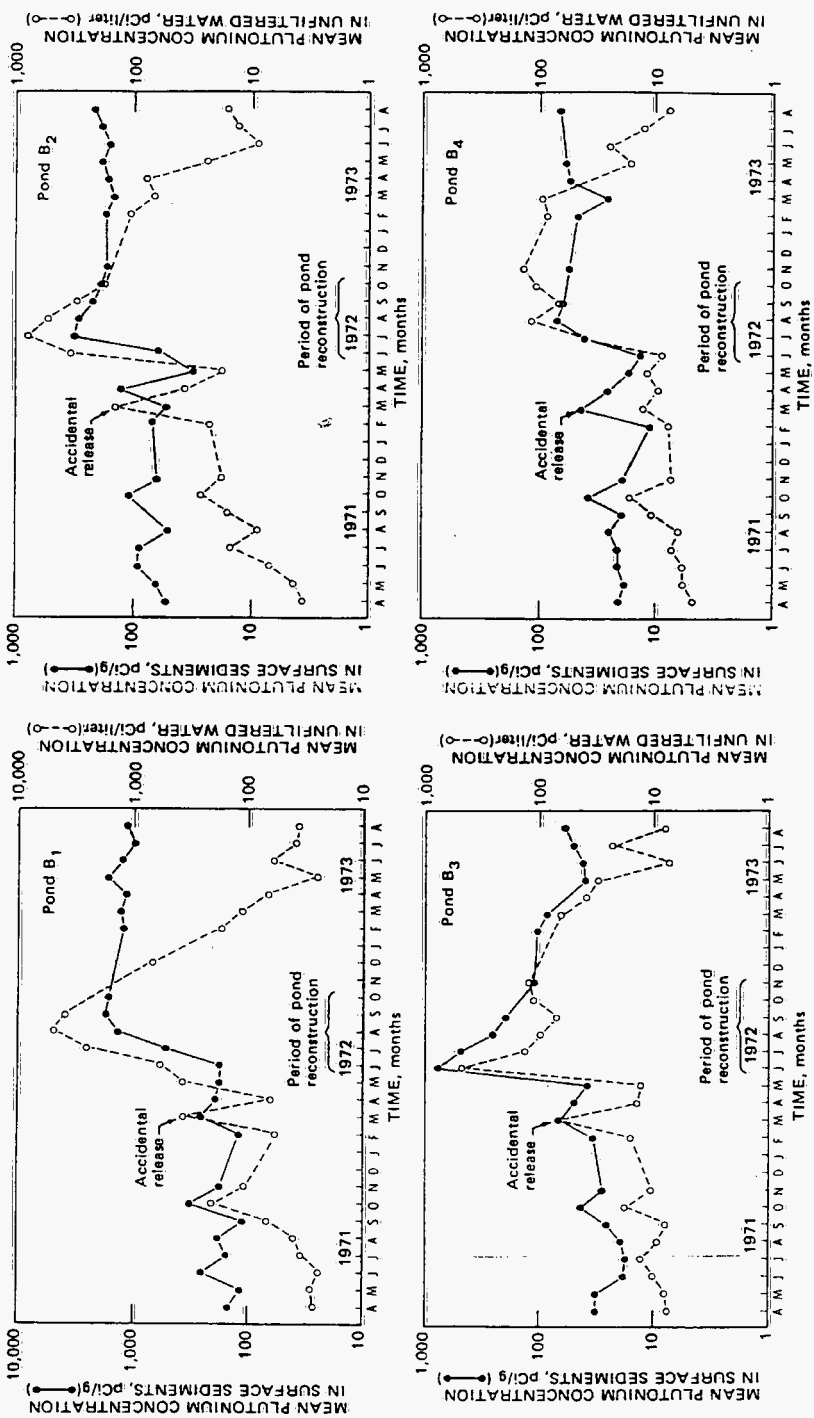
From 20 to 30 surface-sediment cores (approximately the top 5 cm) were obtained during each sampling period (~1 per month) from each pond. The procedure followed that outlined by Hakonson (1972). Additionally, core samples were extracted from the sediment beds of the pond, and the procedure defined by Johnson, Svalberg, and Paine (1974) was used to determine vertical distribution of plutonium within the pond sediments. Incremental samples were composited for analysis. The coefficient of variation determined from composited sediment samples was approximately 30%.

Surface-water samples were initially taken at each sediment sampling location from each pond. Later samples were taken not only at the surface but also at 0.5-m increments to the sediment–water interface. A mechanical water sampler was used to collect the subsurface water samples.

Water samples were filtered in a Millipore filtering apparatus that was modified by adding a brass screen with a pore size of 250 μm to the top of the water intake funnel. The screen removed most of the zooplankton and large organic material from the water sample. The water was pulled through a glass-fiber filter (Whatman GF/A, 4.7-cm diameter) with a vacuum pump to remove the remaining suspended material. The residue was analyzed as a separate component called seston, which included primarily phytoplankton, detritus, and other suspended solids. Seston as defined here does include some small zooplankton. The filtration process was usually carried out within 24 to 48 hr after the collection. Water samples were kept in darkness to inhibit growth until filtration could be accomplished.

The term "zooplankton" was used collectively for all small planktonic animals trapped in a number 10 plankton net (160-μm mesh size). These samples contained seston as well as large aquatic insects. The insects were separated from the samples. It was assumed that most of the sestonic material was probably smaller than the 160-μm mesh size and would pass through the net since the zooplankton sample was rinsed in the collecting net by repeated dunkings in the pond. Zooplankton were identified to species, but biomass estimates were not determined. A 12.7-cm-diameter Clark–Bumpus plankton sampler was towed behind a boat in an attempt to sample organisms.

Bass (*Ictiobus bubalus*) and carp (*Cyprinus carpio*) were collected by seining and angling. No fish were present in the B-series ponds, but minnows (*Hybosis* sp.) were collected in pond C_1 and pond A_1 with a large collecting net. The fish were too small for angling, and seining would have disturbed the bottom sediments. The maximum fish length observed in the ponds was approximately 6 cm. Vegetation (primarily *Juncus balticus*, *Rumex crispus*, and *Typha latifolia*) was collected in and around the ponds, streams, and reservoirs throughout the study period. Generally, the aerial portions of the plant samples were clipped with grass shears, and the roots were extracted separately owing to excessive sediment–soil contamination.


Pond B1
Pond B2
Pond B3
Pond B4
Accidental release
Period of pond reconstruction
1971
1972
1973
TIME, months
MEAN PLUTONIUM CONCENTRATION IN SURFACE SEDIMENTS, pCi/g
MEAN PLUTONIUM CONCENTRATION IN UNFILTERED WATER, pCi/liter

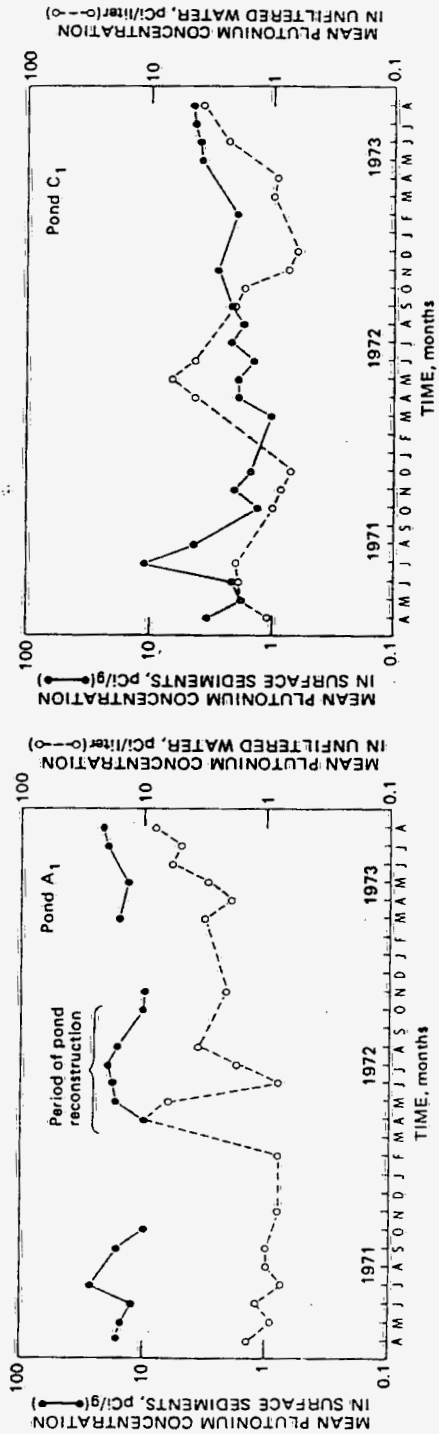


Fig. 3 Mean plutonium concentrations in surface sediments (pCi/g) and mean plutonium concentrations in unfiltered water (pCi/liter) for ponds B_1, B_2, B_3, B_4, A_1, and C_1. The sampling period was from April 1971 through August 1973. The B-series ponds received routine discharges containing low-level plutonium waste.

Small mammals (*Microtus pennsylvanicus modestus* and *Peromyscus nasutus*) were kill-trapped throughout the study period. Mule deer (*Odocoileus hemionus*) samples were collected from road kills.

Results

Sediment

Figure 3 shows the average $^{239,240}Pu$ concentrations in water and surface sediments over the entire study period. The accidental release in March 1971 resulted when process waste solutions low in $^{239,240}Pu$ content, due to be pumped to solar evaporation ponds for concentration, were accidentally released to the sanitary waste system. The resultant elevation over ambient conditions is readily apparent in Figs. 3 and 4. Reconstruction of the pond area had a marked effect on the mean sediment concentrations. Concentration levels increased significantly during construction and remained high during the rest of the study period for most ponds (Table 1). Plutonium concentrations also increased in the sediment sampled at Walnut Creek at Indiana Avenue (baseline reservoir), which indicated that considerable activity escaped the holding-pond system during the period of reconstruction (Fig. 4).

Pond B_1 showed the highest surface concentrations throughout the study period. A slight decrease in mean sediment concentrations was noted in ponds B_2 and B_4 following peak levels. However, pond B_3, which was the first pond to undergo reconstruction and underwent the most extensive remodeling, showed a marked decrease in sediment activity after the period of maximum values. This can be attributed to the deposition of appreciable soil that contained lower concentrations of plutonium during and after the dam and pond remodeling.

Subsurface sediments were probably mixed when the ponds were refilled. Core samples contained highest plutonium concentrations at 20- to 30-cm depths. Some minor construction modifications were made in the effluent bypass system which could have caused redistribution of high-level plutonium sediments from this area. Sewage-treatment modifications in May 1972, before reconstruction, could also have resulted in high-activity flocculate being released to the holding ponds.

Plutonium-239,240 concentrations in pond B_3 sediment peaked in late June 1972; those in pond B_2 peaked in July, and those in ponds B_1 and B_4 peaked in August. This suggests that pond reconstruction played a major role in the redistribution of plutonium since this is the order in which remodeling occurred. In any case it is readily apparent that mean-surface-sediment values increased markedly during the period of pond reconstruction and remained at higher levels except in pond B_3.

The clay sediments showed an extremely high affinity for plutonium, and, if left undisturbed, they appear to be an excellent reservoir for plutonium in an aquatic system.

Water

The mean concentrations of plutonium in unfiltered water samples during the course of this study (Fig. 3) showed that construction played a major role in the redistribution of plutonium from pond to pond. The increase in plutonium concentrations was also detected downstream at the Walnut Creek at Indiana Avenue sampling station (Fig. 4).

The majority of the plutonium in the water component was usually associated with the filterable fraction ($>0.45\,\mu m$) (Table 2). However, ponds A_1 and C_1, the monitoring

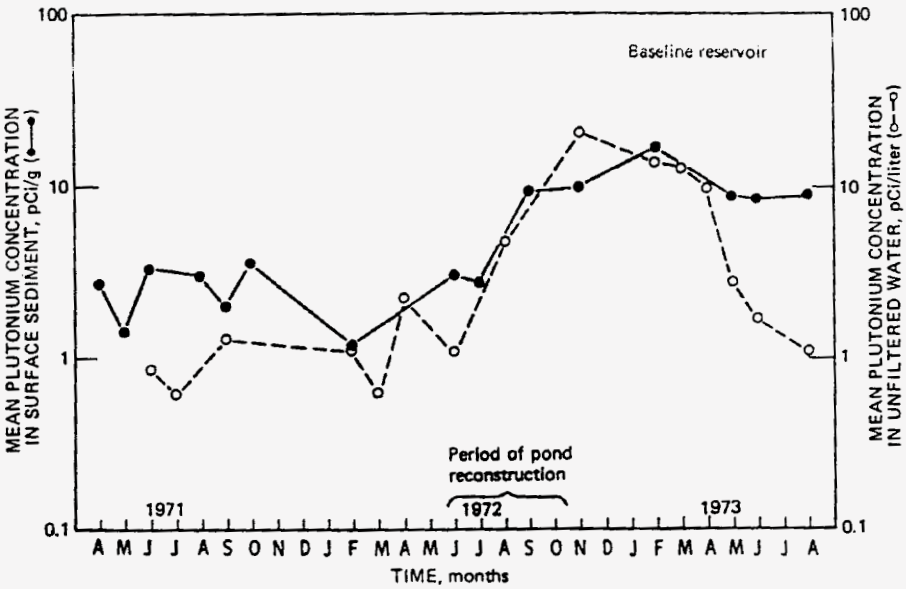


Fig. 4 Mean plutonium concentrations in surface sediment (pCi/g) and mean plutonium concentrations in unfiltered water (pCi/liter) for baseline reservoir. This sampling station is located where Walnut Creek crosses under Indiana Avenue.

TABLE 1 Mean-Surface(Top 5 cm)-Sediment $^{239,240}Pu$ Concentrations During Preconstruction and Postconstruction Periods

Pond	Preconstruction		Postconstruction	
	n*	pCi/g†	n*	pCi/g†
B_1	13	200 ± 70	11	1300 ± 350
B_2	12	80 ± 30	11	200 ± 60
B_3	13	30 ± 10	11	200 ± 200
B_4	14	20 ± 10	10	55 ± 15
C_1	12	3 ± 3	9	3 ± 1
A_1	9	15 ± 5	8	15 ± 4
Baseline reservoir	8	3 ± 1	7	10 ± 4
Bypass dam	2‡	750 ± 150		

*n = number of sampling periods.
†Mean ± standard error.
‡Mean of two samples taken in June 1971.

ponds that were separate from the holding-pond chain, received little contaminated plant effluent and contained a larger fraction of nonfilterable plutonium. Less suspended material, including phytoplankton, in ponds A_1 and C_1 is probably the explanation for this phenomenon. Because of the shallow nature of the pond systems, no apparent vertical distribution of plutonium could be determined.

TABLE 2 Percent of Plutonium Isotopes Associated with Filterable Fraction of Water Samples from Rocky Flats Ponds

Pond	Filterable fraction*
B_1	90 ± 6
B_2	80 ± 12
B_3	80 ± 8
B_4	70 ± 12
C_1	30 ± 30
A_1	35 ± 20

*Mean ± standard error.

Laboratory experiments were performed to study the transfer of plutonium from water to sediment as a function of time. The function appeared to consist of two exponential terms and was described by the equation

$$C(t) = C_0 \left(0.75\, e^{-0.92t} + 0.25\, e^{-0.58t}\right) \tag{1}$$

where C(t) is the concentration of plutonium in water at any time t, t is time (in days), and C_0 is initial concentration of plutonium in water.

This experimental finding fits remarkably well with actual pond limnological data. The average S. Walnut Creek flow into pond B_1 was measured to be 480 m^3/day during 1971. The water volume of pond B_1 was calculated to be 1500 m^3. Therefore the mean lifetime of any parcel of water in pond B_1, if mixing is uniform, can be calculated as follows:

$$t = \frac{1500\ m^3}{480\ m^3/day} = 3.1 \text{ days}$$

According to Eq. 1, 75% of the plutonium in water delivered to pond B_1 should be exchanged to sediment in an average residence time of 3.1 days.

Plutonium concentration as a function of sediment depth for the ponds is illustrated in Table 3. These data were plotted and integrated by a planimeter to determine the area (picocuries-centimeter per gram). This value was then divided by the mean sediment depth to give the mean sediment concentration of plutonium. When multiplied by the estimated sediment volume, these data yielded plutonium inventories for the sediment of the ponds. The same sediment characteristics were assumed for each pond. The variation could be due to shunting of water past ponds at unknown times. The calculated value also assumed that no plutonium was being transferred from pond to pond by suspended materials. The agreement between the calculated and measured inventories is shown for the holding ponds in Table 4.

Seston

Seston was defined as primarily phytoplankton, some detritus, and some small zooplankton. Planktonic algae constituted by far the majority of aquatic plant material found in the holding-pond chain on S. Walnut Creek (B ponds).

TABLE 3 Distribution of Plutonium Concentrations in Depth Profiles of Ponds B_1, B_2, B_3, B_4, and C_1

Depth, cm	Plutonium concentration, (d/min) g^{-1}				
	B_1	B_2	B_3	B_4	C_1
0 – 5	2,000	260	40	430	<1
5 – 10	2,200	80	170	190	<1
10 – 15	10,900	40	370	20	<1
15 – 20	32,100	60	330	4	2
20 – 25	8,800	230	20	7	4
25 – 30	1,100	190	3	7	<1
30 – 35	880	390	3	<1	
35 – 40	900	340	380		
40 – 45	190	100	6		
45 – 50	30	20	6		
50 – 55	100	10	3		
55 – 60	70	9	2		
60 – 65	5	4	2		
70 – 75	7	3			
75 – 80		2			
80 – 85		12			
85 – 90		50			
90 – 95		30			
95 – 100		3			
100 – 105		7			
105 – 110		40			
110 – 115		12			
115 – 120					

TABLE 4 Calculated and Measured Inventories of $^{239,240}Pu$ in Holding Ponds During 1971

Pond	Measured		Calculated,* %
	mCi	%	
B_1	84.5	62.4	74.8
B_2	27.0	19.9	21.9
B_3	19.4	14.3	2.9
B_4	4.6	3.4	0.4

*Calculated values are from the retention function obtained from laboratory experimentation.

TABLE 5 Concentration Ratios (CR's) in Seston, Zooplankton, and Crayfish Relative to Filtered Pond Water

Pond	No. of sampling periods	CR*
	Seston	
A_1	13	$7.5 \pm 1.1\ (10^4)$
B_1	18	$100 \pm 20\ (10^4)$
B_2	19	$1.7 \pm 2.8\ (10^4)$
B_3	19	$2.5 \pm 5.7\ (10^4)$
B_4	21	$16 \pm 3.7\ (10^4)$
C_1	12	$12 \pm 3.4\ (10^4)$
	Zooplankton	
B_2	2	$0.14 \pm 0.02\ (10^4)$
B_4	2	$0.17 \pm 0.02\ (10^4)$
	Whole crayfish	
B_3	2	$0.13 \pm 0.002\ (10^4)$
B_4	4	$0.07 \pm 0.019\ (10^4)$
C_1	2	$0.06 \pm 0.003\ (10^4)$

*pCi ^{239,240}Pu/g acceptor ÷ pCi ^{239,240}Pu/ml water. Mean ± standard error.

The transfer of plutonium from water to seston was extremely high (Table 5). The concentration ratios (CR's) relative to filtered water were of the order of 10^4 to 10^5. Concentration ratio is defined as

$$CR = \frac{\text{picocuries per gram seston (dry weight)}}{\text{picocuries per milliliter water (filtered)}}$$

These CR's were higher than those previously observed in marine systems. Laboratory experiments revealed that the mechanisms involved were more than simple surface sorption (Johnson, Svalberg, and Paine, 1974).

Zooplankton

Although several species of cladocerans, copepods, and amphipods were collected, sufficient biomasses for analysis were never obtained at any one sampling period. This necessitated a pooling of the samples over several months. This was especially true for the B-series ponds, which contained almost no zooplankton throughout the study. Zooplankton showed CR's relative to filtered water in the 10^4 range (Table 5). These CR's are similar to those reported in marine studies. If ingestion is the primary route of transfer in these organisms, then higher concentration factors would be expected from the simple phytoplankton-to-zooplankton food chain. Since an increase in trophic-level concentration of plutonium did not occur, there appears to be a selective mechanism that discriminates against plutonium at this level. This would result in a decreased potential hazard when considering the transfer of plutonium through ingestion routes.

TABLE 6 Concentration of $^{239,240}Pu$ in Fish Inhabiting Rocky Flats Environs

Sample type	Location	n	Sample	Concentration,† pCi/g
Minnow (*Hybosis* sp.)	C_1	5	Whole	1.7 ± 0.2
Minnow (*Hybosis* sp.)	A_1	8	Whole	5.1 ± 1.8
Carp (*Cyprinus carpio*)	Great Western	6	Whole and dissected	<0.02
Bass (*Ictiobus bubalus*)	Pond 7	6	Whole and dissected	<0.02
Minnow (*Hybosis* sp.)	C_1	3*	GI tract	0.6 ± 0.7
			Flesh	<0.02
			Head	0.9 ± 0.9
			Skin	2.3 ± 0.4
			Bone	<0.02
Minnow (*Hybosis* sp.)	A_1	3*	GI tract	0.9 ± 0.9
			Flesh	<0.02
			Head	2.3 ± 2.2
			Skin	4.6 ± 4.2
			Bone	<0.02

*Number of composite fish samples analyzed (5 fish/composite).
†Mean ± standard error.

Crayfish

Crayfish, a large invertebrate common to the pond system, showed CR's relative to unfiltered water in the range of 320 to 1290 with a mean value of 830 (Table 5). These values are similar to those found in other studies. Seventy-seven percent of the plutonium in crayfish was associated with the exoskeleton, even though the crayfish were scrubbed extensively. The benthic origin of these organisms probably explains the high plutonium concentrations associated with the exoskeleton.

Fish

Fish flesh and bone from ponds A and C and reservoirs were never above MDA (0.30 d/min per sample) even when several samples were composited (Table 6). Whole fish, however, contained measurable amounts of plutonium in the gut contents, the head, and the outer skin. This suggests that plutonium is being discriminated against at this trophic level.

Flora

No true aquatic vascular plants and relatively few emergent species existed in the pond systems at Rocky Flats. Bulrush (*Juncus balticus*) rooted sporadically within the ponds, and cattail (*Typha latifolia*) frequently grew with its roots submerged. Dock (*Rumex crispus*) was abundant in the riparian area. Concentration ratios for plants associated closely with pond sediments confirmed the observation that the transfer of plutonium from sediments to aerial portions through roots is higher than that previously reported in laboratory experiments (Romney, Mork, and Larson, 1970) (Table 7). Concentration ratios were in the 10^{-2} to 10^{-1} range. This could suggest that the plutonium associated

TABLE 7 Concentrations of $^{239,240}Pu$ in Vegetation Samples (*Juncus balticus*, *Rumex crispus*, and *Typha latifolia*) Associated with the Rocky Flats Pond System

	Concentration, pCi/g (dry weight)				
	Mean	Min.	Max.	CV	n*
Total roots	11.2	0.31	93.2	2.03	51
Total standing vegetation	5.1	0.01	44.3	2.00	52
A_1 roots	1.69	0.31	4.77	0.76	12
A_1 standing vegetation	1.47	0.28	3.68	0.80	12
B_1 roots	45.4	2.46	93.2	0.76	9
B_1 standing vegetation	18.9	1.23	44.3	0.80	9
B_2 roots	2.45	0.67	4.39	0.55	9
B_2 standing vegetation	2.04	0.01	8.27	1.26	9
B_3 roots	1.16	1.91	1.41	0.30	2
B_3 standing vegetation	0.45	0.33	0.56	0.36	2
B_4 roots	3.89	1.49	6.22	0.50	4
B_4 standing vegetation	1.28	0.21	3.94	1.06	4
C_1 roots	2.84	0.55	7.38	0.55	15
C_1 standing vegetation	1.83	0.12	5.66	0.93	16

*Number of samples.

with the ponds is of a more biologically available form. This appears contradictory to laboratory experiments which do not include a variety of environmental factors that could contribute to an increased uptake of plutonium, such as surface contamination.

Fauna

A variety of small and large mammals were opportunistically captured during the course of this study. The data associated with this compartment were too few except to draw tentative conclusions. However, it would appear that fauna associated with the Rocky Flats area, in general, maintained a relatively low systemic body burden of plutonium (Table 8).

Conclusions

The results obtained in this study were of a very preliminary nature because of the more general systems approach to the study and to the use of an analytical technique that provided no isotopic discrimination. Owing to the cost of sophisticated sample analyses, a majority of activity levels near fallout background and/or analytical detectability, and the overall complexity of a systems approach, only tentative conclusions can usually be ascertained for transuranic elements in the environment. However, the tentative conclusions drawn from this study and others are, in general, the same.

Although the various components of the aquatic system at Rocky Flats are concentrating plutonium to a relatively high degree, there appears to be no direct evidence that concentrations of plutonium observed will result in a biological hazard to

TABLE 8 Plutonium Concentrations in Some Animals Collected at Rocky Flats

Odocoileus hemionus (Rocky Mountain mule deer)

Sample	Concentration, pCi/g (dry weight) Mean	Min.	Max.	CV	n*
Spleen	0.03	0.02	0.05	0.42	3
Kidney	0.08	0.05	0.10	0.41	2
Lung	0.03	0.01	0.10	0.90	7
Broncheoles	0.07				1
Bronchus	0.08				1
Liver	0.03	0.01	0.09	1.43	3
Heart	0.01				1
Hide	0.06	0.03	0.16	0.74	7
Lymph nodes (broncheolar)	0.33				1
Esophagus	0.08				1
Rumen contents	0.05	0.01	0.15	1.08	5
Blood	0.02	0.01	0.02	0.30	5
Muscle	0.33	<0.01	1.80	1.05	6

	Mean	SD	n
Internal =	0.12	± 0.15	7
External =	0.06	± 0.02	6

Microtus pennsylvanicus modestus (meadow mouse)

Sample	pCi/g (dry weight)
Liver	0.58
Lungs	5.10
GI tract	0.17
Bone	0.06

Peromyscus nasutus (white-footed deer mouse)

Sample	pCi/g (dry weight)
Liver	0.99
Lungs	40.10
Flesh	0.07
Bone	0.55

Rana pipiens (leopard frog)

Sample	pCi/g (dry weight)
Liver	0.01
Lungs	14.40
Flesh	0.17
Bone	0.31

*Number of samples.

man through ingestion routes. This was concluded on the basis that (1) the majority of plutonium in the system was associated with sediments; (2) plutonium in unfiltered water leaving the Rocky Flats plant site averaged <10 pCi/liter, even during pond reconstruction, which was below accepted maximum permissible concentration (1600 pCi/liter, International Commission on Radiological Protection); and (3) plutonium concentrations did not increase along simple trophic-level routes to any significant extent.

References

Aarkrog, A., 1971, Radioecological Investigations of Plutonium in an Arctic Marine Environment, *Health Phys.*, 20: 31-47.

Emery, R. M., and D. C. Klopfer, 1976, The Distribution of Transuranic Elements in a Freshwater Pond Ecosystem, in *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms*, pp. 269-285, M. W. Miller and J. N. Stannard (Eds.), Ann Arbor Science Publishers, Ann Arbor, Mich.

Hakonson, T. E., 1972, *Cesium Kinetics in a Montane Lake System*, Ph.D. Dissertation, Colorado State University, Fort Collins, Colo.

——, J. W. Nyham, and W. D. Purtymun, 1976, Accumulation and Transport of Soil Plutonium in Liquid Waste Discharge Areas at Los Alamos, in *Transuranium Nuclides in the Environment*, Symposium Proceedings, San Francisco, Nov. 17–21, 1975, pp. 175-189, STI/PUB/410, International Atomic Energy Agency, Vienna.

Hammond, S. E., 1971, Industrial-Type Operations as a Source of Environmental Plutonium, in *Proceedings of Environmental Plutonium Symposium*, Los Alamos, N. M., Aug. 4–6, 1971, E. B. Fowler, R. W. Henderson, and M. F. Milligan (Coordinators), USAEC Report LA-4756, pp. 25-35, Los Alamos Scientific Laboratory, NTIS.

Johnson, J. E., S. Svalberg, and D. Paine, 1974, *Study of Plutonium in Aquatic Systems of the Rocky Flats Environs*, Final Technical Report, Dept. of Radiology and Radiation Biology and the Dept. of Animal Sciences, Colorado State University.

Keough, R. F., and G. J. Powers, 1970, Determination of Plutonium in Biological Materials by Extraction and Liquid Scintillation Counting, *Anal. Chem.*, 42: 419-421.

Noshkin, V. E., 1972, Ecological Aspects of Plutonium Dissemination in Aquatic Environments, *Health Phys.*, 22: 537-549.

——, V. T. Bowen, K. M. Wond, and J. C. Burke, 1971, Plutonium in North Atlantic Ocean Organisms Ecological Relationships, in *Radionuclides in Ecosystems*, Proceedings of the Third National Symposium on Radioecology, Oak Ridge, Tenn., May 10–12, 1971, D. J. Nelson (Ed.), USAEC Report CONF-710501, pp. 681-688, Oak Ridge National Laboratory, NTIS.

Pillai, K. C., R. C. Smith, and T. R. Folsom, 1964, Plutonium in the Marine Environment, *Nature (London)*, 203: 568.

Romney, E. M., H. M. Mork, and K. H. Larson, 1970, Persistence of Plutonium in Soil, Plants, and Small Animals, *Health Phys.*, 19: 487-491.

Stannard, J. N., 1973, Chemical and Physical Properties of Plutonium, in *Uranium and Plutonium Transplutonic Elements*, pp. 670-686, H. C. Hodge, J. N. Stannard, and J. B. Hursh (Eds.), Springer-Verlag, New York.

Taylor, D. M., 1973, Chemical and Physical Properties of Plutonium, in *Uranium and Plutonium Transplutonic Elements*, pp. 323-347, H. C. Hodge, J. N. Stannard, and J. B. Hursh (Eds.), Springer-Verlag, New York.

DOE/TIC-22800

TRANSURANIC ELEMENTS IN THE ENVIRONMENT

A Summary of Environmental Research on Transuranium Radionuclides Funded by the U. S. Department of Energy Through Calendar Year 1979

Wayne C. Hanson, Editor
Pacific Northwest Laboratory

Prepared for the U. S. Department of Energy
Assistant Secretary for Environment
Office of Health and Environmental Research

1980

Published by
Technical Information Center/U. S. Department of Energy

16/16