IDO-10049

RADIONUCLIDE DISTRIBUTION IN SOIL MANTLE OF THE LITHOSPHERE AS A CONSEQUENCE OF WASTE DISPOSAL AT THE NATIONAL REACTOR TESTING STATION

COMPILED BY

B.L. Schmalz

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DATE 11/29/72

NATIONAL
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DATE PUBLISHED—OCTOBER 1972

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UNITED STATES ATOMIC ENERGY COMMISSION
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"I say apparently, for the actual facts are not sufficiently made out, should further research ever discover them, we must yield to their guidance rather than to that of theory; unless their teachings tally with the indisputable results of observation."

Aristotle -- "On Man in the Universe"

ACKNOWLEDGMENTS

In addition to the references listed in the text, the following significant contributions to this report are acknowledged:

(1) All radiochemical analyses were made by the Analytical Chemistry Branch of the AEC Health Services Laboratory (HSL) under the direction of C. W. Sill. Others involved were D. G. Olson, K. W. Puphal, L. E. Thompson, and C. F. Ching. John B. Echo of the Environmental Branch assisted in collation of data.

(2) Drawings were made by the Graphic Arts Section of the Information and Nuclear Materials Management Branch of the Technical Services Division of Aerojet Nuclear Company (ANC).

(3) Editing and final preparation of this report were performed by the Technical Publications Section, ANC.

(4) The assistance of Mr. Floyd Spraktes of the Computer Science Branch of the Technical Services Division, ANC, is appreciated in the computation of the best fit of the error function (C/C_O) for the cesium data and standard deviation thereof (Figure II-4).

(5) The Theoretical Appraisal Section, II-3, is an extension of work originally initiated by Dr. D. B. Hawkins while employed by the AEC at the Health Services Laboratory (presently at the University of Alaska).

(6) Soil samples from beneath the TRA disposal ponds were obtained by personnel of the U. S. Geological Survey, NRTS project and Hydrologic Laboratory, Denver, Colorado. Samples from the NRTS burial ground during 1970 were taken by Joseph H. Osloond, HSL Environmental Branch.

(7) A report which included a major portion of this manuscript was issued in June of 1970 (IDO-12072, "Radionuclide Distribution in the Regolith as a Result of Waste Disposal at the National Reactor Testing Station" - Schmalz and Polzer) It received very limited distribution due to its interim nature. Subsequent field investigation during late 1969 and 1970 has been included herein. As a Soil Chemist at the Health Services Laboratory, Dr. Polzer made a major contribution by obtaining, analyzing, and evaluating data as well as contributing to the preparation of the original manuscript.

ABSTRACT

This report is a study of the distribution of radionuclides in the soil[a] resulting from disposal of liquid and solid waste at the National Reactor Testing Station (NRTS). The situation involving liquid waste is appraised by: (a) mathematical models using parameter determined in the laboratory; (b) physical models using soil samples and simulated waste solution; and (c) sampling of soil and water where waste is being discharged.

In case of strontium-90, the data obtained indicate that the sorption capacity of the alluvial deposits between the disposal pond bottoms and the basalt bedrock has been reached. The data for cesium were erratic but the most pessimistic interpretation indicates that the capacity of the alluvium has not been reached. The amount of cobalt-60 estimated to be in the alluvium is greater than that reported to have been discharged. The discharge estimates do not take into account the more frequent usage of unsheathed cobalt wires for neutron flux measurements during the early history of the reactors. Cobalt-60 retention in the soil is attributed to reactions other than ion-exchange.

A theoretical appraisal of the migration of radionuclides at the burial ground indicates that the potential hazard is small under well-drained circumstances. Leaching of waste and the migration of some fission products as well as plutonium isotopes and daughter products is shown to have occurred to a very limited extent. This is inferred to have resulted from inundation of waste as a result of poor drainage of snow-melt runoff. The concentrations and distances are small and are not interpreted as a cause for concern in regard to insulting the regional aquifer system.

A hypothetical evaluation is included of the environmental probelms remaining after active operation of a disposal site has been discontinued. It is concluded that disposal sites can be used for other purposes with certain restrictions.

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[a] The word soil, as used in this report, is equivalent to the word regolith meaning the unconsolidated material above the bedrock -- Appendix D defines other terms peculiar to specific disciplines.

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RADIONUCLIDE DISTRIBUTION IN SOIL MANTLE OF THE LITHOSPHERE AS A CONSEQUENCE OF WASTE DISPOSAL AT THE NATIONAL REACTOR TESTING STATION

Compiled By

Bruce L. Schmalz[a]

I. INTRODUCTION

The plain on which the National Reactor Testing Station (NRTS) is located is formed by geologically young volcanic rocks (basalt) with interbeds of unconsolidated soil-like material. The land surface is composed of wind and water lain sediments (regolith). The thickness and distribution of these deposits vary from a few inches to more than 50 feet in conformity with the surface of the underlying basalt. The regional ground water table occurs at depths between 200 and 800 feet below the land surface.

Since 1952, aqueous liquids containing radionuclides have been discharged to seepage ponds and pits excavated in gravelly alluvium of the Lost River flood plain. Solid waste has been buried in a basin-like area in the southwestern section of the Station. This report is an evaluation of the resulting distribution of these nuclides.

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[a] Waste Management Branch, Production and Technical Support Division (Instigated and coordinated the work herein reported while employed as a soil scientist at the Health Services Laboratory, NRTS).

II. LIQUID DISPOSAL

Seepage ponds have been utilized at several locations such as the Test Reactor Area (TRA), Naval Reactor Facility (NRF), and the Special Power Excursion Reactor Test (SPERT). At least 99% of the radioactivity involved has been discharged at the TRA; therefore, investigation has been limited to this area. Waste liquids from the fuel storage basis at the Idaho Chemical Processing Plant (ICPP) were discharged to a shallow seepage crib prior to 1964 and this has been the subject of subsequent monitoring.

1. DESCRIPTION OF DISPOSAL PONDS

The ponds (see Figure II-1) are excavated in gravelly alluvium, approximately 50 feet thick and underlaid with basalt rock. The proportions of sand, silt, and clay vary from place to place[1]. Approximately 30% is less than 2 mm in size and contributes essentially all of the ion exchange capacity. The silt fraction, 2 to 62 microns, consists of quartz, calcite, feldspar, dolomite, montmorillonite, and mica. The clay fraction, less than two microns, consists of montmorillonite, hydromica, kaolin, quartz, calcite, and feldspar[2]. The regional water occurs at a depth of approximately 450 feet below the land surface.

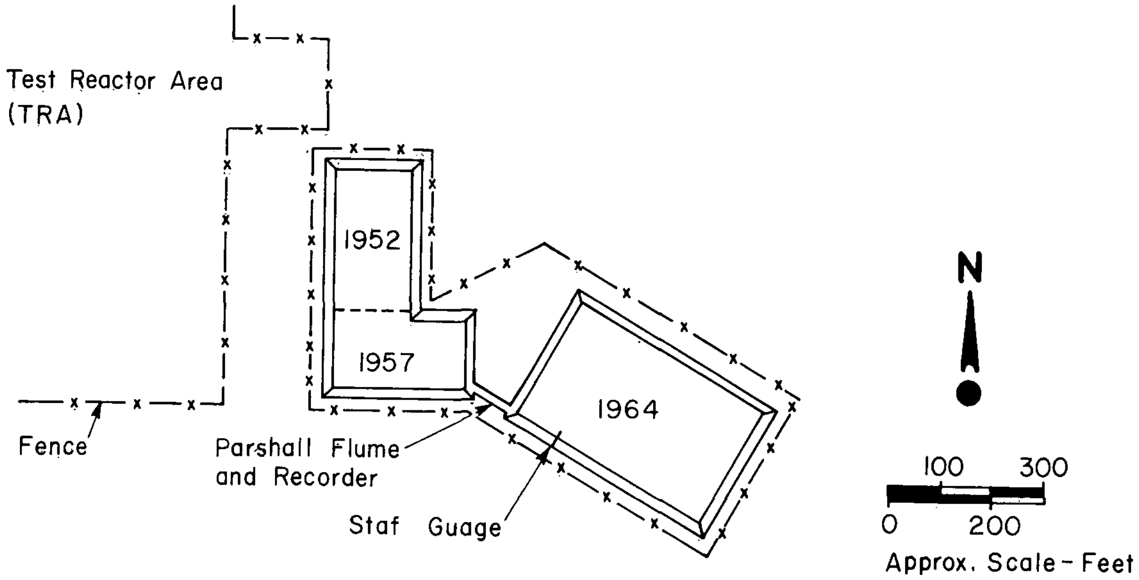

Fig. II-1 Plan sketch and photograph of TRA liquid waste disposal ponds.

Disposal from the Materials Testing Reactor (MTR), via a pond, was started in 1952. This pond had a bottom area of 37,500 ft^2 with sloping slides. In 1957, the Engineering Test Reactor (ETR) was accommodated by excavating an adjacent pond with a bottom area of 28,750 ft^2. By 1959, the intervening embankment was submerged and since that time the two pond sections have not been distinguishable on the surface. A constant depth is maintained in these two sections by an overflow flume which leads to a third section that was put into use during July 1964. This section has a bottom area of 100,000 ft^2.

The infiltration rate used for design was 10-15 gal/day/ft^2 of wetted surface[3]; however, this has varied with water depth, temperature, and time. By 1964, the first two sections became impermeable and when the new section was put into use it accepted practically all of the discharge. By 1966 permeability of the older sections had improved to the extent that they were again accepting about 40% of the flow[4]. By 1970, the 1964 section became relatively impermeable and complete filling was threatened. This situation was arrested by retaining all of the discharge in the first two sections during the months of August and September and allowing the 1964 section to dry up. Improved permeability resulting from this action was attributed to desiccation of the soil and organic matter on the pond bottom.

2. AMOUNTS AND CHARACTERISTICS OF WASTE DISCHARGE TO PONDS

The amount of waste estimated at the time of discharge to the ponds is shown in Table II-1. The mean yearly discharge rate over the 19 year period is 160 million gallons (6 x 10^8 liters) which contained a gross concentration of radionuclides of 4 x 10^{-3} μCi/ml. Approximately 80% of the radioactive contaminants were short lived nuclides with half-lives of less than 30 days. These contaminants are of less consequence or concern as far as deleterious effects on the environment at the NRTS are concerned. The residual curie amounts, corrected for decay, of three relatively long lived nuclides are as follows:

Nuclide	At time of 1968 evaluation (Aug.)	At time of 1970 evaluation (Aug.)
Sr-90	23	35
Cs-137	70	85
Co-60	117	112

As of mid-year 1968, approximately 960 curies of cerium isotopes had been discharged. If all were cerium-144, which has a half-life of 282 days, about 30 curies would remain. Approximately 50 curies of the 1043 curies discharged as of mid-1970 would still remain. A more realistic assumption would be that cerium-144 existed with cerium-141 in the same proportion in the waste that it was produced in the reactor fuel (1:9) in which case only a fraction of that discharged immediately prior to any point in time would be present in the environment, and in any case, less than ten curies...

On the basis of the liquid infiltration history previously referred to, the curies of strontium-90, cesium-137, and cobalt-60 remaining as of mid-1968 is allocated to the ponds as follows:

Nuclide	1952-57 Section	1964 Section	Total
Sr-90	15	8	23
Cs-137	57	13	70
Co-60	68	49	117

As of 1970, the allocation of the residual activity would be:

Nuclide	1952-57 Section	1964 Section	Total
Sr-90	20	15	35
Cs-137	64	21	85
Co-60	57	55	112

The amounts of cobalt shown above involve only that discharged since 1961. Prior to this time, the amount was not quantitatively identified.

Prior to 1962, water processing and cooling tower wastes containing other elements and compounds such as calcium, sodium, sulfates, and chlorides were mixed with that containing radioactive contaminants. After 1962, the water treatment wastes were diverted to a separate pond and in 1964 the cooling tower waste was discharged to a well. Some nonradioactive nuclides still exist in the radioactive waste stream. The concentrations vary however and the effect on the sorption of the radioactive contaminants by minerals is not defined. Table II-2 is a list of representative concentrations in comparison to natural ground waters.

Table II-1

LIQUID WASTE DISCHARGE TO PONDS AT TRA

		Contaminating Radionuclides (Curies)						
Year 19	Gallons X 10^6	Sr-90	Cs-137	Co-60	[b] Ce-141/144	Short Lived	Tritium	Total Activity
70[a]	158	5.2	3	10	42	2,598[c]	474	3,132
69	266	8.1	11	21	29	2,183	748	3,000
68	188	3.1	4	22	28	654	499	1,210
67	181	8.1	5	33	37	825	402	1,310
66	130	1.7	4	7	28	1,050	389	1,480
65	146	1.7	6	14	22	1,048	328	1,420
64	172	1.5	5	39	41	1,084	399	1,570
63	202	1.2	7	15	108	4,274	386	4,790
62	283	0.7	8	27	172	5,552	280	6,040
61	235	1.3	6	[e]	89	2,791	303	3,190[d]
60	221	0.7	13		147	3,185		3,346
59	200	3.3	11		120	4,692		4,826
58	249	2.1	7		73	2,945		3,027
57	103	0.7	2		23	936		962
56	94	0.6	2		20	817		840
55	98	0.9	3		30	1,208		1,242
54	95	0.8	3		27	1,110		1,141
53	15	0.1	1		5	210		216
52	5	0.1	0		2	73		75
TOTAL	3,041	41.9	101	188	1,043			

---

[a] First six months

[b] Cerium-141 has a half-life of 32 days; Cerium-144 has a half-life of 282 days.

[c] The nuclides include: Sr-89, 50 days; I-131, 8 days; Cr-51, 28 days; Ru-Rh-106, 40 days, and 30 sec; Ba-La-140, 13 days and 40 hrs; plus others

[d] Gross activity prior to 1961 does not include tritium.

[e] No analyses performed prior to 1962.

TABLE II-2

CHEMICAL COMPOSITION OF WASTE WATER DISCHARGED TO DISPOSAL PONDS IN COMPARISON TO NATURAL GROUND WATER AND SOIL WATER

	Concentration (ppm)														
Sample	Na	K	Ca	Mg	Li	Cs	NH_4	SO_4	NO_3	PO_4	Cl	F	HCO_3	CO_3	pH
1961[a]	98	3.7	100	26	---	---	---	540	5.5	0.8	33	0.4	---	---	3.1
1968	12	0.8	15	7.2	0.002	<0.004	0.1	59	---	1.6	7.3	<0.5	7.3	58	9.9
1969	19	2.0	38	15	0.004	---	---	180	0.14	0.7	8.9	0.2	6.5	35	9.2
Ground Water[b]	9.6	3.2	39	14	---	---	---	24	2.2	0.1	15	0.2	166	0.6	7.7
	8.4	1.6	51	18	---	---	---	25	5.2	---	14	0.2	213	0.0	7.8
Soil Water 1968[c]	16	5.0	49	12	0.006	---	---	71	---	0.1	25	0.4	136	0	7.7

---

[a] Analyses of prime operating contractor, NRTS, Chemical Technology Section.

[b] R. L. Nace (ed.), Hydrology and Water Resources, Part 3, U.S. Geological Survey, IDO-22034, 1956.

[c] 1968 Analysis by U.S. Geological Survey, Water Quality Laboratory, Portland, Oregon.

3. THEORETICAL APPRAISAL

Laboratory procedures have been developed which simulate field conditions and provide a means of estimating the distribution of radionuclides which have been passed through earth materials. The theoretical concepts on which these procedures are briefly reviewed in the following paragraphs and the results of their application are compared with field investigations.

3.1 Distribution Coefficient

The distribution coefficient is an experimentally determined number and a measure of the preference for a given nuclide shown by soil minerals. It is dependent upon, and applicable only to, specific conditions. It is expressed or defined as:

$$K_d = \frac{\text{Concentration of radionuclide sorbed on the soil } (\mu\text{Ci/g})}{\text{Concentration of radionuclide in solution } (\mu\text{Ci/ml})} \qquad \text{(II-1)}$$

It can be determined in the laboratory by batch techniques, in which solutions containing known amounts of nuclides are allowed to reach equilibrium with soil material. The values shown in Table II-3 were determined using a composite soil (see Table II-5) representing that portion of the alluvium less than 2 mm grain size and a sample of 1969 TRA pond water (Table II-2); the procedure is outlined in the Appendix. The concentration of strontium and cesium was increased by the addition of strontium-85 and cesium-137 to facilitate the analysis with the following final concentration: strontium-85, 7.8×10^{-3} μCi/ml, and cesium-137, 7.0×10^{-3} μCi/ml.

TABLE II-3

DISTRIBUTION COEFFICIENT VALUES (K_d) DETERMINED IN THE LABORATORY (less than 2 mm grain size)

	Kd (ml/g)	
Sample	Sr-85	Cs-137
1	26	589
2	23	804
3	23	1147
4	23	1253
Mean	24	950

As the distribution coefficient changes as a function of chemical composition of the solution it becomes laborious to make separate determinations for every conceivable or encountered combination of solutes in solution. Therefore, equations have been developed by which it can be calculated over a wide range of solution compositions[2]. In the case of strontium and cesium the equations are:

For strontium on soil

$$\begin{aligned}\%R = 67.4 &- 2.56 \times 10^{-2}\,(\text{Na}) + 2.66 \times 10^{-4}\,(\text{Na})(\text{Mg}) \\ &- 7.78 \times 10^{-4}\,(\text{K})(\text{NH}_4) - 3.19 \times 10^{-1}\,(\text{Mg}) \\ &- 2.65 \times 10^{-1}\,(\text{Ca}) + 6.11 \times 10^{-4}\,(\text{Ca})^2 \\ &+ 7.03 \times 10^{-2}\,(\text{S.C.})(\text{pH}) - 4.89 \times 10^{-7}\,(\text{Ca})^3 \\ &- 3.29 \times 10^{-5}\,(\text{S.C.})(\text{Mg})(\text{Ca}).\end{aligned} \qquad \text{(II-2)}$$

For cesium on soil

$$\begin{aligned}\%R = {} & 57.4 + 5.78 \times (S.C.) - 20.6\ (Cs) + 6.55\ (Cs)^2 \\ & - 1.28 \times 10^{-2}\ (Cs)(K) - 4.54 \times 10^{-3}\ (Cs)(Ca) \\ & - 7.88 \times 10^{-2}\ (NH_4) - 6.27 \times 10^{-1}\ (Cs)^3.\end{aligned} \tag{II-3}$$

In these equations, %R is the percent retained per gram of exchanger which is converted to the distribution coefficient by the following equation:

$$K_d = \frac{V \times (\%R \times 10^{-2})}{[1 - (\%R \times 10^{-2})]} \tag{II-4}$$

where V is the volume of liquid equilibrated with one gram of soil.

The chemical symbols in the equation refer to the concentrations of the particular ions in parts per million. The hydrogen ion concentrations are in pH units.

The term (S.C.) is the saturation capacity of the soil material of less than 2 mm grain size for the element involved expressed as milliequivalents (meq) per 100 grams. The values reported by Hawkins were 10 meq/100 g for strontium and 7.1 meq/100 g for cesium.

By solving the above equations using the composition of the pond water [as of 1961, 1968, and 1969 (Table II-2)] as well as the composition of soil water in 1968, the values shown in Table II-4 were obtained.

TABLE II-4

DISTRIBUTION COEFFICIENT (K_d)

DETERMINED BY SORPTION EQUATIONS

	Strontium		Cesium	
Chemical Composition of Solution in	%R	K_d(ml/g)	%R	K_d(ml/g)
1961	38	15	98	1200
1968	68	53	98	1200
1969	59	36	98	1200
Soil-1968	57	33	98	1200

3.2 Ion Exchange Columns

Retention of nuclides in earth materials can be studied by packing soil in a glass or metal tube (ion exchange column). A liquid containing a radionuclide is passed through the column at a flow rate simulating field conditions. Samples of the effluent are collected in quantities which can be related to the volume of the column. The concentration of the nuclide is then determined (C) and compared to the concentration in the influent (C_O). If the ratio (C/C_O) is plotted as a function of volume, a curve such as that shown in Figure II-2 will result. In theory practically all of the nuclide would be removed from the initial volumes of solution and the ratio C/C_O would approach zero. As more solution flows through, less of the nuclide would be removed until the concentration of the effluent is equal to the area above the curve OxP. At a point designated by x, more than one-half of the amount of nuclide added up to this time is retained by the soil. At the point where C/C_0 is just equal to one, one-half of all activity which has been added is retained; the rest passed out with the effluent. If the curve is symmetrical about the 50% point, the cross-hatched area I (above the curve) is equal to the cross-hatched area II (below the curve). Therefore, if area II is substituted for area I, the area of the rectangle 0-a-b-1.0 is equal to the area above the curve and represents the quantity of nuclide which can be sorbed by the soil. This can be expressed numerically as the product of the volume at 50% breakthrough and the original concentration.

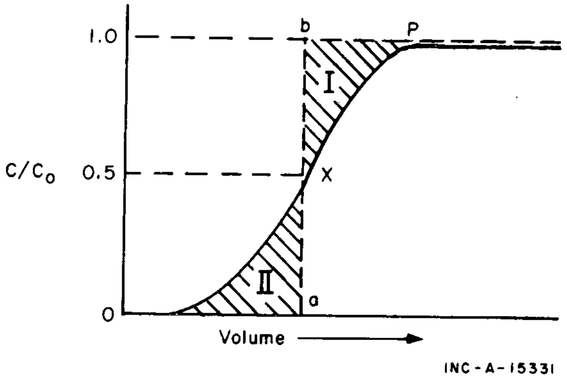

Fig. II-2. Hypothetical breakthrough curve of solution concentration passing through an ion-exchange column.

The distribution coefficient K_d is related to the volume required to load a column to the 50% point (V_{50}) or (x) as follows:

$$V_{50} = \frac{K_d \times W}{2} \qquad \text{(II-5)}$$

where W is the weight in grams of the soil in the column.

If K_d is experimentally determined, the volume at 50% breakthrough can be predicted, and an estimate can also be made of the total amount of nuclide which can be sorbed by a given mass of soil. The volumes estimated in this way are usually lower than those obtained from the column runs, but are reasonably good approximations.

The dispersion, or distribution, of a nuclide can also be represented by an error function plot. In other words, if the breakthrough curve, as shown in Figure II-2, is plotted on log probability paper a straight line results[5]. This technique was utilized to evaluate the TRA situation.

3.21 *Strontium.* Alluvial material from two auger holes was passed through sieves and separated into particle size shown in Table II-5. These separates were then composited to form a soil sample representative of the composition determined from channel samples from the TRA vicinity as reported by Hawkins and Foster[1]. The soil thus composited represents only 30% of the alluvium as it exists in the field with the balance being sand and gravel which has very little exchange capability.

This composite soil was placed in a 41-cc column, 1.85 cm in diameter and 15.1 cm in length. The weight of the soil contained in the column was 66 grams.

The solution passed through the column was taken from the TRA pond and had the same chemical composition as in 1969 as shown in Table II-2. The concentration of strontium-90 and cesium-137 was too low to be easily detected; therefore, it was increased by the addition of strontium-85 and cesium-137 so that the resulting concentration was strontium 85-90 (8.2×10^{-3} μCi/ml)* and cesium-137 (7×10^{-3} μCi/ml). The flow rate through the column was approximately 0.1 ml/min-2.7 cm^2, which simulated a field percolation rate of 13 gal/day-ft^2. The concentration of the effluent samples and the C/C_o ratios are listed in Table II-6 and shown in Figure II-3.

TABLE II-5

COMPOSITION OF COMPOSITE SOIL USED IN COLUMN STUDY

Particle Size (mm)	Percent of Soil Composite
>3.36	---
2.0 to 3.36	---
1.19 to 2.00	16.2
0.59 to 1.19	19.3
0.250 to 0.59	36.5
0.149 to 0.250	16.8
0.074 to 0.149	5.7
<0.074	5.5

*Note: The relatively small molecular weight of the radioisotopes represented by the difference between 8×10^{-3} μCi/ml and 3×10^{-6} μCi/ml causes an insignificant effect of the C/C_o ratio.

TABLE II-6

EXCHANGE COLUMN DATA FOR STRONTIUM-85

Accumulated Volume (ml)	Column Volumes (41 cc)	Sr-85 μCi/ml (C) (corrected for decay)	C/C_o
410	10	3.6×10^{-6}	0.0004
615	15	1.4×10^{-5}	0.0018
656	16	4.8×10^{-5}	0.0059
820	20	1.2×10^{-3}	0.152
1025	25	4.4×10^{-3}	0.541
1230	30	4.1×10^{-3}	0.500
1350	33	5.1×10^{-3}	0.624
1640	40	7.0×10^{-3}	0.861
2050	50	7.8×10^{-3}	0.951

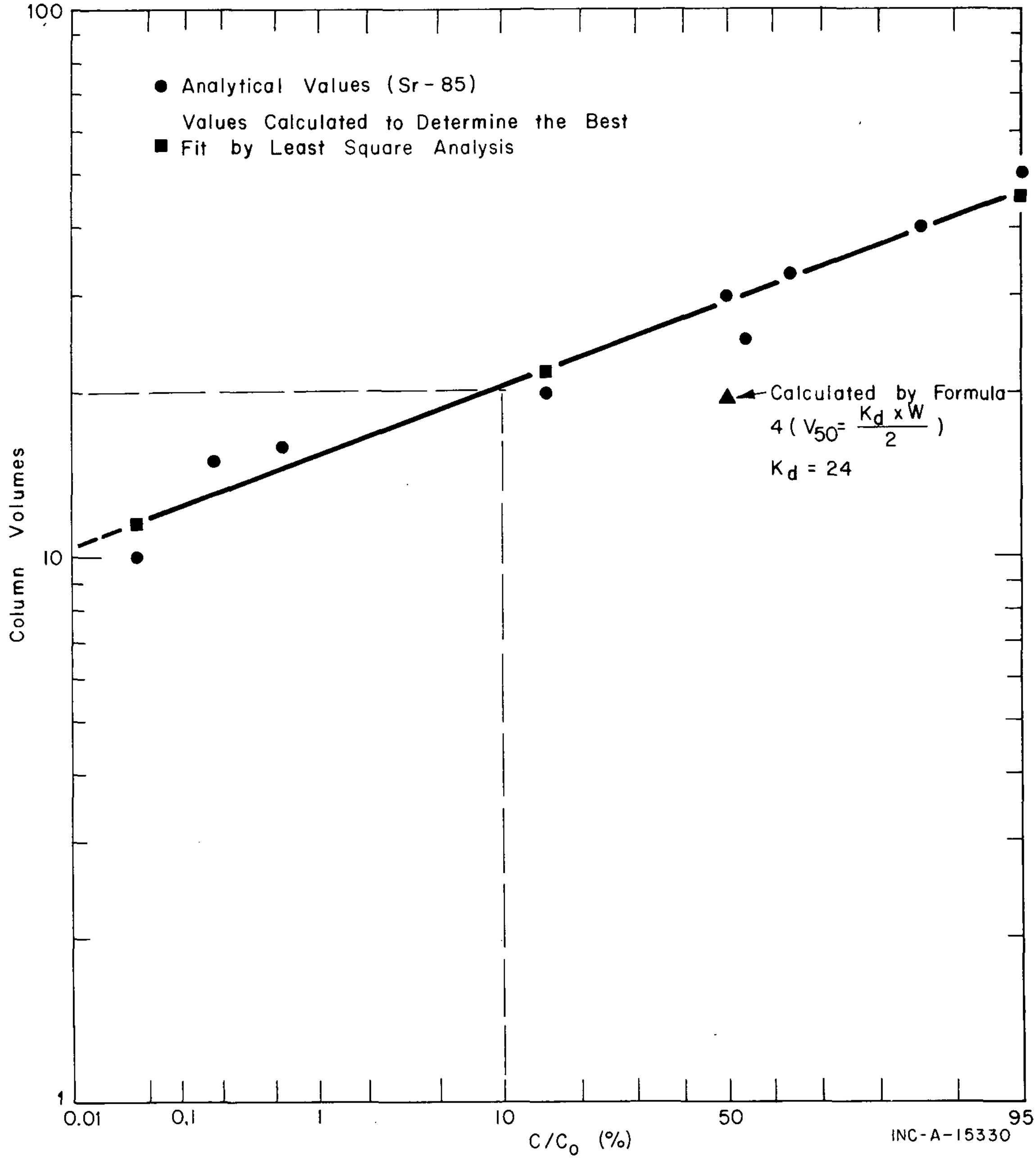

Fig. II-3. Breakthrough distribution for strontium-85.

The effectiveness of the soil minerals in attenuating the concentration of strontium can be evaluated by comparing the ratio of concentration guide limits for radionuclides in drinking water to the concentration of the pond water. For example, the guide limit specified in AEC Manual 0524 is 1.0 x 10^{-5} μCi/ml for an area subject to controlled access such as the NRTS and 3 x 10^{-7} μCi/ml for an area not subject to control. The mean concentration of the pond water is 3 x 10^{-6} μCi/ml which is less than the controlled area guide and, therefore, would not be limiting. If the limit for the uncontrolled area is used, the C/C_0 ratio would be

$$\frac{3 \times 10^{-7}}{3 \times 10^{-6}} = 0.1 \ (10\%). \tag{II-6}$$

This value corresponds to 20-column volumes on Figure II-3, as shown by the broken line. As Figure II-3 is predicated on only 30% of the actual volume of the alluvium, only six column volumes could be decontaminated to this extent in the field.

If the areal extent of the bottom plus the sides of the 1952-57 ponds is taken as 85,000 ft^2 and the thickness of the regolith as 50 feet, the field volume would be 4.2 x 10^6 ft^3 or 3.1 x 10^7 gallons. During the first five years of use, the mean annual discharge to these ponds was 6 x 10^7 gallons (see Table II-1). If the concentration relationships were comparable to those simulated then the six column volume capacity would have been reached during that time.

The total quantity of strontium which the soil media would be capable of holding can be estimated as follows:

$$\frac{(3.1 \times 10^{7}\ \text{gal})\frac{(3.78 \times 10^{3}\ \text{ml})}{\text{gal}}(30\ \text{vol} \ @\ 50\%\ C/C_{o})(0.3^{*})\frac{(3 \times 10^{-6}\ \mu\text{Ci})}{\text{ml}}}{1 \times 10^{6}\ \mu\text{Ci/Ci}} = 3.2\ \text{Ci}. \qquad \text{(II-7)}$$

*Note: The column volumes used here as well as the K_d values shown in Tables II-3 and -4 were obtained using a composite soil which represents only 30% of the field volume. Also see note on page 10.

The 3.2 curies is less than the 18 curies estimated to have been discharged to the pond and which would have been reduced to 15 curies by decay. By the same rationale, the 1964 section would have a capacity of 4.2 curies in comparison to an estimated 8.0 curies which have been discharged (after decay). The capacity of the alluvium having been reached, it is not expected that it would still be effective in attenuating the strontium concentration of the waste solution. Additional evidence in this regard is discussed under "Field Investigations".

The mean value for the distribution coefficient for strontium, which was determined in the laboratory, is 24 (see Table II-3); the valve using the sorption equations is 35 (see Table II-4). Using these values in Formula II-5 and the column volume of the laboratory column, the 50% breakthrough point would occur at 20 and 27 column volumes respectively. These values, especially the sorption equation value, compare favorably with a value of 30 on the Figure II-3 curve.

Although this analysis indicates that the sorptive capacity of the soil minerals in the alluvium beneath the pond for radionuclides has been satisfied, it should not be assumed that the excess has penetrated the underlying rocks to the regional water table. The water table in the TRA vicinity is 450 feet below the land surface and only the first 50 feet is occupied with sand and gravel. After the water seeps below this depth it spreads through underlying basalt rock until it encompasses an area with a diameter varying from 500 to 3,000 feet. According to the logs of 21 wells in the vicinity[6,7] involving 6,257 linear feet of drilled hole, 1,255 feet of unconsolidated sediments were penetrated. In five wells which were drilled to the water table, unconsolidated sediments compose 15 to 40% of the depth. These sediments contain a higher percentage of particles with less than 2 mm size particles than the surface alluvium. Using this information as a basis, a volume of 5 x 10^8 cubic feet, or the equivalent of 3.7 x 10^9 gallons, of unconsolidated sediments must be penetrated before the water table would be reached. As of 1968, the total volume of waste released is about 2.5 x 10^9 gallons or about 1.5 column volumes which would not be sufficient to produce any detectable effect in the regional ground water system.

3.22 *Cesium.* The cesium in the solution used in the strontium study was not detectable in the effluent from the 41-cc column. A smaller column was then used containing three grams of soil. The column was 1.3 cm long and 1.2 cm in diameter in which the soil occupied 1.5 cc.

The solution was the same TRA pond solution "spiked" with cesium-137 so that the concentration was 1.1 x 10^{-3} μCi/ml. The flow rate was approximately 6 ml/hr. This was equivalent to 31 gal/day-ft^2, which is larger than the mean field percolation rate of 13 gal/day-ft^2. This increase in flow was made so that the experiment could be completed in a reasonable period of time. Ninety days were required to collect the data abridged in Table II-7.

TABLE II-7

ABRIDGED EXCHANGE COLUMN DATA FOR CESIUM-137

Accumulated Volume (ml)	Column Volume	C/C_o
1218	812	0.024
1950	1300	0.137
2388	1592	0.190
2844	1896	0.133
3120	2080	0.210
3354	2236	0.248
3870	2580	0.362
4344	2896	0.533
4797	3198	0.448
5068	3379	0.267
5634	3756	0.486
6000	4000	0.210
6330	4220	0.286

The concentration of cesium-137 in the effluent was erratic for reasons unknown. The data were plotted on a log probability diagram (Figure II-4) together with standard deviations. The sorption in the field can then be evaluated as follows: The Concentration Guide limit for cesium-137 within a controlled area is 4 x 10^{-4} μCi/ml and for an uncontrolled area, 2 x 10^{-5} μCi/ml (AEC Manual 0524). The mean concentration of cesium-137 in the liquid waste discharge to the pond has been 1 x 10^{-5} μCi/ml, so neither of the RCG's are controlling. In other words, if the soil media became saturated and no cesium were retained, the cesium concentration in a liquid draining from the soil would be one-half of the uncontrolled area limit.

The total quantity of cesium which the soil would hold can be estimated for the 1952-57 pond sections as:

$$\frac{(3.1 \times 10^{7}\ \text{gal})\frac{(3.78 \times 10^{3}\ \text{ml})}{\text{gal}}(3330\ @\ 50\%\ C/C_o \times 0.3)\frac{(1 \times 10^{-5}\ \mu\text{Ci})}{\text{ml}}}{1 \times 10^{6}\ \mu\text{Ci/Ci}} = 1170\ \text{Ci} \pm 350 \qquad \text{(II-8)}$$

which is much higher than the 57 curies now remaining of the discharge to these sections. The 1964 section would hold 1300 curies in comparison to the remaining 13 estimated as having been deposited.

The mean distribution coefficients for cesium determined in the laboratory for the soil fraction less than 2 mm in diameter were 950 (see Table II-3) and, by the sorption equations, 1200 (see Table II-4). Using these values in Formula 5, the volumes at 50% breakthrough would be 1425 and 1800 ml. Both values are below the 2σ range; however, 1800 ml is equivalent to 1200 column volumes, which would amount to a soil capacity of 950 curies when extrapolated to the field condition using the mean cesium concentration in

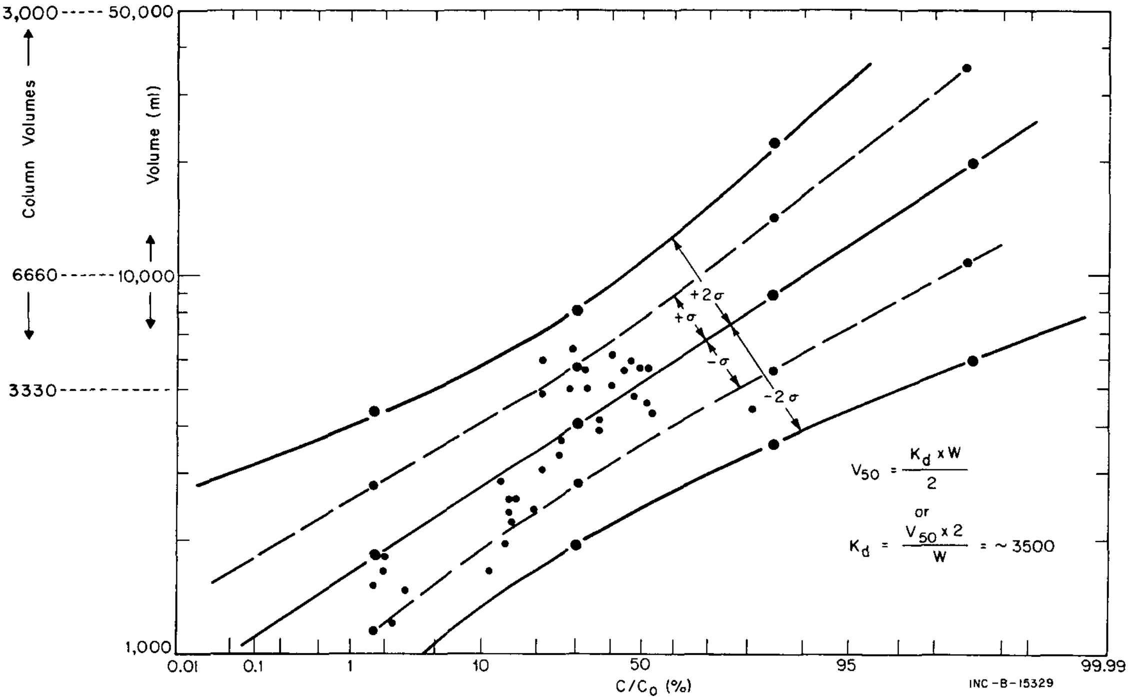

Fig. II-4. Breakthrough distribution for cesium-137.

the waste and the area of both ponds. This is about 10 times the 87 curies estimated to have been discharged. It therefore seems reasonably conservative to infer, that the alluvium is far from saturated in spite of the variable data and variation in distribution coefficients estimated by different methods.

3.23 *Other Nuclides.* The sorption of cobalt-60 by soil materials has been found to be relatively unpredictable in comparison to the alkali or alkali earth metals. In dillute solutions it may form insoluble compounds and precipitate or be sorbed as a colloid[8], or it may form complex anions and under some circumstances may not be sorbed at all. The form in which the radioactive isotopes occur in the waste streams has not been defined. It is also possible that the ionic form is changed by oxidation after release. The total amount that has been released is somewhat doubtful as the waste streams were not analyzed qualitatively or quantitatively for cobalt isotopes prior to 1962.

A distribution coefficient of 56 ml/g has been determined for cobalt using NRTS soil material with a solution not necessarily comparable to the TRA waste[9]. This was verified with a column experiment in which the 50% breakthrough point corresponded to a 30-column volume. The reported cobalt-60 concentration in the waste discharged to ponds during the past seven years has been 3 x 10^{-5} μCi/ml. By using these parameters and Formula 5, the estimated field capacity below the ponds would be between 70 and 100 curies. This capacity estimate is not confirmed, however, by the field study discussed in Section 4 (Field Investigations).

A distribution coefficient for chromiun-51 of 1.2 ml/g has been determined[9]. This value is relatively low which would indicate that the amount discharged would have permeated the regolith. As this isotope has a half-life of only 28 days, it would be attenuated by decay to a level of little concern.

Cerium isotopes also would be reduced by decay and are of minor concern.

4. FIELD INVESTIGATIONS

Five wells have been drilled to depths below the water table which is about 450 feet below land surface, and 20 wells have been terminated in perched water in the basalt at elevations above the water table, all in the vicinity of the TRA disposal pond[6,7]. Water samples have been taken and analyzed for radionuclides at various intervals of time since 1959. Holes have also been augered in the gravely surface regolith. Tritium has been the only radionuclide detected in the regional ground water[3]. Samples of soil and water from the regolith were analyzed in 1962 and various nuclides detected and correlated with moisture within a distance of 400 feet from the pond[10]. Traces of chromium-51, cobalt-60, iodine-131, cerium-144, and tritium have been identified in water samples from the perched zones[11].

4.1 1968 Investigations

Representative samples of gravelly alluvium and its contained water are difficult to obtain, especially from beneath the pond; however, an attempt was made in August 1968. An auger-type drill was used to drill holes at the locations shown in Figure II-5. Samples of the material brought to the surface were obtained from two- to five-foot intervals. The auger was hollow with a removable rod insert. When the hole was completed the rod was removed and replaced with a two-inch pipe. The auger was then reversed and the soil material backfilled leaving the pipe in place. Four holes were drilled at an angle by inclining the rig on an earth ramp as shown in Figure II-6. In this manner an attempt was made to obtain samples from beneath the pond.

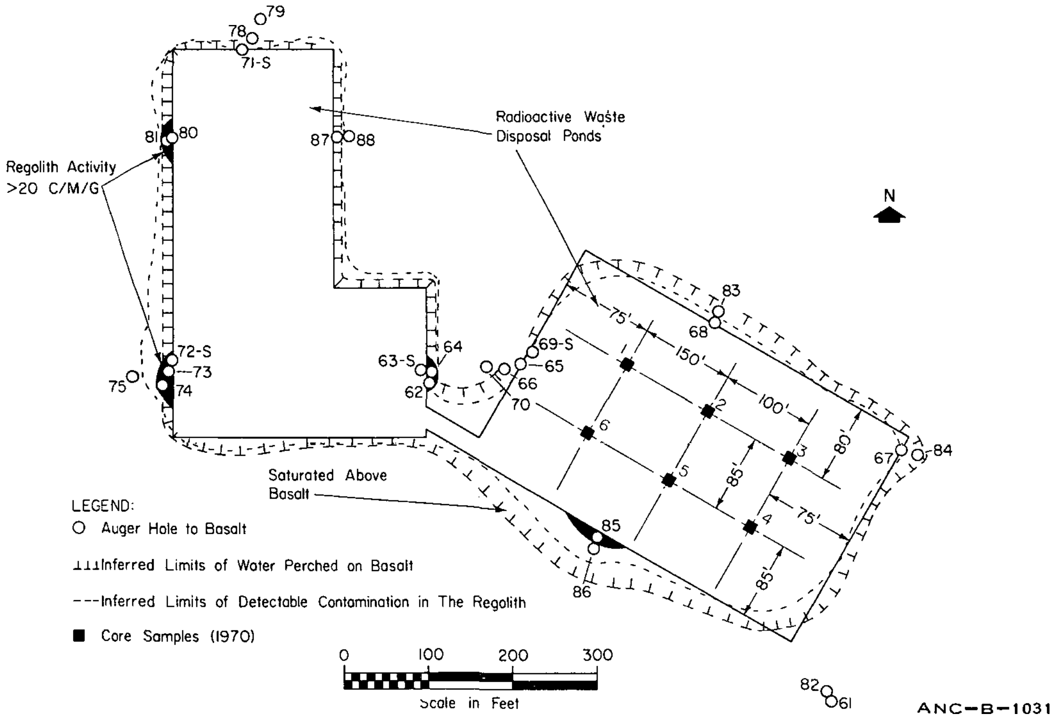

Fig. II-5 Location of test holes and inferred area of saturation and contamination.

Fig. II-6 Auger equipment drilling a sample hole beneath the pond.

Samples from the pond bottom were obtained by driving a core sampler from a raft on the 1952-57 sections of the pond and by wading in the 1964 section. It was not possible to drive the sample by hand any deeper than 21 inches. Samples were taken from four locations in the old sections and from two in the 1964 section. The gross activity of the samples was determined in the laboratory and used as a guide in selecting those for quantitative and qualitative analyses. Water was extracted from the soil by washing with methanol and centrifuging. Water also was obtained from auger holes where the soils were saturated. Core samples from the pond bottoms were separated into six-inch increments for analysis. The results of the gross analysis of the auger samples are tabulated in Appendix Table B. Table II-8 lists the specific activity for selected auger samples and Table II-9 the specific activity of the samples obtained from the pond bottom.

For the purpose of estimating the size of the percolation column, it was assumed that it occupied an area equal to the surface area of the water, that percolation was vertical, and that lateral seepage was relatively small. Based on this assumption, the mass of column increments was multiplied by the activity concentration shown in Table II-9. Estimates of the amount and distribution of the nuclides in the 21-inch profile are shown in Table II-10.

Approximately 70 curies of cesium-137 are estimated to be below the ponds of which about 51% can be accounted for in the 21-inch increment of the profile. If this is indicative of the entire 50-foot profile, it can be inferred that 900 curies could be retained. This is considered congruous with 2500 curies estimated on the basis of the laboratory column experiment.

TABLE II-8

SPECIFIC ACTIVITY FOR SELECTED SOIL AND WATER SAMPLES OBTAINED BY AUGERING -- 1968

Sample		Radioactivity							
		Cesium-137		Strontium-90		Cobalt-60		Cerium-144	
Well No.	Depth (feet)	Soil (pCi/g)	Solution (pCi/ml)*	Soil (pCi/g)	Solution (pCi/ml)	Soil (pCi/g)	Solution (pCi/ml)	Soil (pCi/g)	Solution (pCi/ml)
61	14-19	< 0.5	< 4.6			< 2.1	<25	< 1.4	<17
62	8-10	12.6	< 3.1			247	<17	11.3	<11
	14-16	5.0	< 2.9			540	<16	8.3	<11
	53-54½	< 0.6	< 1.1			67	< 5.8	< 1.8	< 3.9
71	52½-53	0.6	< 2.4			50	<13	< 1.7	< 8.7
73	10-12	2.8	< 6.9	7.0	2.3	1630	<38	5.4	<26
	15-20	48	< 6.1	< 4.0	< 0.8	1950	<33	38	<22
	35-40	21	< 6.6	10.0	2.2	1480	<36	26	<24
74	10-14	< 0.5	< 4.9			< 2.3	<27	< 1.6	<18
	19-24	< 0.5	< 3.4			260	<19	< 1.7	<13
	39-43	74	< 6.3	1.1	< 0.02	610	<35	< 1.8	<23
80	19-24	54	< 8.5			660	<47	< 1.7	<31
	29-34	< 0.6	< 5.0			810	<27	< 1.7	<18
	39-44	< 0.5	<10.2			68	<56	< 1.4	<37
85	9-14	< 0.5	< 5.9			210	<32	< 1.6	<22
	19-24	< 0.6	< 7.7			171	<27	< 1.7	<18
	44-49	< 0.6	< 4.1	14.0	< 0.02	36	<42	< 1.8	<28
86	14-19	< 0.5	< 4.1			39	<22	< 1.4	<15
	19-24	< 0.5	< 5.0	< 0.9	< 0.02	40	<27	< 1.5	<18
	24-29	< 0.6	< 5.3			15	<29	< 2.0	<20
87	14-19	< 0.6	<12			30	<65	< 1.8	<43
	24-29	< 0.6	< 3.9			18	<22	< 1.7	<14
62[a]		---	< 0.3		0.2	---	< 1.6	---	< 1.1
63		< 0.6	< 0.3	3.3	< 0.02	72	< 1.6	1.9	< 1.1
64		---	< 0.3		0.06	---	< 1.6	---	< 1.1
65		---	< 0.3		0.11	---	< 1.6	---	< 1.1
66		1.4	< 0.3		< 0.02	138	< 1.6	1.6	< 1.1
67		8.7	< 0.3	< 0.9	< 0.02	364	< 1.6	23	< 1.1
68		8.3	< 0.3	< 0.9	< 0.02	563	< 1.6	17	< 1.1
72		---	< 0.3		---	---	< 1.6	---	< 1.1
73		---	< 0.3		0.45	---	< 1.6	---	< 1.1
78		---	< 0.3		0.19	---	< 1.6	---	< 1.1
83		8.7	< 0.3	12.0	0.02	475	< 1.6	12	< 1.1
85		< 0.5	< 0.3	< 0.9	< 0.02	113	< 1.6	< 1.6	< 1.1
86		---	< 0.3	---	< 0.02	---	< 1.6	---	< 1.1

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* pCi/ml (pico curies per milliliter) -- 1 pCi equals 1 x 10^{-6} microcurie (μCi/ml)or 1 x 10^{-12} curie (Ci).

[a] All subsequent data are for sediments and water obtained from free water which accumulated in the hole after completion.

TABLE II-9

SPECIFIC ACTIVITY OF SAMPLES OF SOIL AND WATER OBTAINED FROM POND BOTTOM

		Radioactivity							
		Cesium-137		Strontium-90		Cobalt-60		Cerium-144	
Sample	Depth Interval (inches)	Soil (pCi/g)	In Solution (pCi/ml)	Soil (pCi/g)	In Solution (pCi/ml)	Soil (pCi/g)	In Solution (pCi/ml)	Soil (pCi/g)	In Solution (pCi/ml)
#1	0-6	2.6×10^3	< 4.6	1.8×10^2	Not Reliable Data*	3.8×10^4	1.6×10^3	8.1×10^2	< 17
Pond	6-12	3.1×10^3	24.2	7.5×10^1		4.7×10^4	1.9×10^3	1.4×10^3	31
1952	12-18	4.7×10^2	< 6.7	1.0×10^1		3.8×10^3	3.2×10^2	1.5×10^2	< 25
#2	0-6	7.2×10^3	14.0	9.7×10^2		2.4×10^5	2.1×10^3	8.5×10^3	< 12
Pond	6-12	6.7×10^3	4.4	1.8×10^2		1.9×10^5	1.3×10^3	5.9×10^3	< 9.3
1952	12-18	6.5×10^3	< 5.6	1.1×10^2		1.3×10^5	2.9×10^2	4.1×10^3	56
#3	0-6	1.5×10^3	< 3.3	2.0×10^2		2.4×10^4	4.7×10^2	1.0×10^3	< 12
Pond	6-12	3.7×10^2	5.2	4.3×10^1		9.5×10^3	1.3×10^3	3.7×10^2	< 19
1957	12-18	4.7×10^2	< 3.5	3.7×10^1		1.9×10^4	1.2×10^3	8.2×10^2	< 13
	18-21	5.9×10^3	3.1	3.9×10^2		2.2×10^5	7.1×10^2	4.4×10^3	< 5.1
#4	0-6	6.3×10^3	< 2.2	2.1×10^2		9.6×10^4	9.3×10^2	2.8×10^3	< 8.2
Pond	6-12	7.8×10^2	9.0	6.0×10^1		1.7×10^4	1.8×10^3	6.5×10^2	< 19
1957	12-18	1.9×10^2	< 6.1	2.8×10^1		8.8×10^4	1.2×10^3	2.0×10^2	< 22
	18-21	1.2×10^2	< 9.8	4.3×10^1		3.9×10^3	2.0×10^2	1.3×10^2	< 36
#5	0-6	3.5×10^3	< 4.0	7.3×10^1		3.7×10^4	5.1×10^2	3.0×10^3	< 15
Pond	6-12	2.2×10^2	< 5.8	2.5×10^1		5.9×10^3	< 32	3.8×10^2	< 21
1964	12-15	1.1×10^2	< 5.8	1.2×10^2		6.9×10^3	< 38	2.9×10^2	< 21
#6	0-6	4.3×10^3	< 3.9	3.4×10^1		3.6×10^4	< 21	1.6×10^3	< 14
Pond	6-12	2.9×10^2	< 5.2	3.2×10^1		1.0×10^4	< 28	4.4×10^2	< 19
1964									

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* Extraction of water from the soil with methanol was for some reason not effective in removing the dissolved strontium (see p 20).

TABLE II-10

RADIOACTIVITY DISTRIBUTION WITHIN 21 INCHES OF THE TRA POND BOTTOMS

Sample Site	Depth (inches)	Activity (curies)			
		Cesium-137	Strontium-90	Cobalt-60	Cerium-144
Pond 1952 ($47,000\ ft^2$)	0-6	6.4	0.7	180	6.1
	6-12	6.4	0.2	156	4.9
	12-18	4.5	0.1	87	2.8
	Total	17.3	1.0	423	13.8
Pond 1957 ($28,000\ ft^2$)	0-6	4.2	0.2	66	2.1
	6-12	0.6	0.05	14	0.6
	12-18	0.4	0.03	58	0.6
	18-21	1.7	0.1	60	1.1
	Total	6.9	0.38	198	4.4
Pond 1964 ($100,000\ ft^2$)	0-6	11.0	0.15	104	6.7
	6-12	0.7	0.08	23	1.2
	12-15	0.3	0.17	10	0.4
	Total	12.0	0.4	137	8.3
	Total	36.2	1.8	758	26.5

Of the 23 curies of strontium-90 discharged, 1.8 curies were estimated to be retained in the 21-inch zone. If this is extrapolated to the entire 50-foot profile, approximately 40 to 45 curies would be contained in comparison to a theoretical capacity of 8 for both ponds (see Theoretical Appraisal, Section 4, page 12). This discrepancy can plausibly be explained by the fact that the pond bottoms are covered with organic matter accruing from water plants. Algae concentrate strontium in their structure for considerable periods of time[12]. Organic matter also enhances the exchange characteristics of soil[13]. On this basis, the first increments of soil depth should contain more strontium than would be anticipated in the underlying strata.

The 758 curies of cobalt-60 which are estimated to be in the 21-inch profile are more than the 188 curies which have been recorded as having been discharged since 1962 (Table II-1) and which would have been reduced to 117 curies by 1968. Cobalt isotopes were not identified prior to 1962 during which time cobalt was used more extensively for measurement of neutron flux within the reactor vessel. This could have resulted in the cobalt fraction of the total activity being larger than during the period since and could explain the apparent amount in the ponds.

The distribution coefficient for cobalt-60 based on the soil concentrations would be approximately 100 ml/g in comparison to the figure of 56 ml/g determined by Hawkins[9]. As the Hawkins figure was not intended to simulate pond conditions, the two values may, or may not, be congruent.

The 26 curies of cerium in the 21-inch depth was congruous with the estimated 6 to 30 curie residual predicated on discharge records.

Calculated K_d values for cesium obtained with the data in Table II-9 and Equation II-1 ranges between 7 and 1900 as compared to a range between 177 and 376 determined in the laboratory.

The values determined for strontium using the field data did not agree well with the laboratory values. This discrepancy was investigated by extracting water remaining in a laboratory column with methanol as was done with the field samples. The strontium concentration of the extracted moisture was approximately 1/100 of the effluent which had previously drained from the column indicating that the methanol extraction was, for some unexplainable reason, inadequate for strontium determinations.

The results of calculations and analysis of regolith samples suggest that the sorption capacity of the alluvium below the pond for strontium has been reached. Analysis of water samples in the rock strata below the pond area support this conclusion. For example, concentrations of strontium-90 were determined in 10 samples of water perched above the regional ground water system in November 1966[4]. Concentrations of 2.1×10^{-8} to 8.8×10^{-8} μCi/ml were detected in three wells that tapped the perched water within 200 feet of the ponds as compared to 3×10^{-6} μCi/ml in the water at the time of discharge. One well 800 feet from the nearest edge of the pond contained 6×10^{-9} μCi/ml. The concentrations in the six other samples were below the detection limit of 3×10^{-9} μCi/ml. No strontium-90 was detected in samples taken from the regional water system.

During the years 1960 through 1968 the concentration of strontium-90 in the waste discharged to the ponds has averaged 3×10^{-6} μCi/ml. During the more recent period from January 1968 through August 1969 it was 6×10^{-6} μCi/ml. Samples of water, obtained from 14 monitoring wells which penetrate into the water perched in the rock below the ponds, contained strontium-90 in September 1969. The elevations at which the water occurs diminishes with distance from the ponds; however, isopleths of inferred concentrations are projected on the horizontal plane shown in the sketch shown in Figure II-7. Strontium-90 concentrations in the water range from 1.5×10^{-7} to 3.9×10^{-9} μCi/ml indicating that the strontium has passed through the ion-exchange column formed by the soil. If these concentrations are extrapolated back toward the pond, it appears that the strontium is leaving the soil with little attenuation in concentration. This is substantiated by the analysis of the water extracted from soil as shown in Table II-8. The fact that samples of the regional ground water taken in 1969 from Wells 58, 65, 76, and 70 do not contain any detectable strontium or other contaminants, except tritium, demonstrates the apparent effectiveness of the interbedded sediments in sorbing strontium.

4.2 1970 Investigations

Beginning in 1969, the permeability of the soil material in the 1964 section of the pond decreased while the TRA discharge volume increased. This resulted in filling the pond to within about a foot of the top. As a means of restoring the permeability, discharge to the pond was stopped in early August and it was allowed to dry until the end of September. This dry period presented an opportunity to obtain more samples on which estimates could be made with a greater degree of confidence.

Samples of the fine grain bottom sediments were taken at three locations. The samples covered an area of 100 cm^2 to a depth of 2 cm. The radionuclide analysis of the dried composite samples is shown in Table II-11[14].

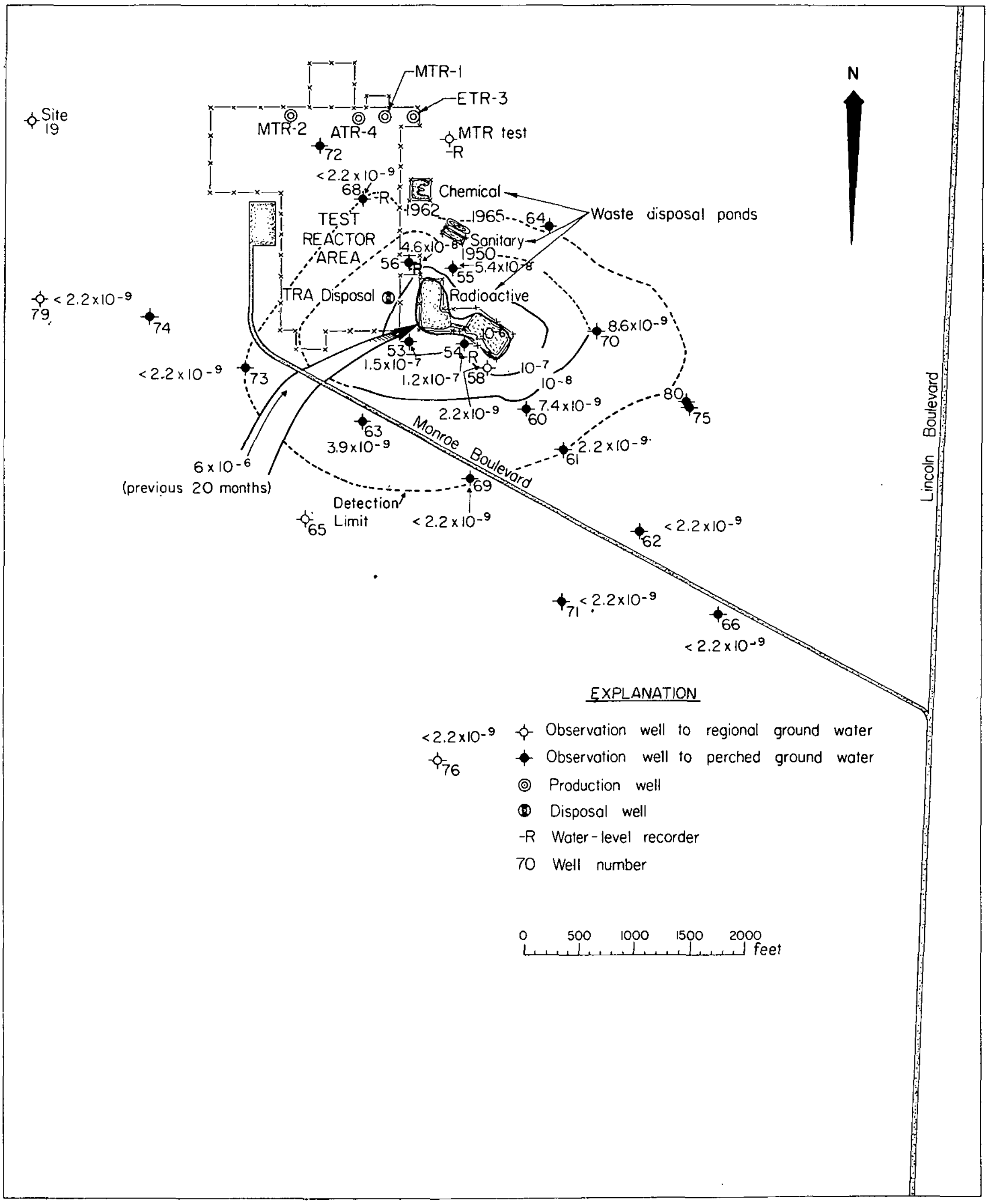

Fig. II-7 Isopleths of strontium-90 concentrations in water below soil.

TABLE II-11

ACTIVITY IN SEDIMENT SAMPLES FROM 1964 POND

Nuclide	Specific Activity (pci/g)	Percent of Total Activity	Curies in 2 cm Layer of Pond Bottoms
Co-60	8.6×10^4	56.1	19
Cs-137	4.0×10^4	25.7	8.9
Ce-144	1.0×10^4	6.5	2.2
Zn-65	6.8×10^3	4.3	1.5
Cs-134	5.0×10^3	3.2	1.1
Sr-90	3.0×10^3	1.4	0.5
Cr-51	1.3×10^3	0.8	0.3
Mn-54	1.3×10^3	0.8	0.3
ZrNb-95	6.8×10^2	0.4	0.1
Co-58	4.0×10^2	0.3	0.1
Others		0.6	<0.1
TOTAL		100	34

The purpose of these samples was to obtain an order of magnitude estimate of the radionuclides associated with a health physics appraisal. Correlation of results with discharge estimates or other sample results was only incidental and the estimate was not adjusted in recognition of the proportion that the fine grained sediments contributed to the gravelly soil. In other samples in which the grain size distribution was determined, the fine grained portion ranged between 20 and 33% with a mean of 30%. On this basis the activity shown in Table II-11 should be considered as a maximum and when applied to the in situ field situation should logically be reduced by a factor of two or three which would then make these figures congruent with other data presented in this report.

Core samples were also taken at six locations (see Figure II-5) by hand driving a tube sampler. The fine grained <2mm fraction was separated from three-inch (7.5 cm) increments of the cores and analyzed for cesium-137, strontium-90, cobalt-60, and cerium-144. The concentration of these four nuclides is shown in Table II-12. These concentrations have been reconciled with the total mass of the strata sampled; in other words, the activity pertains to total mass of sand, gravel, and fine grained fractions.

The mean concentrations are shown at the bottom of the columns. Using these mean concentrations, the amount of nuclide contained in the soil profile sampled was estimated.

TABLE II-12

SPECIFIC ACTIVITY OF SAMPLES OF SOIL AND WATER FROM 1964 POND -- 1970

		Radioactivity							
		Cesium-137		Strontium-90		Cobalt-60		Cerium-144	
Location	Depth Interval (inch)	Soil (pCi/g)	Water (pCi/ml)	Soil pCi/g	Water pCi/ml	Soil pCi/g	Water pCi/ml	Soil pCi/g	Water pCi/ml
1	0-3	1,271	<	96	2	5,072	17	286	
	3-6	<	<	36	0.9	1,276	16	114	
	6-9	<	<	<	0.5	842	15	<	
	9-12	<	<	<	0.5	187	14	<	
2	0-3	19,394	20	240	6	44,684	49	9,700	
	3-6	797	6	39	1.3	1,700	16	1,670	
	6-9	190	<	29	0.6	466	16	460	
	9-12	<	<	9	0.4	109	16	<	
	12-16	61	<	16	0.5	193	14	<	NONE DETECTED
3	0-3	5,898	13	66	5	10,007	31	3,050	
	3-6	631	<	36	0.9	1,843	16	200	
	6-9	492	5	19	0.6	1,268	14	<	
	9-12	<	<	44	0.5	622	16	<	
	12-15	<	<	58	0.4	624	15	<	
	15-18	<	<	53	0.4	769	14	<	
4	0-3	46,500	<	780	10	16,756	56	1,400	
	3-6	1,955	5	76	5.0	8,549	12	700	
	6-9	256	<	38	1.4	1,616	17	180	
	9-12	<	<	29	0.9	695	11	<	
	12-15	<	<	4	0.7	435	13	<	
5	0-3	18,919		662	9	75,833	21	542	
	3-6	384	<	48	1.3	2,679	15	196	
	6-9	<	<	8	0.5	181	14	89	
	9-12	<	<	33	1.5	183	15	<	
	12-15	<	<	lost	0.4	262	18	<	
	21-24	<	<	37	0.4	<	16	<	
	24-27	<	<	30	0.5	<	15	<	
	27-30	<	<	32	0.4	<	16	<	
	30-33	<	<	47	0.4	<	15	<	
	33-36	<	<	27	0.5	<	15	<	
	36-39	<	<	31	0.5	<	12	<	
6	0-3	9,924	<	210	5	46,335	29	8,100	
	3-6	137	<	71	1	1,208	16	<	
	6-9	<	<	76	0.5	1,219	13	<	
	9-12	<	<	51	0.5	682	15	<	
	12-15	<	<	32	0.4	270	14	<	
Mean	0-3	17,000		345	6	40,614		3,846	
	3-6	650		51	1.7	2,875		480	
	6-9	156		28	0.7	932		121	
	9-12	<		28	0.7	354		<	
	12-15	<		22	0.5	357		-	
	>15	<		-	-	-		-	

Note: Soil concentration pertains to in-place-field-condition.
"<" means not detected.

All of the detectable cesium-137 was contained in the first nine inches. By multiplying the mean concentration by the mass of the profile increments, it appears that 23 curies were in the first three inches, 0.9 curie in the second, and 0.2 curie in the third for a total of 24.1 curies[a]. This compares with 21 curies estimated to be in the pond on the basis of

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[a] Area of pond bottom is 1 x 10^5 ft^2 or 9.3 x 10^7 cm^2. A three-inch increment in depth is 7.6 cm; volume of the increments is 7.1 x 10^8 cm^3; density approximately 2; weight of increment is 1.4 x 10^9 g.

infiltration history (see page 5) and 12 curies estimated on the basis of two samples taken in 1968 (see Table II-10). The agreement between the 1970 estimate and the amount estimated to be in the pond is considered to be good.

Liquid extracts were obtained by adding 40 ml of waste effluent to two grams of the soil with the assumption that equilibrium would ensue if it had not previously existed in situ. The nuclide concentration in aliquots was then determined.

Only in locations 2 and 3 were concentrations of cesium-137 detectable in the liquid extract from the first three-inch increment. Using these figures the distribution coefficient values are 970 and 453 ml/g, which are comparable with the values determined in the laboratory that ranged between 235 and 1000 with a mean of 550. These values together with the smaller values determined at lower increments confirm the previous conclusions that the alluvial regolith still has a reserve capacity for cesium.

The estimated content of strontium-90 in the first three-inch increment of the profile is 0.48 curie, in the second 0.07, in the third 0.04, in the forth 0.03, and 0.03 in the fifth, for a total of 0.65 in the 15 inch depth. This compares to a content of 0.4 curie based on the 1968 work.

The samples at locations 5, below 15 inches, indicate that the concentration is comparatively uniform with an average of 34 pCi/g. Assuming that this concentration prevails for the remaining depth of 45 feet, the entire profile would be retaining about 9 curies in comparison to the theoretical capacity of 4.2 curies (see page 12) and the residual from discharge of 15 curies. The mean values for the distribution coefficient for the various increments are: 0-3"-57, 3-6"-30, 6-9"-40, 9-12"-40, and 12-15"-40ml/g. These values compare with 10 determined by laboratory and theoretical techniques for the entire soil mass. These figures lend credence to the previous assumption that the alluvial regolith is essentially saturated with strontium-90.

On the basis of the samples at two locations in 1968 it was estimated that the residual cobalt-60 in the 15 inch thick profile of the 1964 pond section was 137 curies. The estimate based on samples from six locations in 1970 is 64 curies which is more congruent with the residual of 55 curies estimated on the basis of the discharge history. The distribution coefficients range from 300 to 3600 ml/g in the first three-inch depth increment which is interpreted as being due to precipitation or colloid absorption. In the lower increments the values range about a mean of about 50 which is congruent with the value of 56 predicted by Hawkins[9].

On the basis of similar rationale, about 6.2 curies of cerium-144 appear to be retained in a 15 inch section of the pond in comparison to 8.3 curies estimated on the basis of the 1968 samples and less than a ten curie residual based on discharge records.

4.3 1962-63 Disposal at ICPP

During 1962 and 1963 approximately 33 curies of strontium-90, 34 curies of cesium-137, and 254 curies of tritium were contained in 7.3 million gallons of water which was discharged to a seepage pit near the fuel storage building in the Chemical Processing Plant Complex. No discharge of contaminated liquids was reported after 1964. The distribution of the water was investigated in 1963[15]. A total of 27 observation holes was augered through the alluvium to the basalt and the distribution of the liquid defined. It was concluded that the volume of water was larger than that which could be retained by sorption and that water was seeping into the underlying basalt.

The distribution of radionuclides was not studied in detail; however, the alluvial regolith is very similar to that at the TRA disposal area. The amount of dissolved substances other than the radioactive contaminants was not determined. The distribution coefficient for strontium-90 determined for the TRA area should be applicable, within reasonable limits. The volume and weight of the alluvium that the waste contacted can be estimated on the basis of geometry of the pit and wet soil. This amounts to 10^8 cc or 2 x 10^8 grams. Assuming a distribution coefficient for strontium, of '30', only six curies would be retained and the remainder would be below in the basalt sequences. Some evidence, not entirely conclusive, that this has occurred is shown in Table II-13 which shows concentration of strontium in water samples taken during 1970 from wells which penetrate below the water table in the vicinity. The retention of cesium-137 by the alluvial sediments can be postulated with the same logic and supported by the fact that it is not evidenced in the ground water.

TABLE II-13

CONCENTRATIONS OF ^{90}Sr IN REGIONAL GROUND WATER VICINITY OF ICPP[16]

Well Sampled	^{90}Sr pCi/ml
No. 40	0.061
No. 41	0.036
No. 42	0.014
No. 43	<0.002
No. 47	0.060
No. 48	0.023
No. 49	0.098
No. 51	<0.002
No. 52	0.024
No. 59	0.007

5. SUMMARY

(1) In using the distribution coefficient to evaluate the capability of the soil to sorb and retain cesium-137 and strontium-90 from waste solutions the field values were higher than predicted by laboratory techniques which indicates that more activity is being retained than would have been expected on the basis of theory. The values are summarized in Table II-14.

(2) The capacity of the soil to retain cesium-137 is far from depleted.

(3) The capacity of the regolith in the TRA Area to sorb strontium-90 has apparently been reached. The quality of water in the regional ground water system has not been compromised because of the retention capacity of the underlying rock with interbedded strata of fine grained sediments.

(4) The amount of cobalt-60 estimated in the bottom of the 1964 section of the pond is congruent with that based on discharge history to the extent of approximately 60 curies.

(5) The capacity of the regolith to retain strontium in the ICPP area has has also been reached.

TABLE II-14

COMPARISON OF DISTRIBUTION COEFFICIENTS (Kd - ml/g)

Determined by	Cs-137	Sr-90
Laboratory Batch Technique	285	7.2
Sorption Equations	360	10.5
Exchange Column Experiment	1000	10.5
Field Data (68)	600	---
Field Data (70)	450-950	40

III. SOLID WASTE

1. DESCRIPTION OF THE WASTE

Most of the volume of solid waste is composed of nonradioactive materials such as broken equipment, paper, filters, glass, scrap metals, and any kind of solid debris normally present in an industrial or research establishment. The radionuclides which contaminate solid waste are classified as (1) activation products typified by cobalt-60, chromium-51, and zirconium-niobium-95; (2) fission products such as strontium-90 and cesium-137; and (3) fissionable fuel material such as uranium and plutonium isotopes. These wastes have been placed in the NRTS burial ground since 1952. Trenches have been utilized for waste products originating at the NRTS. Pits excavated with tractor-drawn scrapers have been used for the fissionable materials which have originated primarily at the plutonium processing plant near Golden, Colorado.

The amount of radioactivity in solid waste has been estimated by gross methods and is listed in Table III-1. The curie amounts apply to the time of placement. The amount remaining at any time after disposal would be less than the amounts shown due to decay. A precise estimate of the amount is difficult to make without a definitive inventory of the contributing nuclides; however, most of the waste emanating from reactor areas is contaminated with activation products and that from the Idaho Chemical Processing Plant with fission products. On the basis of recent estimates, approximately 90% of the activity originating at the NRTS is activation products; five years after disposal less than 50% would remain and after ten years less than 25%. Assuming that the fission product waste consisted of a typical mixture, the amount remaining after five years would be about 18% of that which was buried. After ten years about 15% would remain, composed of 24% strontium-90 and 18% cesium-137.

Decay does not reduce significantly the radioactivity of the waste originating at Golden, Colorado (Rocky Flats). In fact, activity contributed by a nuclide such as americium-241 may increase for a short time as it is a daughter product of plutonium-241. An estimate of the activity at the burial ground has been made, based on the composition of waste during the period 1954 to 1969 as shown in Table III-2[17].

Assuming that all of the waste shipped during the period 1954-1959 was buried in 1957 and that from 1960-1968 was buried in 1965, the amount of activity in future years is computed as shown in Table III-3. Theoretically, 67 isotopes would be present. Only the six shown are present in sufficient quantity to be of interest.

TABLE III-1

QUANTITY OF WASTE AT THE NRTS BURIAL GROUND ESTIMATED DURING YEAR OF PLACEMENT[18]

	On-Site		Off-Site		Total	
Year	Volume (ft^3 x 10^3)	Activity[a] (kCi)	Volume (ft^3 x 10^3)	Activity[b] (kCi)	Volume (ft^3 x 10^3)	Activity (kCi)
1952-54, Inclusive	---	---	---	---	54	2
1955	---	---	---	---	67	1
1956	97	10	38	---	135	10
1957	115	15	60	---	175	15
1958	209	10	35	1	244	11
1959	99	23	59	1	158	24
1960	122	9	69	1	191	10
1961	93	134	165	22	258	156
1962	90	112	131	6	221	118
1963	116	240	193	14	309	254
1964	111	143	132	2	243	145
1965	144	749	121	10	265	759
1966	161	848	171	17	332	865
1967	135	836	206	12	341	848
1968	140	269	345	9	485	278
1969	168	935	242	37	410	972

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[a] Predominantly activation products.

[b] Includes only plutonium-239, uranium-235 and -238, and americium-241; excludes associated isotopes of these two nuclides which are shown in Table III-3.

TABLE III-2

AMOUNT OF WASTE SHIPPED TO NRTS
FROM ROCKY FLATS, COLORADO

	Isotopic wt%	kg
For Calendar Years 1954 through 1959		
U-238	99.85	13,001.0
U-235	0.15	20.102
Pu-238	0.009	0.001
Pu-239	93.762	16.340
Pu-240	5,858	1.020
Pu-241	0.355	0.062
Pu-242	0.016	0.003
Am-241	100.0	0.234
For Calendar Years 1960 through 1968		
U-238	99.96	160,389.0
U-235	0.04	57.91
Pu-238	0.009	0.025
Pu-239	93.670	264.731
Pu-240	5.853	16.542
Pu-241	0.452	1.277
Pu-242	0.016	0.045
Am-241	100.0	7.82
For Calendar Year 1969		
U-238	99.84	22,721.335
U-235	0.16	36.259
Pu-238	0.009	0.003
Pu-239	93.750	38.046
Pu-240	5.857	2.377
Pu-241	0.368	0.149
Pu-242	0.016	0.006
Am-241	100.0	4.875

TABLE III-3

QUANTITY OF RADIOACTIVE FISSIONABLE MATERIAL ORGINATING AT ROCKY FLATS AS OF 1970[a] -- PROJECTED

		Mass (g)	Radioactivity (curies) By Year				
Element	Half-Life (Years)	1970	1970	1980	2070	2470	2970
U-238	4.50×10^9	1.961×10^8	65				65
Pu-238	89	2.907×10	490	461	230	9.5	0.2
Pu-239	2.44×10^4	3.191×10^5	2.0×10^4	2.0×10^4	2.0×10^4	1.93×10^4	9.94×10^3
Pu-240	6.76×10^3	1.993×10^4	4.5×10^3	4.5×10^3	4.45×10^3	4.27×10^3	4.05×10^3
Pu-241	13	1.173×10^3	1.3×10^5	7.6×10^4	886	0	0
Am-241	4.58×10^2	1.317×10^4	4.2×10^4	4.6×10^4	4.2×10^4	2.21×10^4	9.94×10^3

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[a] As of end of 1969.

2. DESCRIPTION OF THE BURIAL GROUND

The NRTS burial ground consists of 88 acres of land approximately seven miles east of the western boundary of the station and four miles north of the southern boundary. The terrain is rolling and the burial ground is located in a depression or small valley with no marked drainage channel. Figure III-1 is a topographic map of the vicinity.

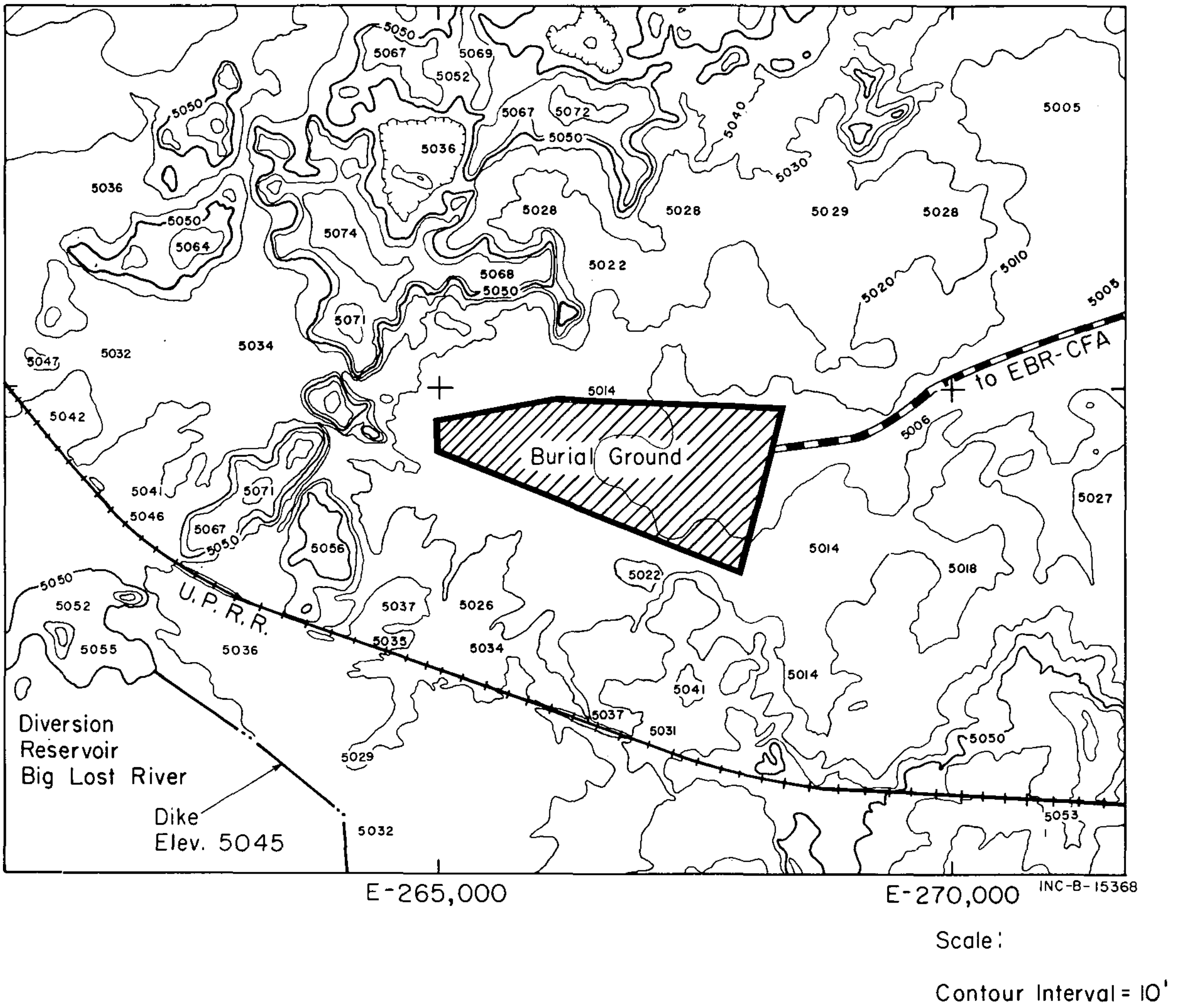

Fig. III-1 Topographic map of NRTS burial ground vicinity.

The soil depth varies from 20 feet to less than 5 feet with exposed rock being common at the higher elevations surrounding the area. The soil has not been classified in any detail or correlated with any taxonomic units. Figure III-2 is a sketch of the burial ground showing areas of soils delineated primarily on the basis of depth. One soil profile occupying a meandering area includes a strata of sedimentary sand of varying thickness at a depth of about three feet below the land surface. Presumably, this was deposited at some prehistoric time when the Big Lost River flowed through the defile in the ridge west of the burial ground (see Figure III-1). The surface soils are silt loams derived from loessial depositions. The texture of the soil changes with depth through silty clay loams to a silty clay which covers the basalt rock[19]. Table III-4 gives the mean grain size distribution of

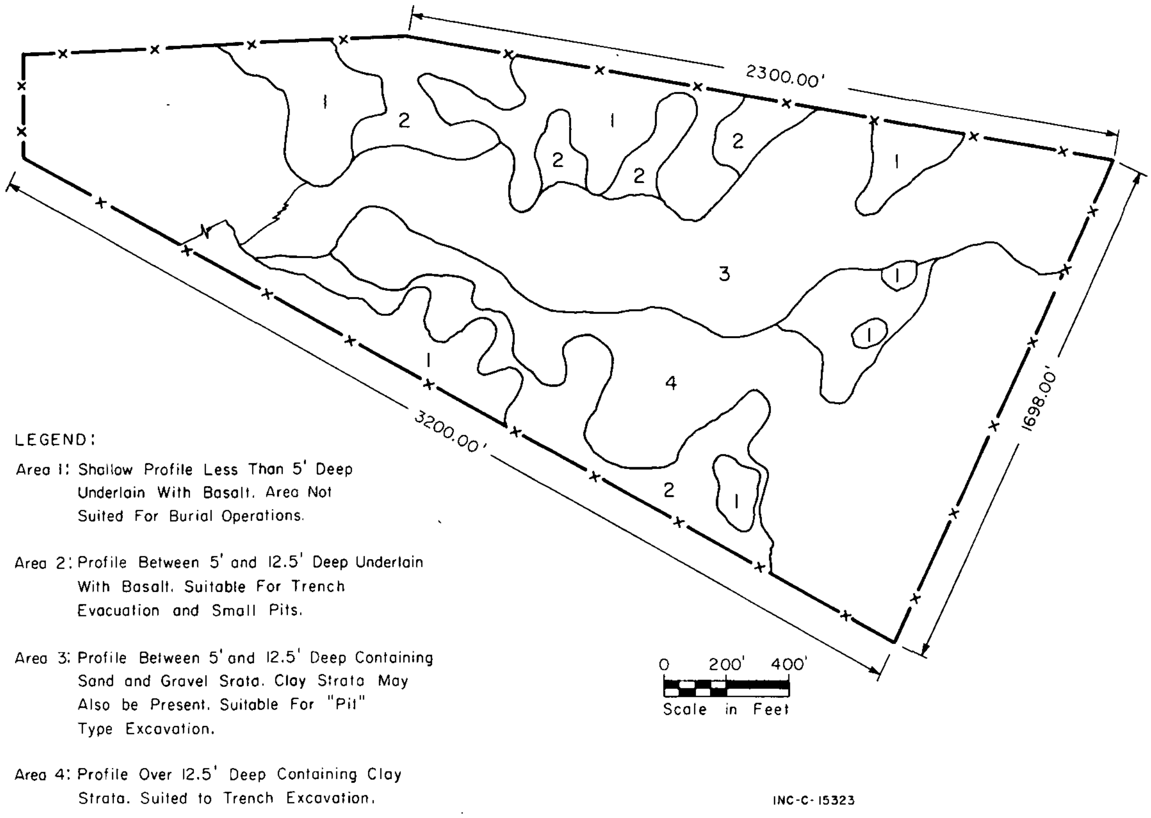

Fig. III-2 Soil map of NRTS burial ground.

TABLE III-4

GRAIN SIZE DISTRIBUTION OF SOIL AT THE NRTS BURIAL GROUND (MEAN OF THREE SAMPLES)

Depth Interval (cm)	Grain Size Distribution (%)		
	Clay <0.004 mm	Silt 0.004 to 0.625 mm	Sand <0.625 mm
0-15	29 ± 9	61 ± 3	10 ± 6
97-107	14 ± 0.7	74 ± 7	12 ± 6
234-244	28 ± 16	58 ± 9	14 ± 6

soil samples taken from three locations in the burial ground vicinity. Caliche deposits occur at various depths which indicate that the development of soil has been interrupted by sequential depositions of parent material.

Contamination of the ground water by leachate from the buried waste is of interest in pollution control. Collection of factual data with which to mollify or substantiate this concern is difficult to obtain, particularly under the arid conditions at the NRTS where the soil is not saturated to such an extent that free water samples can be obtained.

3. HAZARD APPRAISAL

3.1 Related Investigations

Contamination of ground water by domestic waste in sanitary landfills has been studied in an investigation conducted in California[20]. Two cells were constructed containing 19 feet of fill which was covered with two feet of soil. One cell was left bare and the other covered with turf. During 42 months, the bare cell was irrigated with 170 inches of water and the turf cell with 237 inches. During the first 30 months, no leachate was collected in any of the collecting devices placed at various levels within the fill in the bare cell. Only a small amount was collected in the uppermost points in the cell in which the turf was growing. During the last 12 months, leachate was not collected at any point although an increase in the moisture content was observed. In view of the amount of water that was applied, it was inferred that the water moved between the refuse fill and the sides of the cell. This experience demonstrates the difficulty in studying the movement of waste with a technique involving the collection of water samples, especially under NRTS circumstances where the average annual rainfall is less than 10 inches (which is insufficient to saturate the soil except where ponding occurs).

3.2 Theoretical Appraisal

The movement of water through the soil under unsaturated conditions at the NRTS has been studied by taking soil samples at three locations in the vicinity of the burial ground[19]. The soil in the upper seven feet of the profile contained 6% water (dry weight) and 13% in the subsoils. This water was extracted and analyzed for tritium and the content in the soil profile compared with the amount that was estimated to have been deposited by rain and snow during the previous 15-year period. This comparison indicated that between 3 and 4% remained in the 13-foot profile. The following formula, which is a derivation of a differential equation describing heat transfer, was used to rationalize the distribution:

$$c = \frac{M}{2\theta A\sqrt{\pi Dt}} \exp\left[-\frac{(x - \bar{v}t)^2}{4Dt}\right] \qquad \text{(III-1)}$$

where

c = Concentration of the trace component

M = Amount of tracer added

θ = Volume of water per unit volume of soil

A = Area of the soil column which is unity

D = Total mass transfer coefficient or rate of transfer of fluid across a given plane

$\bar{v}$ = Velocity of convective flow

x = Distance traveled in vertical coordinates

t = Travel time.

The equation was solved using values of $\bar{v}$ and D derived from a nonlinear least squares analysis for various depths using observed values of input and moisture conditions. Within limits of acceptable error, values of $\bar{v}$ ranging between 32 and 40 cm/year and of D between 9×10^{-7} and 9×10^{-6} cm^2/sec were obtained.

When the concentration of a trace element in soil, including the contained water, is desired, the moisture term (θ) is not used in the numerator of Formula III-1. When the movement of nuclides such as strontium and cesium is delayed by sorption, allowance is provided by modifying the exponential term of the formula and by using a value for D which reflects the reduced flux induced by ion-exchange as follows:

$$c = \frac{M}{2A\sqrt{\pi D_{rn} t}} \exp -\left[\frac{(x - \bar{v}_{rn} t)^2}{4D_{rn} t} + \lambda t \right] \qquad \text{(III-2)}$$

where

D_{rn} = Flux coefficient of the radionuclide

λ = Disintegration constant of the radionuclide

t = Time involved

$\bar{v}_{rn}$ = Velocity of the radionuclide which has been related to the velocity of water in sandy aquifers as follows[21]:

$$\bar{v}_{rn} = v_w \left[\frac{1}{1 + K_d (e/\theta)} \right] \qquad \text{(III-3)}$$

where

v_w = Velocity of water

K_d = Distribution coefficient

e = Bulk density

θ = Volume of water per unit of solid volume.

Strontium-90 and cesium-137 are the longest lived fission product nuclides in waste. By using values outlined in the following paragraphs for the terms in Formula III-2, an approximate theoretical distribution of these nuclides in soil below buried waste can be made for the case of unsaturated conditions.

For the purpose of this analysis the amount of nuclide (M) is expressed in microcuries and represents the amount of radioactivity in 1 ml of solution, or approximately 4% of the mean annual precipitation of 8.5 inches (22 cm). A gross beta concentration of 1.3×10^{-5} μCi/ml was used based on a sample of water which had inundated waste at the burial ground. It is realized that this concentration might be more, or less, than that resulting from the leaching of poorly defined waste with a small amount of slowly moving water; however, it was hypothesized that this represented the concentration of strontium-90 and also cesium-137, and that this amount was added sequentially once each year for 300 years.

The velocity of the radionuclide (v_{rn}) was determined by using a soil moisture of 20% by volume, a velocity of 0.1 cm/day[19], and a bulk density of 1.4. The distribution coefficient (K_d) for cesium and strontium in burial ground soils was determined in the laboratory to be: strontium 53 ± 14, cesium 4736 ± 2224. When used in Formula III-3, the velocity for strontium is 0.11 ± 0.02 cm/year and for cesium $1.2 \pm 0.4 \times 10^{-3}$ cm/yr.

The transfer, or flux coefficient, (D) is expressed as the number of molecules, or ions, which move across a unit area (cm^2) in a unit of time (sec). Where an ion, such as strontium or cesium, is subject to sorption, the rate of movement is slower than would be the case for nonsorbing ion such as tritium. Specific coefficients for these nuclides have not been determined for NRTS soil conditions; therefore, values of 10^{-7} and 10^{-9} cm^2/sec were used for both strontium and cesium, based on the work of others[22,23]. Differences exist in the coefficients of the x, y, and z direction. Accurate calculations should provide for these differences; however, as they are relatively small, only the x dimension is considered in this approximation.

The trenches at the burial ground are usually dug until the equipment encounters the underlying rock, leaving about 30 to 35 cm of soil in the bottom of the excavation. This soil is an effective ion exchange medium; therefore, concentrations of strontium-90 and cesium-137 were calculated at 5-cm increments to a total of 35 cm for reaction times of 10, 100, and 300 years. The results of these calculations are shown in Figures III-3 and -4 from which the following conclusions may be inferred:

(1) The concentration of the radionuclides in the first 5 cm of soil increased above the initial concentration of the solution which is consistent with the anticipated sorption by the soil.

(2) In both cases involving the lower dispersion rate of 3.2×10^{-2} cm^2/yr (10^{-9} cm^2/sec), the concentration decreased conspicuously below 5 cm and was not detectable within the 10-year period at the scale on which the curves are plotted. After 300 years, the strontium concentration at the 35-cm depth is approximately three orders of magnitude less than at the 5-cm depth. In the cesium case it does not reach a depth of 35-cm during the times considered.

(3) At the higher dispersion rate of 3.2 cm^2/yr (10^{-7} cm^2/sec), the distribution within 10 years is comparable to that resulting in 300 years at the lower rate of 3.2×10^{-2} cm^2/yr (10^{-7} cm^2/sec). As time passes, however, the radionuclides become distributed

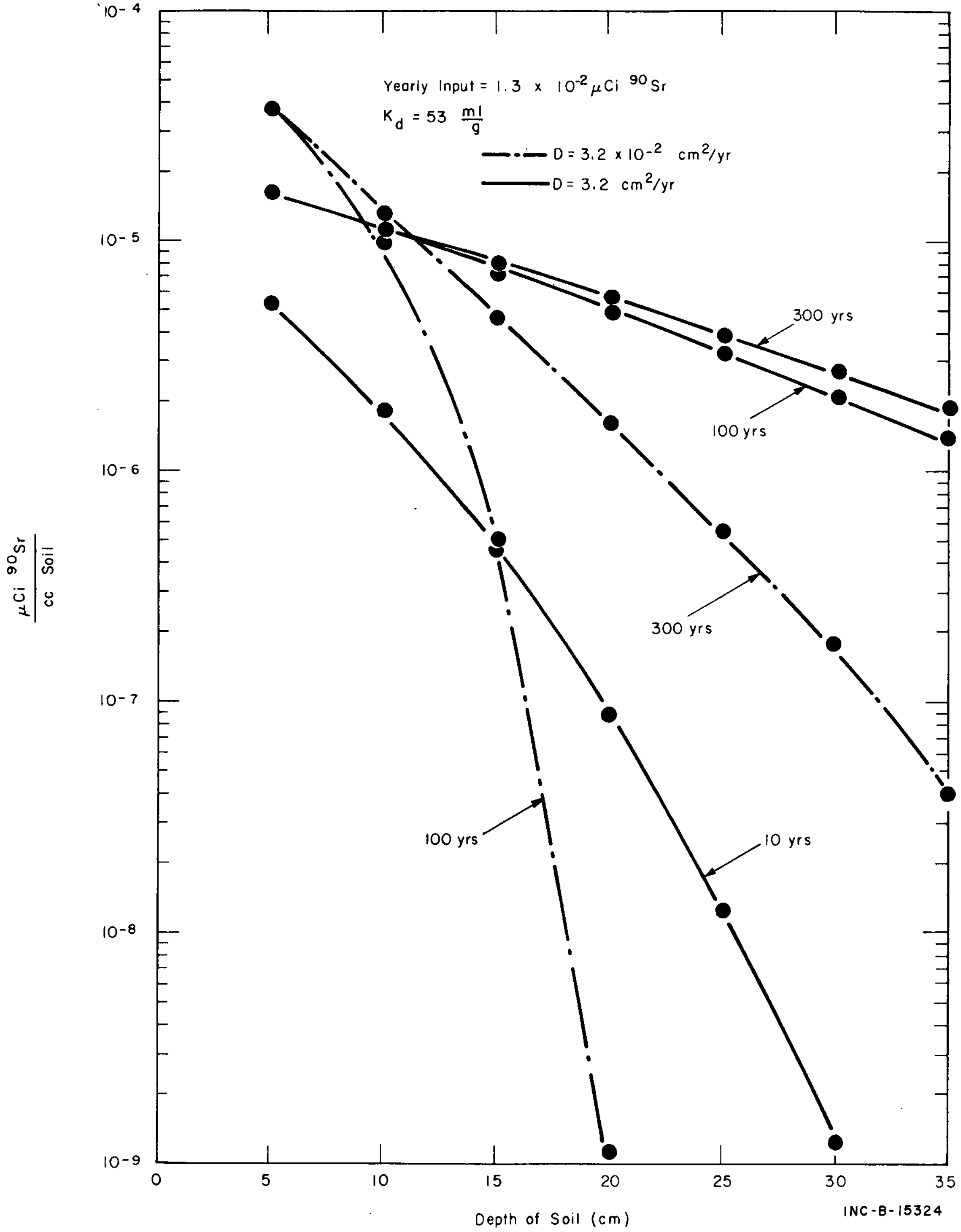

Fig. III-3 Hypothetical concentration of strontium-90 in soil as a function of depth and time.

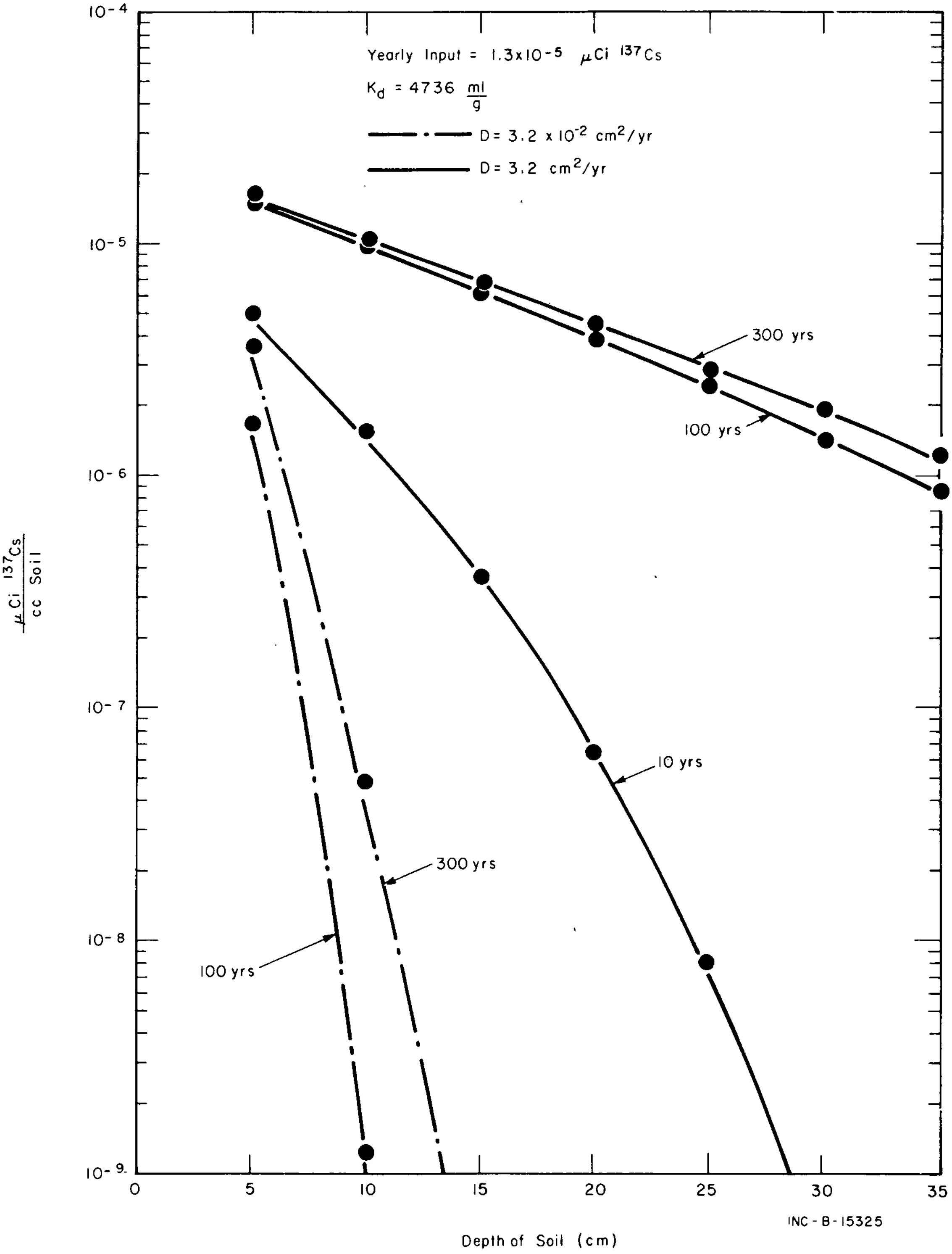

Fig. III-4 Hypothetical concentration of cesium-137 in soil as a function of depth and time.

throughout the 35-cm profile until after 100 years the effect of time is less pronounced as indicated by the 100- and 300-year curves which are almost coincident.

The concentration shown in Figures II-3 and -4 are for the entire soil mass which includes both the solid and liquid phase. The concentration in the soil water, or liquid phases of the soil system, may be estimated on the basis of the distribution coefficients (K_d's) and the following formula:

$$\frac{\text{Activity}_{(\text{of solution}}}{\text{ml}} = \frac{\dfrac{\text{Activity}}{\text{cc}_{(\text{of soil})}}}{(K_d)(1.4)^{[a]}} \qquad \text{(III-4)}$$

The strontium-90 activity in the soil at 10 cm after 100 years would be 10^{-5} μCi/ml in Figure III-3. The calculated concentration in the soil water would be 1.3×10^{-7} μCi/ml. In the case of cesium where the concentration in the soil after 100 or 300 years would be about 10^{-5} μCi/cc of the soil, the concentration in the contained water would be 1.5×10^{-9} μCi/ml. These concentrations are below the standards for drinking water and would present no threat to the ground water aquifer system which is 600 feet below.

Distribution and dispersion coefficients for plutonium and americum have not been determined for NRTS conditions. These elements are sorbed by soils at the Hanford AEC establishment in southeastern Washington where they have accumulated in the upper 24 inches of soil as a result of aqueous waste disposal[24]. Laboratory experiments show that only 0.1% of the plutonium and 7.5% of the americum could be leached from the soil and that this is accomplished with less than 20 column volumes of water. After being leached, the velocity of plutonium in the lower soil layers is 10^4 times less than the velocity of the carrier solution, which is comparable with the velocity of cesium in NRTS soils. The apparent diffusion coefficient of plutonium (essentially the same as the dispersion coefficient) under unsaturated conditions of 20% water, by volume, was calculated from laboratory tests to be 4.8×10^{-12}cm^2/sec, which would result in movement of 8.5 cm in 10 half-lives or 2.4×10^5 years. A comparison of these parameters, $\overline{v}$ and D, with those used in the above strontium and cesium calculations indicates that theoretically these nuclides do not present a potential hazard. Field investigations which are described in the following section indicate, however, that plutonium and americum have been leached from the waste under saturated conditions and have been deposited in the soil lining the pits. Soil and waste characterisitics at the NRTS and Hanford locations may be different, and such differences as might exist have not been reconciled.

The long half-lives of plutonium and americum isotopes are a characteristic which compromises long time predictions of waste behavior as a result of environmental conditions. Since moisture movement is the principal transporting factor, any action which would inhibit water entry into the contaminated zone would be desirable and provide additional assurance that the nuclides would not migrate.

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[a] Bulk density.

4. FIELD INVESTIGATIONS

Ten holes were drilled adjacent to buried waste in the western section of the burial ground shown in Figure III-5. Essentially, this section was filled prior to 1960, and since that time these holes have been under surveillance for the presence of water. On three occasions a small amount of water has been found. On two occasions this was definitely attributed to unseasonable warm rainy weather which caused snow melting while the soil was still frozen resulting in accumulation of run off in the open pits and trenches. These conditions occurred in March 1962 and in January 1969. Samples of the 1969 flood water, taken near the east side of the burial ground and from a pond in Pit 10, were analyzed with the results shown in Table III-5. The concentration of naturally occurring radioactivity in NRTS well and rain water are shown for comparison indicating that the flood water has been contaminated by the waste.

No contamination was detected in the water samples obtained from the monitoring holes in 1962. In 1965 water was obtained from holes No. 5 and No. 7. That from No. 5 contained 7 x 10^{-5} μCi/ml strontium and 3.3 x 10^{-5} μCi/ml cesium and that from No. 7 contained 3.5 x 10^{-5} μCi/ml strontium. The source and fate of this water was not determined. Water also was obtained in 1969 which was filtered, and both the residue and filtrate analyzed with the results shown in Table III-6. No specific nuclides were identified in the liquid phase; however, cesium-137 was detected by scintillation spectrometry in solids filtered from two samples. New holes were augered within a foot of the cased holes to determine, or confirm, the extent of this contamination. The only qualitative identification of radioactivity in soil samples taken from these holes was due to naturally occurring nuclides such as thorium and uranium isotopes. The results of the gross radioactivity analysis are shown in Table III-7. These results do not explain or confirm the presence of the fission products detected in the original monitoring holes.

4.1 1969 Investigations

Two holes were augered in February 1969 near Trench 48 (see Figure III-5) which had contained submerged waste. The nearest hole was four feet from the edge of the excavation and the other 45 feet away. Cerium-144, cesium-137, and zirconium and niobium-95 were detected soil samples from the nearest hole by gamma-ray scintillation spectrometry; however, the amounts were too small to be quantified by the sampling and analytical procedures employed. Samples taken from the hole 45 feet from the trench did not contain any apparent excess amount of moisture or radioactivity which could be attributed to the flooding. The gross alpha and gamma radioactivity in these samples is tabulated in Figure III-6. Interpretation of these results was complicated by the problem of differentiating between natural radioactivity and the amount which might have been due to contamination by waste.

Holes were also augered 4 and 55 feet from the edge of Pit 10, which had been filled with water. The nearest hole penetrated the sandy subsoil which was supersaturated, causing the hole to fill with water. The gross alpha concentration was 3 x 10^{-9} μCi/ml, which was less than uncontaminated well water. The silty clay below the sand was moist to the extent of field capacity. Radionuclides other than those which occur naturally were not detected in soil or water sampled from either location. The analytical results are shown in Figure III-7.

TABLE III-5

RADIOACTIVITY CONCENTRATION OF 1969 FLOOD WATER AT NRTS BURIAL GROUND IN COMPARISON WITH NATURAL NRTS WATER

Sample Description	Concentration (μCi/ml) Gross Beta	Gross Alpha
Surface Pond[a]	1.3×10^{-5}	3.2×10^{-7}
Surface Pond[a]	4.1×10^{-6}	4.5×10^{-9}
Pond Pit 10	-	2.7×10^{-6}
Well Water	5.0×10^{-9}	3.0×10^{-7}
Rain Water	3.0×10^{-7}	1.0×10^{-7}

---

[a] Samples collected and analyzed by Idaho Nuclear Corporation.

TABLE III-6

RADIOACTIVITY IN SOIL AND WATER SAMPLES FROM MONITORING HOLES AT THE NRTS BURIAL GROUND -- 1969

Hole No.	Radioactivity (μCi/ml) In Liquid Alpha	Beta	Gamma
4	2×10^{-8}	$<2 \times 10^{-8}$	3×10^{-7}
5	1×10^{-8}	9×10^{-7}	4×10^{-7}
7	$<4 \times 10^{-9}$	1.4×10^{-6}	3.8×10^{-7}
	Radioactivity (μCi/g) On Filtered Solids		
4	1.4×10^{-5}	4.7×10^{-4}	5.8×10^{-4}
5	$<4 \times 10^{-6}$	7.0×10^{-4}	3.1×10^{-4}
7	3×10^{-6}	4.2×10^{-4}	1.8×10^{-4}

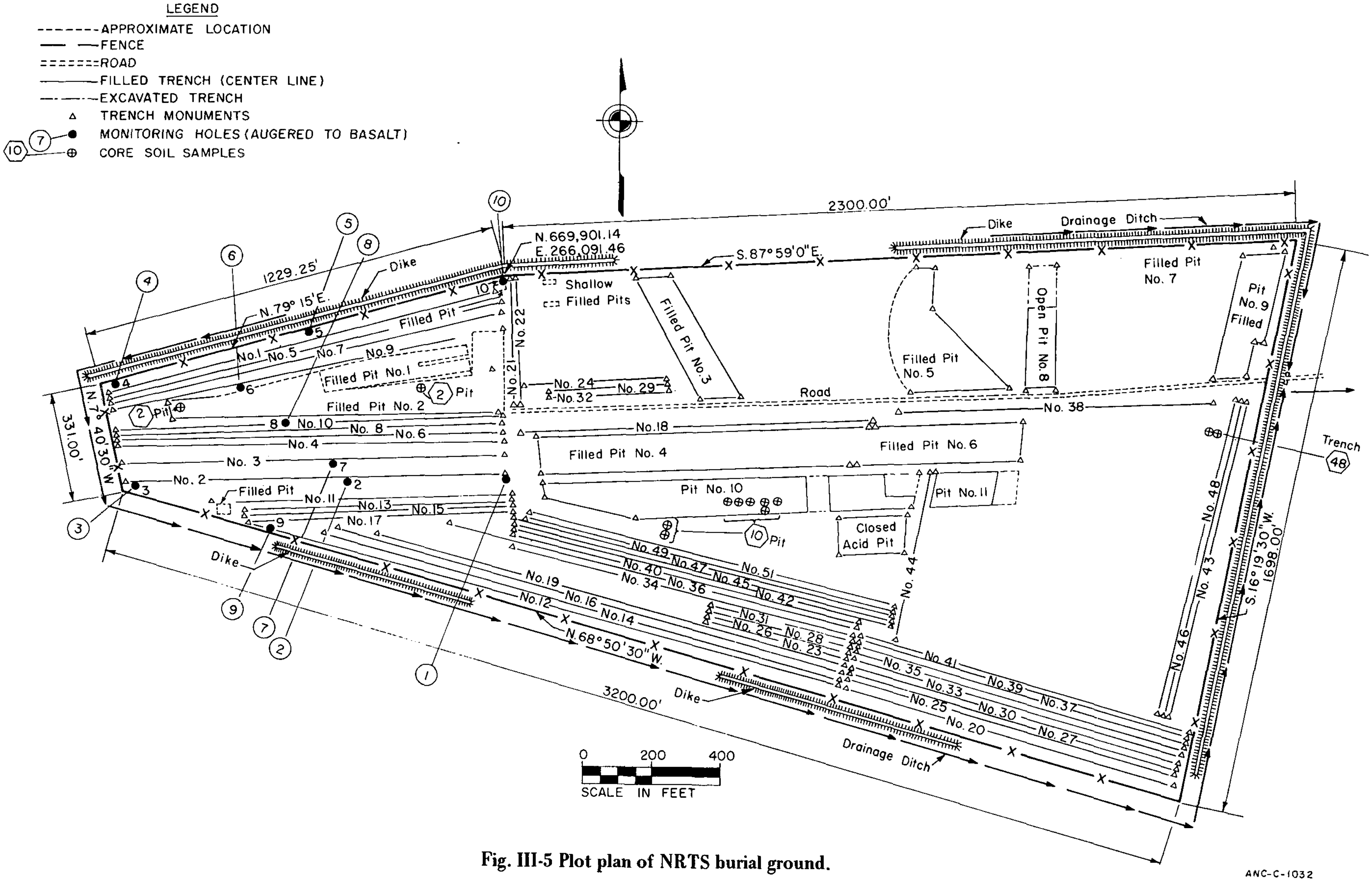

Fig. III-5 Plot plan of NRTS burial ground.

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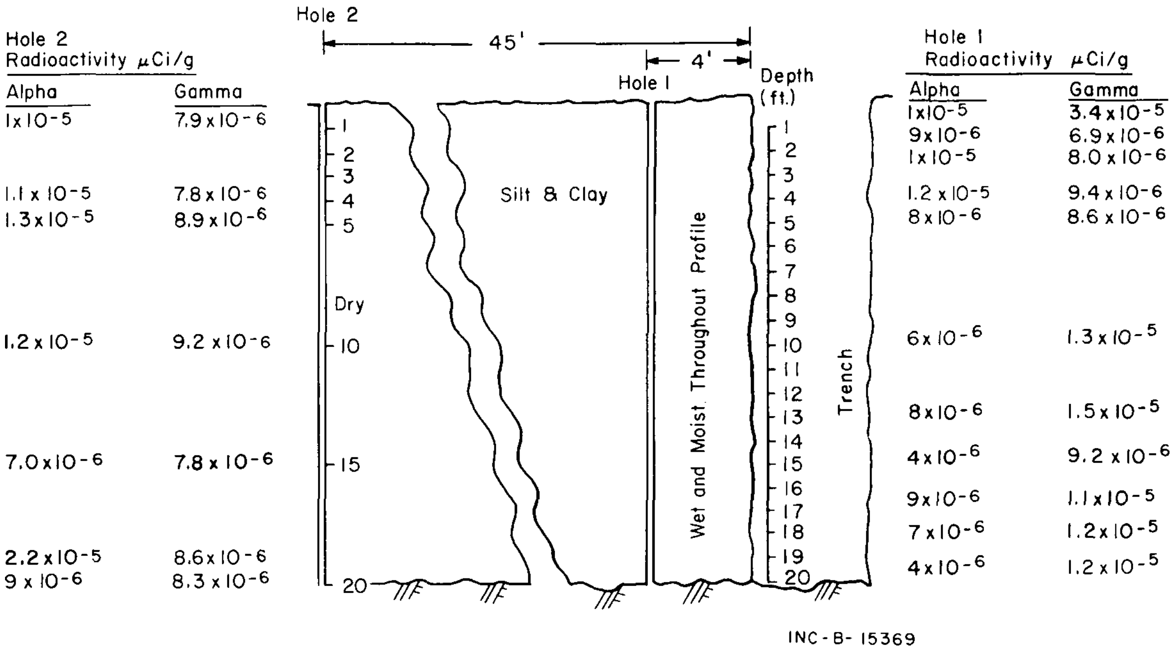
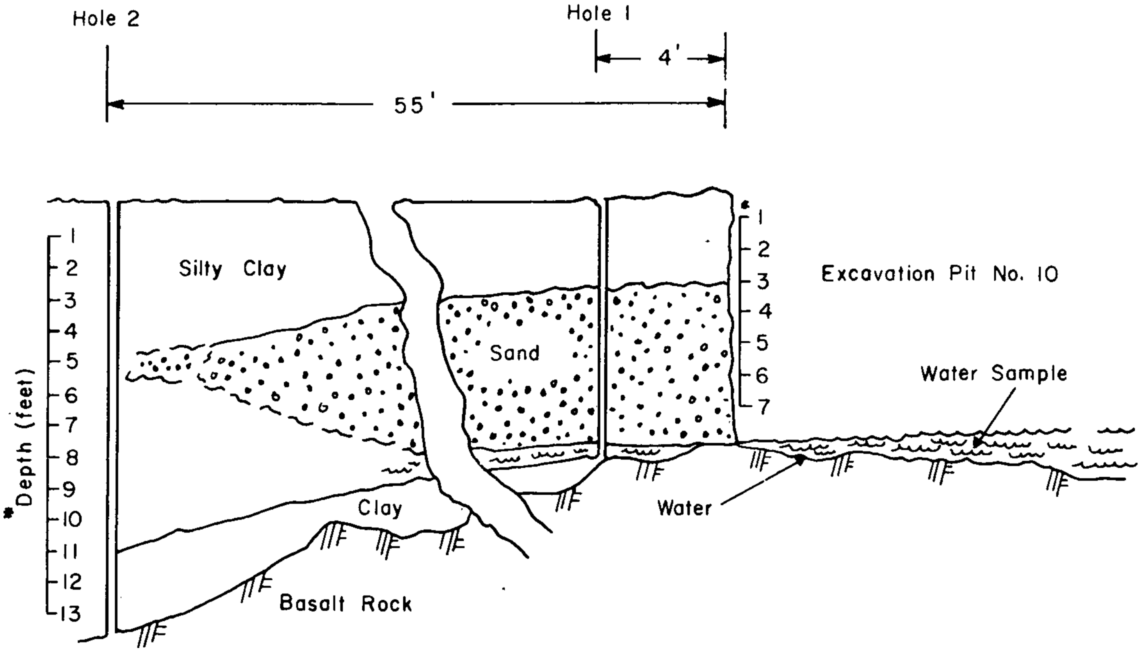


Fig. III-6 Cross section of Trench 48 and sampling (monitoring) holes showing gross radioactivity in soil samples taken in 1969.

TABLE III-7

RADIOACTIVITY IN SOIL SAMPLES ADJACENT TO MONITORING HOLES AT NRTS BURIAL GROUND -- 1969

Location	Depth	Activity μCi/g	
Hole Adjacent To		Gross Alpha	Gross Gamma
4	Surface	1.3×10^{-5}	1.1×10^{-5}
	5 feet	1.3×10^{-5}	8.0×10^{-6}
	5.5 feet	4×10^{-6}	7.5×10^{-6}
5	Surface	7×10^{-6}	1.2×10^{-5}
	2.5 feet	6×10^{-6}	4.7×10^{-6}
7	Surface	1×10^{-5}	7.8×10^{-6}
	5 feet	5×10^{-6}	8.6×10^{-6}
	9 feet	1×10^{-5}	8.4×10^{-6}
	10 feet	1×10^{-5}	7.9×10^{-6}



Hole	Depth	Sample Description	Gross Radioactivity .. Ci/g	
			Alpha	Gamma
1	3"	Silt	1.3×10^{-5}	9.4×10^{-6}
	1.5'	Silt Moist	8×10^{-6}	8.6×10^{-6}
	3'	Clay	8×10^{-6}	6.5×10^{-6}
	5'	Sand Moist	3×10^{-6}	8.0×10^{-6}
	6.5'	Sand Wet	8×10^{-6}	9.4×10^{-6}
	8'	Sand Wet	8×10^{-6}	7.8×10^{-6}
	8.5'	Clay Wet	1×10^{-5}	8.3×10^{-6}
	8'	Water	3×10^{-9} μci/ml	$< 10^{-9}$
2	3"	Silt	8×10^{-6}	8.5×10^{-6}
	5'	Silt Wet	8×10^{-6}	8.5×10^{-6}
	10'	Silt Moist	1.0×10^{-5}	7.4×10^{-6}
	14'	Clay Moist	6×10^{-6}	7.2×10^{-6}

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Fig. III-7 Cross section of Pit 10 and sampling holes showing gross radioactivity in soil samples taken in 1969.

The pit contained waste from Rocky Flats which was contaminated with alpha emitting plutonium, uranium, and americium isotopes. After the water had seeped into the soil, samples from the bottom and side of the excavation were taken with a core sampler as shown in Figure III-8. Thirty-nine samples from six cores were examined by gross counting techniques. The results are shown in Table III-8. Whereas the gross alpha activity in the samples from previously augered holes had been less than 1 x 10^{-5} μCu/g, these samples contained as much as 1.8 x 10^{-4} μCi/g, thus indicating contamination from waste. Samples from three of these locations were then selected for quantitative analysis by decomposition by fusion and extraction of the radioactive elements. The results are shown in Table III-9 and also in Figure III-9. Cores 1 and 2 were from the lowest point in the pit where the water remained the longest. The following inferences are derived from these results:

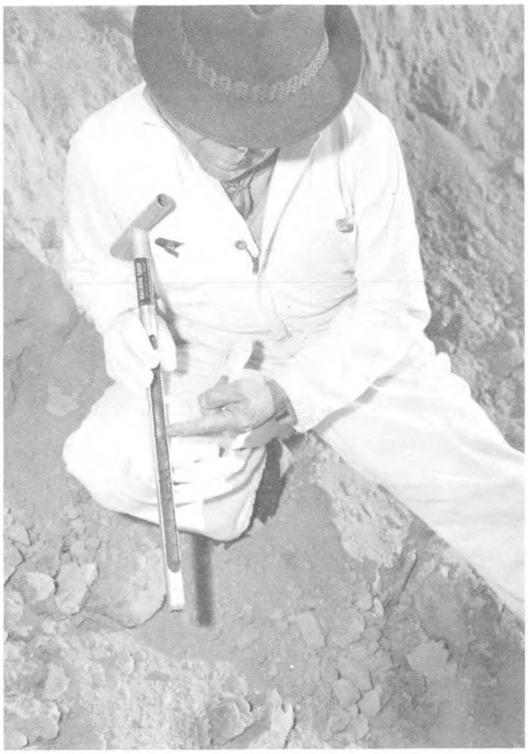


Fig. III-8 Core samples taken from bottom of burial pit.

(1) Uranium, plutonium, and americium isotopes were deposited in the soil lining the pit as evidenced by data pertaining to Cores 1 and 2

(2) The concentration of plutonium-239 between seven and eight inches was 1/50 of that in the surface inch in Core 1 and 1/20 of that in Core 2, which is evidence of sorption by the soil

(3) Americium-241 appears to be concentrated in the first two inches with the amount below this level being so low that its presence is questionable

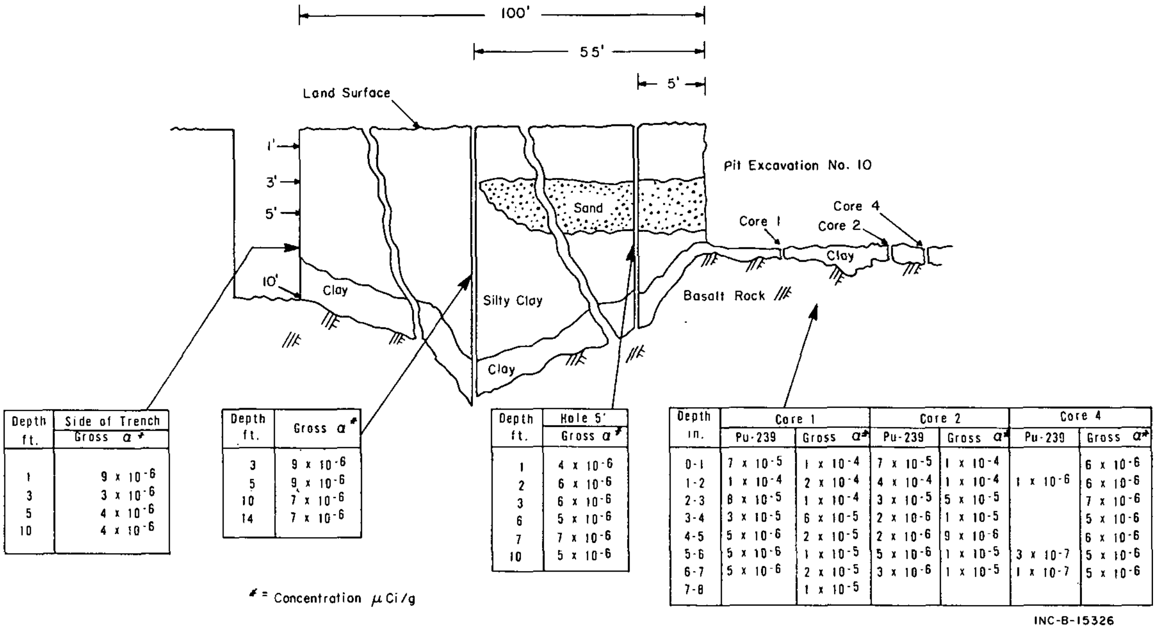
(4) Uranium-234 appears to be concentrated in the top two or three inches; however, the curie amount of U-234 is ordinarily about the same as the amount of U-238 under normal situations. As these results are not congruent with this ratio they are subject to question.

TABLE III-8

GROSS ALPHA ACTIVITY IN CORE SAMPLES FROM DISPOSAL PIT 10 AT NRTS BURIAL GROUND

Depth Interval (inches)	Gross Alpha Activity - μCi/g (air dry)					
	Core No.					
	1	2	3	4	5	6
0-1	1.0×10^{-4}	1.4×10^{-4}	2.3×10^{-5}	1.3×10^{-5}	4×10^{-6}	8×10^{-6}
1-2	1.4×10^{-4}	6.7×10^{-5}	2.6×10^{-5}	2.3×10^{-5}	9×10^{-6}	1.0×10^{-5}
2-3	1.8×10^{-4}	5.2×10^{-5}	9×10^{-6}	1.8×10^{-5}	1.4×10^{-5}	1.4×10^{-5}
3-4	8.3×10^{-5}	3.4×10^{-5}	1.9×10^{-5}	1.2×10^{-5}	1.8×10^{-8}	6×10^{-6}
4-5	2.3×10^{-5}	3.4×10^{-5}	6×10^{-6}	7×10^{-6}	1.4×10^{-5}	1.7×10^{-5}
5-6	2.3×10^{-5}	3.9×10^{-5}		9×10^{-6}		8×10^{-6}
6-7	2.1×10^{-5}	2.6×10^{-5}		9×10^{-6}		
7-8	2.1×10^{-5}	2.8×10^{-5}			(Side of Pit)	

NOTE: The analytical error becomes larger as the concentration becomes smaller -- eg, in the magnitude of 10^{-4} μCi/g the error ranges from 5 to 10%, and in the 10^{-6} range the error ranges from 20 to 30%.



Depth ft.	Side of Trench Gross α*
1	9×10^{-6}
3	3×10^{-6}
5	4×10^{-6}
10	4×10^{-6}

Depth ft.	Gross α*
3	9×10^{-6}
5	9×10^{-6}
10	7×10^{-6}
14	7×10^{-6}

Depth ft.	Hole 5' Gross α*
1	4×10^{-6}
2	6×10^{-6}
3	6×10^{-6}
6	5×10^{-6}
7	7×10^{-6}
10	5×10^{-6}

Depth in.	Core 1		Core 2		Core 4	
	Pu-239	Gross α*	Pu-239	Gross α*	Pu-239	Gross α*
0-1	7×10^{-5}	1×10^{-4}	7×10^{-5}	1×10^{-4}		6×10^{-6}
1-2	1×10^{-4}	2×10^{-4}	4×10^{-4}	1×10^{-4}	1×10^{-6}	6×10^{-6}
2-3	8×10^{-5}	1×10^{-4}	3×10^{-5}	5×10^{-5}		7×10^{-6}
3-4	3×10^{-5}	6×10^{-5}	2×10^{-6}	1×10^{-5}		5×10^{-6}
4-5	5×10^{-6}	2×10^{-5}	2×10^{-6}	9×10^{-6}		6×10^{-6}
5-6	5×10^{-6}	1×10^{-5}	5×10^{-6}	1×10^{-5}	3×10^{-7}	5×10^{-6}
6-7	5×10^{-6}	2×10^{-5}	3×10^{-6}	1×10^{-5}	1×10^{-7}	5×10^{-6}
7-8		1×10^{-5}				

* = Concentration μCi/g

Fig. III-9 Cross-sectional diagram of sampling locations at Pit 10.

TABLE III-9

RADIOACTIVITY IN CORE SAMPLES FROM BOTTOM OF PIT 10

DETERMINED BY ALPHA SCINTILLATION SPECTROMETRY OF EXTRACTED NUCLIDES

	Radioactivity µCi/g (air dry)					
Sample	U-235 U-238	U-234	Pu-239	Pu-238 Am-241	Other Natural Nuclides	Gross α
Core 1 (in.)						
0-1	Nil	4.3×10^{-5}	7.2×10^{-5}	1.3×10^{-5}	Insignificant	1.3×10^{-4}
1-2	Nil	5.7×10^{-5}	1.2×10^{-4}	3.1×10^{-5}	1.2×10^{-5}	2.2×10^{-4}
2-3	6×10^{-6}	4.7×10^{-5}	8.4×10^{-5}	7×10^{-6}	6×10^{-6}	1.5×10^{-4}
3-4	1.3×10^{-6}	2.5×10^{-5}	2.8×10^{-5}	9.0×10^{-6}	1.7×10^{-6}	6.5×10^{-5}
4-5	1.5×10^{-6}	8.2×10^{-6}	4.6×10^{-6}	Nil	2.7×10^{-6}	1.7×10^{-5}
5-6	6.0×10^{-7}	4.5×10^{-6}	4.7×10^{-6}	7.5×10^{-7}	5.7×10^{-6}	1.5×10^{-5}
6-7	1.1×10^{-6}	6.8×10^{-6}	5.4×10^{-6}	1.1×10^{-6}	4×10^{-6}	1.8×10^{-5}
7-8	1.6×10^{-6}	5.3×10^{-6}	1.4×10^{-6}	Nil	5×10^{-6}	1.3×10^{-5}
Core 2						
0-1	9×10^{-7}	5.7×10^{-5}	6.8×10^{-5}	2.1×10^{-5}	3.1×10^{-6}	1.5×10^{-4}
1-2	1.5×10^{-7}	9.6×10^{-5}	3.8×10^{-5}	6.0×10^{-6}	1×10^{-5}	1.5×10^{-4}
2-3	4.7×10^{-7}	1.7×10^{-5}	2.6×10^{-5}	1.9×10^{-7}	3.3×10^{-6}	4.7×10^{-5}
3-4	1.7×10^{-6}	5.1×10^{-6}	2.3×10^{-6}	6.5×10^{-7}	3.4×10^{-6}	1.3×10^{-5}
4-5	1.1×10^{-6}	4.1×10^{-6}	1.6×10^{-6}	7.0×10^{-7}	1.3×10^{-6}	8.8×10^{-6}
5-6	1.3×10^{-6}	5.1×10^{-6}	5.0×10^{-6}	6.3×10^{-7}	3×10^{-6}	1.5×10^{-5}
6-7	1.1×10^{-6}	4.6×10^{-6}	3.2×10^{-6}	7.2×10^{-7}	3×10^{-6}	1.2×10^{-5}
7-8	1.5×10^{-6}	3.2×10^{-6}	3.2×10^{-6}	4.8×10^{-7}	2.4×10^{-6}	9.5×10^{-6}
Core 4						
0-1						6.2×10^{-6}
1-2			1.0×10^{-6}			6.4×10^{-6}
2-3						6.6×10^{-6}
3-4		Essentially Background Levels				5.2×10^{-6}
4-5						6.2×10^{-6}
5-6						5.2×10^{-6}
6-7						4.9×10^{-6}

Soil samples taken from a hole about five feet from the excavation (see Figure III-9) and from a newly excavated trench about 100 feet away were analyzed by alpha spectrometry of extracted nuclides. The results are shown in Table III-10. Only uranium isotopes were identified at a concentration of approximately 2×10^{-6} μCi/g. If these values are accepted as indicative of the natural concentration, then it might be inferred that the concentrations in the core samples of the pit bottom, which ranged between 5×10^{-6} and 9.6×10^{-5} μCi/g, indicated migration of uranic waste isotopes to a depth of at least eight inches. These samples also indicate that the mean concentration of all natural alpha emitting nuclides such as uranium and thorium in the soil at the burial ground is $6 \pm 4 \times 10^{-6}$ μCi/g. In comparison, however, two samples of soil from 25 miles southeast of the burial ground contained less than 6×10^{-7} μCi/g. This could be due to natural differences of the soil. For instance, the soil at the burial ground is derived from parent material, most of which is alluvial deposition of the Big Lost River which drains from the mountains north of the Snake River Plain in which naturally occurring radionuclide deposits are known to exist. The two samples of soil with less radioactivity are derived from eolian materials, the origin of which is not well defined. In any case, the number of samples is not sufficient to define the precision and accuracy of these determinations.

After exhuming some waste, soil samples were obtained from a pit (No. 2) which was filled between 1959 and 1963. The soil from the bottom of the pit as well as the interstitial fill between the barrels was sampled. These samples were from the west end of the pit where waste was deposited in 1963 and from the east end filled in 1959 (see Figure III-5). The waste from the west end, shown in Figure III-10, appeared to be relatively dry. A core sample four inches long from the floor of the pit, below the waste, contained 11% moisture on a dry weight basis. This can be compared to a theoretical total capacity of 34%[a] This sample was analyzed and the results of the analyses are shown in Table III-11.

The core samples of the residual soil below the waste at the east end of the pit contained between 18 and 20% moisture. The soil covering the waste contained 5% and the interstitial soil fill between the barrels was nearly saturated with 30 to 35% moisture. The results of the radiological analyses also are included in Table II-11.

It is postulated that the moisture and radioactivity found in the sample resulted from flooding in 1962. The higher amount of moisture in the soil from the east end is difficult to explain. The only plausible explanations are (a) the soil had retained a higher amount of residual water from the 1962 flood due to the fact that it became saturated after the waste had been deposited and covered; (b) that the pit had become saturated after covering as a result of horizontal seepage through the sand strata from Pit 10, which was filled with water in January 1969; or (c) that water had entered the pit through a "sink" hole and filled the interstitial spaces. Water was extracted from the soil and analyzed for tritium in an attempt to age-date the moisture, but the results were not conclusive.

---

[a]

$$\text{Percent moisture (volume)} = \text{percent pore space} = \frac{\text{real density} - \text{apparent density}}{\text{real density}}$$

where apparent density = 1.4 and real density = 2.6

$$\text{Percent moisture (weight)} = \frac{\text{percent moisture (volume)}}{\text{apparent density}}$$

The radioactivity contained in the soil samples from the east end where the moisture was highest was less than in the west end samples where the moisture was lower, which is difficult to explain. It can be postulated that the activity was leached or transported below the soil horizon; however, this is not congruous with the fact that the uranium isotopes and plutonium-239 are concentrated in the surface inches of the sample profiles as well as in the fill material.

TABLE III-10

RADIOACTIVITY IN SOIL SAMPLES NEAR PIT 10

	Radioactivity (μCi/g)						
Sample	U-234 U-238	U-234	Pu-239	Pu-238 Am-241	Other Natural Nuclides	Gross α	Soil Texture
Hole -- 5 Feet From Pit 10 (feet)							
1	-	-	None Identified		-	4.9×10^{-6}	Silty clay loam
2	9.9×10^{-7}	1.1×10^{-6}	"		4×10^{-6}	6.2×10^{-6}	Sandy loam
3	4.6×10^{-7}	5.5×10^{-7}	"		4.5×10^{-6}	5.6×10^{-6}	Sand
6	9.5×10^{-7}	1.4×10^{-6}	"		2.5×10^{-6}	4.9×10^{-6}	Sand
7	-	-	"		-	6.7×10^{-6}	Silty clay
10	8.2×10^{-7}	1.1×10^{-6}	"		2.7×10^{-6}	4.8×10^{-6}	Clay
Trench -- 100 Feet From Pit 10							
1	3.3×10^{-6}	3.5×10^{-6}	None Identified		2.4×10^{-6}	9.3×10^{-6}	
3	4.5×10^{-7}	6.7×10^{-7}	"		1.7×10^{-6}	2.8×10^{-6}	
5	8.6×10^{-7}	1.2×10^{-6}	"		1.9×10^{-6}	4.2×10^{-6}	
6	7.5×10^{-7}	8.7×10^{-7}	"		1.9×10^{-6}	3.7×10^{-6}	

TABLE III-11

RADIOACTIVITY IN CORE SAMPLES FROM BOTTOM OF PIT 2

Sample	Radioactivity -- µCi/g (air dry) U-235 U-238	U-234	Pu-239	Pu-238 Am-241	Other Natural Nuclides	Gross α
Core -- West End Pit 2 -- Bottom (inches)						
0-1	$<8 \times 10^{-7}$	2×10^{-6}	7×10^{-5}	7×10^{-6}	-	7.8×10^{-5}
1-2	2×10^{-6}	2×10^{-6}	6×10^{-5}	5×10^{-6}	-	6.4×10^{-5}
2-3	$<3 \times 10^{-6}$	2×10^{-6}	2.0×10^{-4}	2×10^{-5}	-	2.2×10^{-4}
3-4	$<4 \times 10^{-6}$	$<4 \times 10^{-6}$	3.2×10^{-4}	4×10^{-5}	-	3.6×10^{-4}
Core -- East End Pit 2 -- Bottom						
0-1	9×10^{-6}	1×10^{-5}	8×10^{-7}	-	2×10^{-6}	2.1×10^{-5}
1-2	3×10^{-5}	7×10^{-6}	3×10^{-6}	$<4 \times 10^{-7}$	-	3.4×10^{-5}
2-3	5×10^{-5}	2×10^{-5}	$<2 \times 10^{-5}$	$<2 \times 10^{-6}$	-	6.3×10^{-5}
3-4	4×10^{-6}	5×10^{-6}	$<3 \times 10^{-7}$	$<2 \times 10^{-7}$	1×10^{-6}	1.1×10^{-5}
4-5	3×10^{-6}	4×10^{-6}	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	1×10^{-6}	8×10^{-6}
5-6	1×10^{-6}	2×10^{-6}	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	2×10^{-6}	5×10^{-6}
6-7	3×10^{-6}	3×10^{-6}	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	1×10^{-6}	7×10^{-6}
7-8	2×10^{-6}	3×10^{-6}	$<2 \times 10^{-7}$	$<3 \times 10^{-7}$	-	5×10^{-6}
8-9	2×10^{-6}	2×10^{-6}	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	1×10^{-6}	5×10^{-6}
12	1×10^{-6}	1×10^{-6}	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	-	3×10^{-6}
Silt -- Pit 2 -- (Fill) -- Bottom of Waste Pile						
1	1.3×10^{-5}	4×10^{-6}	8.7×10^{-5}	6×10^{-6}	-	1.1×10^{-4}
2	8×10^{-6}	1×10^{-5}	$<3 \times 10^{-7}$	$<3 \times 10^{-7}$	3×10^{-6}	2.1×10^{-5}
3	6×10^{-6}	7×10^{-6}	$<2 \times 10^{-7}$	$<2 \times 10^{-7}$	1×10^{-6}	1.4×10^{-5}
Silt -- Pit 2 -- (Fill) -- Center Six Feet						
	2×10^{-6}	3×10^{-6}	5×10^{-6}	$<8 \times 10^{-7}$	-	1×10^{-5}

Fig. III-10 Exhumed waste located in west end of Pit 2.

2

4.2 1970 Investigations

Additional soil samples were taken during 1970 by means of excavations adjacent to Trench No. 1 and No. 9 and Pit No. 1. As shown in Figure III-11, Trench No. 1 was filled during 1952-54 and Pit No. 1 between 1957 and 1959. The purpose was to extend or verify the results of the 1969 work and to make use of the improvements in analytical procedures achieved by the Analytical Branch of the Health Services Laboratory since the 1969 samples were analyzed[25]. These improvements increased the sensitivity for the detection of alpha emitting nuclides from about 10^{-6} to 10^{-8} μCi/g.

Four samples were also taken at locations both within and outside of the burial ground which were considered to be beyond any probable area of contamination resulting from burial of waste. The analytical results of these samples are listed in Table III-12. These figures have an error of approximately 10% at the 68% confidence level. The ratio of the uranium isotopes are congruous with the ratios which are found in uncontaminated earth materials. For example, ratio of U-234 to U-238 expressed in curies is slightly less than one. When expressed in mass units the ratio is 23,000 in comparison with 17,000 for the natural abundance ratio reported in the literature[26]. This ratio is also congruous with that derived on the basis of the rationale of decay. The amounts of exotic nuclides Pu-239 and Am-241 are paradoxical and can only be rationalized on the bases of fallout or contamination in the laboratory or by reagents. Although the numbers seem to be real the amounts are very small and cannot be reconciled with field contamination.

Thirty-four samples were taken in the excavations adjacent to the waste repositories at various depths and horizontal distances from the waste. The analytical results are shown in Table III-13. The majority of these samples contained no activity above the normal background or detection limits. Those which indicate a possibility of contamination are as follows:

> Samples 1-10-1 through 1-12-1 indicate possible contamination from uranium isotopes as the $^{234}U/^{238}U$ ratio is 1.04 to 1.14 in comparison to the natural abundance ratio of one or less. This increase is very small and may not be significant. One sample indicates a slightly higher concentration of fission activation products of 1.6 x 10^{-6} μCi/g which is slightly above the activity in adjacent samples; however, such a concentration was previously considered to be background.
>
> Samples 2-5-1.5 and 2-7-1.5 have a $^{234}U/^{238}U$ ratio of 1.13 and 1.20 which could possibly be due to contamination. These samples also have a concentration of fission and activation products of 1.3 x 10^{-6}.
>
> Sample 5-5-1 has a $^{234}U/^{238}U$ ratio of 4.8 which indicates a change from the natural abundance ratio presumably due to contamination. The presence of fission or activation products is not indicated or expected as the adjacent waste in the pit did not contain these products originally. Samples 5-7-1 and 5-13-1 have ratios slightly above one.
>
> Samples 6-7-B_6 and 6-10-B_{12} show increased amounts of U-234 with ratios with U-238 of 1.75 and 6.07, respectively. These samples are below buried waste.
>
> Samples 7-5-B and 7-5-B_4 are also below buried waste and show a $^{234}U/^{238}U$ ratio slightly above one.

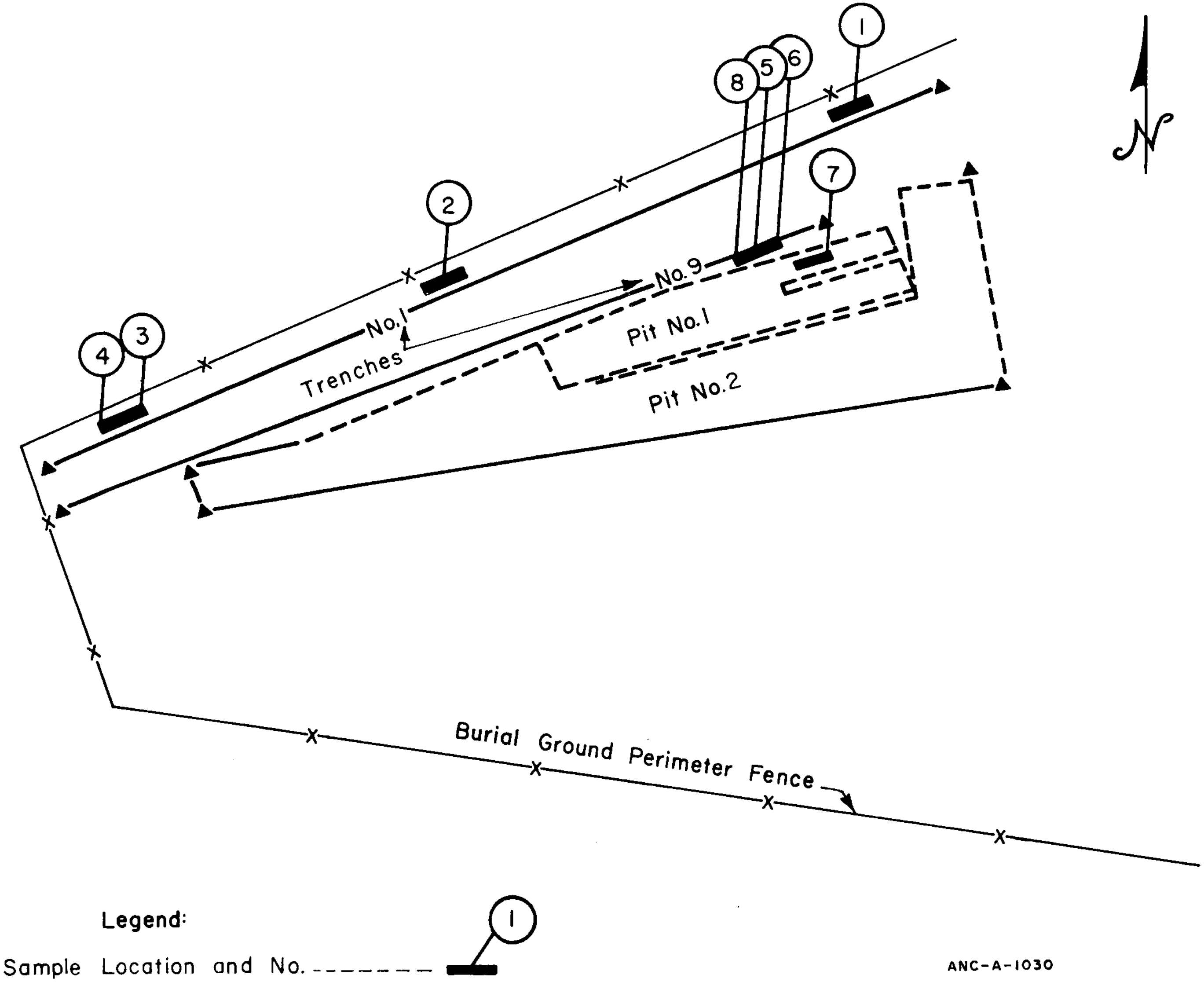


Fig. III-11 Excavations during 1970.

TABLE III-12

NATURAL RADIOACTIVITY IN SOIL-VICINITY OF NRTS BURIAL GROUND

	Radioactivity μCi/g					
Location	U-234	U-235	U-238	Pu-238	Am-241	Fission P.
2-samples inside Burial Ground fence	8.6×10^{-7}	3×10^{-8}	8.9×10^{-7}	2×10^{-8}	2×10^{-8}	Below detection limit
2-samples outside Burial Ground fence	6.5×10^{-7}	2.5×10^{-8}	6.8×10^{-7}	4×10^{-8}	1.5×10^{-8}	($< 1 \times 10^{-7}$ μCi/g)

TABLE III-13

RADIOACTIVITY IN SOIL ADJACENT TO BURIED WASTE

Sample Description[a]	Radioactivity in μCi/g						
	U-234	U-235	U-238	Pu-239	Am-241	Fission Activation	$^{234}U/^{238}U$
1-S-1	- [b]	-	-	-	-	6×10^{-7}	-
-S-1	6.8×10^{-7}	3.8×10^{-8}	7.2×10^{-7}	9×10^{-9}	1×10^{-8}	6×10^{-7}	0.94
-1-1	-	-	-	-	-	9×10^{-7}	-
-6-1	7.7×10^{-7}	3×10^{-8}	8.2×10^{-7}	2×10^{-9}	-	8×10^{-7}	0.94
-6-1	8.8×10^{-7}	3×10^{-8}	9.2×10^{-7}	4×10^{-8}	2×10^{-8}	-	0.96
-10-1	1.0×10^{-6}	4×10^{-8}	9.6×10^{-7}	2×10^{-9}	1×10^{-8}	-	1.04
-10-1	8.0×10^{-8}	4×10^{-8}	7.0×10^{-8}	-	-	16×10^{-6}	1.14
-10-1	8.8×10^{-7}	4×10^{-8}	8.5×10^{-7}	1×10^{-8}	5×10^{-9}	5×10^{-7}	1.04
-12-1	8.8×10^{-7}	3×10^{-8}	8.0×10^{-7}	-	9×10^{-8}	-	1.11
-12-1	5.6×10^{-7}	4×10^{-8}	6.0×10^{-7}	-	4×10^{-8}	6×10^{-7}	0.92
-12-1	5.9×10^{-7}	3×10^{-8}	6.0×10^{-7}	-	1×10^{-8}	2×10^{-7}	0.95
2-3-1.5	-	-	-	-	-	-	-
-4-1.5	-	-	-	-	-	1.3×10^{-6}	-
-5-1.5	1.1×10^{-6}	-	9.4×10^{-7}	4×10^{-9}	-	-	1.13
-6-1.5	4.9×10^{-7}	-	5.3×10^{-7}	4×10^{-9}	-	9×10^{-7}	0.93
-7-1.5	9.2×10^{-7}	-	7.7×10^{-7}	-	-	-	1.20
3-3-2	-	-	-	-	-	5×10^{-7}	-
-6-2	-	-	-	-	-	-	-
-11-2	-	-	-	-	-	4×10^{-7}	-
4-6-2	-	-	-	-	-	-	-
-6-2	8.8×10^{-7}	-	9×10^{-7}	2×10^{-9}	2×10^{-8}	-	0.96
-12-2	1.2×10^{-6}	-	1.2×10^{-6}	4×10^{-9}	1×10^{-8}	7×10^{-7}	1.00
5-5-1	3.5×10^{-6}	-	7.2×10^{-7}	5×10^{-9}	2×10^{-8}	-	4.8
-7-1	1.5×10^{-6}	-	1.0×10^{-6}	2×10^{-7}	5×10^{-8}	-	1.4
-13-1	6.5×10^{-7}	-	7×10^{-7}	3×10^{-7}	2×10^{-8}	-	0.9
-13-1	6.0×10^{-7}	-	6×10^{-7}	2×10^{-7}	3×10^{-7}	-	1.05
-13-1	3.5×10^{-7}	-	3.6×10^{-7}	6×10^{-9}	2×10^{-8}	-	0.98
6-7-B6	3.2×10^{-6}	-	1.8×10^{-6}	7×10^{-6}	3×10^{-7}	6×10^{-7}	1.75
-10-B12	4.3×10^{-5}	-	7.0×10^{-6}	2×10^{-8}	4×10^{-8}	-	6.07
7-5-B	9.4×10^{-7}	-	9×10^{-7}	3×10^{-7}	7×10^{-8}	-	1.03
-5-B4	1.3×10^{-6}	5×10^{-8}	1.2×10^{-6}	2×10^{-7}	3×10^{-8}	-	1.09
-5-B8	1.1×10^{-6}	4×10^{-8}	1.1×10^{-6}	2×10^{-8}	1×10^{-8}	-	0.96
8-7-3	-	-	-	-	-	-	-
-13-3	8.2×10^{-7}	3×10^{-8}	8.7×10^{-7}	3×10^{-9}	1×10^{-8}	4×10^{-7}	0.94

---

[a] 1-S-1
↑
Number[c]

1-S-1
↑
Depth below land surface (ft) -- where repeated it indicates 4 in. sequential increments.

1-S-1
↑
Distance from waste (ft) -- "B" indicates 4 in. incremental samples below waste.

[b] No data, or below detection limit.

[c] Sample

No. 1 East end, Trench No. 1	No. 5 North side, Pit No. 1
No. 2 Mid-section, Trench No. 1	No. 6 North side, Pit No. 1
No. 3 West end, Trench No. 1	No. 7 Directly in Pit No. 1
No. 4 West end, Trench No. 1	No. 8 By Trench No. 9

If the concentrations of uranic, or heavier elements, listed in Table III-12 represent the situation in which the soil is uncontaminated with waste, then the samples from the vicinity of Pit No. 1 bearing the numbers 5, 6, and 7 indicate the presence of plutonium-239. The concentrations range between 2×10^{-7} to 7×10^{-6} =Ci/g. The latter sample, 6-7-B_6, which was taken below the waste, is congruent with the 1969 samples taken in Pit No. 2.

In summary, these figures are congruent with the results obtained in 1969. The only evidence of the presence of contamination at distances of one foot from the waste is the increase in the U-234/U-238 ratio. Only in the case of the excavations near Pit No. 1 and below the drums is the evidence conclusive.

5. SUMMARY

(1) Under circumstances where adequate land surface drainage is provided, the percolation of meteoric water through the soil and waste will not leach the waste to an extent sufficient to carry contamination in significant quantity through 35 cm of soil within a period of 300 years. Any burial practices which would provide such drainage and inhibit contact of water with waste would ensure greater safety.

(2) Where drainage is inadequate and inundation of waste occurs as a result of runoff ponding, there is evidence that leaching and dissolution of waste occurs although the concentrations are below present-day standards or guide limits. The dissolved radionuclides are sorbed on the soil as the solution percolates through. Radioactivity from buried waste was not measurable in soil beyond one foot as a result of two such occurrences at the NRTS burial ground.

(3) In case of waste that is contaminated with nuclides which will remain radioactive indefinitely such as the transuranic wastes, it is imperative that percolating water be excluded from contact with the waste.

(4) There is no evidence, either theoretical or factual, that waste nuclides have thus far moved below the burial ground to an extent that would insult in any way the quality of the ground water.

IV. FUTURE IMPLICATION OF WASTE IN THE REGOLITH[a]

1. STATEMENT OF THE PROBLEM

One aspect of the emphasis on environmental pollution control is the concern that the sites used for waste disposal (both solids and liquid) will require perpetual care and inconvenience. Using the situations previously described as examples, this section is an attempt to appraise such a possibility.

2. HYPOTHETICAL LAND USE

Land previously used as a disposal site could be used for four general purposes:

2.1 Open Acess

Direct radiation at the land surface is a primary consideration in this case. At the NRTS solid waste burial ground the waste must be covered with three feet of soil and the radiation level reduced to 1 mR/hr at a point three feet above the land surface. Radiation could be reduced further by additional covering or disinterment and removal. Decay also would reduce the radiation. At the present time, however, it seems logical that the radiation would preclude unrestricted access to the area.

With respect to the sites where liquid waste is discharged, it is hypothesized that the TRA ponds are no longer needed and can be allowed to dry by percolation and evaporation. After the ponds are dried to dampness, they can be backfilled, involving an area of between four and five acres. Strontium-90 and cesium-137 would be the remaining radionuclides of concern because of their relatively long half-lives. For the purpose of this analysis, a hypothetical assumption of 50 curies of strontium-90 and 100 curies of cesium-137 was retained in the alluvium within a three foot deep section below the pond bottom. Although the assumed amounts were in excess of that discharged as of 1970 and also in excess of the amount retained, they would not be detectable at the land surface after being covered by the backfill. Even if it is assumed that the inventory were located at a single point it would not be detectable by virtue of the following rationale:

(1) One hundred curies of Cs-137 produce a radiation level of about 400 to 450 R/hr at one foot (in air).

(2) The gamma radiation shielding properties of alluvium are about the same as concrete, which has a half-value layer thickness, for 1 meV gamma, of 4.65 cm. The over-burden of 12 feet would provide 79 half-value layers, resulting in no measureable radiation at the surface.

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[a] Adopted from a theoretical study performed by C. A. Hawley, Jr. and W. L. Polzer for internal use, April 1969.

On this basis, buried contamination would cause no restriction to access or length of residence in the backfilled area, and the land would be used for any desired surface use.

2.2 Above Surface Construction

This would be limited to the extent discussed under Section 2.1. Obviously, radiation emanating from the land surface and the relatively shallow depth of the waste at the NRTS burial ground would limit occupancy and hinder construction.

Were the pond area to be abandoned, previous calculations also indicate there would be no significant increase in radiation levels (above background) at a depth of six to eight feet. In other words, gamma radiation from the contaminated zone would penetrate upward in significant amounts no more than three to four feet. Consequently, foundations from buildings could be constructed to six feet below the surface, and buildings erected on these foundations could be occupied full time without any increase in the occupant's or constructions workers' radiation dose.

2.3 Subsurface Construction

This would not be possible at the burial ground unless the waste were removed. If excavation were made for a building at the abandoned pond area it would require restriction to depths less than 10 to 12 feet. If it were to pass the 12 to 15 foot depth, residual strontium and cesium would be disturbed. This would present hazards of inhalation, radiation, and contamination spread. Normal building practices would probably result in sufficient shielding so that subsurface structures would be occupied without significant occupant exposure.

2.4 Agricultural Activities

Obviously, this would be excluded at the solid waste burial ground with the exception of range-type grazing. It is possible that the area at the TRA pond could be used for the planting and harvesting of row crops, cereals, and shallow-rooted forage. Alfalfa, with its deep roots, possibly could transfer the contamination to the human food chain. It has been estimated that alfalfa roots supply about 5% of the plant nutritional requirements from depths of 7 to 12 feet[27]. On this basis it is assumed that the contaminated zone would contribute about 1% of the total nutrients of a crop planted on this location. The relation between the uptake of calcium and strontium by plants has been shown to average 1.5 μCi Sr-90 per gram calcium where the contaminative level is one curie strontium-90 per square kilometer in the plow layers[28]. Based on this assumption, the following calculations can be made.

1 km^2 = 10^6 m^2

1 acre = 4×10^3 m^2

1 Ci/km^2 = 1 μCi/m^2

1 μCi/m^2 x 4×10^3 m^2/acre = 4×10^3 μCi/acre, which is the contamination level in Fredricksson's study

50 Ci Sr-90/4.0 acres = 1.2×10^7 μCi/acre, which is the contamination level in this hypothetical situation

1.2×10^7 μCi/acre = 3.0×10^3, which is the factor which must be applied to Fredricksson's data to adjust for the higher contamination level expected in the zone contaminated by the pond.

Therefore,

$$(3.0 \times 10^{3})(1.5 \times 10^{-3}) \text{ μCi of Sr-90/g-Ca.}$$

Alfalfa contains 2×10^{-29} Ca/g dry weight[29]. Since the ratio of strontium to calcium is 4.5 μCi/g-Ca, the expected strontium-90 content of alfalfa grown in the contaminated area would be

$$(4.5 \times 10^{-6} \text{ Ci Sr-90/g-Ca})(2 \times 10^{-2} \text{ g Ca/g dry matter})$$
$$= 9 \times 10^{-8} \text{ Ci Sr-90/g dry matter.}$$

Only about 1% of this level would be reached, however, because the plants take only 1% of their nutrients from the contaminated zone; therefore, the expected strontium-90 content of the alfalfa harvested from the backfilled area would be

$$(9 \times 10^{-8} \text{ Ci } {}^{90}\text{Sr/g dry matter}) \ (1 \times 10^{-2})$$
$$= 9 \times 10^{-10} \text{ Ci of } {}^{90}\text{Sr/g dry matter.}$$

A cow eats about 20 kg (2×10^4g) of dry matter per day so,

$$(9 \times 10^{-10} \text{ Ci } {}^{90}\text{Sr/g dry matter}) \ (2 \times 10^{4}) = 1.8 \times 10^{-5} \text{ Ci/day.}$$

It has been reported that a cow secretes about 0.08% of the digested strontium per liter of milk[30]; therefore, a cow eating alfalfa would secrete milk contaminated to the extent of about

$$(2 \times 10^{-5} \text{ Ci/day}) \ (8 \times 10^{-4} \text{ -which is 0.08\%}) = 1.6 \ 10^{-8} \text{ Ci/liter or}$$
$$1.6 \times 10^{-2} \text{ μCi/liter.}$$

It also has been reported that clover removes 4.4% of the strontium-90 and 0.13% of cesium-137 contamination in soil in a single crop where the entire root system is contained in a contaminated soil[31]. Using this data for comparative purposes, the following rationale may be applied assuming 50 curies of strontium-90 as the critical nuclide spread over 4.0 acres:

$$(50 \text{ Ci } {}^{90}\text{Sr}) \ (0.04 \text{ -uptake}) = 2.0 \text{ Ci in hay on four acres.}$$

Assuming 4 tons per acre yield, then

$$(4 \text{ tons}) \ (4 \text{ acres}) = 16 \text{ tons or } 1.4 \times 10^{7} \text{ grams}$$

and

$$\frac{2.0 \times 10^{6} \text{ μCi}}{1.4 \times 10^{7} \text{ g hay}} = 1.4 \times 10^{-1} \text{ μCi/g hay}$$

and further assuming: 1% contribution from the contaminated zone:

$$(1.4 \times 10^{-1}\ \mu Ci/g)\ (0.01) = 1.4 \times 10^{-3}\ \mu Ci/g$$

and that a cow eats 35 kg/day; then

$$(3.5 \times 10^{4} g)\ (1.4 \times 10^{-3}\ \mu Ci/g) = 49\ \mu Ci/day/cow$$

and

$$(49\ \mu Ci/day)\ (8 \times 10^{-4}\ \text{-which is } 0.08\%) = 3.9 \times 10^{-2}\ \mu Ci/\text{liter milk.}$$

The 3.9×10^{-2} µCi/liter is in fair agreement with the 1.6×10^{-2} µCi/liter derived in the previous analysis.

The Radiation Concentration Guide limit for strontium in water is 3×10^{-7} µCi/ml[32]. Assuming that the consumption of milk is comparable to water, the above concentrations of 1.6×10^{-5} or 3.9×10^{-5} µCi/ml would require dilution or attenuation by a factor of at least 100. The assumptions used in the above analyses are conservative, and additional dilution factors can be postulated. For example, it is not likely that four acres would be used by themselves for alfalfa production. If alfalfa were grown on this ground it would probably be a part of a larger farming unit or field. The crop produced on other parts of the farm would not be contaminated and would dilute the amount fed to the cow over a season's feeding period. As far as the general public is concerned, milk produced from these four acres would probably be bulked with milk from other farms and would be further diluted.

3. DISCUSSION

Of the four land uses considered above, only that involving re-interment of the waste or contaminated soil would entail radiological problems. In order to prevent this from happening, the areas should be dedicated as a repository for a period of at least 300 years and in perpetuity in the case of the burial ground which contains long-lived fuel type nuclides. Movement of the contaminants by leaching water can be postulated; however, the resulting concentration of radionuclides in the leachate will probably not exceed the Radiation Guide limits.

Insurance that the areas will not be disturbed could be provided by physical means such as covers constructed with concrete or other impermeable material. This would stabilize the deposit of radioactivity by minimizing the movement of leaching water and would serve as a monumented notice to excavators.

4. CONCLUSIONS

(1) A tract of land which has been used for the disposal of waste can be used for other purposes, although use may be limited.

(2) Safeguards designed to control land use must be established and may be construed as perpetual.

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APPENDIX A

APPENDIX A

PROCEDURE AND SPECIAL EQUIPMENT NEEDS FOR DETERMINATION OF BATCH K_d'S

Equipment: 25 ml, screw-cap Pyrex culture tube; mixing wheel or device to agitate soil-liquid mixture; it is assumed that laboratory balances, breakers, pipettes, and beta and gamma counters are available.

Procedure: Weigh one grain of soil (minus 2 mm size-fraction) into culture tubes. Add 20 ml of mock waste solution containing the radionuclides to be studied. Tighten cap and agitate on mixing wheel for 24 hours. Remove from wheel, centrifuge, and transfer a 15 ml portion of the *clear*, supernatant liquid to a counting bottle. Also transfer 20 ml of the mock waste solution for use as a standard. It is best to count both sample and standard in the same counter and to use sufficientsactivity and counting time to minimize errors due to poor counting statistics.

The quantity of radionuclide sorbed on the soil is calculated by differences between standard and sample. The distribution coefficient can then be calculated from Equation 1. The distribution coefficient can also be calculated directly from

$$K_d = \left[\frac{(A_{std})(V_{liq})}{(A_{liq})(V_{std})} - 1\right]\left(\frac{V_T}{W}\right) \qquad (1)$$

where

A_{std} = Activity of the standard solution in counts per minute (cpm)

A_{liq} = Activity (CPM) in the aliquot of the liquid phase at equilibrium taken for analysis

V_{liq} = Volume (ml) of the liquid phase sample counted

V_{std} = Volume (ml) of the standard solution counted

V_t = Total column of liquid equilibrated with the soil

W = Weight in grams of the dry soil.

APPENDIX B

APPENDIX B

TABLE A

GROSS GAMMA ACTIVITY (cpm/g) AND PERCENT MOISTURE (by volume) AT SOIL VICINITY OF TRA POND

Hole Number									
61		62		64		65		66	
Depth Internal (feet)	Gross γ (cpm/g)	Depth Internal (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)
0-4	5.2	0-4	11	0-2	32	0-4	5.4	0-4	6.6
4-9	5.2	4-6	7.7	2-4	6.8	4-6	4.8	4-6	5.6
9-14	4.6	6-8	5.7	4-7	5.6	6-9	4.7	6-9	5.2
14-19[a]	4.5	8-10[a]	39	7-9	4.9	9-11	5.4	9-11	4.9
19-24	5.0	10-12	38	9-11	5.4	11-14	5.3	11-14	4.9
24-29	5.5	12-14	44	11-14	9.6	14-16	5.3	14-16	5.1
29-34	5.0	14-16[a]	58	14-16	11	16-19	6.5	16-19	5.1
34-39	4.9	16-18	54	16-19	17	19-21	5.0	19-21	5.0
39-44	5.4	18-20	46	19-22	15	21-24	5.1	21-24	5.0
		20-24	31	22-24	15	24-29	5.9	24-26	4.8
		24-26	31	24-26	49	29-35	5.2	26-29	5.2
		26-28	32	26-29	17	35-29	5.7	29-31	4.8
		28-32	36	29-34	18	39-44	5.3	31-34	4.7
		32-36	26	34-39	17	44-49	6.4	34-39	4.6
		36-38	23	39-44	14	49-54	5.9	39-44	5.4
		38-42	19	44-49	13	54-58	8.0	44-49	5.7
		42-46	19	49-52				49-54	
		46-50	17		11				5.4
		53-54½[a]							

TABLE A (Contd.)

Hole Number									
67		68		70		73		74	
Depth Internal (feet)	Gross γ (cpm/g)	Depth Internal (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)
0-4	9.3	0-4	5.5	0-4	5.5	0-5	5.5	0-4	8.4
4-7	5.1	4-6	4.9	4-6	4.5	5-7½	4.8	4-10	5.2
7-9	4.5	6-9	4.9	6-9	4.4	7½-10	7.2	10-14[a]	11
9-11	5.6	9-11	4.2	9-12	4.6	10-12[a]	11	14-19	22
11-14	5.0	11-14	5.6	12-14	6.0	12-15	-	19-24[a]	41
14-16	4.8	14-16	5.4	14-17	4.5	15-20[a]	159	24-29	27
16-19	5.6	16-19	5.0	17-19	4.3	20-25	121	29-32	26
19-24	4.9	19-24	4.6	19-24	5.0	25-30	101	34-39	22
24-26	4.6	24-29	5.5	24-29	4.6	30-35	91	39-43[a]	22
26-29	5.3	29-34	4.8	29-34	5.3	35-40[a]	78		
29-34	5.2	34-39	5.4	34-39	4.1				
34-39	5.3	39-44	5.1	39-44	4.9				
39-44	5.0	44-48	5.3	44-49	4.9				
44-47	5.0			29-54	4.8				

TABLE A (Contd.)

Hole Number									
82		83		84		85		86	
Depth Internal (feet)	Gross γ (cpm/g)	Depth Internal (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)
0-2	5.6	0-4	5.2	0-4	5.0	0-4	6.8	0-4	5.7
2-4	5.0	4-9	4.4	4-9	3.4	4-9	5.6	4-9	4.6
4-6	4.6	9-14	5.7	9-14	5.4	9-14[a]	17	9-14	5.1
6-8	4.4	14-19	4.4	14-19	4.3	14-19	16	14-19[a]	10
8-10	4.0	19-24	5.8	19-24	5.0	19-24[a]	36	19-24[a]	12
10-12	4.8	24-29	5.3	24-29	5.1	24-29	20	24-29[a]	8.2
12-14	4.4	29-34	6.0			29-34	12	29-34	6.0
14-16	4.4	34-39	5.8			34-39	14	34-39	6.7
16-18	5.4	39-44	5.5			39-44	15	39-44	7.7
18-20	4.8	44-48	5.5			44-49[a]	14	44-49	5.9
20-22	5.3								
22-24	4.6								
24-26	5.0								
26-28	3.1								
28-30	4.7								
30-32	5.4								
32-34	4.5								
34-36	4.8								
36-38	4.7								
38-42	4.4								
42-44	4.8								

TABLE A (Contd.)

Hole Number									
87		88		63-S[b]		71-S[b]		69-S and 72-S[c]	
Depth Internal (feet)	Gross γ (cpm/g)	Depth Internal (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)	Depth (feet)	Gross γ (cpm/g)
0-4	13	0-4	8.2	48½-49 (core)	19	52½-53	16		
4-9	6.2	4-9	6.1	57½-58	13				
9-14	5.6	9-14	5.6						
14-19	7.3[a]	14-19	4.8						
19-24	7.4	19-24	4.3						
24-29	9.7[a]	24-29	5.7						
20-34	7.7	29-34	5.5						
34-39	7.2	34-39	5.0						
39-43	7.3	39-42	6.3						

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[a] Selected for spectrometric analysis (see Table II-8).

[b] Drilled at an angle.

[c] Samples were not obtained.

APPENDIX C

APPENDIX C

DERIVATION OF THE CONCENTRATION OF RADIONUCLIDES IN THE SOIL SOLUTION

$$(1)\quad \frac{\text{Activity of Nuclide}}{\text{cc}_{\text{soil}}} = \frac{\text{Activity}_{\text{soil solution}}}{\text{cc}_{\text{soil}}} + \frac{\text{Activity}_{\text{soil}}}{\text{cc}_{\text{soil}}}$$

$$(2)\quad \frac{\text{Activity in soil solution}}{\text{cc}_{\text{soil}}} = \left(\frac{\text{Activity}_{\text{solution}}}{\text{ml}}\right)\left(\frac{\text{ml-solution}}{\text{cc}_{\text{soil}}}\right)$$

$$(3)\quad \frac{\text{Activity sorbed}_{\text{soil}}}{\text{cc}_{\text{soil}}} = \left(\frac{\text{Activity sorbed}}{\text{g}_{\text{soil}}}\right)\left(\frac{\text{g}_{\text{soil}}}{\text{cc}_{\text{soil}}}\right)$$

$$(4)\quad \frac{\text{Activity sorbed}}{\text{g}_{\text{soil}}} = \left(\frac{\text{Activity sorbed}}{\text{g}_{\text{soil}}}\right)\left(\frac{\text{ml-solution}}{\text{Activity in sol}}\right)\left(\frac{\text{Activity in sol}}{\text{ml}_{\text{sol}}}\right)$$

$$(5)\quad K_d = \left(\frac{\text{Activity sorbed}}{\text{g}_{\text{soil}}}\right)\left(\frac{\text{ml-solution}}{\text{Activity in}_{\text{sol}}}\right)$$

Therefore:

K_d (Equation 5) can be substituted for 3rd and 4th term in Equation 4 resulting in:

$$(6)\quad \frac{\text{Activity}}{\text{g}_{\text{soil}}} = K_d\left(\frac{\text{Activity solution}}{\text{ml}_{\text{sol}}}\right)$$

then:

Equations 2 and 6 can be substituted in Equation 1 resulting in:

$$(7)\quad \frac{\text{Activity of Nuclide}}{\text{cc}_{\text{soil}}} = \left(\frac{\text{Activity}_{\text{sol}}}{\text{ml}_{\text{sol}}}\right)\left(\frac{\text{ml}_{\text{sol}}}{\text{cc}_{\text{soil}}}\right) + K_d \left(\frac{\text{Activity}_{\text{sol}}}{\text{ml}_{\text{sol}}}\right)\left(\frac{\text{g}_{\text{soil}}}{\text{cc}_{\text{soil}}}\right)$$

$$(8)\quad \frac{\text{Activity}_{\text{sol}}}{\text{ml}_{\text{sol}}} = \frac{\dfrac{\text{Activity}}{\text{cc}_{\text{soil}}}}{\dfrac{\text{ml}_{\text{sol}}}{\text{cc}_{\text{soil}}} + K_d \dfrac{\text{g}_{\text{soil}}}{\text{cc}_{\text{soil}}}}$$

where:

$$K_d \frac{\text{g}_{\text{soil}}}{\text{cc}_{\text{soil}}} >> \frac{\text{ml}_{\text{sol}}}{\text{cc}_{\text{soil}}} \text{, then}$$

$$(9)\quad \frac{\text{Activity}_{\text{sol}}}{\text{ml}_{\text{sol}}} = \frac{\dfrac{\text{Activity}}{\text{cc}_{\text{soil}}}}{K_d \left(\dfrac{\text{g}_{\text{soil}}}{\text{cc}_{\text{soil}}}\right)} .$$

Note:

$\frac{\text{ml}_{\text{sol}}}{\text{cc}_{\text{soil}}}$ = moisture content by volume (20%)

$\frac{\text{g}_{\text{soil}}}{\text{cc}_{\text{soil}}}$ = bulk density (1.4).

APPENDIX D

APPENDIX D

DEFINITIONS

alluvium	Clay, silt, sand gravel, or similar detrital material deposited by running water[33].
alpha	Used with respect to radiation -- a positively charged particle consisting of two protons and two neutrons[34].
aquifer	Water-bearing stratum of permeable rock[33].
beta	Used with respect to radiation -- a negatively charged particle emitted from the nucleus of an atom and having a mass and charge equal in magnitude to those of an electron[34].
basalt	Dark gray to black, dense, fine-grained, igneous rock consisting of plagioclase, augite, and magnitite[33].
caliche	A crust of calcium carbonate that forms in soil or on rock in arid regions[33].
cc (also ml)	Abbreviation for a cubic centimeter or a milliliter.
count	A measure of radioactivity meaning the quantity of a nuclide disintegrating at the rate of 3.7 x 10^{10} atoms per second; abbreviated as Ci; a microcurie (μCi) is one millionth of a curie (3.7 x 10^{4} disintegrations per second); a pico curie (pCi) is one millionth of a microcurie; a kilo curie is one thousand curies[34].
curie	A radiation measurement or indication of a device designed to enumerate disintegrations or events. It may refer to a single detected event or a total registered in a given period of time. It should not be confused with disintegration, as the two terms do not mean the same. The relationship between count and disintegration must be established by a calibration procedure[34].
gamma	Relates to radioactivity and means a ray of short wave length which is emitted from a disintegrating nucleus[34].
half-life	Refers to the time that a substance is radioactive -- the time required for a radioactive element to lose 50% of its activity. Each nuclide has a unique half-life[34].
infiltration	Refers to water entering soil by penetrating the interstices[33].
isotope	One of several forms of one element having the same number of protons in the nucleus and thus the same atomic number, but differing in the number of neutrons and thus a different mass number; eg, strontium-89, strontium-90 and strontium-91 all with atomic number 38[34].
leach	To subject to the action of percolating water or other liquid in order to separate and remove soluble compounds[33].

leachate	The percolating solution.
loam	A soil consisting of a friable mixture of varying proportions of clay, silt, and sand[33].
loessial	A buff to yellowish brown loamy deposit (soil) believed to have been deposited by wind[33].
nuclide	A species of atom characterized both by number of protons and neutrons; eg, strontium-90, atomic number 38 and cesium-137, atomic number 55[34].
percolate	To pass through a permeable substance, to penetrate[33].
regolith	Mantle rock[33]. As used in this report it is intended to mean the unconsolidated soil-like material having no definite and specific morphology, a regosol, alluvial, loessial deposition, or weathered material which covers the basaltic rock.
water table	The upper limit of the portion of the ground wholly saturated with water -- a plain or surface[33]. The natural water table is different from a perched water table, which is usually caused by the activity of man such as waste disposal or irrigation, etc. Perched water, whether caused by man or other natural causes, is localized in extent at a higher elevation than the natural or regional water table.
vadose	Of or relating to or being in the earth crust above the permanent ground water level