ORNL/TM-6272

Weldon Spring Dose Calculations

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ABSTRACT

In response to a request by the Oak Ridge Operations (ORO) Office of the Department of Energy (DOE) for assistance to the Department of the Army (DA) on the decommissioning of the Weldon Spring Chemical Plant, the Health and Safety Research Division of the Oak Ridge National Laboratory (ORNL) performed limited dose assessment calculations for that site. Based upon radiological measurements from a number of soil samples analyzed by ORNL and from previously acquired radiological data for the Weldon Spring site, source terms were derived to calculate radiation doses for three specific site scenarios. These three hypothetical scenarios are (1) a wildlife refuge for hunting, fishing, and general outdoor recreation; (2) a school with 40 hr per week occupancy by students and a custodian; and (3) a truck farm producing fruits, vegetables, meat, and dairy products which may be consumed on site. Radiation doses are reported for each of these scenarios both for measured uranium daughter equilibrium ratios and for assumed secular equilibrium. Doses are lower for the nonequilibrium case.

INTRODUCTION

Weldon Spring Chemical Plant (WSCP), St. Charles County, Missouri, consists of 219.73 acres in fee and 32 acres of sewer easement located approximately 13 miles southwest of the city of St. Charles and 25 miles due west of St. Louis. It is accessible by Missouri State Highway 94 approximately 2 miles from the intersection of Highway 94 and U.S. Route 40.

The site is bordered on the north by the August A. Busch Memorial Wildlife Area, administered by the Missouri State Department of Conservation; on the west and south by the U.S. Army Reserve and National Guard Training Area, under administrative control of the Fifth U.S. Army, Fort Leonard Wood; and on the east by agricultural land belonging to the University of Missouri. Activities within a 1-mile radius of the site boundaries include a state highway maintenance operation, administrative buildings for the Army training area, headquarters for the Busch Wildlife Area, a university extension office, and the Francis Howell High School servicing that area of St. Charles County. Weldon Spring, Missouri, population 70, is the closest community (2 miles away) at the intersection of U.S. Route 40 and State Highway 94. Of the total acreage, the U.S. Army occupies 169.08 acres in fee which constitutes the major portion of the site, including the former Atomic Energy Commission (AEC) Feed Materials Plant, and possesses the 32-acre sewer easement across University of Missouri property. The DOE, as successor to the AEC, is responsible for 50.65 acres in fee consisting of four nuclear processing waste basins (raffinate pits) and 0.52 acre in land easement on the U.S. Army area, including a small building formerly used to store uranium concentrates.

Portions of the WSCP were transferred from the U.S. Army to the former AEC for construction and operation of a Feed Materials Plant in support of the atomic energy program. The uranium and thorium processing subsequently conducted between 1957 and 1966 resulted in the radioactive contamination of the facility and the immediate terrain.[1] The AEC operation was closed out, the facility excessed, and the bulk of it returned to the DA in 1967. With the formation of a new office with-

in the DA having responsibility for dealing with contamination existing at some U.S. Army installations (Installation Restoration Program), the task of survey and assessment of the WSCP was given to the Department of the Army Project Manager for Chemical Demilitarization and Installation Restoration (PM-CDIR). This office contacted ORO for assistance in making dose calculations for the WSCP site. In turn ORO asked ORNL to make the calculations described in this report.

DOSE CALCULATIONS

The purpose of the ORNL dose assessment calculations was to provide data to be used in the DA proposals to the Nuclear Regulatory Commission (NRC) defining acceptable uranium and thorium soil concentrations for unrestricted release of the Weldon Spring site.

It was agreed through discussions with DA and ORO that doses would be calculated for three hypothetical cases or scenarios:

I The 169 fee acres and 32 sewer easement acres are used as a wildlife refuge for hunting, fishing, and general outdoor recreation. Exposure would be occasional and limited. Consumption of game animals and fish would be evaluated.

II The above acreage is used as a school. An 8-hr day, 5 days per week should be used for student-teacher exposure and a full 52 week/year exposure for a custodian.

III The same land is used for farming with a 24 hr per day occupancy. Soil is tilled to about 2 ft, and various fruits and vegetables are consumed. Meat and dairy products from the site also are consumed. Irrigation from surface ponds is assumed. (Worst case)

The calculations were made for unit concentrations of uranium and thorium in the soil. Two parent-daughter equilibrium ratios were used, secular equilibrium and equilibrium measured from selected soil samples taken from the WSCP site. In order to determine the nature of the residual radioactive contamination at that site, a dozen soil samples were obtained from the site for analysis at ORNL. These samples were collected by the DA and mailed to Oak Ridge in polyethylene bottles. At ORNL the samples were dried for 25 hr at 100°C and then pulverized to a particle size of -35 mesh (500 μm). The samples were sealed in counting vials and stored for approximately one month to allow the radon daughters to reach equilibrium in order to assess the Ra-226 activity in the samples. These samples have been counted using a Ge(Li) spectroscopy technique,[2] and the data have been analyzed by computer techniques to obtain concentrations of selected radionuclides. Thorium-230 analyses were performed by hot HNO_3 leaching of soil samples and subsequent alpha particle counting. In addition, a uranium analysis was performed using a neutron activition analysis technique[3] which allowed an independent assessment of U-238 concentrations in the samples. The results of this analytical work are summarized in Table 1.

From a soil sampling program associated with the DOE excess site resurvey program, background samples were obtained by an ORNL survey team in the general vicinity of Weldon Spring which indicated background levels in soil of 1.25 pCi/g, 1.1 pCi/g, and 1.0 pCi/g for U-238, Ra-226 and Th-232, respectively. Based on this evaluation, only 6 of 11 samples

Table 1. Concentration in Weldon Spring Chemical Plant soil samples

Sample No.	Location	Radionuclide concentration[a] (pCi/g) U-238	Th-230	Ra-226	Th-232	Ra-228	Ac-227
1	110 ft S of SE corner of Bldg. 301	18.9	6.4	0.7	-	-	-
2	W end of culvert under road near Inhoff tank	19.4	0.9	1.1	0.6	N.F.	N.F.
3	By NW corner of of slab 303	38.0	4.5	2.4	3.1	2.4	N.F.
4	15 ft N of rubble pile	978	12.3	3.2	-	-	-
5	S of ash pond 70 ft N of road near 50 gal tank	8.8	0.6	1.0	1.1	1.0	N.F.
6	In drainage ditch 20 ft S of road near raffinate pits	40.7	9.5	2.7	2.9	3.2	1.1
7	Center of nitric acid tank farm	21	0.9	1.1	2.2	2.5	N.F.
8	50 ft N of NE corner of 101 slab	11.7	1.6	5.1	-	-	-
9	Frog pond by SW corner inlet	151	26.8	4.8	-	-	-
10	Frog pond S center drainage ditch	24.3	2.0	1.7	3.6	2.7	N.F.
11	30 ft from E side Bldg. 404	21.9	1.0	0.8	0.8	-	N.F.
12	Background 9 mi NE of site	1.1	0.6	1.0	1.2	1.2	N.F.
Average background in vicinity of WSCP		1.25	-	1.1	1.0	-	-

[a]A dash indicates that a measurement was not made. N.F. indicates that the measurement was made but a measurable concentration of the nuclide was not found within the limits of the analytical methods (see ref. 2) used.

taken on the WSCP site showed Ra-226 levels above background. The equilibrium ratio for these samples ranged from 0.002 to 0.041 with the exception of sample No. 8 which gave a ratio of 0.38. This suggests that the only location on the site where Ra-226 might be present in significant quantities is in the vicinity of Building 101, the former plant for incoming raw materials. The average Ra/U equilibrium ratio, excluding sampling No. 8 was 0.026, and this value was used for the dose calculations.

If the background level of Th-230 is assumed to be equal to the background level of U-238, 7 of the 11 samples taken on the WSCP site showed Th-230 levels above background. The ratio of Th-230 to U-238 ranged from 0.01 to 0.28 with an average of 0.12 which was used for the dose calculations.

In addition to the assumptions stated in the scenarios, other assumptions which were made included:

1. Fish will be consumed from the ash pond, fish pond, and Busch Wildlife ponds (Cases I and III).
2. Irrigation will be used from the ash pond and frog pond in Case III.
3. The DOE raffinate pits will be specifically excluded from contribution to radiation doses on the DA portion of the site.

The dose calculation methodology which was used was developed at ORNL.[4] This methodology has been applied to dose calculations for environmental impact statements and other specific dose assessments. The doses are expressed in terms of 50-year dose commitments that accrue as a result of exposure to the assumed source terms for a period of one year. It be-

came necessary for Case III (farm scenario) to consider the 50-year dose commitment that occurred as a result of exposure to a specific pathway (inhalation) for a period of one day. This dose was termed the daily dose commitment for the sake of brevity especially in footnotes to the tables.

RESULTS

Source Terms

The source terms used for doses from terrestrial contamination are given in Table 2. These source terms were determined by assuming a unit concentration of U-238 and Th-232 and taking the measured equilibrium level for U-238 daughters beginning with Th-230. The U-235 source terms were determined from the natural abundance of U-235 (0.7% by weight) in a unit concentration of uranium.

The source terms for dose from aquatic contamination are given in Table 3. These source terms represent a summary for the data from previously reported measurements[1] on the WSCP site and those accumulated by ORO.[5]

Summary of Doses for Case I

Using the source terms given in Tables 2 and 3, the 50-year dose commitment from one year's exposure at the WSCP site was calculated for the case of the site becoming a game refuge (Case I). It was assumed that the maximum individual spent 20 days during the year hunting, fishing, and camping on the site. In calculating the doses from the inhalation pathway, an intake of 23 m^3 of air per day was assumed. The doses from this pathway were based on a resuspension factor of 10^{-9} m^{-1}. For the direct external gamma radiation pathway, it was assumed that the "hunter" spends

Table 2. Source terms[a] for doses from terrestrial contamination

Radionuclide	Concentration in soil (pCi/g)
U-238 series	
U-238	1.0
Th-234	1.0
Pa-234m	1.0
U-234	1.0
Th-230	0.12
Ra-226	0.026
Rn-222	0.026
Po-218	0.026
Pb-214	0.026
Bi-214	0.026
Po-214	0.026
Pb-210	0.026
Bi-210	0.026
Po-210	0.026
Th-232 series	
Th-232	1.0
Ra-228	1.0
Ac-228	1.0
Th-228	1.0
Ra-224	1.0
Ra-220	1.0
Pb-212	1.0
Bi-212	1.0
Po-212	1.0
Tl-208	1.0
U-235 series	
U-235	0.046
Th-231	0.046
Pa-231	0.046
Ac-227	0.046
Th-227	0.046
Ra-223	0.046
Rn-219	0.046
Pb-211	0.046
Bi-211	0.046
Tl-207	0.046

[a]Unit concentrations of U-238 and Th-232 were assumed. The U-238 daughters from Th-230 on were measured. The U-235 was assumed to occur in natural abundance (0.7% by weight).

Table 3. Source terms[a] for dose from aquatic (ponds) contamination

Radionuclides	Concentration in water (pCi/ml)
Frog pond	
U-234	1.1E0
U-235	5.1E-2
U-238	1.1E0
Ra-226	8.0E-4
Th-232	8.0E-5
Ash pond	
U-234	9.0E-2
U-235	4.1E-3
U-238	9.0E-2
Ra-226	5.0E-4
Ra-228	9.0E-4
Th-232	2.0E-5

[a]Measured values.

all of his time out-of-doors without shielding; consumption of wild game meat was assumed to be 0.3 kg/day (20 days); and consumption of fish was assumed to be 20 g/day (20 days). The resulting doses are given in Table 4.

Summary of Doses for Case II

Doses were calculated for the case of the site being turned into a school. The maximum individual would be a custodian working 40 hr/week for 52 weeks. In this case, the pathways are essentially limited to inhalation and direct exposure to contaminated ground. The same air intake and resuspension factors have been used for this case as for Case I. A conservative direct exposure was calculated by assuming all exposure occurred out-of-doors (i.e., no credit was given for inherent shielding by the school structure). The doses for this case are summarized in Table 5.

Summary of Doses for Case III

Case III, that of a farm on the WSCP site, represents the maximum conditions of exposure. It was assumed that the farmer spends all of his time out-of-doors (as in the case of the custodian) and that all his food is produced on the farm. Doses from the affected pathways could be modified easily by assuming whatever fraction of out-of-doors exposure time and total food supply would be more appropriate. Daily intakes were assumed to be 23 m^3 of air, 1 liter of milk, 0.3 kg of beef and 0.25 kg of vegetables. Irrigation from the frog pond (the most highly contaminated surface water on the site) was assumed in the amount of 15 in. of water per growing season. The doses for Case III are summarized in Table 6.

Table 4. Case I - game refuge: summary of doses[a] from hunting and camping in the game refuge for 20 days during the year

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	3.0E-2	8.5E-1	1.0E0	1.1E0
Exposure from ground[c]	6.4E-1	7.1E-1	5.1E-1	5.9E-1
Ingestion (wild game)[d]	2.0E-2	1.6E-1	2.2E-2	2.0E-2
Eating fish from frog pond[e]	2.5E-2	4.0E-1	8.7E-2	2.53-2
Total	7.2E-1	2.1E0	1.6E0	1.7E0

[a] Fifty-year dose commitment from one year's intake of radionuclides.

[b] Assumed intake of 23 m^3 of air per day. Dose calculations based on resuspension factor of $10^{-9}m^{-1}$ (taken from ref. 4).

[c] Hunter spends all of his time out-of-doors without shielding. Concentrations per unit area ($\mu Ci/cm^2$) are based on an average depth of contamination being 15 cm and a soil density of 1.5 g/cm^3.

[d] Assumed ingestion of 0.3 kg of meat per day for 20 days.

[e] Assumed intake of 20 g of fish per day for 20 days.

Table 5. Case II - school: summary of doses[a] to the custodian working 40 hr/week for 52 weeks

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	1.4E-1	3.7E0	4.2E0	8.5E-1
Exposure from ground[c]	2.8E0	3.1E0	2.0E0	2.6E0
Total	2.9E0	6.8E0	6.2E0	3.4E0

[a]Fifty-year dose commitment based on one year's intake of radionuclides.

[b]Assumed intake of 23 m^3 of air per day. A resuspension factor of $10^{-9}m^{-1}$ used in calculating air concentrations.

[c]Custodian is assumed to spend 100% of his time out-of-doors with no shielding. Concentrations per unit area ($\mu Ci/cm^2$) are based on an average contamination depth of 15 cm and a soil density of 1.5 g/cm^3.

Table 6. Case III - farm: summary of doses[a] to the farmer (24 hr/day occupancy)

Pathway	Dose (millirem/year) Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	5.4E-1	15.6E0	17.9E0	3.7E0
Exposure from ground[c]	11.6E0	13.0E0	9.2E0	10.8E0
Ingestion[d] of				
Milk	8.6E-1	6.5E0	8.7E-1	8.6E-1
Beef	3.8E-1	2.9E0	4.0E-1	3.8E-1
Food crops (contaminated by root uptake)	2.8E-1	3.8E0	4.6E0	2.8E-1
Food crops (contaminated above surface)	2.4E-1	2.1E0	6.9E-1	2.4E-1
Irrigation[e]	4.3E-2	7.0E-1	1.7E-2	4.3E-2
Total	13.9E0	44.6E0	33.8E0	16.3E0

[a]Fifty-year dose commitments from one year's intake of radionuclides.

[b]Assumed intake of 23 m^3 of air per day. Calculations of air concentrations based on resuspension factor of 10^{-9} m^{-1}. Using a resuspension factor of 5×10^{-7} m^{-1} for mechanically disturbed soil, a farmer tilling soil for 8 hr/day would receive a daily dose commitment of 0.25 millirem to the total body, 7.1 millirem to the bone, 8.2 millirem to the kidney, and 1.7 millirem to the lung. Contributions from this activity must be added to the dose commitments given in the table.

[c]Assumed farmer spent all of his time out-of-doors with no shielding. Contamination per unit area ($\mu Ci/cm^2$) based on an average contamination depth in soil of 15 cm and a soil density of 1.5 g/cm^3.

[d]Assumed daily intakes of 1 liter of milk, 0.3 kg of beef, and 0.25 kg of vegetables.

[e]Assumed application of 15 in. of water per season from frog pond (highest contamination) over 169 acres area under cultivation.

Approximately 83% of the total-body dose was due to direct exposure from contaminated ground. This could be reduced considerably if credit were to be taken for shielding offered in structures where the farmer may spend 1/2 to 3/4 of his time.

Dose via the inhalation pathway results from the resuspension of radioactive material from the soil surface. For radioactive material that has been deposited on a surface for a long period of time, say of the order of years, a resuspension factor of 10^{-9} m^{-1} is appropriate.[6] However, for recent mechanical disturbances, the resuspension factor can be significantly greater. A resuspension factor for estimating exposures during mechanical disturbances, such as tilling the soil, has been estimated based on experimental data[7] to be 5×10^{-7} m^{-1}. Using this factor, a farmer tilling soil for 8 hr/day would receive a daily dose commitment of 0.25 millirem to the total body, 7.1 millirem to the bone, 8.2 millirem to the kidney and 1.7 millirem to the lung. The contribution to annual doses from this type of activity may be calculated by estimating the number of days per year the farmer would be engaged in this type of activity, multiplying by the daily dose commitment values and adding the results to the annual doses listed in Table 6.

An analysis of doses by radionuclide was done by Case III. In Table 7, it is shown that Tl-208 contributes more than 70% of the external dose from the exposure-to-contaminated-ground pathway and an additional 17.5% is due to Ac-228. For the inhalation pathway, the largest contributors were Th-228 with 13.8% and Th-232 with 61.0% of the dose by this pathway. The highest ingestion dose of 0.86 millirem/year resulted from drinking milk. Almost all of the total-body dose (98%) from this pathway was due to Ra-228.

Table 7. Case III - farm: major radionuclides contributing to total-body dose by pathway

Radionuclide	% Total-body dose						
			Ingestion				
	Inhalation (resuspension)	Exposure from ground	Crops (root uptake)	Crops (above surface)	Milk	Beef	Irrigation
Tl-208		70.1					
Pb-210			33.6				
Pb-212		3.9	7.7				
Bi-212		2.9					
Ra-226			1.2	4.3	2.4	4.6	
Ra-228	7.4		28.7	87.5	97.7	92.1	
Th-228	13.8		2.6				
Ac-227	4.2						
Ac-228		17.5					
Th-230	5.6		1.1				
Pa-231	6.1						
Th-232	61.0		11.4	2.7			53.5
U-234			4.8	1.8			
U-235							2.2
U-238			4.1	1.6			44.2

Of the organs, the bone received the highest dose, 44.6 millirem/year (Table 6). Thirty-five percent (see Table 6) of the bone dose was due to inhalation of resuspended radionuclides, primarily Th-228 (14.8%) and Th-232 (68%) (see Table 8). An additional 29% of the bone dose resulted from exposure to contaminated ground with Tl-208, Ac-228, and Pb-212 contributing most significantly to this pathway.

Doses for Secular Equilibrium Assumption

All the radionuclides in the U-238, Th-232, and U-235 decay chains were assumed to be in secular equilibrium for another set of calculations involving the same scenarios as before with exactly the same assumptions regarding exposure conditions. Consequently, the doses were calculated assuming 1 pCi/g of all the radionuclides listed in Table 2 present in the soil and the water. The summary of the doses for Case I - game refuge, Case II - school, and Case III - farm are given in Tables 9, 10, and 11, respectively.

Doses for U-238 Series

For another set of calculations, it was assumed that only contamination from the U-238 series existed on the WSCP site. Doses were calculated using the U-238 series source terms listed in Table 2 for the scenarios previously described. The summary of the doses for Case I - game refuge, Case II - school, and Case III - farm are given in Table 12, 13, and 14, respectively.

SUMMARY AND CONCLUSIONS

In the event that the WSCP site is contaminated with both uranium and thorium ores in secular equilibrium, the projected dose commitments

Table 8. Case III - farm: major radionuclides contributing to the bone dose by pathway

Radionuclide	% Bone dose						
			Ingestion				
	Inhalation (resuspension)	Exposure from ground	Crops (root uptake)	Crops (above surface)	Milk	Beef	Irrigation
Tl-208		67.7					
Pb-210			51.2				
Pb-212		5.5	5.1				
Bi-212		3.0					
Ra-226				4.8	3.0	7.0	
Ra-228	2	1.8	11.8	76.2	96.9	88.4	
Th-228	14.8		4.1				
Ac-227						1.7	
Ac-228		17.7					
Th-230	7.0		1.8				
Pa-231						2.8	
Th-232	68		19.3	9.5			
U-234			4.1	3.5			51.4
U-235							2.1
U-238			3.7	3.0			45.7

Table 9. Case I - game refuge: summary of doses[a] from hunting and camping in the game refuge for 20 days during the year assuming secular equilibrium in the uranium and thorium series found in the soil

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	1.1E-1	2.8E0	1.3E0	1.5E-1
Exposure from ground[c]	9.7E-1	1.1E0	9.5E-1	9.1E-1
Ingestion (wild game)[d]	7.1E-2	7.3E-1	1.1E-1	7.1E-2
Eating fish from frog pond[e]	2.5E-2	4.0E-1	8.7E-2	2.5E-2
Total	1.2E0	5.0E0	2.4E0	1.2E0

[a] Fifty-year dose commitments from one year of intake of radionuclides. Based on a unit concentration of 1 pCi/g of all radionuclides in soil.

[b] Assumed intake of 23 m^3 of air per day. Based on resuspension factor of $10^{-9} m^{-1}$.

[c] Hunter spends 100% of his time out-of-doors without shielding. Concentrations per unit area ($\mu Ci/cm^2$) are based on an average depth of contamination being 15 cm and a soil density of 1.5 g/cm^3.

[d] Assumed ingestion of 0.3 kg of meat per day for 20 days.

[e] Assumed intake of 20 g of fish per day for 20 days.

Table 10. Case II - school: summary of annual doses[a] to the custodian working 40 hr/week for 52 weeks on the site assuming secular equilibrium in the uranium and thorium series found in the soil

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	4.7E-1	12.1E0	5.7E0	1.3E0
Exposure from ground[c]	4.2E0	4.8E0	3.3E0	3.9E0
Total	4.7E0	16.9E0	9.0E0	5.2E0

[a]Fifty-year dose commitment from one year of intake of radionuclides based on a unit concentration of 1 pCi/g of all radionuclides in soil.

[b]Assumed intake of 23 m^3 of air per day. Resuspension calculation based on factor of $10^{-9}m^{-1}$.

[c]Custodian is assumed to spend 100% of his time outside the building with no shielding. Concentrations per unit area ($\mu Ci/cm^2$) are based on an average contamination depth of 15 cm and a soil density of 1.5 g/cm^3.

Table 11. Case III - farm: summary of annual doses[a] to the farmer (24 hr/day occupancy) assuming secular equilibrium in the uranium and thorium series found in the soil

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	2.0	49.7	24.0	5.8
Exposure from ground[c]	17.7	20.4	14.0	16.5
Ingestion[d] of				
Milk	1.7	14.2	1.7	1.7
Beef	1.3	13.3	1.7	1.3
Food crops (root uptake)	3.6	95.7	80.2	3.6
Food crops (above surface contamination)	0.71	7.8	2.3	0.71
Irrigation[e]	0.31	4.4	3.3	0.31
Total	27.3	205.5	127.2	29.9

[a]Fifty-year dose commitments from one year of intake of radionuclides based on a unit concentration of 1 pCi/g of all radionuclides in soil and water.

[b]Assumed intake of 23 m^3 of air per day. Based on resuspension factor of 10^{-9} m^{-1}. Using a resuspension factor of 5×10^{-7} m^{-1} for mechanically disturbed soil, a farmer tilling soil for 8 hr/day would receive a daily dose commitment of 0.9 millirem to the total body, 22.7 millirem to the bone, 11.0 millirem to the kidney and 2.6 millirem to the lung. Contributions from this activity must be added to the dose commitments given in the table.

[c]Assumed exposure for 100% of the time without shielding. Contamination per unit area ($\mu Ci/cm^2$) based on average depth in soil of 15 cm and soil density of 1.5 g/cm^3.

[d]Assumed daily intakes of 1 liter of milk, 0.3 kg of beef, and 0.25 kg of vegetables.

[e]Assumed application of 15 in. of water per season. Doses are from usage of frog pond water.

Table 12. Case I - game refuge: summary of doses[a] from the U-238 series source term from hunting and camping in the game refuge for 20 days during the year

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	2.0E-3	8.0E-2	1.3E-2	1.8E-2
Exposure from ground[c]	1.1E-2	1.5E-2	8.8E-3	1.1E-2
Ingestion (wild game)[d]	1.2E-3	1.2E-2	1.9E-3	1.2E-3
Eating fish from frog pond[e]	2.5E-2	4.0E-1	8.7E-2	2.5E-2
Total	3.9E-2	5.1E-1	1.1E-1	5.5E-2

[a]Fifty-year dose commitment from one year's intake of the U-238 series in the measured equilibrium ratio.

[b]Assumed intake of 23 m^3 of air per day. Dose calculations based on resuspension factor of $10^{-9}m^{-1}$.

[c]Hunter spends all of his time out-of-doors without shielding. Concentrations per unit area ($\mu Ci/cm^2$) area based on an average depth of contamination being 15 cm and a soil density of 1.5 g/cm^3.

[d]Assumed ingestion of 0.3 kg of meat per day for 20 days.

[e]Assumed intake of 20 g of fish per day for 20 days.

Table 13. Case II - school: summary of doses[a] from the U-238 series source term to the custodian (works 40/hr week for 52 weeks)

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	1.0E-2	3.0E-1	7.0E-2	8.0E-2
Exposure from ground[c]	5.1E-2	6.4E-2	3.9E-2	4.4E-2
Total	6.1E-2	3.6E-1	1.1E-1	1.2E-1

[a]Fifty-year dose commitment based on one year's intake of the U-238 series in the measured equilibrium ratio.

[b]Assumed intake of 23 m^3 of air per day. A resuspension factor of $10^{-9}m^{-1}$ used in calculating air concentration.

[c]Custodian is assumed to spend 100% of his time out-of-doors with no shielding. Concentrations per unit area ($\mu Ci/cm^2$) are based on an average contamination depth of 15 cm and a soil density of 1.5 g/cm^3.

Table 14. Case III - farm: summary of doses[a] from the U-238 series source term to farmer (24 hr/day occupancy)

Pathway	Dose (millirem/year)			
	Total body	Bone	Kidney	Lung
Inhalation (resuspension)[b]	4.0E-2	1.2E0	2.0E-1	4.0E-1
Exposure from ground[c]	2.2E-1	2.7E-1	1.6E-1	1.8E-1
Ingestion[d] of				
Milk	2.1E-2	2.1E-1	2.7E-2	2.1E-2
Beef	2.2E-2	2.1E-1	3.4E-2	2.2E-2
Food crops (contaminated by root uptake)	1.1E-1	1.7E0	2.1E0	1.1E-1
Food crops (contaminated above surface)	2.0E-2	2.8E-1	7.7E-2	2.0E-2
Irrigation[e]	4.3E-2	7.0E-1	1.7E-2	4.3E-2
Total	4.8E-1	4.6E0	2.6E0	8.0E-1

[a] Fifty-year dose commitments from one year's intake of the U-238 series in the measured equilibrium ratio.

[b] Assumed intake of 23 m^3 of air per day. Calculations of air concentrations based on resuspension factor of 10^{-9} m^{-1}. Using a resuspension factor of 5×10^{-7} m^{-1} for mechanically disturbed soil, a farmer tilling soil for 8 hr/day would receive a daily dose commitment of 0.12 millirem to the total body, 4.4 millirem to the bone, 0.9 millirem to the kidney, and 0.6 millirem to the lung. Annual doses may be calculated by estimating the number of days per year the farmer was engaged in this activity.

[c] Assumed farmer spent all of his time out-of-doors with no shielding. Contamination per unit area ($\mu Ci/cm^2$) based on an average contamination depth in soil of 15 cm and a soil density of 1.5 g/cm^3.

[d] Assumed daily intakes of 1 liter of milk, 0.3 kg of beef, and 0.25 kg of vegetables.

[e] Assumed application of 15 in. of water per season from frog pond (highest contamination) over 169 acres under cultivation.

per unit concentration of the parent radionuclides in soil and measured concentrations in water for the maximum individual (farm scenario) could be relatively large as compared to existing standards and guidelines concerning radiation exposure.[8-11] Whole-body dose commitments could exceed 25 millirem/year and organ dose commitments could exceed 200 millirem/year (see bone dose in Table 11). Based upon analyses of environmental samples from the WSCP site, it appears more likely that the site may be contaminated with low levels of processed uranium. If that is the case, the dose commitments to the maximum individual from a unit concentration of U-238 in soil (assuming daughters in the measured ratios) and measured concentrations of radionuclides in water could be less than 0.5 millirem/year to the total body and 5 millirem/year to any reference organ. One should bear in mind that the dose commitments in Tables 6, 11, and 14 do not include contributions from inhalation doses produced when a farmer mechanically disturbs contaminated soil. Since the resuspension factor is greater when soil is being tilled than when it lies quiescent, the exposure from this pathway is increased when the farmer is actively tilling soil. Consequently, one must add the contribution from this enhanced pathway as described in footnotes to the pertinent tables. To arrive at dose commitments lower than the ones discussed here, one must assume the future uses of the site do not include truck farming but are limited to uses such as a game refuge (the lowest calculated dose commitments) or a school (which produces dose commitments intermediate between the farm and game refuge scenarios).

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