

*Environmental Radiation Program*

**THE PRESENCE OF  
RADIONUCLIDES IN  
SEWAGE SLUDGE AND  
THEIR EFFECT ON  
HUMAN HEALTH**

December, 1997



Environmental Health Programs

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# **THE PRESENCE OF RADIONUCLIDES IN SEWAGE SLUDGE AND THEIR EFFECT ON HUMAN HEALTH**

**Michael J. Brennan**  
December, 1997



**For more information or  
additional copies of this report contact:**

**Division of Radiation Protection  
Airdustrial Center, Building 5  
P. O. Box 47827  
Olympia, Washington 98504-7827**

**360-586-8948  
SCAN 321-8948  
FAX 753-1496**

**Debra McBaugh, Head  
Environmental Radiation Section**

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**EXECUTIVE  
SUMMARY**

In the early 1990's concern was raised about radioactive material in sewage systems. In 1994, two federal agencies, the U.S. Nuclear Regulatory Commission and the U.S. Environmental Protection Agency, issued a joint letter suggesting the possibility that radioactive material might concentrate in sewage sludge. The Washington State Department of Health initiated a study to evaluate the presence of radionuclides in sewage sludge.

This report discusses the sampling, analysis, and potential health effects of radionuclides in sewage sludge. Samples were collected by the Washington Department of Health, in 1994 at six waste water treatment plants.

Although natural and man-made radioisotopes were found at all sites, no health impact was found. At most sites, the man-made isotopes can be attributed to worldwide fallout from weapons testing or nuclear medicine programs. The exceptions are Richland and Bremerton. The sources of some of the radionuclides found at these two sites have not yet been determined.

The two most likely scenarios by which humans could be exposed to radionuclides from sewage sludge were evaluated. In the first scenario, potential radiological doses to farmers who use sludge as fertilizer were calculated. These doses are very low and do not pose a significant human health risk. The second scenario evaluated potential radiological doses to workers at a landfill where sludge was used as a cover. These doses were very low for five of the facilities. The dose calculated for the Richland sludge is higher than the others, but still does not pose a human health risk.

This study concludes that from a radiological stand point, it is safe to use sewage sludge contaminated with radionuclides at the levels seen in this study as fertilizer in farming or for cover at landfills. In the near future the U.S. Nuclear Regulatory Commission and the U.S. Environmental Protection Agency will be conducting a nationwide study. These results will be compared with this report when they become available.

## **INTRODUCTION**

In November 1991 the Washington Department of Health (DOH) collected sludge samples from the waste water treatment plants at Renton and West Point in Seattle. Detectable levels of naturally occurring beryllium 7 (Be-7) and potassium 40 (K-40) were observed. Cesium 137 (Cs-137) from fallout, iodine 131 (I-131) and thallium 201 (Tl-201), which are commonly used medical isotopes, were also observed. While the evaluation of the data indicated that there was not an immediate radiological health hazard, the presence of the short-lived medical isotopes in the sludge suggested further research.

In 1992, the Nuclear Regulatory Commission (NRC) published a report identifying significant amounts of radioactive material found in the biosolids of selected municipal waste water treatment plants [NRC92]. This report also evaluated a number of possible exposure scenarios. In 1994, concern about possible reconcentration of radioactive material in sewage systems prompted the NRC and the Environmental Protection Agency to send a joint letter to state agencies [BA94]. In the light of these documents, and the pre-existing concerns about isotopes disposed to the sewer, DOH began a program to evaluate the radiological characteristics of sludge from selected facilities throughout the state.

This program sought to evaluate the presence of radioisotopes in sewage sludge that enter the sewer system from natural sources, through legal disposal by licensed users of radioactive material, and from medical procedures. The NRC's standard for sewer disposal is based on the assumption that the radioactive material will be sufficiently diluted as it passes through the system so it will not cause a human health or environmental threat. Sewage systems' improvements in reducing the volume of sludge through dewatering, incineration, and other technologies result in a reconcentration of radionuclides and caused the NRC to reconsider the limits for discharge.

Various aspects of radioisotopes in sludge have been examined in a number of states [MI96], [LA95]. For this study, DOH decided to obtain data from representative and particular interest treatment plants and apply that data to realistic scenarios to evaluate possible public health impact.

## THE PRESENCE OF RADIONUCLIDES IN SEWAGE SLUDGE

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### **SAMPLING AND ANALYSIS**

Sewage treatment plants from six sites were selected for sampling. Five of the plants serve major population centers: Bremerton, Seattle, Renton, Richland, and Tacoma. Seattle and Renton were selected because they had been sampled before, and thus would have historical data for comparison. Richland was selected because of the number of licensed users of radioactive material that use the sewer system. The Bremerton plant was selected because previous environmental monitoring of crabs, mussels, and seaweed collected near the outfall contained small amounts of I-131 [An94].

Wenatchee, which does not serve a major population, was selected as a background site (one not located near facilities which use radioactive materials). This turned out to be an error, as a clinic that provides radiopharmaceutical services for a large rural area is connected to the Wenatchee sewer system.

Details concerning operations of the treatment plants are given in Appendix A.

Samples were transported to the Department of Health Public Health Laboratory in Seattle, Washington, as quickly as possible after collection. When the samples arrived at the laboratory, they were processed and analyzed in accordance with DOH laboratory procedures. The following analyses were performed: gamma spectroscopy, gross beta, strontium, technetium-99, and uranium (Richland only).

### **RESULTS**

The results of analysis of the 1994 data are given in Table 1. The results are reported in pCi/g  $\pm$  2 sigma counting error on a dry weight basis.

Sixteen radionuclides were found in the sludge samples. Table 2 summarizes the radioisotopes detected in sludge collected for this study.

These isotopes and their possible origins are discussed in Appendix B.

TABLE 1  
 Analysis of Sludge Samples Collected in 1994  
 (pCi/g ± 2 Sigma Counting Error Dry Weight)

Location	Be-7		Co-57		Co-58		Co-60		Cs-137		Gross Beta	
	Result	Error	Result	Error								
RENTON	1.10	0.30	0.05	0.02	<LLD		<LLD		0.04	0.02	5.50	1.50
BREMERTON	4.70	0.40	<LLD		<LLD		0.05	0.01	0.07	0.02	8.50	1.60
SEATTLE	3.50	0.30	<LLD		<LLD		<LLD		0.10	0.02	8.80	1.70
WENATCHEE	6.10	0.50	<LLD		<LLD		<LLD		0.05	0.03	9.40	1.70
TACOMA	1.20	0.30	<LLD		<LLD		<LLD		0.04	0.02	7.20	1.60
RICHLAND	<LLD		0.04	0.02	0.17	0.09	24.2	0.30	0.69	0.08	46.0	3.80

Location	I-131		K-40		Mn-54		Sr-89		Sr-90		Tc-99	
	Result	Error										
RENTON	2.90	0.20	2.60	0.40	<LLD		0.78	0.21	0.08	0.02	<LLD	
BREMERTON	3.30	0.30	5.70	0.40	<LLD		<LLD		0.03	0.01	<LLD	
SEATTLE	1.70	0.10	2.80	0.30	<LLD		<LLD		0.08	0.01	<LLD	
WENATCHEE	32.8	2.20	4.00	0.50	<LLD		<LLD		0.05	0.01	<LLD	
TACOMA	0.69	0.09	2.80	0.40	<LLD		0.87	0.14	0.52	0.11	<LLD	
RICHLAND	3.00	0.40	2.30	0.60	0.40	0.10	<LLD		<LLD		44.0	4.0

Location	Tl-201		Total U		U-234		U-235		U-238		Zn-65	
	Result	Error	Result	Error	Result	Error	Result	Error	Result	Error	Result	Error
RENTON	<LLD		NA		NA		NA		NA		<LLD	
BREMERTON	15.2	1.00	NA		NA		NA		NA		<LLD	
SEATTLE	<LLD		NA		NA		NA		NA		<LLD	
WENATCHEE	<LLD		NA		NA		NA		NA		<LLD	
TACOMA	<LLD		NA		NA		NA		NA		<LLD	
RICHLAND	<LLD		57.3	0.90	42.7	0.80	2.3	0.10	12.3	0.40	3.90	0.30

NA denotes not analyzed.  
 <LLD indicates that analysis was done for that isotope, but that the results were less than the lower limit of detection.

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**TABLE 2**  
**Summary of Radioisotopes Detected in Sludge During Study**

ISOTOPE	HALF-LIFE	HIGHEST CONCENTRATION (pCi/G DRY)	# OF SAMPLES ABOVE LLD	PROBABLE ORIGIN
Be-7	53 d	6.1	5	N
Co-57	270 d	0.05	2	M
Co-58	71 d	0.17	1	M
Co-60	5.2 y	24.2	2	I
Cs-137	30.2 y	0.69	6	F, I
Gross Beta	NA	46	6	N
I-131	8 d	32.8	6	M
K-40	1.2X10 <sup>9</sup> y	5.7	6	N
Mn-54	312 d	0.4	1	I
Sr-89	50.5 d	0.87	2	M
Sr-90	29.9 y	0.52	6	F
Tc-99	213,000 y	44	1	M, I
Tl-201	3 d	15.2	1	M
Total U	NA	57.2	1	N, I
U-234	2.4X10 <sup>5</sup> y	42.7	1	N, I
U-235	7.0X10 <sup>8</sup> y	2.3	1	N, I
U-238	4.5X10 <sup>9</sup> y	12.3	1	N, I
Zn-65	243.9 d	3.9	1	I

**Abbreviations:**

**Half -life:**

d=day

y=year

**Probable Origins:**

M = Medical

F = Fallout

I = Industrial

N = Natural

**HUMAN  
HEALTH  
EFFECTS**

To evaluate the possible health effects of the radioactive material in the sludge, DOH used scenarios that corresponded to real world situations and not hypothetical worst case situations. After considering many possible scenarios, one was selected to be evaluated qualitatively and two were selected to be evaluated quantitatively.

Exposure to workers in the waste water treatment plant was evaluated qualitatively. This is because the geometry of the pipes, tanks, pools, sewage and sludge is so complex as to be impossible to accurately model. Additionally, the movements of people at the plant vary too greatly to model in a meaningful manner. Based on the amounts of radioactive material found in the sludge, DOH concluded that exposure to workers under normal circumstances would be vanishingly small. If more definitive dose information becomes necessary, a dosimetry program for selected workers would be the best way of obtaining it.

Exposure to a farmer using sludge as a fertilizer on a wheat farm was selected because that is the end use of sludge from several of the plants and is assumed to be comparable to other agricultural uses that are more difficult to model. Use as cover in a landfill was also evaluated because that is the end use of sludge from the Richland Treatment plant. The farm and landfill scenarios were evaluated using the RESRAD computer program for calculating dose.

The discussion of the modeling for the farm and the landfill scenarios are in Appendix C. The assumptions used for each model are included.

Several radioisotopes found in the various sludge samples were not included in the model. RESRAD does not include isotopes with half-lives less than 180 days. This means Be-7, I-131, Tl-201, Co-58, and Sr-89 are not included in the analysis. Although I-131 and Tl-201 were detected in relatively large concentrations, comparison of their short half-lives to the lengths and patterns of exposure in the scenarios shows they can be disregarded without noticeably affecting the results.

K-40 was not be included in the analysis. K-40 is a naturally occurring isotope of potassium. The concentrations in the sludge

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samples analyzed for this study were lower than the concentrations in most natural soils analyzed by DOH. It is, therefore, reasonable to conclude that the addition of sludge to the soil will not increase anyone's exposure to K-40.

Table 3 summarizes the results for the family farm scenario. As can be seen in Table 3, the dose projections for all locations are extremely small. Even Richland, which is three orders of magnitude higher than the other sites, is small compared to the average annual background radiation dose for that region, which is approximately 630 mrem [Hu].

Table 4 summarizes the results for the landfill scenario. The first line of Table 4 assumes that the public would have access to the closed out landfill immediately, as this is the most conservative case. The second line assumes access will not occur for 30 years or more, which is the current plan [Pe]. Annual background levels for the state range from 200-700 mrem.

**TABLE 3**  
**Summary of Dose in Family Farm Scenario**

	Renton	Bremerton	Seattle	Wenatchee	Tacoma	Richland
Maximum Dose (mrem/yr)	0.003	0.006	0.004	0.003	0.002	2

**TABLE 4**  
**Summary of the Landfill Disposal Scenario**  
**(mrem/year)**

	Renton	Bremerton	Seattle	Wenatchee	Tacoma	Richland
Immediate Occupancy	0.009	0.03	0.01	0.005	0.004	12
Occupancy after 30 years	0.002	0.004	0.005	0.003	0.002	0.5

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### **SUMMARY**

This study looked for the presence of radioisotopes in sewage sludge and evaluated the potential human health impact posed by these radionuclides. The results show that the sewer plant processes reconcentrate radionuclides in sewage sludge. This finding is supported by the 1994 NRC study (NRC94), which details the physical and chemical processes related to movement of radionuclides through the sewage system.

All samples contained radioisotopes derived from natural, medical, fallout or industrial sources. The Richland sample contained the greatest variety of isotopes. Of particular interest, Co-60, Mn-54, Zn-65 and the uranium isotopes, were found at levels much greater than samples from any other site.

A number of radioactive material licensees in Richland legally dispose of dilute, soluble radioactive material into the sewer. The DOH is assessing the licensees disposal practices in the Richland area to assure all sewage disposal meets regulatory requirements. Both the NRC and DOH are evaluating the definition of "soluble" to determine whether licensees are disposing only soluble material as required by the regulations.

The 1994 NRC study reports the difficulty of quantitatively calculating the concentration of radionuclides in sludge given the activity released by a licensee. A more accurate understanding of site-specific processes that affect reconcentration is needed to better model the fate of radionuclides and will assist the NRC in determining whether changes in the sanitary sewer disposal regulations are needed. The decision will further depend on the dose limit set for members of the public from radioactive material in non-licensed facilities.

Without the benefit of an accurate predictive model, the 1994 NRC study used worst case exposure criteria and calculated that an individual's dose could exceed the federal limits.

In the DOH study, measured activities and known disposal practices were used to calculate dose. Based on this study, there is no indication that radioactive material in the waste water treatment system poses a human health risk. From a radiological standpoint, it is safe to use sewage sludge contaminated with radionuclides at the levels seen in this study as fertilizer in farming or for cover at landfills. At this time, no further sampling is recommended.

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## **APPENDIX A: TREATMENT PLAN OPERATIONS**

All the wastewater treatment plants sampled operated in a similar manner. Wastewater and associated solids enter, are mechanically and biologically processed, and the treated water discharged to a river or Puget Sound. The solids are dewatered to a varying amount, and disposed of in several different ways.

While the time that plant operations were observed was admittedly short, several common features were noted. The plants were uniformly clean, with obvious attention to housekeeping. Workers showed great attention to personnel contamination control. This was especially true concerning internal contamination. The number of people involved in running these complex facilities was remarkably small, and the majority of their time was spent in control rooms and shops that were not immediately adjacent to the treatment equipment. The nearest residence at each facility was too distant for direct gamma to be a factor. All of these factors lead to the conclusion that the potential for radiation dose to the public at the facility was small, and would be extremely difficult to model. Should it become vital to know the dose to the workers, providing individual dosimetry would be superior to attempting to devise a model.

The sludge from the facilities is disposed of in several ways, which are subject to change as political and economic conditions change. At the time of the sampling, Bremerton dewatered their sludge only to about 2% solid, transported it by tanker truck to designated nearby forest areas. There the sludge was sprayed out over a large area to fertilize young trees.

Renton, Seattle, and Tacoma compost some of their sludge. The sludge is mixed with other organic matter, such as sawdust, and composted for use as a soil amendment. Some of the compost is bagged for consumer use, and some is used by institutions and in large scale landscaping. In neither case are people in long term close contact with the sludge, although there is undoubtedly some degree of short term external contamination.

Some sludge from Tacoma is used on pasture land. The sludge is spread on the pasture in the same manner as cow manure.

The sludge from Richland is mixed with soil and used to cover layers of solid waste in the landfill. The sludge stabilized the very sandy soil, preventing it from being blown off. Eventually, the sludge/soil mixture will be used as a cover when the landfill is closed.

**THE PRESENCE OF RADIONUCLIDES IN SEWAGE SLUDGE**  
**APPENDIX A: CONTINUED**

**TABLE A1**  
**Treatment Plant Operations**

	<b>Renton</b>	<b>Bremerton</b>	<b>Seattle</b>	<b>Wenatchee</b>	<b>Tacoma</b>	<b>Richland</b>
<b>Waste Water (Millions of gallons per day)</b>	50	5	110	3.2	24	6.2
<b>Sludge output per day</b>	35 tons	30,000 gal (a)	25 tons	1.5 tons	11 tons	0.67 tons
<b>Moisture Content</b>	80%	98%	80%	80%	74%	82%
<b>Disposal Method</b>	Farms Compost	Forest	Farms Compost	Farms	Compost Pasture	Landfill

(a) The amount of sludge per day for Bremerton is given in gallons rather than tons, as Bremerton disposes of its sludge in a liquid form.

Sludge is disposed of in several ways, with economics driving the choice. The choice varies between facilities and with time, as different options are available. The options used by the plants in this study include:

- Farm:** shipped to farming areas, where it is used by farmer to enrich soil to help grow such crops as wheat, hops, and orchard fruit.
- Compost:** composted and used for soil amendment.
- Forest:** spread in forests to improve timber growth.
- Pasture:** spread on pasture land.
- Landfill:** disposed in landfills, sometimes as a cover.

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### **APPENDIX B: DESCRIPTION OF ISOTOPES FOUND IN SAMPLES**

Below is a list of the isotopes detected (as well as gross beta and total uranium). The half life, energy, and decay mode [ICRP38] and information about possible sources for the isotopes found in the sludge are given.

**Beryllium-7** (Be-7)  
Half Life 53.3 days Gamma  
Energy .0494 MeV

Be-7 is a naturally occurring radioisotope, produced by interactions of cosmic radiation and the upper atmosphere. Be-7 could enter the waste water system through the water supply, or from rain water run off in a combined system, or in wash water which has picked up dust.

**Cesium-137** (Cs-137)  
Half Life 30 years Beta, Gamma  
Energy .662 MeV

Cs-137 is a fission product produced in nuclear reactors and explosions. It is encountered virtually everywhere in the world, as a result of atmospheric testing of nuclear weapons. The Cs-137 found in waste water systems arrived from the water supply (if not supplied by wells), run off in combined systems, and from people via the food chain.

**Cobalt-57** (Co-57)  
Half Life 270 days Gamma  
Energy .144 MeV

Co-57 is produced in accelerators. The source of Co-57 in sludge is not apparent, although it is used in some medical procedures.

**Cobalt-58** (Co-58)  
Half Life 70.9 days Gamma  
Energy 1.01 MeV

Co-58 is produced in accelerators. The source of Co-58 in sludge is not apparent, although it is used in some medical procedures [Ba].

**Cobalt-60** (Co-60)  
Half Life 5.2 years Beta, Gamma  
Energy 2.60 MeV

Co-60 is usually produced in nuclear reactors when neutrons are absorbed by Co-59 atoms in the steel. It is not readily apparent where Co-60 in sewer systems come from.

#### **Gross Beta**

Gross Beta analysis is a screening tool used to determine if further analysis of Beta emitting isotopes are needed. This is desired because analyses for some of these isotopes are expensive and time consuming.

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## APPENDIX B: CONTINUED

**Iodine-131** (I-131)  
Half Life 8 days Beta, Gamma  
Energy .570 MeV

I-131 can be created as a fission product in a nuclear reactor or weapon, or by irradiating material in a reactor or accelerator. I-131 is used in a number of medical procedures, usually concerning the thyroid [Ba], [Sh]. I-131 found in sludge most likely was from medical procedures, and entered the sewer system as excreta from patients.

**Manganese-54** (Mn-54)  
Half Life 312 days  
Energy .835 MeV

Mn-54 is an activation product, produced in nuclear reactors. The Mn-54 found in this study probably came from the decontamination of equipment and clothing used in the nuclear industry.

**Potassium-40** (K-40)  
Half Life 1.28E9 years Beta, Gamma  
Energy .679 MeV

K-40 is a natural occurring radioisotope, unrelated to nuclear power, weapons, or medicine. 0.01% of all potassium is K-40. The K-40 in the sludge enters the system in excrement, and possibly from fertilizer if the waste water and storm water systems are interconnected.

**Strontium-89** (Sr-89)  
Half Life 50.5 days Beta  
Energy .583 MeV

Sr-89 is a fission fragment produced in nuclear reactors and weapons explosions. It can also be produced in accelerators. It has a short half life. If the exact source of radioactive strontium is unknown, it is necessary to analyze for Sr-89 so that Sr-90 is not over estimated. Sr-89 is sometimes used in medical procedures [Ba].

**Strontium-90** (Sr-90)  
Half Life 29 years Beta  
Energy .196 MeV

Sr-90 is a fission fragment produced in nuclear reactors and weapons explosions. The Sr-90 found in the environment is from weapons test fallout, and can travel up the food chain.

**Thallium-201** (Tl-201)  
Half Life 3 days Gamma  
Energy .137 MeV

Tl-201 is produced in accelerators and used in examining heart function [Ba]. All of the Tl-201 in the sludge comes from medical uses.

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### **APPENDIX B: CONTINUED**

#### **Technetium-99 (Tc-99)**

Half Life 213,000 years Beta

Energy .101 MeV

Tc-99 is usually created as a fission fragment; one of the pieces made when a Uranium atom is split in a nuclear reactor or weapon. Tc-99 (metastable) has a number of medical uses [Ba], [Sh]. It is possible that Tc-99 found in sludge entered the system by passing through medical patients. The relatively high concentration found at Richland tends to indicate an industrial source.

#### **Total Uranium (Total U)**

It can be useful to analyze uranium isotopically, the ratio of U-234 to U-235 and U-238 will be different if the uranium is in its natural form or has been processed, especially if it has been irradiated in a reactor. Uranium in the waste water system can arrive from the water supply (especially if supplied by wells), run off in combined systems, and wash water, especially in areas with high uranium content in the soil, or if the waste water system is used by facilities that process uranium, or clean clothing or equipment that is contaminated with uranium.

#### **Uranium-234 (U-234)**

Half Life 2.4E5 years Alpha, Gamma

Energy 4.86 MeV

U-234 is a naturally occurring isotope of uranium.

#### **Uranium-235 (U-235)**

Half Life 7.0e8 years alpha

Energy 4.67 MeV

U-235 is a naturally occurring isotope of uranium. In most reactor fuels, U-235 will be "enriched", or in higher than natural concentration.

#### **Uranium-238 (U-238)**

Half Life 4.5e9 years alpha, spontaneous fission

Energy 4.28 MeV

U-238 is a naturally occurring isotope of uranium. It accounts for over 99% of the uranium in natural concentrations.

#### **Zinc-65 (Zn-65)**

Half Life 243.9 days Electron Capture, Positron

Energy 0.591 MeV

Zinc-65 is a neutron activation product, usually associated with nuclear reactors.

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## APPENDIX C: RESRAD PARAMETERS

### Scenario 1: Family Farm

This scenario assumes that the recipient of the dose is a farmer, growing wheat in Eastern Washington. This is a common use of sludge from several of the facilities sampled. The farm is assumed to be 1000 acres, and the farmer eats food grown there and drinks water from an on site well. The application rate, based on conversations with an area extension agent [Kr], is assumed to be 3.5 dry tons per acre. All pathways were considered, and the default RESRAD parameters were used with the following exceptions:

RO11 Item 1: Area of Contamination: 40,469,000 m<sup>3</sup>

1000 acres of field fertilized with sludge

RO11 Item 2: Thickness of Contaminated Zone: 0.003 m

3.5 dry tons per acre, sprayed on the field with a manure spreader, estimated at 1/8 inch thick with 25% total coverage. As the sludge will be tilled into the field several times to different depths over the course of a year, this becomes an increasingly difficult parameter to model.

R013 Item 3: Contaminated Zone Erosion Rate: 0 m/y

While some sludge is undoubtedly lost in disking and tilling operations, it is small and difficult to model. The fields have a vegetative cover, which would limit wind and water erosion.

RO17 Item 6A: Time Factors-Indoors: 0.0

This assumption is based on the field being some distance from the house, and that the house is not built on sludge covered ground.

R017 Item 6B: Time Factors-Outdoors: 0.10

Based on 1000 acres of field, with an average rate of 10 acre per hour for 4 tillings, 2 weedings, 1 planting, and 1 harvesting. Total time in the field estimated to be 800 hrs per year, or approximately 10% of the farmers time.

### Scenario 2: Landfill Cover

This scenario is based on the current planned usage of sludge at a landfill in Eastern Washington [Pe]. The sludge is spread on a field, disked into the soil repeatedly until mixed 50-50 with native soil, and stockpiled for eventual use as a final cover on closed out sections of the landfill. The sludge/soil mixture will be spread 6 to 12 inches (0.152 to 0.305 meters) and seeded with

**APPENDIX C: CONTINUED**

grass or planted with other vegetation. While final disposition of the closed out landfill has not been decided, a park with recreation fields is most likely. Residential use is precluded for the foreseeable future.

In modeling this scenario for RESRAD, only External Gamma, Inhalation, and Soil Ingestion pathways were considered. The thickest application rate was used, but the radioisotope concentrations were halved to simulate the mixing with soil. The concentrations were also multiplied by 0.2, to account for the higher moisture content and lower density of the sludge delivered to the field compared to the sludge prepared and analyzed in the laboratory. The individual modeled was a maintenance worker working 40 hours per week on site, of which 75% is spent outside. Doses were calculated assuming immediate access to the site, as well as access 30 years after closure, which is more realistic. The changes from the RESRAD default settings are:

R02 Pathway 3 through 7: Suppressed

R011 Item 2: Thickness of Contaminated Zone: 0.305 m

R013 Item 9: Precipitation: 0.178 m

The average annual precipitation for the site is 7 inches (0.178 m).

R017 Item 6A: Time Factors - Indoors: 0.06

$[(40 \text{ hours per work week}) \times (50 \text{ work weeks per year}) / (8760 \text{ hours per year})] \times 0.25$

R017 Item 6B: Time Factors - Outdoors: 0.17

$[(40 \text{ hours per work week}) \times (50 \text{ work weeks per year}) / (8760 \text{ hours per year})] \times 0.75$

