APPENDIX O

EXPOSURE SCENARIOS AND UNIT DOSE FACTORS FOR THE HANFORD IMMOBILIZED LOW-ACTIVITY TANK WASTE PERFORMANCE ASSESSMENT

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Exposure Scenarios and Unit Dose Factors for the Hanford Immobilized Low-Activity Tank Waste Performance Assessment

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Performance assessment (PA) dose calculations involve models and parameters from many disciplines to predict the migration of radioactive material from low-level disposal sites and the potential impacts this may have on members of the public in the future. Of particular interest is the dose calculation assumptions employed for the Hanford Immobilized Low-Activity Tank Waste (ILAW) Performance Assessment (PA). Exposure scenarios and model parameters must be selected which will be acceptable to the DOE as well as local technical experts on the Hanford Environmental Dose Overview Panel (HEDOP).

The particular combination of activities by which an individual accumulates radiation dose from a disposal site is known as an exposure scenario. For the ILAW PA the exposure scenarios are constructed from the land use scenarios (HNF-EP-0828, Rev 2), of which there are three general categories.

(1) The water infiltration rate at the disposal site is very low due to an engineered barrier. Ground water contamination is expected to be very small, or even non-existent. The main contaminants leaving the waste site are gases and vapors which diffuse upward through the soil to the ground surface. Potential exposure scenarios involve individuals living 100 meters downwind from the waste, or directly above the waste, where the contaminant emission rate is greatest.

(2) The water infiltration rate at the disposal site remains similar to present natural infiltration rates. Large scale irrigation for commercial farming is excluded. Potential exposure scenarios include people living 100 meters from the waste once contamination has reached the groundwater, and individuals living above the waste who drill a well through it.

(3) The water infiltration rate at the disposal site is much larger than the present natural infiltration rate due to widespread irrigation of the central plateau of the Hanford Site. Potential exposure scenarios involve ways that water from a well 100 meters from the disposal site may be used. Onsite exposures are precluded by the active irrigation.

Since many waste disposal site performance assessments have been prepared, both for the Hanford Site and other DOE-managed facilities, there is a body of knowledge associated with these assessments. Future PA documents must be consistent with previous PA documents to a considerable degree. However, there is always room for improvement. One such area is the range of potential doses to individuals who may live on or near the disposal site some time in the future. The reason for doing this is to ensure that potential doses are not underestimated. The low end of the dose range will be zero. The high end depends on the assumed exposure scenarios and the model parameters selected to describe the scenario. This report describes possible exposure scenarios, selects average (or typical) model parameters, and calculates unit dose factors for these scenarios. This approach enables meaningful comparisons between scenarios, and provides assurance that bounding cases have indeed been considered.

1.0 EXPOSURE SCENARIO DESCRIPTIONS

The potential exposure scenarios are divided into two general categories, offsite and onsite. These originated by considering the delays in exposure which can be generally expected from waste disposal sites on the Hanford Site. The offsite location receives the majority of the dose after contaminants have migrated from the disposal site into the groundwater and are brought to the surface through a well. Exposure of the offsite individual requires considerable delay between site closure and the eventual appearance of radioactivity in the ground water. Only radionuclides with long half lives, such as plutonium, will be significant hazards. Radionuclides with shorter half lives, such as cesium-137 and strontium-90, normally will decay to insignificant amounts before becoming part of the groundwater contamination. In order for the short half life nuclides to be significant exposure hazards, someone must actively expose themselves to the buried waste by moving onto the disposal site and digging into it. Hence the onsite scenarios were developed.

The general features of the exposure scenarios used in performance assessments are shown in Table 1.

Table 1. General Features of Performance Assessment Exposure Scenarios.

Feature	Onsite Receptor	Offsite Receptor
Time delay following site closure	no less than 100 years	any time after site closure
Receptor location	directly over the waste disposal site	no closer than 100 meters from the edge of the buried waste
Contamination sources	(1) gases & vapors - migrate upward from the waste (2) well water (3) exhumed waste	(1) gases & vapors carried by the wind to the offsite location (2) well water
Exposure scenarios	(1) well driller - person actually drilling through the waste (2) residential - person living near the well	(1) industrial - people working at some commercial enterprise (2) residential - person living near the well (3) farmer - subsistence farming operation (4) native American Indian

The offsite exposures occur as a result of the environmental transport of radioactive contamination to locations near the waste disposal site. The usual location is 100 meters from the edge of the buried waste, or wherever the ground water contamination would be greatest. The principal transport mechanism is the migration of contaminants from the waste through the vadose soil and into the ground water. For most nuclides this involves a considerable time delay (i.e., hundreds of years) between site closure and arrival of the contamination. In addition, different nuclides travel at different rates through the soil, so they arrive at the well at times which may differ by more than the 70 year lifetime of the offsite individual. The offsite individual is also exposed to any airborne emissions from the waste disposal site. The airborne emissions result from the upward migration of certain radionuclides. The airborne emissions normally lead to less dose than the ground water contamination.

The onsite exposures are the result of human activity directly over the buried waste, for example, a residence or business. Since local regulations would prohibit such activities, the onsite exposure scenarios are assumed to be delayed for 100 years following site closure. After this delay, it is assumed that knowledge of the disposal site location is lost or ignored, and individuals unknowingly trespass. To establish bounding doses for this individual, it is assumed that a well is drilled through the waste. The waste materials brought to the surface are not recognized as waste. It is assumed that the appearance of the exhumed waste differs little from the native soil, and it becomes part of a garden.

The intent of these exposure assumptions is to establish reasonable bounds on the potential doses resulting from the waste disposal site. The exposure scenarios result from consideration of how the radioactivity can move, where it moves, and how people might be exposed to it in future years.

1.1 No Water Infiltration Exposure Scenarios

Since the water infiltration rate is expected to be very low due to the presence of an engineered barrier, little contamination will reach the ground water. However, gases and vapors will diffuse from the waste through the soil. These gaseous contaminants enter the air above the disposal site and may be carried by the wind to receptors located near the site. In addition, there may be inadvertent intrusion into the disposal site.

Table 2 summarizes the various exposure scenarios analyzed for the no water infiltration case. Note that skin absorption refers to radioactive materials on the skin being absorbed into the body by passage through the skin. Note also that the first scenario (Offsite Farmer) applies any time after site closure, while the remaining scenarios require a minimum of 100 years delay before they can occur.

One exposure scenario requires modeling the average dilution and dispersion of gases released from the surface as they travel downwind to someone living nearby. Since the airborne emission from the disposal site is in the form of gases and vapors, there will be no appreciable deposition of radioactivity on ground. However, plants and animals do absorb certain gases directly from the air, leading to an ingestion dose to individuals consuming such produce. The emission rate from the ground surface may vary with time as the waste ages and radioactivity decays. The bounding doses for this scenario are achieved sometime after site closure.

A second exposure scenario involves a residence located above the disposal site with a porous floor. Gas concentrations in the dwelling would depend on the emission rate from the soil and the assumed ventilation rate in the dwelling. For an individual to be living above the disposal site, all knowledge of the site must have been lost. The dose calculation cannot begin until 100 years have elapsed from site closure.

Table 2. Exposure Scenarios for the No Water Infiltration Case.

Offsite Farmer -- gas/vapor emanations from the disposal site are carried downwind to a subsistence farm
‣ inhalation of plume ‣ ingestion (plants & animals) ‣ external radiation exposure from plume ‣ skin absorption from air
Onsite Resident -- gas/vapor emanations into a residence over the disposal site
‣ inhalation (higher concentrations in a dwelling) ‣ external radiation exposure (from soil and air) ‣ skin absorption (from air)
Intruder -- individual present while a well is being drilled through the waste disposal site
‣ inhalation (resuspended dust & gaseous emissions) ‣ ingestion (trace amounts of soil) ‣ external radiation exposure ‣ skin absorption (contact with soil)
Post-intrusion Resident -- lives near the exhumed waste
‣ inhalation (resuspended dust & gaseous emissions) ‣ ingestion (trace amounts of soil & garden produce) ‣ external radiation exposure (working in garden) ‣ skin absorption (contact with soil)

Notes: "Skin absorption" refers to radioactivity on the skin being absorbed into the body by passage through the skin. The first scenario applies any time after site closure, while the other three require a delay of at least 100 years before they can occur.

The third and fourth exposure scenarios listed on Table 2 assume the waste is unintentionally disturbed by human activity such as drilling a well through it. It is assumed that such intrusion is prevented for the first 100 years following site closure. After this period, it is assumed that knowledge of the disposal site becomes unavailable or is ignored. In addition, any markers or warnings are ignored. Compliance with performance objectives for the intruder (HNF-EP-826, Rev 2) is measured through reasonable exposure scenarios during and after the inadvertent intrusion.

Exposure scenario development begins with listing various ways the intruder can be exposed to the exhumed waste. These include inhalation of resuspended dust & gaseous emissions, ingestion of trace amounts of soil in the course of other activities, ingestion of garden produce, external radiation exposure, and absorption of contaminants that come in contact with skin.

There are two primary exposure scenarios for the intruder. The first describes the exposure to an individual digging a well through the disposal site. The second describes the exposure to an individual residing near the well afterward. Other forms of intrusion, such as digging footings for buildings, are considered unlikely due to the depth of the waste.

In this scenario, one or more individuals are exposed to the waste because the waste site has been returned to the public and no restrictions on land use prevent such an event. The drilling of water wells is a fairly common occurrence. However, the likelihood of a driller actually encountering the buried waste is low, since there are many places to drill, but few are over the buried waste.

The well extends from the ground surface to the unconfined aquifer. The diameter of the well could range from 4 inches up to 12 inches. The larger the diameter, the more waste will be brought to the surface. Prior Hanford performance assessments assumed that the well diameter is 12 inches (30 cm). This value certainly establishes an upper bound on the volume exhumed by a well-drilling operation. A more common diameter for a well is 6 inches (15 cm). This average diameter (15 cm) will be assumed in this report.

The total volume of soil produced by the well drilling is the product of the well cross sectional area and the thickness of soil between the unconfined aquifer and the ground surface. In the 200 Areas, for example, this thickness is about 80 meters. In this example, the total volume of soil excavated is 1.4 m^3.

$$\text{Soil volume from well} = (3.14159)(0.15\text{m}/2)^2(80\text{ m}) = 1.4\text{ m}^3$$

The volume of waste exhumed is the product of the well cross sectional area and the waste thickness. The disposal facility design will determine the waste thickness. By way of example, if the waste is 8 meters thick, then the total volume of waste excavated by the drilling operation would be 0.14 m^3. For comparison, the Grouted Waste PA (WHC-SD-WM-EE-004) used a waste volume of 0.64 m^3.

The individuals doing the drilling are exposed to the waste through inhalation of resuspended dust and gaseous emissions, ingestion of trace amounts, external exposure to the contamination, and dermal contact with the contaminated soil. The total exposure time is assumed to be 5 working days, or 40 hours. A portion of the waste at the time of drilling may still be in a form that cannot be resuspended and inhaled. An example is waste in the form of glass beads which are corroding slowly with time.

The dose to the driller depends on the area over which the contamination is spread. In the Grouted Waste performance assessment (WHC-SD-WM-EE-004, Rev 1) the area used was 100 m^2. This value will also be used in the present calculations. The 200 West Area Burial Ground performance assessment (WHC-EP-0645, Rev 0) did not consider doses to the driller in detail, since for all nuclides, the dose to the driller is less than the dose to the post-drilling resident. Previous PAs that calculate dose to the driller also assumed the activity is uniformly mixed in the top 15 cm of soil. Thus the exhumed waste is diluted to a total volume of $(100\ m^2)(0.15\ m) = 15\ m^3$.

After the drillers leave, the mound of exhumed material is assumed to be spread around to level the ground for a garden. It will be assumed that the waste appears no different than the normal soil and thus is treated just like soil would be. Three important parameters affect the eventual dose received by the individual who works the garden. These are the depth of contamination in the soil, the area over which the contamination is spread, and the portion of the person's diet which comes from the garden. This section discusses these parameters and establishes values for them.

The customary tilling to prepare the soil for planting is assumed to only affect the top 15 cm (6 inches) of soil. This 15 cm tilling depth has been used in prior Hanford Site performance assessments. The greatest tilling depth likely to be encountered is about 60 cm, while the most shallow depth would be no tilling at all. The deeper the soil is tilled, the more dilute the waste becomes in the surface layer. The 15 cm depth is typical for root systems of garden vegetables. The nuclide concentration in plants due to root uptake is based on the average concentration to which the roots are exposed. If the tilling depth were greater than the root depth, the concentration in the material inhaled and ingested would be reduced. This would also lower the resulting doses. The 15 cm tilling depth will be assumed in the base analysis case. The upper bound on the soil concentration will be assumed to be the 10 cm depth, while the lower bound will be assumed to be the 60 cm depth. Many garden plants have root systems which penetrate deeper than 15 cm. However, it will be assumed that most of the nutrients taken from the soil will come from the top 15 cm, so that corrections for root depth will not be necessary.

Having chosen a tilling depth, the dose received by the gardener is proportional to the product of the soil concentration and the quantity of garden produce consumed. The proportionality with soil concentration assumes the contaminants are present in trace amounts which neither affect the growth of the plant, nor exceed solubility limits in the plant tissues. This relationship is summarized in the equation below.

$$\text{Gardener Dose} \propto (\text{Soil Conc})(\text{Quantity Eaten}) \qquad (1)$$

In general, the soil concentration is inversely proportional to the area over which the waste is spread. For estimating soil concentration in the garden, the smallest and largest areas can be tied to reasonable spreading thicknesses. The smallest reasonable thickness is 1 cm, because thinner layers require excessive effort to achieve. The largest useful thickness is the tilling depth, 15 cm. The garden area is the total volume of soil exhumed by drilling divided by the assumed thickness. In the 200 Area example where 1.4 m^3 is exhumed, the range of distributed thicknesses gives rise to a range of garden areas from 10 m^2 to 140 m^2. For areas between these limits, the soil concentration is inversely proportional to the area over which the material taken from the well is spread. Larger areas are possible, but the distribution of waste activity will be non-uniform.

The quantity of food derived from the garden is proportional to the garden size. To estimate food production per unit garden area, two approaches are used. The first is commercial food production in Washington State (WA Department of Agriculture 1994). Using the statewide food production per acre figures, the estimated garden area can be computed. The computed total garden area (194 m^2) is mostly for production of grain.

The second approach to estimating garden size uses garden production estimates published by the Washington State University (WSU) Cooperative Extension (1980). The document provides estimates of pounds of produce per 10 foot row in a garden. In addition, it gives recommended row spacings. The spacing was treated as the row width to compute production per unit area. The WSU production estimates are higher than the commercial production averages hence the needed garden area is smaller (161 m^2). These were assumed to be optimum values under excellent growing conditions.

Thus an efficiently planned and maintained garden of 200 m^2 can be assumed to supply most of one average person's garden produce needs. The quantity of food obtained from the garden by one person is proportional to the area of the garden up to a maximum of 200 m^2. Beyond 200 m^2 there is more food than the individual can eat. With more than one person in the household, the needed garden area increases proportionately. However, since the typical gardener obtains about 25% of his vegetable diet from a garden (see Section 2.2.3) a family of four would have a garden no larger than 200 m^2.

Recall that (1) the soil concentration is inversely proportional to the garden area, and (2) the quantity eaten is directly proportional to the garden area. Thus, the gardener's ingestion dose is largely independent of the garden area up to a maximum area of about 200 m^2. Once the garden area exceeds this maximum area, the ingestion dose decreases in proportion to the area. This maximum garden area will be assumed in the ILAW PA.

The chosen garden area of 200 m^2 differs considerably from prior Hanford performance assessments (eg., WHC-SD-WM-EE-004 and WHC-EP-0645) which have used a garden area of 2500 m^2. The more realistic area of 200 m^2 leads to ingestion doses which are 12.5 times greater than before for the same volume of waste exhumed. One justification for the larger area assumption used in prior performance assessments is that after a few hundred years the waste has not yet decomposed into fine particles suitable for uptake into plants. The large particles cannot be resuspended into the air, and prevent the plants from absorbing as much. In effect, the dilution factor is one or more orders of magnitude greater. In the present performance assessment, the unavailable portion will be estimated from glass corrosion characteristics.

For the post-intrusion resident, the range of possible contaminated garden sizes will be taken to be 10 m^2 to 200 m^2. Not all of the larger garden could be contaminated by the exhumed waste, but the individual collects food from all parts of the garden so the effect is the same.

The tilling assumption affects the dose calculations only by making the surface soil concentrations more uniform. Without tilling, the nuclide concentrations in the surface soil could range from that of the waste matrix to zero (background radioactivity is not considered). Conceivably some plants might be unable to grow in certain parts of the garden due to the high waste concentration. The tilling assumption ensures that the vegetable pathways will contribute to the overall dose to the gardener. In practice, the exhumed waste will not be uniformly spread over the garden area. However, the gardener roams the garden and averages out the exposure rate and soil ingestion. The produce grown in the garden will have varying levels of contamination, but the individual consumes portions grown in various parts of the garden, so that assuming an average soil concentration approximates the average produce concentration.

1.2 Low Water Infiltration Exposure Scenarios

In this land use category, the natural water infiltration causes contaminants in the disposal site to migrate into the ground water. Any human activities directly over the waste disposal site are assumed to be delayed at least 100 years. Human activities related to radiation exposure offsite begin after site closure, but really don't become interesting until the ground water plume reaches a well located 100 meters from the disposal site. Although there could be two general categories for the exposure scenarios, human intrusion and offsite scenarios, only the offsite scenarios will be considered (HNF-EP-0828).

The offsite scenarios establish compliance with performance objectives at the point of highest projected dose or concentration beyond a 100 meter buffer zone surrounding the disposal site (HNF-EP-0826). Exposure scenario development begins with listing various ways the well water could be used and selecting those activities that could lead to significant radiation exposure. Table 3 lists potential dose contributors. Some of the listed pathways turn out to be insignificant. Because the irrigation activities are not directly over the disposal site water infiltration at the disposal site is not affected. Also note that skin absorption refers to radioactive materials on the skin being absorbed into the body by passage through the skin.

The per capita water withdrawal rate from domestic wells mentioned in Miller (1980) (page 27), is 65 gallons per day, or 90,000 liters per year. This figure covers the principal domestic uses, namely, washing and bathing, drinking and cooking for one person.

Table 3. Exposure Pathways for the Low Water Infiltration Case.

(1) Drinking the well water (also cooking with it)
‣ ingestion
(2) Showering and bathing with the well water
‣ inhalation (sprays) ‣ ingestion (small amounts) ‣ external radiation exposure (immersion) ‣ skin absorption (contact with water)
(3) Irrigating a garden
‣ inhalation (sprays & resuspended dust) ‣ ingestion (produce & trace amounts of soil) ‣ external radiation exposure (while in garden) ‣ skin absorption (contact with soil)
(4) Drinking water for house pets and livestock
‣ ingestion (eggs, poultry, milk) ‣ external radiation exposure (proximity to animal)
(5) Irrigating livestock pastures
‣ inhalation (sprays & resuspended dust) ‣ ingestion (beef & milk) ‣ external radiation exposure (while in pasture)
(6) Sleeping on soil contaminated by irrigation
‣ inhalation (resuspended dust) ‣ external radiation exposure (while on ground) ‣ skin absorption (contact with soil)
(7) Sweat lodge/wet sauna
‣ inhalation (steam) ‣ skin absorption (contact with steam) ‣ external radiation exposure (soil, walls, steam)

As ground water enters the Columbia River, it is diluted by the large flow of surface water. From 1989 to 1999 the average flow rate measured at Priest Rapids Dam is about 3360 cubic meters per second (PNNL-6415). Radioactive contamination in the ground water would then be transported to various water intakes for use as irrigation and public drinking supplies. Doses to an individual irrigating from the Columbia River would be orders of magnitude smaller than doses to the same farmer irrigating from a well which penetrates the aquifer down gradient from the waste site. For this reason, the dose to an individual irrigating from the Columbia River will not be considered. However, since a large number of people would be affected by contamination in the river, a total population dose will be estimated.

As in prior performance assessments (eg., WHC-SD-WM-EE-004 and WHC-EP-0645) a total population of 5 million people between the Hanford Site and the Pacific Ocean will be assumed to derive all of their drinking water from the Columbia River. The population estimate is an upper bound. The lower bound is the population at an earlier time, assumed to be 1 million persons.

In addition, the average irrigation rate along the river will be assumed to be 25 cm/y (WHC-SD-WM-EE-004). This value was obtained as an average in counties along the Columbia River, and thereby differs from the irrigation rate assumed for individuals living near the Hanford Site. Again, this average over a large population will have an insignificant range.

Offsite exposure scenarios will use one or more of the listed pathways. Some pathways may be ruled out by characteristics of the environmental setting. For example, irrigation of a garden from a well is reasonable, but irrigation of pastures may not be possible, depending on the bounding pumping rate from the well. Possible exposure scenarios have been selected to represent future uses of the land. They are listed in Table 4.

The exposure scenarios listed in Table 4 use the naming convention of DOE/RL-91-45, *Hanford Site Risk Assessment Methodology* (HSRAM), Revision 3. The customary disposal site performance assessment all-pathways scenarios is included as an alternate for the agricultural scenario. Differences in modelling assumptions are discussed in later sections.

The native american subsistence resident (NASR) is based on discussions presented in DOE/RL-96-16. This individual represents a bounding case whose intakes of contaminated foodstuffs and exposures to environmental contamination are maximized.

Table 4. Exposure Scenarios for the Low Water Infiltration Case.

Industrial Scenario - represents potential doses to workers in a commercial industrial setting. Drinking water comes from the well (1), as does water used in showering (2), but no other pathway applies.
Residential Scenario - represents potential doses to individuals living in a community near the disposal site. These individuals drink from the well (1), shower regularly (2), irrigate a garden (3), give it to their pets (4), water a lawn and sleep on it occasionally (6).
Agricultural Scenario - represents potential doses to individuals who may take up residence on the Hanford Site to operate a subsistence farm. These individuals drink from their well (1), shower regularly (2), irrigate a garden (3), give it to their pets and livestock (4), irrigate a pasture for their cow (5), water a lawn and sleep on it occasionally (6). This scenario includes all of the pathways listed in Table 3 except the sauna.
Native American Subsistence Resident (NASR) Scenario - represents potential doses to individuals practicing the traditional subsistence lifestyle of the native American Indian. This includes hunting, fishing, gathering wild produce, and using a sweat lodge. These individuals also have a well for drinking, bathing, irrigating, and providing water for pets and livestock. All of the pathways listed on Table 3 are used.

1.3 High Water Infiltration Exposure Scenarios

In this land use category, the water infiltration rate at the disposal site is much larger than the present natural infiltration rate due to widespread irrigation of the central plateau of the Hanford Site. The higher infiltration rate changes the rate at which radioactivity is released from the disposal site as well as the rate at which it travels through the vadose zone. In addition, it acts to dilute the radioactivity entering the ground water. Thus the resulting ground water concentrations could be higher or lower than in the low infiltration case.

As with the low infiltration case, compliance with performance objectives is measured at the point of highest projected dose or concentration beyond a 100 meter buffer zone surrounding the disposal site (HNF-EP-0826). The offsite exposure scenarios discussed for the low water infiltration case also apply here. The only difference is the contaminant concentration in the ground water pumped from the well. Since water concentrations determine the dose, it is essential to have a credible model for the release and transport of waste contaminants through the soil.

2.0 EXPOSURE PATHWAY PARAMETERS

This section summarizes the recommended parameters and models to be used in calculating the radiation doses for the various scenarios in the ILAW PA. What follows is a description of each parameter, typical values, and the justification for the values chosen for this performance assessment. Where these parameters differ from prior performance assessments for Hanford disposal sites, the differences are explained. The mathematical models are described to illustrate how the parameters are used in calculations.

For the most part this is simply an expanded version of a previous supporting document (WHC-SD-TI-707). The discussion of data and models is divided into several topical areas, namely, nuclear properties, human activities, animal, plant, and soil characteristics.

An additional consideration is the potential effects on special groups of individuals who may be exposed in unique ways not normally considered. Information relevant to the modeling of dose to these special groups is included in each section.

2.1 Nuclear Parameters

The first parameters of interest are basic nuclear properties of the radionuclides which may be found in waste buried on the Hanford Site. The two main selection criteria for these nuclides is the radioactive half-life and the projected inventory in typical N-Reactor fuel. Radionuclides with half-lives greater than approximately one year are considered.

Table 5 shows the decay half-life and the decay chain branching ratios. A branching ratio is the fraction of decays of a parent nuclide which produce a given progeny nuclide. These parameters are needed to determine the amount of a nuclide, and any radioactive progeny, which is present as a function of time. Values are taken from the Evaluated Nuclear Data File, Release VI (ENDF/B-VI). The conversion from seconds to years was carried out using the value 365.25 days per year. Also shown on this table are the short-lived progeny which are assumed to be in secular equilibrium with the parent. These short half-life progeny are also called "implicit daughters" because their radioactive emissions are not considered separately, but combined with the parent nuclide.

As noted in DOE/RL-97-69, *Hanford Immobilized Low-Activity Tank Waste Performance Assessment* (section 3.4.7.4), new measurements of the half lives for Se-79 and Sn-126 show substantial increases. The newer values have been used in Table 5.

Table 5. Radionuclides to be Considered and Their Half Lives.

Nuclide	Half life (years)	Short-lived progeny in equilibrium with parent
H-3	12.33	
Be-10	1.600E+06	
C-14	5,730	
Na-22	2.6019	
Si-32+D	329.56	P-32
Cl-36	300,992	
K-40	1.277E+09	
Ti-44+D	47.30	Sc-44
V-49	0.92539 (338 d)	
Mn-54	0.85454 (312.12 d)	
Fe-55	2.7299	
Co-60	5.2713	
Ni-59	74,999	
Ni-63	100.10	
Se-79	805,000	
Rb-87	4.800E+10	
Sr-90+D	28.149	Y-90
Zr-93	1.530E+06	
Nb-91	680	
Nb-93m	16.13	
Nb-94	20,300	
Mo-93	3,500	
Tc-99	211,097	
Ru-106+D	1.01736 (371.59 d)	Rh-106
Pd-107	6.50E+06	

Table 5. Radionuclides to be Considered and Their Half Lives.

Nuclide	Half life (years)	Short-lived progeny in equilibrium with parent
Ag-108m+D	127.00	Ag-108 (0.087)
Cd-109	1.26653 (462.6 d)	
Cd-113m	14.10	
In-115	4.410E+14	
Sn-121m+D	54.998	Sn-121 (0.776)
Sn-126+D	246,000	Sb-126m, Sb-126 (0.14)
Sb-125	2.7299	
Te-125m	0.15880 (58 d)	
I-129	1.570E+07	
Cs-134	2.0619	
Cs-135	2.30E+06	
Cs-137+D	29.999	Ba-137m (0.9443)
Ba-133	10.520	
Pm-147	2.6233	
Sm-147	1.060E+11	
Sm-151	89.997	
Eu-150	35.798	
Eu-152	13.330	
Eu-154	8.5919	
Eu-155	4.680	
Gd-152	1.080E+14	
Ho-166m	1,200	
Re-187	5.000E+10	
Tl-204	3.7801	
Pb-205	1.520E+07	
Pb-210+D	22.300	Bi-210

Table 5. Radionuclides to be Considered and Their Half Lives.

Nuclide	Half life (years)	Short-lived progeny in equilibrium with parent
Bi-207	32.198	
Po-209	102.0	
Po-210	0.37886 (138.38 d)	
Ra-226+D	1,600	Rn-222, Po-218, Pb-214, Bi-214, Po-214(0.9998)
Ra-228+D	5.7498	Ac-228
Ac-227+D	21.769	Th-227(0.9862), Fr-223(0.0138), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, Tl-207(.99725), Po-211(.00275)
Th-228+D	1.9129	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212(0.6406), Tl-208(0.3594)
Th-229+D	7,340	Ra-225, Ac-225, Fr-221, At-217, Bi213, Po-213(0.9784), Tl-209(0.0216)
Th-230	75,380	
Th-232	1.405E+10	
Pa-231	32,759	
U-232	69.799	
U-233	159,198	
U-234	245,694	
U-235+D	7.037E+08	Th-231
U-236	2.342E+07	
U-238+D	4.468E+09	Th-234, Pa-234m, Pa-234 (0.0013)
Np-237+D	2.140E+06	Pa-233
Pu-236	2.8999	
Pu-238	87.697	
Pu-239	24,110	
Pu-240	6,563	
Pu-241+D	14.350	U-237 (2.39E-05)
Pu-242	373,507	
Pu-244+D	8.000E+07	U-240 (0.9988), Np-240m, Np-240 (0.0012)

Table 5. Radionuclides to be Considered and Their Half Lives.

Nuclide	Half life (years)	Short-lived progeny in equilibrium with parent
Am-241	432.70	
Am-242m+D	141.00	Am-242(0.9955), Np-238(0.0045)
Am-243+D	7,370	Np-239
Cm-242	0.44611 (162.94 d)	
Cm-243	28.499	
Cm-244	18.100	
Cm-245	8,500	
Cm-246	4,730	
Cm-247+D	1.600E+07	Pu-243
Cm-248	339,981	
Cm-250+D	11,300	Pu-246(0.25), Am-246(0.25), Bk-250(0.14)
Bk-247	1,394	
Cf-248	0.91294 (333.45 d)	
Cf-249	350.60	
Cf-250	13.080	
Cf-251	897.98	
Cf-252	2.6449	

Note: Parentheses show (1) half-lives that are normally given in days, and (2) branching ratios that differ from 1.00.

Table 6 shows the radioactive decay chains which will be computed prior to and during the exposure scenarios. Radioactive decay normally reduces the dose that a receptor could receive. However, in the cases shown on Table 6, the ingrowth of the progeny nuclides with time may increase the dose from the parent nuclide. One example of this is Th-232, which has a very long half-life so that there is essentially no change in its activity during the year of exposure. Since the initial activity of the progeny nuclides (Ra-228 and Th-228) is assumed to be zero any increase will have maximum effect on the Th-232 doses. In addition, since the progeny accumulate according to their much shorter half-lives, they are able to increase the dose from Th-232 significantly.

The decay chains used in these calculations are limited to four radioactive members by the assumption that the decay times will be less than 1000 years.

Table 6. Decay Chains Actually Computed.

Zr-93	→	Nb-93m				
Mo-93	→	Nb-93m				
Sb-125	→ .230	Te-125m				
Pm-147	→	Sm-147				
Eu-152	→ .2792	Gd-152				
Pb-210	→	Po-210				
Po-209	→ .9974	Pb-205				
Ra-226	→	Pb-210	→	Po-210		
Ra-228	→	Th-228				
Th-230	→	Ra-226	→	Pb-210	→	Po-210
Th-232	→	Ra-228	→	Th-228		
Pa-231	→	Ac-227				
U-232	→	Th-228				
U-233	→	Th-229				
U-234	→	Th-230	→	Ra-226	→	Pb-210
U-235	→	Pa-231	→	Ac-227		
Pu-236	→	U-232	→	Th-228		
Pu-238	→	U-234				
Pu-241	→	Am-241	→	Np-237		
Pu-244	→	Pu-240				
Am-241	→	Np-237				

Table 6. Decay Chains Actually Computed.

Am-242m	→ .827	Cm-242	→	Pu-238	→	U-234
	→ .173	Pu-242				
Am-243	→	Pu-239				
Cm-242	→	Pu-238	→	U-234		
Cm-243	→	Pu-239				
	→ .0024	Am-243				
Cm-244	→	Pu-240				
Cm-245	→	Pu-241	→	Am-241	→	Np-237
Cm-247	→	Am-243				
Cm-250	→ .14	Cf-250	↓			
	→ .25	Cm-246	←			
Bk-247	→	Am-243				
Cf-248	→	Cm-244	→	Pu-240		
Cf-249	→	Cm-245	→	Pu-241	→	Am-241
Cf-250	→	Cm-246				
Cf-251	→	Cm-247				
Cf-252	→	Cm-248				

Notes:

Decay times are assumed to be less than 1000 years so that the ingrowth of progeny with long half-lives can be ignored.

There is a slight increase in the Pu-238 and U-234 for the Am-242m decay chain that is not shown. This is a result of the low-probability alpha decay of Am-242m. The complete chain is, Am-242m(0.00455)--->Np-238--->Pu-238--->U-234.

2.2 Human Parameters

Parameters for humans represented in the various exposure scenarios are the internal and external dose factors, and the food types and consumption rates for typical humans currently living near the Hanford Site.

2.2.1 Internal Dose Factors

Internal dose factors specify the effective dose equivalent (EDE) from a unit intake (ingested or inhaled) of a radionuclide. The dose is accumulated over a period of 50 years, known as the dose commitment period. This dose commitment period was set by the ICRP in Publication 26 (1977) when determining internal dose and relating it to whole body exposure.

If the nuclide has radioactive progeny with short half-lives, then the internal dose factors for these progeny are included with the parent isotope. It is assumed that the progeny are in secular equilibrium with the parent nuclide.

Currently, internal dose factors are based on the methods and assumptions of the International Commission on Radiological Protection (ICRP) prior to 1990. In 1990, the ICRP published Report Number 60 which revised these methods. Regulatory bodies in the United States have not yet adopted the improved methods, so they are not included here.

There are three internal dose factor collections which will be considered. The first is widely used in performance assessments for the United States Department of Energy (DOE/EH-0071). The second was prepared under the sponsorship of the United States Environmental Protection Agency (EPA-520/1-88-020). This set is also acceptable for use in performance assessments at DOE sites (DOE/LLW-93 and DOE M 435.1-1 Implementation Guide Chapter IV). The third was computed for the GENII software (PNNL-6584), which is often used at the Hanford Site. The GENII internal dose factors were recently revised (WHC-SD-WM-TI-596).

The dose factors from the three collections have been converted to the common units of mrem per pCi intake in Tables 7 and 8 below. For the ingestion dose factors, Table 7 shows the assumed values for f1, which is the fraction of the activity ingested that enters body fluids. "DF" is an abbreviation for dose factor. For the inhalation dose factors, Table 8 lists the assumed lung model category. The "V" for tritium stands for vapor, and includes a 50 percent increase due to absorption through the skin. The "Org" for C-14 means that the carbon is assumed to have an organic chemical form. The "D", "W", and "Y" mean the material clears the lungs in a matter of days, weeks, or years, respectively.

Comparison ratios of the GENII and DOE dose factors divided by the EPA dose factors are shown in Tables 7 and 8. Dose factors that differ less than 5% from the EPA numbers are not shown in the ratio columns. The only nuclides with differences greater than 25 percent are

Co-60, Nb-94, Tc-99, Ru-106, Ag-108m, In-115, Sn-126, Re-187, Bi-207, Ra-226, Ra-228, Th-228, Np-237, Pu-241, and Bk-247.

The internal dose factors for Nb-91 are not listed in any dose factor collection and were assumed to be bounded by the values for Nb-93m. Both nuclides emit low energy electrons and photons, as shown on the nuclear decay data summary of Table 9. For Nb-91, there is a continuous spectrum of low energy photons associated with the electron capture and positron decay. However, this continuous spectrum is a minor addition to the photon spectrum. The total electron plus photon energy for Nb-91 (15 keV) is less than that for Nb-93m (26 keV). Therefore, the internal dose factor for Nb-91 should be less than that for Nb-93m.

An additional consideration is the half-life of the two isotopes compared with expected residence times in the body. Inhalation class Y niobium is retained in the lungs for a considerable length of time. Most is removed during the first several years, but some is retained indefinitely. The organ with the largest dose for class Y Nb-93m is the lungs. Most (87%) of the dose from Nb-93m accrues during the first 10 years after inhalation. Thus, the effect of Nb-93m's shorter half-life is small. It will be assumed that the internal dose factors for Nb-91 are bounded by those for Nb-93m.

In addition to Nb-91, the internal dose factors for Po-209 are not listed in any dose factor collection and had to be computed by comparison with Po-210. Corrections were made for the energy of the alpha particles emitted, and the decay half-life using the equation shown below.

$$\text{Dose Factor} \propto \frac{E_\alpha}{\lambda_{eff}}\left[1 - e^{-\lambda_{eff} T_d}\right] \qquad (2)$$

where,

- $E\alpha$ = total alpha energy per decay. For Po-209 this is 4.882 Mev per decay, while for Po-210 this is 5.3045 Mev per decay.
- λ_{eff} = effective removal constant, which combines both the biological elimination and the radioactive decay of the nuclide.
- T_d = dose commitment period used in the dose factor collections shown in Tables 7 and 8, namely, 50 years.

The biological removal half time for polonium is 50 days (ICRP 30). The decay half-life of Po-209 is 102 year, thus its λ_{eff} is 0.01388 per day. The decay half-life of Po-210 is 138 days, thus its λ_{eff} is 0.01889 per day. Since these are so large, the dose integration term in brackets is nearly 1 after 50 years. The ratio of Po-209 to Po-210 internal dose factors is shown below. This ratio was applied to the Po-210 inhalation and ingestion dose factors to arrive at the Po-209 internal dose factors.

Po-209 Dose Factor ——— = 4.882 Mev * 0.01889 per day ——— = 1.252

Po-210 Dose Factor 5.3045 Mev * 0.01388 per day

The dose factor collection from the EPA (EPA-520/1-88-020) will be used in the ILAW PA. These are the only internal dose factors currently approved by the DOE for use in performance assessments (DOE M 435.1-1). The differences with the other collections is minor. Ratios of the GENII and EPA internal dose factors to the DOE dose factors are shown in Table 8.

Special groups of people such as children and diabetics, will have different internal dose factors due to differences in organ mass and retention times in the various tissues of the body. Internal dose factors for different age groups have been computed by the ICRP in Publication 56 (1989). However, these dose factors are for a limited number of nuclides. Unit dose factors for individuals whose metabolic characteristics differ considerably from those of the reference individual will also differ from those presented in Tables 7 and 8. As explained in DOE M 435.1-1 Chapter IV, the use of dose factors for representative members of the public is desirable to avoid overly conservative results. A bounding case exposure scenario evaluates possible upper limits.

Absorption through the skin, and injection from an injury are not considered since they are not likely to add significantly to the doses computed in the intruder and irrigation scenarios. These may be computed using an internal dosimetry program such as CINDY (PNNL-7493). Values have been published (PNNL-10190) and are basically the ingestion dose factor divided by the internal transfer factor (f1).

Any special exposure pathways associated with extended dermal contact with contaminated soil or vegetation will require appropriate dermal absorption dose factors. Dermal absorption methods for radionuclides were recently included in a revision to the MEPAS[1] program (PNNL-10523).

[1]MEPAS is a registered trademark of Battelle Memorial Institute.

Table 7. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII/EPA	DOE/EPA
H-3	1	6.12E-08	6.40E-08	6.30E-08		
Be-10	0.005	4.70E-06	4.66E-06	4.20E-06		0.90
C-14	1	2.06E-06	2.09E-06	2.10E-06		
Na-22	1	1.06E-05	1.15E-05	1.20E-05	0.92	
Si-32+D	0.01	1.11E-05	1.10E-05	9.40E-06		0.85
Cl-36	1	2.95E-06	3.03E-06	3.00E-06		
K-40	1	1.79E-05	1.86E-05	1.90E-05		
Ti-44+D	0.01	2.35E-05	2.46E-05	1.91E-05		0.78
V-49	0.01	6.04E-08	6.14E-08	5.40E-08		0.88
Mn-54	0.1	2.76E-06	2.77E-06	2.70E-06		
Fe-55	0.1	6.15E-07	6.07E-07	5.80E-07		
Co-60	0.3	2.65E-05	2.69E-05	2.60E-05		
Ni-59	0.05	2.05E-07	2.10E-07	2.00E-07		
Ni-63	0.05	5.72E-07	5.77E-07	5.40E-07		0.94
Se-79	0.8	8.33E-06	8.70E-06	8.30E-06		
Rb-87	1	4.73E-06	4.92E-06	4.80E-06		
Sr-90+D	0.3	1.31E-04	1.53E-04	1.40E-04	0.86	0.92
Zr-93	0.002	1.64E-06	1.66E-06	1.60E-06		
Nb-91	0.01	5.05E-07	5.22E-07	5.30E-07		
Nb-93m	0.01	5.05E-07	5.22E-07	5.30E-07		
Nb-94	0.01	7.25E-06	7.14E-06	5.10E-06		0.71
Mo-93	0.8	1.21E-06	1.35E-06	1.30E-06	0.90	
Tc-99	0.8	2.23E-06	1.46E-06	1.30E-06	1.53	0.89
Ru-106+D	0.05	2.73E-05	2.74E-05	2.10E-05		0.77
Pd-107	0.005	1.50E-07	1.49E-07	1.40E-07		0.94
Ag-108m+D	0.05	7.58E-06	7.62E-06	7.50E-06		
Cd-109	0.05	1.32E-05	1.31E-05	1.20E-05		0.92
Cd-113m	0.05	1.62E-04	1.61E-04	1.50E-04		0.93
In-115	0.02	8.68E-05	1.58E-04	1.40E-04	0.55	0.89

Table 7. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Sn-121m+D	0.02	2.24E-06	2.25E-06	1.99E-06		0.88
Sn-126+D	0.02	2.08E-05	2.11E-05	1.83E-05		0.87
Sb-125+D	0.1	2.83E-06	2.81E-06	2.60E-06		0.93
Te-125m	0.2	3.72E-06	3.67E-06	3.40E-06		0.93
I-129	1	2.49E-04	2.76E-04	2.80E-04	0.90	
Cs-134	1	6.82E-05	7.33E-05	7.40E-05	0.93	
Cs-135	1	6.86E-06	7.07E-06	7.10E-06		
Cs-137+D	1	4.74E-05	5.00E-05	5.00E-05	0.95	
Ba-133	0.1	3.05E-06	3.40E-06	3.20E-06	0.90	0.94
Pm-147	0.0003	1.06E-06	1.05E-06	9.50E-07		0.90
Sm-147	0.0003	1.86E-04	1.85E-04	1.80E-04		
Sm-151	0.0003	3.87E-07	3.89E-07	3.40E-07		0.87
Eu-150	0.001	6.34E-06	6.36E-06	6.20E-06		
Eu-152	0.001	6.48E-06	6.48E-06	6.00E-06		0.93
Eu-154	0.001	9.61E-06	9.55E-06	9.10E-06		
Eu-155	0.001	1.53E-06	1.53E-06	1.30E-06		0.85
Gd-152	0.0003	1.61E-04	1.61E-04	1.50E-04		0.93
Ho-166m	0.0003	8.13E-06	8.07E-06	7.80E-06		
Re-187	0.8	1.45E-08	9.51E-09	8.30E-09	1.52	0.87
Tl-204	1	3.46E-06	3.36E-06	3.20E-06		
Pb-205	0.2	1.64E-06	1.63E-06	1.50E-06		0.92
Pb-210+D	0.2	5.40E-03	5.37E-03	5.11E-03		
Bi-207	0.05	5.49E-06	5.48E-06	4.90E-06		0.89
Po-209	0.1	2.39E-03	2.38E-03	2.00E-03		0.84
Po-210	0.1	1.90E-03	1.90E-03	1.60E-03		0.84
Ra-226+D	0.2	9.51E-04	1.33E-03	1.10E-03	0.72	0.83
Ra-228+D	0.2	8.44E-04	1.44E-03	1.20E-03	0.59	0.83
Ac-227+D	0.001	1.44E-02	1.48E-02	1.46E-02		
Th-228+D	0.0002	5.79E-04	8.11E-04	7.54E-04	0.71	0.93

Table 7. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Th-229+D	0.0002	3.87E-03	4.03E-03	3.91E-03		
Th-230	0.0002	5.48E-04	5.48E-04	5.30E-04		
Th-232	0.0002	2.73E-03	2.73E-03	2.80E-03		
Pa-231	0.001	1.06E-02	1.06E-02	1.10E-02		
U-232	0.05	1.31E-03	1.31E-03	1.30E-03		
U-233	0.05	2.90E-04	2.89E-04	2.70E-04		0.93
U-234	0.05	2.84E-04	2.83E-04	2.60E-04		0.92
U-235+D	0.05	2.67E-04	2.67E-04	2.51E-04		0.94
U-236	0.05	2.69E-04	2.69E-04	2.50E-04		0.93
U-238+D	0.05	2.70E-04	2.68E-04	2.43E-04		0.91
Np-237+D	0.001	5.22E-03	4.44E-03	3.90E-03	1.18	0.88
Pu-236	0.001	1.16E-03	1.17E-03	1.30E-03		1.11
Pu-238	0.001	3.19E-03	3.20E-03	3.80E-03		1.19
Pu-239	0.001	3.53E-03	3.54E-03	4.30E-03		1.21
Pu-240	0.001	3.53E-03	3.54E-03	4.30E-03		1.21
Pu-241+D	0.001	6.79E-05	6.85E-05	8.60E-05		1.26
Pu-242	0.001	3.35E-03	3.36E-03	4.10E-03		1.22
Pu-244+D	0.001	3.32E-03	3.32E-03	4.00E-03		1.20
Am-241	0.001	3.62E-03	3.64E-03	4.50E-03		1.24
Am-242m+D	0.001	3.50E-03	3.52E-03	4.20E-03		1.19
Am-243+D	0.001	3.62E-03	3.63E-03	4.50E-03		1.24
Cm-242	0.001	1.15E-04	1.15E-04	1.10E-04		
Cm-243	0.001	2.50E-03	2.51E-03	2.90E-03		1.16
Cm-244	0.001	2.01E-03	2.02E-03	2.30E-03		1.14
Cm-245	0.001	3.73E-03	3.74E-03	4.50E-03		1.20
Cm-246	0.001	3.70E-03	3.70E-03	4.50E-03		1.22
Cm-247+D	0.001	3.40E-03	3.42E-03	4.10E-03		1.20
Cm-248	0.001	1.36E-02	1.36E-02	1.60E-02		1.18
Cm-250+D	0.001	7.76E-02	7.77E-02	7.77E-02		

Table 7. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Bk-247	0.001	3.81E-03	4.70E-03	2.30E-03	0.81	0.49
Cf-248	0.001	3.39E-04	3.34E-04	2.80E-04		0.84
Cf-249	0.001	4.75E-03	4.74E-03	4.60E-03		
Cf-250	0.001	2.13E-03	2.13E-03	1.90E-03		0.89
Cf-251	0.001	4.82E-03	4.85E-03	4.60E-03		0.95
Cf-252	0.001	1.09E-03	1.08E-03	9.40E-04		0.87

Notes:
(1) GENII Internal DF are from the July 1999 library revision by PDR. EPA Inhalation & Ingestion dose factors from Federal Guidance Report Number 11, EPA-520/1-88-020, Sept 1988. DOE Ingestion & Inhalation dose factors from DOE/EH-0071, (DE88-014297), July 1988. All are 50 year committed EDE.
(2) "DF" means dose factor. "f1" is the fraction of ingested activity reaching body fluids.
(3) The short-lived radioactive progeny shown on Table 5 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been added to the parent dose factor to give the values shown.
(4) The last two columns show ratios of GENII and DOE ingestion dose factors to the EPA dose factors. Ratios of dose factors within 5% of the EPA value are not shown.

Table 8. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII/EPA	DOE/EPA
H-3	H_2O	9.02E-08	9.60E-08	9.45E-08	0.94	
Be-10	Y	3.54E-04	3.54E-04	3.50E-04		
C-14	Organic	2.06E-06	2.09E-06	2.10E-06		
Na-22	D	7.11E-06	7.66E-06	8.00E-06	0.93	
Si-32+D	Y	1.02E-03	1.03E-03	1.01E-03		
Cl-36	W	2.21E-05	2.19E-05	2.00E-05		0.91
K-40	D	1.19E-05	1.24E-05	1.20E-05		
Ti-44+D	D	4.18E-04	4.52E-04	4.50E-04	0.92	
V-49	W	3.46E-07	3.45E-07	2.80E-07		0.81
Mn-54	W	6.36E-06	6.70E-06	6.40E-06	0.95	
Fe-55	D	2.74E-06	2.69E-06	2.60E-06		
Co-60	Y	2.00E-04	2.19E-04	1.50E-04	0.91	0.68
Ni-59	D	1.28E-06	1.32E-06	1.30E-06		
Ni-63	D	3.06E-06	3.10E-06	3.00E-06		
Se-79	W	9.49E-06	9.84E-06	8.90E-06		0.90
Rb-87	D	3.18E-06	3.23E-06	3.30E-06		
Sr-90+D	D	2.10E-04	2.48E-04	2.37E-04	0.85	
Zr-93	D	3.16E-04	3.21E-04	3.20E-04		
Nb-91	Y	2.94E-05	2.92E-05	2.80E-05		
Nb-93m	Y	2.94E-05	2.92E-05	2.80E-05		
Nb-94	Y	3.91E-04	4.14E-04	3.30E-04	0.94	0.80
Mo-93	Y	2.80E-05	2.84E-05	2.80E-05		
Tc-99	W	9.00E-06	8.33E-06	7.50E-06	1.08	0.90
Ru-106+D	Y	4.75E-04	4.77E-04	4.40E-04		0.92
Pd-107	Y	1.29E-05	1.28E-05	1.30E-05		
Ag-108m+D	Y	2.58E-04	2.83E-04	2.00E-04	0.91	0.71
Cd-109	D	1.15E-04	1.14E-04	1.00E-04		0.88
Cd-113m	D	1.54E-03	1.53E-03	1.40E-03		0.92
In-115	D	2.02E-03	3.74E-03	3.40E-03	0.54	0.91

Table 8. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Sn-121m+D	W	1.18E-05	1.19E-05	9.26E-06		0.78
Sn-126+D	W	1.00E-04	1.01E-04	7.54E-05		0.75
Sb-125+D	W	1.23E-05	1.22E-05	9.80E-06		0.80
Te-125m	W	7.18E-06	7.29E-06	6.70E-06		0.92
I-129	D	1.51E-04	1.74E-04	1.80E-04	0.87	
Cs-134	D	4.28E-05	4.63E-05	4.70E-05	0.92	
Cs-135	D	4.49E-06	4.55E-06	4.50E-06		
Cs-137+D	D	2.98E-05	3.19E-05	3.20E-05	0.93	
Ba-133	D	6.00E-06	7.81E-06	6.90E-06	0.77	0.88
Pm-147	Y	3.92E-05	3.92E-05	3.40E-05		0.87
Sm-147	W	7.48E-02	7.47E-02	7.10E-02		
Sm-151	W	3.01E-05	3.00E-05	2.90E-05		
Eu-150	W	2.50E-04	2.68E-04	2.70E-04	0.93	
Eu-152	W	2.11E-04	2.21E-04	2.20E-04		
Eu-154	W	2.78E-04	2.86E-04	2.60E-04		0.91
Eu-155	W	4.12E-05	4.14E-05	3.90E-05		0.94
Gd-152	D	2.44E-01	2.43E-01	2.40E-01		
Ho-166m	W	7.46E-04	7.73E-04	7.20E-04		0.93
Re-187	W	5.86E-08	5.44E-08	4.90E-08	1.08	0.90
Tl-204	D	2.46E-06	2.41E-06	2.30E-06		
Pb-205	D	3.97E-06	3.92E-06	3.70E-06		0.94
Pb-210+D	D	1.39E-02	1.38E-02	1.32E-02		
Bi-207	W	1.96E-05	2.00E-05	1.40E-05		0.70
Po-209	D	1.19E-02	1.18E-02	1.01E-02		0.86
Po-210	D	9.65E-03	9.40E-03	8.10E-03		0.86
Ra-226+D	W	8.22E-03	8.60E-03	7.91E-03		0.92
Ra-228+D	W	4.40E-03	5.08E-03	4.49E-03	0.87	0.88
Ac-227+D	D	6.71E+00	6.72E+00	6.72E+00		
Th-228+D	W	3.47E-01	3.45E-01	3.13E-01		0.91

Table 8. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Th-229+D	W	2.16E+00	2.16E+00	2.02E+00		0.94
Th-230	W	3.27E-01	3.26E-01	3.20E-01		
Th-232	W	1.64E+00	1.64E+00	1.60E+00		
Pa-231	W	1.29E+00	1.28E+00	1.30E+00		
U-232	Y	6.56E-01	6.59E-01	6.70E-01		
U-233	Y	1.35E-01	1.35E-01	1.30E-01		
U-234	Y	1.32E-01	1.32E-01	1.30E-01		
U-235+D	Y	1.24E-01	1.23E-01	1.20E-01		
U-236	Y	1.26E-01	1.25E-01	1.20E-01		
U-238+D	Y	1.18E-01	1.18E-01	1.20E-01		
Np-237+D	W	6.32E-01	5.40E-01	4.90E-01	1.17	0.91
Pu-236	W	1.45E-01	1.45E-01	1.60E-01		1.10
Pu-238	W	3.90E-01	3.92E-01	4.60E-01		1.17
Pu-239	W	4.30E-01	4.29E-01	5.10E-01		1.19
Pu-240	W	4.30E-01	4.29E-01	5.10E-01		1.19
Pu-241+D	W	8.17E-03	8.25E-03	1.00E-02		1.21
Pu-242	W	4.08E-01	4.11E-01	4.80E-01		1.17
Pu-244+D	W	4.03E-01	4.03E-01	4.80E-01		1.19
Am-241	W	4.41E-01	4.44E-01	5.20E-01		1.17
Am-242m+D	W	4.24E-01	4.26E-01	5.10E-01		1.20
Am-243+D	W	4.41E-01	4.40E-01	5.20E-01		1.18
Cm-242	W	1.75E-02	1.73E-02	1.70E-04		
Cm-243	W	3.07E-01	3.07E-01	3.50E-01		1.14
Cm-244	W	2.48E-01	2.48E-01	2.70E-01		1.09
Cm-245	W	4.55E-01	4.55E-01	5.40E-01		1.19
Cm-246	W	4.51E-01	4.51E-01	5.40E-01		1.20
Cm-247+D	W	4.15E-01	4.14E-01	4.90E-01		1.18
Cm-248	W	1.65E+00	1.65E+00	1.90E+00		1.15
Cm-250+D	W	9.43E+00	9.40E+00	9.40E+00		

Table 8. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Bk-247	W	4.65E-01	5.74E-01	5.50E-01	0.81	
Cf-248	Y	5.11E-02	5.07E-02	4.30E-02		0.85
Cf-249	W	5.77E-01	5.77E-01	5.50E-01		
Cf-250	W	2.63E-01	2.62E-01	2.20E-01		0.84
Cf-251	W	5.87E-01	5.88E-01	5.60E-01		
Cf-252	Y	1.55E-01	1.57E-01	1.30E-01		0.83

Notes:
(1) GENII Internal DF are from the July 1999 library revision by PDR. EPA Inhalation & Ingestion dose factors from Federal Guidance Report Number 11, EPA-520/1-88-020, Sept 1988. DOE Ingestion & Inhalation dose factors from DOE/EH-0071, (DE88-014297), July 1988. All are 50 year committed EDE.
(2) "DF" means dose factor. "Lung" refers to the ICRP lung model classification, "H2O" is tritium vapor (which includes skin absorption), "Organic" means organic carbon, "D" is days, "W" is weeks, and "Y" is years.
(3) The short-lived radioactive progeny shown on Table 5 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been added to the parent dose factor to give the values shown.
(4) The last two columns show ratios of GENII and DOE inhalation dose factors to the EPA dose factors. Ratios of dose factors within 5% of the EPA value are not shown.

Table 9. Nuclear Decay Data for Nb-91 and Nb-93m.

Nb-91 (680 y)	Particle energy, keV	fraction of decays	Weighted energy, keV
EC	1254.6	0.99836	417.51
positron	232.6	0.00164	0.13
electron	13.47	0.2348	3.16
photon	15.69	0.18319	2.87
	15.77	0.35027	5.52
	17.66	0.10136	1.79
	511	0.00328	1.68
		Total for electrons + photons:	15 keV
Nb-93m (16.13 y)	**Particle energy, keV**	**fraction of decays**	**Weighted energy, keV**
IT	30.77	1	30.77
electron	11.78	0.1440	1.70
	14.15	0.0365	0.52
	28.07	0.1340	3.76
	28.31	0.0262	0.74
	28.40	0.4710	13.38
	30.39	0.1360	4.13
photon	16.52	0.0310	0.51
	16.61	0.0590	0.98
	18.61	0.0175	0.33
	30.77	5.5 E-06	0.00
		Total for electrons + photons:	26 keV

Note: The last column shows the product of the particle energies and the fraction of decays with this energy particle. Although the Nb-93m half life is short enough that the total retained in the body (and hence the dose) decreases partly by radioactive decay, its total electron plus positron energy is large enough to make up for the loss by decay. Data from ENDF/B-VI.

2.2.2 External Dose-Rate Factors

External dose-rate factors give the expected dose equivalent rate to an individual standing in the center of a large contaminated area. The dose rate factors have units of dose equivalent rate per unit soil concentration. The contamination is assumed to be uniformly spread over a very large area. The dose rate factors are derived for infinite sources of varying thickness. If the area becomes smaller than a few hundred square meters, then the dose rate factors must be adjusted downward. The thickness of the contaminated layer affects the dose rate and must be considered. For typical exposure scenarios the soil thickness is 15 cm. Radionuclides are assumed to be uniformly distributed through this thickness as a result of cultivating the soil for the purpose of growing a garden.

External dose rates from a layer of contaminated surface soil are available from various sources. Three sources that have been used on the Hanford Site are the DOE surface gamma dose-rate conversion factors (DOE/EH-0070), the EPA values in Federal Guidance Report Number 12 (EPA-402-R-93-081), and the external dose factors recently computed for the GENII program. The three sets of external dose rate factors are shown in Table 10. They have been converted to the common units of mrem/hour per Ci/m² for purposes of comparison.

The DOE surface gamma conversion factors (DOE/EH-0070) are derived from an assumed contamination thickness of zero. The contamination lies on top of the soil surface in a layer which is infinitely thin, perfectly flat, and infinite in extent. These assumptions necessarily exaggerate the dose rates for the ILAW PA. Strong beta-emitting nuclides such as Sr-90 produce no external dose since the bremsstrahlung radiation was ignored.

The GENII external dose rate factors (PNNL-6584) were computed using a version of the ISOSHLD program known as EXTDF which is part of the GENII software package. Bremsstrahlung radiation is computed for all beta emitters. The dose rate factors assume the contamination is distributed through the top 0.15 meters (6 inches) of soil. The surface soil is given a density of 1.5 grams per cubic centimeter. Again the surface layer is perfectly flat and infinite in extent. The finite thickness adds realism, since the contamination is worked into the soil during normal tilling operations. These dose rate factors have been used in prior Hanford Site performance assessments.

The EPA external dose rate factors (EPA-402-R-93-081) were computed using a Monte Carlo approach with the best available input data and dosimetric models, except that ICRP 30 organ weighting factors rather than ICRP 60 weighting factors were used. These are considered to be the best external dose rate factors currently available and will be used in the ILAW PA. The EPA values are for a soil contamination thickness of 15 cm. The number shown for Eu-150 is listed as Eu-150b in the EPA compilation. The reference does not give values for Nb-91 and Po-210. Therefore, the values computed by EXTDF were used instead.

Table 10. External Dose Rate Factors, mrem/h per Ci/m².

Nuclide	GENII	EPA	DOE	GENII/EPA	DOE/EPA
H-3	3.49E-08	0.0	0.0	EPA=0	
Be-10	4.33E-01	5.37E-01	0.0	0.806	DOE=0
C-14	7.51E-03	6.82E-03	0.0		DOE=0
Na-22	6.75E+03	5.98E+03	2.40E+04	1.13	4.01
Si-32+D	9.62E+00	5.70E+00	0.0	1.69	DOE=0
Cl-36	8.58E-01	1.16E+00	5.32E-04	0.740	0.000459
K-40	4.87E+02	4.33E+02	1.56E+03	1.12	3.60
Ti-44+D	7.10E+03	6.00E+03	2.57E+04	1.18	4.28
V-49	0.0	0.0	8.60E-01		EPA=0
Mn-54	2.53E+03	2.27E+03	9.59E+03	1.11	4.22
Fe-55	1.07E-01	0.0	2.52E+00	EPA=0	EPA=0
Co-60	7.51E+03	6.87E+03	2.59E+04		3.77
Ni-59	1.31E-01	0.0	4.75E+00	EPA=0	EPA=0
Ni-63	1.91E-04	0.0	0.0	EPA=0	
Se-79	5.37E-03	9.44E-03	0.0	0.569	DOE=0
Rb-87	4.02E-02	7.13E-02	0.0	0.564	DOE=0
Sr-90+D	1.97E+01	1.17E+01	0.0	1.68	DOE=0
Zr-93	1.34E-04	0.0	0.0	EPA=0	
Nb-91	5.74E+00	5.74E+00	8.36E+01		14.6
Nb-93m	4.33E-02	5.28E-02	1.17E+01	0.820	222
Nb-94	4.67E+03	4.29E+03	1.81E+04		4.22
Mo-93	2.43E-01	2.99E-01	6.59E+01	0.813	220
Tc-99	5.04E-02	6.35E-02	7.14E-03	0.794	0.112
Ru-106+D	7.32E+02	5.83E+02	2.40E+03	1.26	4.12
Pd-107	4.16E-06	0.0	0.0	EPA=0	
Ag-108m+D	5.37E+03	4.37E+03	1.90E+04	1.23	4.35

Table 10. External Dose Rate Factors, mrem/h per Ci/m².

Nuclide	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Cd-109	2.61E+00	7.47E+00	1.08E+02	0.349	14.5
Cd-113m	4.28E-01	3.24E-01	0.0	1.32	DOE=0
In-115	2.56E-01	2.01E-01	0.0	1.27	DOE=0
Sn-121m+D	5.15E+00	1.07E+00	0.0	4.81	DOE=0
Sn-126+D	6.56E+03	5.36E+03	2.37E+04	1.22	4.42
Sb-125+D	1.49E+03	1.12E+03	5.05E+03	1.33	4.51
Te-125m	8.78E+00	7.67E+00	2.40E+02	1.14	31.3
I-129	5.54E+00	6.57E+00	2.51E+02	0.843	38.2
Cs-134	5.23E+03	4.24E+03	1.80E+04	1.23	4.25
Cs-135	1.46E-02	1.94E-02	0.0	0.753	DOE=0
Cs-137+D	1.82E+03	1.53E+03	6.59E+03	1.19	4.31
Ba-133	1.10E+03	9.36E+02	4.78E+03	1.18	5.11
Pm-147	2.74E-02	2.53E-02	4.68E-02		1.85
Sm-147	0.0	0.0	0.0		
Sm-151	1.95E-03	4.99E-04	5.93E-02	3.91	119
Eu-150	5.04E+03	3.96E+03	0.0	1.27	DOE=0
Eu-152	3.60E+03	3.05E+03	1.27E+04	1.18	4.16
Eu-154	3.74E+03	3.34E+03	1.38E+04	1.12	4.13
Eu-155	8.98E+01	9.24E+01	8.16E+02		8.83
Gd-152	0.0	0.0	0.0		
Ho-166m	4.67E+03	4.64E+03	1.88E+04		4.05
Re-187	0.0	0.0	0.0		
Tl-204	1.93E+00	2.04E+00	1.48E+01		7.25
Pb-205	8.75E-02	3.58E-03	8.61E+00	24.4	2410
Pb-210+D	3.85E+00	3.00E+00	3.42E+01	1.28	11.4
Bi-207	4.92E+03	4.11E+03	1.72E+04	1.20	4.18
Po-209	8.95E+00	8.95E+00	4.10E+01		4.58
Po-210	2.68E-02	2.32E-02	9.81E-02	1.16	4.23
Ra-226+D	5.61E+03	4.78E+03	1.92E+04	1.17	4.02

Table 10. External Dose Rate Factors, mrem/h per Ci/m².

Nuclide	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Ra-228+D	3.04E+03	2.62E+03	1.04E+04	1.16	3.97
Ac-227+D	1.08E+03	9.61E+02	5.00E+03	1.12	5.20
Th-228+D	4.92E+03	4.20E+03	1.66E+04	1.17	3.95
Th-229+D	9.04E+02	7.45E+02	4.09E+03	1.21	5.49
Th-230	4.11E-01	6.05E-01	1.03E+01	0.679	17.0
Th-232	2.13E-01	2.63E-01	7.60E+00	0.810	28.9
Pa-231	9.09E+01	9.11E+01	4.08E+02		4.48
U-232	3.10E-01	4.52E-01	1.17E+01	0.686	25.9
U-233	4.81E-01	6.86E-01	5.70E+00	0.701	8.31
U-234	1.89E-01	2.03E-01	9.21E+00		45.4
U-235+D	2.52E+02	3.74E+02	2.17E+03	0.674	5.80
U-236	9.85E-02	1.08E-01	8.36E+00		77.4
U-238+D	7.10E+01	5.87E+01	2.81E+02	1.21	4.79
Np-237+D	7.13E+02	5.28E+02	3.06E+03	1.35	5.8
Pu-236	9.45E-02	1.14E-01	1.13E+01	0.829	99.1
Pu-238	1.06E-01	7.65E-02	9.79E+00	1.39	128
Pu-239	1.59E-01	1.44E-01	4.31E+00	1.10	29.9
Pu-240	7.29E-02	7.43E-02	9.35E+00		126
Pu-241+D	9.43E-03	9.29E-03	4.40E-02		4.74
Pu-242	9.57E-02	6.49E-02	7.78E+00	1.47	120
Pu-244+D	1.17E+03	9.04E+02	3.86E+03	1.29	4.27
Am-241	1.45E+01	2.22E+01	3.41E+02	0.653	15.4
Am-242m+D	3.58E+01	3.28E+01	2.66E+02		8.11
Am-243+D	4.49E+02	4.42E+02	2.94E+03		6.65
Cm-242	5.97E-02	8.59E-02	1.07E+01	0.695	125
Cm-243	2.90E+02	2.86E+02	1.67E+03		5.84
Cm-244	5.09E-02	6.39E-02	9.46E+00	0.797	148
Cm-245	1.32E+02	1.71E+02	9.74E+02	0.772	5.7
Cm-246	4.19E-02	5.89E-02	8.37E+00	0.711	142

Table 10. External Dose Rate Factors, mrem/h per Ci/m².

Nuclide	GENII	EPA	DOE	GENII/EPA	DOE/EPA
Cm-247+D	1.30E+03	8.74E+02	4.16E+03	1.49	4.76
Cm-248	3.83E-02	4.45E-02	6.71E+00	0.861	151
Cm-250+D	1.20E+03	8.55E+02	4.40E+03	1.40	5.15
Bk-247	2.32E+02	2.14E+02	0.0		DOE=0
Cf-248	3.43E-02	6.32E-02	7.68E+00	0.543	122
Cf-249	9.82E+02	8.71E+02	4.02E+03	1.13	4.62
Cf-250	5.37E-02	6.01E-02	7.81E+00	0.894	130
Cf-251	2.40E+02	2.62E+02	1.55E+03		5.92
Cf-252	4.25E-02	8.91E-02	7.23E+00	0.477	81.1

Notes:
(1) GENII external DRF were computed using the EXTDF program. EPA external DRF are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). DOE external DRF are from DOE/EH-0070 (July 1988).
(2) Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide.
(3) The conversion to area units from volume units assumes a thickness of 0.15 meters. The density correction applied to the EPA (1993) dose rate factors is 1.067. Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used.
(4) The last two columns show ratios of GENII and DOE external dose rate factors to the EPA dose rate factors. Ratios within 10% of the EPA value are not shown.

The GENII and EPA external dose rate factors are listed as dose rate per unit concentration in the soil. The unit concentration was converted to a unit area by multiplying by the contamination thickness of 15 cm. The DOE dose rate factors are already in area units. Note that the EPA dose rate factors were developed for a soil density of 1.6 g/cc. However, the ILAW PA will use a soil density for the surface layer of 1.5 g/cc. Therefore, the EPA dose rate factors were multiplied by the density correction factor of 1.067 to give the values shown on Table 10.

The three external dose factor collections are compared in Table 10. What is shown on this table are ratios of the GENII and DOE collections divided by the EPA collection. Differences less than 10 percent are not shown. Ratios for dose rate factors which are zero were not computed.

The GENII external dose rate factors agree fairly well (within 26%) for nuclides that emit penetrating gamma rays and have the largest dose rate factors. Examples are Na-22, Ti-44, Mn-54, Co-60, Nb-94, Ag-108m, Sn-126, Cs-134, Cs-137, Eu-150, Eu-152, Eu-154, Ho-166m, Bi-207, Ra-226, Ra-228, and Th-228. The disagreement between GENII and the EPA collections is over the low energy photon emitters. However, for these nuclides the internal doses are typically much greater than the external, so the disagreement would not affect the total doses.

In general, the DOE external dose rate factors are larger than the EPA dose rate factors by more than a factor of 4. The exceptions (Be-10, C-14, Si-32, Cl-36, Se-79, Rb-87, Sr-90, Tc-99, Cd-113m, In-115, Sn-121m, Cs-135, and Pm-147) are for nuclides which produce most of their photons through bremsstrahlung. For these nuclides, the DOE external dose rate factors are much too small.

In all three references used in Table 10 the dose rates were computed at a height of 1 meter above the soil. The actual height has little effect on the dose rate. Table 11 demonstrates this by comparing dose rate factors computed by the EXTDF program at 100 cm and 10 cm. The table shows the ratios of the 10 cm dose rate divided by the 100 cm dose rate for nuclides where the difference between dose rate factors was greater than 10 percent. It must be noted that all these nuclides have external dose rates which are insignificant compared with the internal. The exclusively low energy photons emitted by these nuclides are noticeably attenuated by the additional 90 cm of air.

Table 11. Ratios of Dose Rate Factors at Two Elevations.

Nuclide	Ratio	Nuclide	Ratio
H-3	1.61	U-236	1.26
Fe-55	1.61	Pu-236	1.35
Ni-59	1.18	Pu-238	1.27
Ni-63	1.18	Pu-240	1.37
Zr-93	1.20	Pu-242	1.46
Nb-93m	1.61	Cm-242	1.46
Mo-93	1.61	Cm-244	1.48
Pd-107	1.52	Cm-246	1.52
Sm-151	1.21	Cm-248	1.46
Pb-205	1.61	Cf-248	1.55
Th-232	1.12	Cf-250	1.36
U-232	1.13	Cf-252	1.42
U-234	1.16		

Note: The ratios are the dose rate factor (DRF) at 10 cm above the soil surface divided by the dose rate factor at 1 meter above the soil.
Nuclides having DRFs within 10% at the two elevations are not shown. DRFs were computed using the EXTDF program, which is part of the GENII software package.

External dose rate factors for immersion in contaminated air are listed in Table 12 below. Values are from Federal Guidance Report Number 12 (EPA-402-R-93-081). The dose rate factors were computed assuming the individual is located at the center of a hemisphere of infinite extent. Hence these are also referred to as semi-infinite cloud dose rate factors. Values for Nb-91 and Po-209 are from the EXTDF program of the GENII software package. The columns labeled "Ratio" compare the external dose from submersion in contaminated air with the inhalation dose that accrues during the same period. The inhalation dose is computed as the product of the air concentration, the exposure time, the breathing rate, and the inhalation dose factor. The submersion dose is computed as the product of the air concentration, the exposure time, and the submersion dose rate factor. Thus the ratio of inhalation dose to submersion dose is the product of the breathing rate and the inhalation dose factor divided by the submersion dose factor. This ratio is shown in Table 12 for the daily average breathing rate (0.95 m^3/h) and EPA inhalation dose factors. The light activity breathing rate could also be used, but leads to larger ratios. For the nuclides used in this report (Table 5), the smallest ratio is 5.06 for Na-22. Nuclides notable for large inhalation doses, like insoluble transuranic (TRU) isotopes, have ratios greater than 1 million. Because the activity inhaled by the individual is considerably smaller than the activity ingested, the inhalation dose for non-TRU isotopes is a small part of the total. Therefore, the submersion dose will not be included in the dose calculation.

Table 12. External Dose Rate Factors for Air, mrem/h per pCi/m^3.

Nuclide	Air DRF	Ratio	Nuclide	Air DRF	Ratio
H-3	4.41E-12	1.38E+04	Re-187	0.0	
Be-10	1.49E-10	2.26E+06	Tl-204	7.45E-10	3.07E+03
C-14	2.98E-12	6.64E+05	Pb-205	6.74E-12	5.53E+05
Na-22	1.44E-06	5.06E+00	Pb-210+D	1.19E-09	1.10E+07
Si-32+D	1.33E-09	7.37E+05	Bi-207	1.00E-06	1.89E+01
Cl-36	2.97E-10	7.02E+04	Po-209	2.22E-09	5.04E+06
K-40	1.07E-07	1.10E+02	Po-210	5.54E-12	1.61E+09
Ti-44+D	1.47E-06	2.92E+02	Ra-226+D	1.18E-06	6.92E+03
V-49	0.0		Ra-228+D	6.37E-07	7.58E+03
Mn-54	5.45E-07	1.17E+01	Ac-227+D	2.47E-07	2.58E+07
Fe-55	0.0		Th-228+D	1.08E-06	3.05E+05

Table 12. External Dose Rate Factors for Air, mrem/h per pCi/m^3.

Nuclide	Air DRF	Ratio	Nuclide	Air DRF	Ratio
Co-60	1.68E-06	1.24E+02	Th-229+D	1.98E-07	1.04E+07
Ni-59	0.0		Th-230	2.32E-10	1.33E+09
Ni-63	0.0		Th-232	1.16E-10	1.34E+10
Se-79	4.04E-12	2.32E+06	Pa-231	2.29E-08	5.32E+07
Rb-87	2.42E-11	1.27E+05	U-232	1.89E-10	3.31E+09
Sr-90+D	2.63E-09	8.94E+04	U-233	2.17E-10	5.92E+08
Zr-93	0.0		U-234	1.02E-10	1.24E+09
Nb-91	1.23E-09	2.26E+04	U-235+D	1.03E-07	1.13E+06
Nb-93m	5.91E-11	4.70E+05	U-236	6.67E-11	1.79E+09
Nb-94	1.03E-06	3.84E+02	U-238+D	1.57E-08	7.15E+06
Mo-93	3.36E-10	8.04E+04	Np-237+D	1.38E-07	3.71E+06
Tc-99	2.16E-11	3.66E+05	Pu-236	8.46E-11	1.63E+09
Ru-106+D	1.39E-07	3.27E+03	Pu-238	6.50E-11	5.73E+09
Pd-107	0.0		Pu-239	5.65E-11	7.22E+09
Ag-108m+D	1.04E-06	2.59E+02	Pu-240	6.33E-11	6.44E+09
Cd-109	3.92E-09	2.77E+04	Pu-241+D	2.87E-12	2.73E+09
Cd-113m	9.24E-11	1.57E+07	Pu-242	5.34E-11	7.31E+09
In-115	5.99E-11	5.92E+07	Pu-244+D	2.17E-07	1.77E+06
Sn-121m+D	8.26E-10	1.37E+04	Am-241	1.09E-08	3.87E+07
Sn-126+D	1.28E-06	7.49E+01	Am-242m+D	1.02E-08	3.96E+07
Sb-125	2.69E-07	4.31E+01	Am-243+D	1.32E-07	3.18E+06
Te-125m	6.03E-09	1.15E+03	Cm-242	7.58E-11	2.17E+08
I-129	5.06E-09	3.26E+04	Cm-243	7.83E-08	3.73E+06
Cs-134	1.01E-06	4.36E+01	Cm-244	6.54E-11	3.60E+09
Cs-135	7.53E-12	5.74E+05	Cm-245	5.28E-08	8.20E+06
Cs-137+D	3.63E-07	8.36E+01	Cm-246	5.94E-11	7.22E+09
Ba-133	2.37E-07	3.13E+01	Cm-247+D	2.14E-07	1.84E+06
Pm-147	9.23E-12	4.04E+06	Cm-248	4.52E-11	3.48E+10
Sm-147	0.0		Cm-250+D	2.11E-07	4.23E+07

Table 12. External Dose Rate Factors for Air, mrem/h per pCi/m^3.

Nuclide	Air DRF	Ratio	Nuclide	Air DRF	Ratio
Sm-151	4.81E-13	5.92E+07	Bk-247	6.27E-08	8.68E+06
Eu-150	9.55E-07	2.67E+02	Cf-248	6.30E-11	7.64E+08
Eu-152	7.53E-07	2.79E+02	Cf-249	2.11E-07	2.60E+06
Eu-154	8.18E-07	3.32E+02	Cf-250	5.99E-11	4.15E+09
Eu-155	3.32E-08	1.19E+03	Cf-251	7.43E-08	7.52E+06
Gd-152	0.0		Cf-252	6.74E-11	2.21E+09
Ho-166m	1.13E-06	6.52E+02			

Notes:
(1) External DRF for submersion in contaminated air are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used. Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide. The nuclide is dispersed uniformly in a hemisphere of infinite extent. The receptor is at the center of the hemisphere.
(2) The "Ratio" columns are computed as the inhalation dose factor times the daily average breathing rate (0.95 m^3/h) divided by the submersion dose rate factor.

2.2.3 Ingestion Rates for People

In this section the ingestion rates for all types of produce for all exposure scenarios are presented and compared. In addition, consumption rates for water and trace amounts of soil are given. Finally, garden size is discussed because the assumed garden size controls soil concentration in the garden of the post-intrusion resident.

The diets compiled by the EPA to represent averages in different parts of the United States have been used in prior Hanford Site disposal facility performance assessments. The consumption parameters for the "West" region in a national survey were used (Yang and Nelson 1986). These are listed in Table 13 below, under the column "g/d". In contrast, a somewhat different set of values has become established for Hanford dose assessments. These are found in DOE/RL-91-45 Revision 3, *Hanford Site Risk Assessment Methodology* (HSRAM). The consumption parameters listed in that document for the industrial, residential and agricultural scenarios are presented in Table 14.

In Table 13 the last two columns of numbers are computed from the first column using 365 days per year consumption. Note that the usual 365.25 d/y has been rounded to simplify calculations. The values shown in the second column under "Observed Intakes" are the same as the values in the first column, except that the units have been changed from grams per day to kilograms per year.

The last column gives the consumption rates used for an average individual in the residential and all-pathways farmer scenarios. These have been adjusted for the fraction of the individual's diet which is locally produced based on the fractions given in the EPA Exposure Factors Handbook (EPA/600/8-89/043). The adjustment for garden produce is that 25 percent of the vegetable diet actually comes from the garden, and is contaminated. The other 75 percent is assumed to be obtained from uncontaminated sources. For animal products, it is assumed that 50 percent of the animal products (except for fish) are locally produced and thus contaminated.

Table 13. Human Food Consumption: Traditional Models.

Item Consumed	Observed Intakes		Residential & Farmer Intakes
	g/d	kg/y	kg/y
Leafy produce	45.3	16.53	4.1
Other veg. (protected)	152.5	55.66	13.9
Fruit (exposed + misc)	105.3	38.43	9.6
Cereal (grain)	202.6	73.95	18.5
Meat (beef & pork)	115.0	41.98	21.0
Milk	283.5	103.48	51.7
Poultry	28.9	10.55	5.3
Eggs	29.1	10.62	5.3
Fish	18.5	6.75	6.75
Drinking Water	1480	540	540
Trace Soil Ingestion	0.1	0.0365	0.0365

Notes: Annual intakes are computed as 365 days of daily intakes. Values in the last column are adjusted for average diet fraction locally produced, namely, 25% for garden produce and 50% for animal products.

"Leafy" refers to vegetables whose leafy parts are normally eaten, such as lettuce, cabbage and spinach. "Other veg." are termed "protected" produce because the edible portion is underground or has some type of non-edible covering. Examples of protected produce are potatoes, onions, peanuts, and sweet corn. "Fruit" is termed "exposed" produce because airborne contaminants may deposit on the edible portion, but the surface area is small compared to leafy vegetables. Examples of exposed produce are apples, asparagus, cherries, grapes, snap beans, squash, and tomatoes. "Grains" refers to cereals consumed by humans, such as corn (for meal), oats, soybeans, and wheat.

The next grouping of foods, namely, "Meat", "Milk", "Poultry", and "Eggs" refers to animal products that may be contaminated because the animals ingest contaminated feed and drink. The various animals raised for foods are separated into the two categories "Meat" and "Poultry". If the animal resembles a cow (e.g. goats or pigs), it is "Meat". If the animal resembles a bird (e.g. ducks and turkeys), it is "Poultry". The names simply refer to the most likely animal. In addition, no distinction is made between goat's milk and cow's milk. The method for estimating animal product concentrations is too coarse.

Other animal products can be postulated, such as wild animals or commercial food items (not grown locally). However, neither is contaminated by exhumed waste or ground water, so no dose accrues from them. Wild animals that are hunted for food, such as deer and waterfowl, would acquire some contamination once the ground water reaches the Columbia River. These are not explicitly included, because only the population dose is of interest from the Columbia River. Game animals are a small part of the total population dose.

The non-dairy beverage consumption rates measured by the EPA (Yang and Nelson 1986) for the western region is 1.48 liters per day (1480 g/d). The grouted waste performance assessment used 1.84 liters per day (Roseberry and Burmaster 1992). The traditional assumption commonly used in other performance assessments is 2 liters per day, which is 35 percent higher than the EPA average and 9 percent higher than the grouted waste PA. The EPA value (540 L/y) will be used for the residential and all-pathway farmer cases, while the 2 L/d value is considered the bounding value.

Inadvertent soil ingestion is assumed to occur at the rate of 100 mg per day for adults, and at twice this rate for children (EPA/600/8-89/043). This is a trace amount associated with hand-mouth contact, licking the lips, and similar motions. Deliberate soil ingestion is not considered. A survey of measurements of soil ingestion is presented in NUREG/CR-5512, Section 6.3.2.

In the drilling scenario, the worker is exposed for a period of 5 days. At 100 mg/d, the worker ingests 500 mg soil. Since 0.14 m^3 waste was spread over a 15 m^3 soil volume [(15 m^3)=(100 m^2)(0.15 m)], the amount of waste ingested is shown in the calculation below.

Driller soil ingestion = (100 mg/d)(5 d) = 500 mg soil

Driller waste ingestion = (500 mg)(0.14 m^3)/(15 m^3) = 4.7 mg waste

In the post-intrusion gardening scenario, the resident is exposed for a period of 365 days. At 100 mg/d, the resident ingests 36,500 mg soil. Since 0.14 m^3 waste was spread over a 30 m^3 soil volume [(30 m^3)=(200 m^2)(0.15 m)], the amount of waste ingested is shown in the calculation below.

Gardener soil ingestion = (100 mg/d)(365 d) = 36,500 mg soil

Gardener waste ingestion = (36,500 mg)(0.14 m^3)/(30 m^3) = 170 mg waste

Note that the amount ingested by the post-intrusion resident is substantially larger than the amount ingested by the driller. In addition, the ingestion amounts can be normalized to unitless fractions, the activity ingested per unit activity exhumed. This is illustrated below using an area density of 225 kg/m² based on a soil density of 1500 kg/m³ and a tilling depth of 0.15 cm. This method of comparison avoids the need to know the waste thickness and well diameter.

Driller ingestion fraction = (500 mg)/(225 kg/m^2)/(100 m^2)
= 2.22 x 10^{-8} Ci ingested per Ci exhumed

Gardener ingestion fraction = (36,500 mg)/(225 kg/m^2)/(200 m^2)
= 8.11 x 10^{-7} Ci ingested per Ci exhumed

For exposure of the population along the Columbia River, parameters are scaled up by the assumed total population of 5 million. Two exceptions are water intake and fish consumption. The average drinking rate of 540 L/y per person (Yang and Nelson 1986) will be used. About half of this number is water, while the rest is various other beverages, most of which are derived from drinking water supplies.

The quantity of fish consumed by the population is limited by what the river is able to produce. The total mass of fish harvested from the Columbia River annually and consumed locally is approximately 15 metric tons (PNNL-9823). The average amount of fish consumed by 5 million people is thus 3 grams per year per person.

The range of consumption rates for a large population is small since the individual differences are averaged out. Thus the total food consumed by the population depends primarily on the size of the population. The one exception is fish consumption, which is assumed to remain constant at 15 metric tons per year.

The HSRAM ingestion rates are shown in Table 14 for the industrial and agricultural scenarios. The ingestion rates for the residential scenario are the same except that the meat and milk pathways are absent. Game meat (deer) and fish are listed even though they would not be contaminated by exhumed soil, or by the irrigation of a subsistence farm from a well. The game rate is based on one 45 kg deer per year. Half the mass is edible, and is divided among a family of four.

Estimated food intake rates are from DOE/RL-96-16 (April 1997 draft) for the Native American Subsistence Resident (NASR) (Table 5.7). The total vegetable intake rate was divided among the four types of produce using the same relative proportions as shown in Table 13. The animal protein intake rate (150 g/d) was assumed to be made of meat (120 g/d) and deer (30 g/d). Note that the deer intake rate is assumed to be twice the game intake rate given in the HSRAM. In DOE/RL-96-16 a value for organ intake rate is given as 54 g/d. This has been added to the meat to give the total shown. Values for waterfowl (70 g/d), upland game birds (18 g/d), and wild bird eggs (45 g/d) have been added to the deer assumption to give the total game intake rate shown (163 g/d). These daily intake rates are converted to annual intake rates using 365 days per year.

Overall, the native american food intake rates are roughly twice the all-pathways farmer intake rates. Thus the resulting scenario dose factors will be roughly twice as great also.

Table 14. Human Food Consumption: New Models.

Item Consumed	Industrial	Agricultural	NASR
Leafy produce	0	3.7	20
Other veg. (protected), kg/y	0	11.0	67
Fruit (exposed + misc), kg/y	0	15.3	46
Cereal (grain), kg/y	0	14.6	108
Meat (beef & pork), kg/y	0	21.9	42
Milk, L/y	0	110	219
Poultry, kg/y	0	5.5	11
Eggs, kg/y	0	0	11
Fish, kg/y	0	9.9	197
Game (deer & birds), kg/y	0	5.5	59
Water, L/y	250	730	1095
Soil, kg/y	0.0125	0.0365	0.073

The industrial and agricultural are from HSRAM (DOE/RL-91-45). The HSRAM residential scenario has the same intake rates as the agricultural except that the meat, milk, poultry and egg intakes are zero. The HSRAM vegetable intake rate of 80 g/d has been separated into 10 g/d leafy, 30 g/d other vegetables, and 40 g/d grain. The HSRAM meat intake rate of 75 g/d has been separated into 60 g/d meat and 15 g/d poultry. The HSRAM daily intakes were converted to annual intakes using 365 days per year.

The native american subsistence resident (NASR) intakes are from DOE/RL-96-16 (April 1997). The daily vegetable intake rate of 660 g/d has been divided into 55 g/d leafy, 184 g/d other vegetables, 127 g/d fruit, and 295 g/d grains based on the distribution shown in Table 13. Similarly, the animal protein intake rate of 150 g/d has been separated into 135 g/d meat and 15 g/d deer. The organ intake of 54 g/d has been added to the meat intake for a total of 189 g/d. Daily intakes are converted to annual intakes using 365 days per year.

<u>Garden Area Determination:</u> From the estimated annual intakes of garden produce it is possible to estimate the minimum garden area needed to supply an individual. This area is needed for intruder calculations in which the exhumed waste is spread over a garden.

The quantity of food derived from the garden is proportional to the garden size. To estimate food production per unit garden area, two approaches were considered. The first is commercial food production in Washington State (WA Department of Agriculture 1994). Values for production per acre and per square meter are shown on Table 15. "cwt" means 100 pounds. Bushels of grain were assumed to have a density 70 percent that of water (700 kg/m^3). Thus a bushel of grain is assumed to weigh about 54 lb. The categories used for human consumption are from Table 13. The average person consumes the amount shown, in kg/y. Based on the average food production rate, the necessary garden area is 194 m^2. This total area is mostly needed for production of grains. This area also requires an efficient gardening operation to succeed.

The second approach to estimating garden size uses garden production estimates published by the Washington State University (WSU) Cooperative Extension (1980). Values are listed in Table 16. The document provides estimates of pounds of produce per 10 foot row in a garden. In addition, it gives recommended row spacings. The spacing was treated as the row width to compute production per unit area. The same average annual consumption rates from Table 13 were used to determine garden area needs. The WSU production estimates are higher than the commercial production averages hence the needed garden area is smaller (161 m^2). These were assumed to be optimum values under excellent growing conditions.

For performance assessment gardens, an efficiently planned and maintained garden of 200 m^2 will be assumed to supply 100% of the garden produce needs of a single adult over a year's time, or 25% of the garden produce needs of a family of four. Note that this represents a marked decrease from previous performance assessments. Ingestion doses from the post-intrusion garden are thus expected to increase due to the higher soil concentration.

Table 15. Commercial Food Production as a Basis for Garden Size.

Type of Produce	Yield per acre	Yield kg/m^2	Garden Area
Leafy Vegetables	**16.5 kg/y**	**2.35**	**7.0 m^2**
Cabbage			
Chard			
Lettuce	210 cwt	2.35	
Spinach			
Exposed Produce	**38.4 kg/y**	**1.79**	**21.5 m^2**
Apple	17 tons	3.81	
Apricots	6.23 tons	1.40	
Asparagus	35 cwt	0.39	

Table 15. Commercial Food Production as a Basis for Garden Size.

Type of Produce	Yield per acre	Yield kg/m²	Garden Area
Broccoli			
Brussel Sprouts			
Bushberries	7000 lb	0.78	
Cauliflower			
Cherry	6.93 tons	1.55	
Cucumber			
Eggplant			
Grape	10.83 tons	2.43	
Peach	10 tons	2.24	
Pear	15 tons	3.36	
Plums & Prunes	8.4 tons	1.88	
Rhubarb			
Snap Bean	90 cwt	1.01	
Strawberry	7000 lb	0.78	
Tomato			
Protected Produce	**55.7 kg/y**	**2.48**	**22.5 m²**
Bean (dry)	19 cwt	0.21	
Beet			
Carrot	580 cwt	6.50	
Kohlrabi			
Lentils	1340 lb	0.15	
Muskmelon			
Onion	360 cwt	4.04	
Parsnip			

Table 15. Commercial Food Production as a Basis for Garden Size.

Type of Produce	Yield per acre	Yield kg/m²	Garden Area
Peas	38 cwt	0.43	
Potato	590 cwt	6.61	
Radishes			
Squash			
Sweet Corn	150 cwt	1.68	
Tree Nuts	0.87 tons	0.20	
Turnip			
Watermelon			
Grains	**74.0 kg/y**	**0.52**	**143.3 m²**
Barley	67 bu	0.41	
Corn (for meal)	190 bu	1.16	
Hops	1884 lb	0.21	
Oats	68 bu	0.41	
Rye			
Wheat	63.6 bu	0.39	
		Total Garden Area:	**194 m²**

Notes: Food production data is from *Washington Agricultural Statistics 1993-1994*. Average consumption rates are from Yang and Nelson, 1986. A bushel of grain is assumed to have a density 70% of water, so that a bushel weighs 54 lb.

Table 16. Homeowner Food Production as a Basis for Garden Area.

Type of Produce	Yield lb/10'	Row Spacing inches	Yield kg/m²	Garden Area
Leafy Vegetables	**16.5 kg/y**		**4.48**	**3.7 m²**

Table 16. Homeowner Food Production as a Basis for Garden Area.

Type of Produce	Yield lb/10'	Row Spacing inches	Yield kg/m^2	Garden Area
Cabbage	10	24	2.44	
Chard	30	18	9.76	
Lettuce	10	18	3.25	
Spinach	5	12	2.44	
Exposed Produce	**38.4 kg/y**		**2.26**	**17.0 m^2**
Apple		12		
Apricots		12		
Asparagus	5	24	1.22	
Broccoli	10	24	2.44	
Brussel Sprouts	10	24	2.44	
Bushberries		12		
Cauliflower	8	24	1.95	
Cherry		12		
Cucumber	12	24	2.93	
Eggplant	8	36	1.30	
Grape		12		
Peach		12		
Pear		12		
Plums & Prunes		12		
Rhubarb	15	36	2.44	
Snap Bean	6	18	1.95	
Strawberry		12		
Tomato	30	48	3.66	

Table 16. Homeowner Food Production as a Basis for Garden Area.

Type of Produce	Yield lb/10'	Row Spacing inches	Yield kg/m^2	Garden Area
Protected Produce	**55.7 kg/y**		**3.85**	**14.4 m^2**
Bean (dry)		12		
Beet	10	12	4.88	
Carrot	12	12	5.86	
Kohlrabi	7	18	2.28	
Lentils		12		
Muskmelon	30	72	2.44	
Onion	10	12	4.88	
Parsnip	10	18	3.25	
Peas	10	18	3.25	
Potato	20	24	4.88	
Radishes	4	6	3.91	
Squash	25	48	3.05	
Sweet Corn	10	24	2.44	
Tree Nuts		12		
Turnip	20	18	6.51	
Watermelon	40	96	2.44	
Grains	**74.0 kg/y**		**0.59**	**126.2 m^2**
Barley	0.1	1	0.59	
Corn (for meal)	0.1	1	0.59	
Hops	0.1	1	0.59	
Oats	0.1	1	0.59	
Rye	0.1	1	0.59	

Table 16. Homeowner Food Production as a Basis for Garden Area.

Type of Produce	Yield lb/10'	Row Spacing inches	Yield kg/m²	Garden Area
Wheat	0.1	1	0.59	
			Total Garden Area:	**161 m²**

Notes: Food production data from *Home Gardens*, WSU Cooperative Extension Report EB-422. Average consumption rates are from Yang and Nelson, 1986.

2.2.4 Inhalation Rates for People

To determine the internal dose from the inhalation of resuspended particulate matter, one must be able to compute the total activity inhaled. Values are needed for the average air concentration, the time exposed at that concentration, and the average breathing rate during the exposure period.

A mass loading approach is used to estimate airborne concentrations of radionuclides for scenarios involving resuspension of contaminated soil as well as scenarios involving aerosolization of contaminated water. It is assumed that the air contains some average amount of contaminated soil or water per unit volume. This is then inhaled at a characteristic breathing rate for a length of time appropriate to the activity to calculate the total inhalation intake.

<u>Radionuclides Dispersed in Soil:</u> For scenarios with inhalation of radionuclides dispersed in soil, the average mass loading in air depends on what is happening to the contaminated soil. Active gardening produces the largest average mass loading, at 0.5 mg/m³. Routine activities outdoors are assume to take place at an average air concentration of 0.1 mg/m³. Indoor activities are assumed to take place at the lowest air concentration, 0.05 mg/m³. The basis for these air concentrations is presented very effectively in NUREG/CR-5512, Section 6.3.1.

In the well-drilling scenario, the individual is assumed to be exposed for 40 hours, spread over 5 days. This is the time needed to drill the well. During this time the individual breathes at the light activity rate for reference man (ICRP 23), 1.2 cubic meters per hour. The actual inhalation scenario is highly variable. The worker can be exposed to a high concentration when the waste material comes out of the hole. However, this material is soon buried by clean material coming from farther down the hole. In addition, the material is likely wetted as part of the drilling operation and to minimize fugitive dust emissions. Another modeling approach is to average the contamination over the assumed spreading area and compute the total inhaled over the 40 hour work period.

In the Grouted Waste performance assessment (WHC-SD-WM-EE-004) the well-drilling worker inhales resuspended dust at a concentration of 0.1 mg/m³ for one hour. However, the air concentration was not based on the waste concentration, but rather on the average soil concentration after spreading. In effect, the 0.64 m^3 of exhumed waste is diluted to a total volume of 15 m^3. These assumptions lead to the inhalation of 0.12 mg soil containing 0.0051 mg of waste, as shown in the calculations below.

Soil Inhaled (Grout PA) = $(1\ h)(1.2\ m^3/h)(0.1\ mg/m^3)$
= 0.12 mg soil inhaled

Waste Inhaled (Grout PA) = $(0.12\ mg\ soil)(0.64\ m^3)/(15\ m^3)$
= 0.0051 mg waste inhaled

If the well-driller's dust is undiluted waste, the worker would inhale 0.12 mg of waste. However, the actual inhalation time is probably greater than one hour. Since the waste layer is about 10% of the total well volume, and the well takes 40 h to drill, the time of exposure to the waste is (40 h)(0.10)=4 h. This would mean the worker inhales 4.8 mg of soil containing 0.48 mg of waste, as shown in the calculations below.

Soil Inhaled (ILAW PA) = $(40\ h)(1.2\ m^3/h)(0.1\ mg/m^3)$
= 4.8 mg soil inhaled

Waste Inhaled (ILAW PA) = $(4.8\ mg\ soil)(0.14\ m^3)/(1.4\ m^3)$
= 0.48 mg waste inhaled

For estimating inhalation exposure in the post-drilling residential scenario, the individual spends the entire year living in the contaminated area. The Grouted Waste performance assessment (WHC-SD-WM-EE-004) used an average inhalation rate of 8520 m^3 per year and an average air concentration of 0.1 mg/m^3. The annual amount of soil inhaled was 852 mg. The 200 West Area Burial Ground performance assessment (WHC-EP-0645) used more detailed inhalation assumptions based on PNNL-6312. The inhalation dose was based on an annual inhalation of 445 milligrams.

Inhalation dose for the ILAW PA will be based on a refinement of the model used for the 200 West Area Burial Ground. It is also very similar to the method discussed in NUREG/CR-5512.

The air concentrations shown in Table 17 are used to estimate the equivalent time of exposure to an average air concentration of 0.1 mg/m^3. The actual air concentrations used in the table are discussed at length in NUREG/CR-5512, Section 6.3.1. The values chosen represent conservative bounds on likely concentrations for the activities indicated. The exposure times are also based on the NUREG/CR-5512, although the document is not as explicit as to the assumptions behind the time periods used. It appears that NUREG/CR-5512 includes a vacation period of 2 weeks away from the residence. This is a minor (3%) reduction in the mass inhaled, and is not included in the ILAW PA. The combinations shown on Table 17 for the residential scenario lead to the annual inhalation of 573 milligrams of soil, which lies between the values used in the prior Hanford Site performance assessments. This value will also be used for the all-pathways farmer scenario.

The Columbia River population average is based on an exposure of 12 hours per day at the daily average breathing rate. This leads to an annual inhalation of 416 milligrams of soil, as shown below. In the 200 West Area Burial Ground PA (WHC-EP-0645) the annual inhalation was twice as great based on wide-spread irrigation leading to contaminated airborne material over a much larger region. This is unrealistically high, since the air concentration of contaminated material is bounding. There are other sources of airborne material that are not contaminated. Hence the lower estimate will be used in the ILAW PA for population dose.

(8766 h/y)(0.5)(0.95 m3/h)(0.1 mg/m3) = 416 mg/y

In Table 17 the 2920 hour period asleep is 8 hours per day, 365 days per year. For 180 days the individual works in or near his fields for 10 hours, making a total of 1800 hours outdoors. Of this 1800 hours, 100 hours is spent in dusty conditions. The remainder of the year (4046 hours) is spent indoors. The breathing rates shown on the table are from ICRP Report Number 23 on Reference Man (ICRP 23). No adjustment is made for the finite area of the contamination because the individual spends most of the year close to the emission source. Adjustment for a 4 week period away from home would reduce the annual inhalation intake by less than 10 percent. Therefore, the above value will be used for both the post-intrusion garden as well as the irrigated farm.

Table 17. Calculation of the Inhalation Time for the Residential Gardener.

Activity	Air Concentration (mg/m^3)	Exposure Time (h/y)	Breathing Rate (m^3/h)	Mass Inhaled (mg/y)
Asleep	0.05	2,920	0.45	65.7
Indoors	0.05	4,046	1.2	242.8
Outdoor	0.1	1,700	1.2	204.0
Gardening	0.5	100	1.2	60.0
Away		0		0.0
	Total Time:	8,766		572.5
	Averages:	6,030	0.95	573

Note: The individual spends 8 hours per day, 365 days per year asleep. For 180 days the individual spends 10 hours each day in the fields. Of this time, 100 hours are spent in relatively dusty conditions.

For routine exposure calculations, a daily average breathing rate (0.95 m^3/hr or 22.8 m^3/d) and air concentration (0.1 mg/m^3) must be used. Using these values, the annual intake of 573 mg requires an inhalation exposure time of 6030 hours, as shown in the last line of Table 17. Note also that the amount of waste actually inhaled depends on the garden size. If 0.14 m^3 of waste are exhumed and spread over a 200 m^2 garden that is tilled to a depth of 0.15 meter, then the 573 mg of soil contains 2.7 mg of waste. This assumes the densities of the waste and soil are nearly the same.

$$\text{Waste Inhaled} = (573 \text{ mg soil})(0.14 \text{ m}^3)/(200 \text{ m}^2)/(0.15 \text{ m}) = 2.7 \text{ mg}$$

The result for the post-intrusion resident is substantially larger than the amount inhaled by the driller. In addition, the inhaled masses can be normalized to a unitless fraction, the activity inhaled per unit activity exhumed. This is illustrated below using an area density of 225 kg/m^2 based on a soil density of 1500 kg/m^3 and a tilling depth of 0.15 cm. This method of comparison avoids the need to know the waste thickness and well diameter.

$$\text{Driller inhalation fraction} = (4.8 \text{ mg})/(225 \text{ kg/m}^2)/(100 \text{ m}^2)$$
$$= 2.13 \times 10^{-10} \text{ Ci inhaled per Ci exhumed}$$

Gardener inhalation fraction = (573 mg)/(225 kg/m^2)/(200 m^2)
= 1.27 x 10^{-8} Ci inhaled per Ci exhumed

In the HSRAM scenarios, the average air concentration is 50 μg/m³. The daily inhalation rate is 20 m³/d. Thus the individuals inhale 1.0 mg soil each day. In the industrial scenario, the annual inhalation time is 250 days so that the total annual inhalation is 250 mg soil. In the residential and agricultural scenarios the annual inhalation time is 365 days so that the total annual inhalation is 365 mg soil. The HSRAM inhalation intakes are therefore lower than the residential gardener commonly used in Hanford Site performance assessments.

The native american subsistence resident scenario (DOE/RL-96-16 Table 5.7) has the individual inhaling 30 m³/d at an average concentration of 100 μg/m³. Thus the daily intake rate is 3.0 mg/d, and the annual intake is 1095 mg soil. As with the food pathways, this is roughly twice the intake of the all-pathways farmer. Therefore, the inhalation dose from resuspended soil should be roughly twice as great also.

Radionuclides Suspended in Water: For scenarios with inhalation of radionuclides suspended in water, two situations are modeled. The first is the inhalation of spray created by a shower. The second is inhalation of steam in a wet sauna or "sweat lodge". A mass loading approach is used to estimate intakes for both cases.

The two parts of the mass loading approach are droplet suspension in air, and evaporation of water. The average water droplet concentration in air during these activities is about 10 mg liquid/m³, a value characteristic of fogs (Hinds 1982). The evaporation of the contaminated water leads to partially saturated water vapor (a gas) in the shower or sauna. The assumed temperature and relative humidity determines the water vapor concentration. Note that only a small fraction of the radioactivity in the evaporating water becomes airborne. In *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Volume 1* (DOE-HDBK-3010-94) data for the sudden depressurization of superheated aqueous solutions is presented in Table 3-5 for various initial pressures and volumes. With a source volume of 0.35 L at a pressure of 60 psig, the respirable release fraction is 0.006. A somewhat larger value of 0.01 will be used to represent the resuspension from pouring water on hot rocks in the sweat lodge, and for the spray of a shower. (The only exception to this is tritium. Since it is assumed to be oxidized, 100% of the tritium becomes airborne.) From data cited in DOE-HDBK-3010-94, it will be assumed that 99% of the radioactive contaminants (except for tritium) are not aerosolized when the water evaporates. The assumed temperatures and relative humidities for the shower and sweat lodge are listed in Table 18 below. Values for ambient conditions at the irrigation site are calculated from the average temperature and relative humidity at the Hanford Site (PNNL-12087) during the irrigation months (April through September). The evaporative entrainment fraction is assumed to be an order of magnitude smaller, again based on data cited in DOE-HDBK-3010-94 for lower temperature conditions without spray sources.

Also shown in Table 18 are the vapor concentrations calculated from the vapor pressure and relative humidity for the assumed temperature. The percents are by volume. The row labeled "Evaporated Water" is the concentration of water in the air. It is calculated using the formula weight for water (18.0153 g/gmole) and the ideal gas law, as shown below. Note that the temperature is in degrees kelvin rather than celsius, and also that Table 18 uses cubic meters (m^3) as the unit for volume.

Mass of water vapor per unit volume =
(18.0153 g/gmole)(Vapor Conc)/(0.08057 L·atm/gmole/°K)/(Temperature)

The line labeled "Entrained Water" is 1% of the "Evaporated Water" line to reflect the fact that evaporation leaves most of the contaminants behind. The line labeled "Droplets" is the bounding droplet concentration of a fog. Under ambient conditions normally found at the irrigation site there is no fog. The fog is only found in the shower and sauna.

Table 18 shows the effective total concentration of ground water in the air in the line labeled "Total Water". This line is the sum of the "Entrained Water" and "Droplets" lines. The line labeled "Tritium Total" is the sum of the "Evaporated Water" and "Droplets" lines.

The "Dilution Adjustment" is for the ambient humidity exposure only. It divides the year into two halves: irrigation and no irrigation. During the irrigation season the ground water is diluted by natural precipitation. As discussed in Section 2.5, this leads to a factor of 94%. During the remainder of the year (without irrigation) the contaminated fraction of the humidity is assumed to be reduced to 50%. Activities such as cooking and cleaning supply the contaminated portion of the humidity. For ambient conditions, the adjustment is calculated as shown below.

Ambient Dilution Adjustment = (94%)(0.5) + (50%)(0.5) = 72%

The annual exposure times depend on the exposure scenario, and determine the annual inhalation intake. Parameters for the ILAW PA are listed in the lower half of Table 18. The last lines in the table are calculated as the product of the "Annual Count", the "Event Duration", the "Breathing Rate", the "Dilution Adjustment", and the total water intake. Values are given for both tritium and all other nuclides. The assumed density of the irrigation water is 1.0 kg/L.

Table 18. Airborne Ground Water Intakes.

Parameter	Ambient	Shower			Sauna
Temperature	19.3°C (66.8°F)	40°C (104°F)			50°C (122°F)
Relative Humidity	39.8%	80%			80%
Water Vapor Concentration	0.87%	5.82%			9.74%
Evaporated Water, g/m³	6.5	41			66
Entrained Contaminants, g/m³	0.0065	0.41			0.66
Droplets, g/m³	0	0.01			0.01
Total Water, g/m³	0.0065	0.42			0.67
Tritium Total, g/m³	6.5	41			66
Dilution Adjustment	72%	100%			100%
Breathing Rate, m³/h	0.95	1.2			1.2
Exposure Scenario	All-Pathways and NASR	All-Pathways	HSRAM Industrial	HSRAM Residential, Agricultural	NASR
Event Duration, h/d	24	0.25	0.167	0.167	1
Annual Count, d/y	365	365	250	365	180
Total Inhaled, L/y	0.039	0.046	0.021	0.031	0.14
Total Tritium, L/y	39	4.5	2.1	3.1	14

Notes:

Ambient conditions are those found at the irrigation site. The average temperature and relative humidity during the irrigation season (April through September) are from PNNL-12087. No aerosol droplets are present. The "Dilution Adjustment" is based on the presence of natural precipitation during the irrigation season and half the normal during the remainder of the year.

The shower temperature is based on typical hot water settings. The relative humidity during the shower is a value selected from the likely range of 60% to 100%.

The sauna or sweat lodge experience lasts one hour and is repeated approximately every other day during the year. The temperature and relative humidity are reasonable assumptions.

The evaporative entrainment from ambient sources is assumed to be 0.1%, while the entrainment during showers and saunas (sweat lodge) is assumed to be 1%.

The listed breathing rates are from ICRP 23. The assumed density of the ground water is 1.0 kg/L.

Because the total groundwater inhaled is considerably smaller than the total groundwater ingested during the year the moisture inhalation dose should be smaller also. These moisture inhalation pathways were not used in prior Hanford performance assessments.

The "Sauna" for the NASR is also the "Sweat Lodge" used in DOE/RL-96-16. The assumed exposure conditions for the ILAW PA scenario leads to an inhalation of 0.14 L/y. The exposure conditions in DOE/RL-96-16 lead to the much larger inhalation of about 57 L/y. The reason for the difference is the extreme exposure conditions found in DOE/RL-96-16. For example, the sweat lodge temperature is 60 °C (140 °F) with a relative humidity of 100%, which means the air in the sauna is 20% water vapor. The sudden 20% reduction in oxygen concentration would certainly result in labored breathing, possibly fainting. The exposure to high temperature at saturated conditions for one hour would lead to skin burns over most of the body. Most of the difference is due to the assumption that 100% of the dissolved impurities become airborne when the water evaporates.

2.2.5 External Exposure Times

During the drilling operation, the worker is exposed to varying dose rates. Until the waste is exhumed this dose rate is zero. While the waste comes from the hole, the dose rate is high. Since the radiation source is small (about 0.14 m^3), the dose rate varies inversely with the square of the worker's distance from the waste. The waste is soon covered with clean soil from deeper in the well, which reduces the dose rate. To represent the potential dose to the worker, the waste is assumed to be spread into a layer 15 cm thick over an area of 100 m^2. The external dose rate factors of Table 10 are used to estimate the dose from 40 hours of exposure. This is the same approach used in the Grouted Waste performance assessment.

It should be noted that this assumption for the drilling operation exaggerates the external dose to the worker. If a flattened mound is placed 2 meters to the side of the worker, the dose rates are actually less than those from a 100 m^2 slab, even though the nuclide concentration is higher. With a general area contamination, the worker is standing on a portion of the contamination and receives higher dose rates.

The external dose rate factors of Table 10 apply to the center of the contaminated area. As one moves away from the center the dose rate decreases sharply with distance, unlike the resuspended dust concentration in the air. The airborne dust concentration decreases by diffusion and turbulent mixing rather slowly with distance, falling to half the peak value at a distance of about 100 m. By contrast, external dose rates at the edge of the contaminated area are half the value at the center of the contaminated area. At a distance of 10 meters from the edge of the contamination the dose rates are less than 10 percent of the center value.

For the post-intrusion resident, only the garden is contaminated, while for the irrigation scenarios most of the area near the person's dwelling is contaminated. The extent of the contaminated areas will affect the calculation of external dose in the two exposure situations. The exposure to soil contamination is divided into two time periods during the year. The first period is the time actually spent standing in the contamination. The second period is the total time near the contamination, or indoors.

In the post-intrusion garden scenario, the external exposure time is taken to be half the total time outdoors, or 900 hours. In other words, the individual spends a time equivalent to 900 hours during the year standing in the center of his garden. Since the dose rate decreases rapidly with distance from the small garden, the time away from the garden has zero exposure.

In the irrigation scenarios, it is assumed that the entire time outdoors (1800 hours) is spent in exposure conditions similar to the center of an irrigated field. However, the dose rate indoors is reduced by a factor of 3. This factor of 3 is discussed in detail in NUREG/CR-5512, Section 6.7.4. Therefore the effective time of exposure at the unshielded dose rate is 4120 hours, as shown below.

$$(1800 \text{ hr}) + (6966 \text{ hr})/3 = 4120 \text{ hours}$$

Prior Hanford Site performance assessments used different values. The Grouted Waste performance assessment used an effective time of 4383 hours for both the post-intrusion gardener, the all-pathways irrigator, and the populations. The 200 West Area Burial Ground performance assessment used an effective time of 3260 hours for individuals and 4383 hours for populations. The effective exposure times selected for the ILAW performance assessment differ from the values used in prior Hanford performance assessments. Note that the average exposure time for the Columbia River population is chosen to be 4383 hours to be consistent with prior calculations.

For the HSRAM scenarios, the external exposure in the industrial scenario is 8 h/d, 146 d/y for an annual total time of 1,168 h. The residential and agricultural scenarios use an exposure time of 24 h/d, 365 d/y for an annual total of 8760 h/y. All external doses are reduced using the factor 0.8 to account for shielding from building walls. Therefore, the annual exposure time for the industrial scenario is 934 hours, and for the residential/agricultural scenarios is 7008 hours. The NASR also uses 7008 h/y for the effective external annual exposure time.

Comparison of the Driller and Post-Intrusion Resident. To compare the driller and the post-intrusion resident, note that the intake parameters are directly proportional to the dose from each pathway. For a few nuclides there are additional differences due to removal processes such as radioactive decay or leaching from the surface layer. Ignoring these details, Table 19 summarizes the important parameters for comparing doses. The inhaled and ingested amounts are in terms of the grams of waste exhumed. (Waste density is assumed to be the same as surface soil density.) The external exposure time has been adjusted by the waste volume to garden volume ratio to correct for the different garden sizes. In each pathway, the intake by the Driller is significantly smaller than the intake by the Gardener. Thus the dose to the Driller will be less than the dose to the Gardener for all nuclides.

Table 19. Comparison of the Intake Parameters for the Intruders.

Pathway	Driller	Gardener	Ratio
Waste Ingested	4.7 mg	170 mg	0.03
Vegetables ingested	0.0	43 kg	0.00
Waste Inhaled	0.48 mg	2.7 mg	0.18
External factor	$(40h)(0.14m^3)/(15m^3)$ = 0.37 h	$(900h)(0.14m^3)/(30m^3)$ = 4.2 h	0.09

Note: The above values assume 0.14 m^3 of waste are exhumed and spread over 100 m^2 for the Driller and 200 m^2 for the Gardener. In both scenarios the soil mixing depth is 0.15 meter.

Some of the external exposure pathways noted in Table 3 are much smaller than internal pathways that accompany the external exposure. For example, the external exposure to an individual whose livestock and household pets drink contaminated well water is much smaller than the internal dose resulting from the consumption of animal products (milk, meat, poultry, and eggs). This follows from the observation that the dose resulting from a given amount of radioactivity outside the body (leading to an external dose) is orders of magnitude lower than the dose resulting from the same amount of radioactivity ingested or inhaled (leading to an internal dose). Admittedly, the individual will not eat all of the radioactivity present in an animal, since the radioactivity will be present in organs and tissues that are not normally eaten. However, the use of all four animal pathways combined with the observation that the individual is in close proximity to the animal for only short periods during the day gives assurance that this external pathway can be ignored.

A more detailed evaluation of the external dose from submersion in contaminated air is needed in order to eliminate it from further consideration. Table 12 shows the submersion dose rate factor as well as the ratio between the inhalation dose and the submersion dose. The smallest ratio is 5.06 for Na-22. Hence the submersion dose can be ignored since it will never be a significant part of the total dose.

2.2.6 Absorption Through the Skin

Each exposure scenario includes dermal contact with the contaminated medium. The driller and post-intrusion resident get the contaminated soil on their skin. The ground water scenarios have contaminated water being used for showers and saunas. These two will be treated separately to demonstrate that the likely intake from contamination being absorbed through the skin into body fluids is negligible compared to other ingestion pathways.

An exception is for tritium as water vapor. The inhalation dose factor for tritium includes absorption through the skin in addition to the lungs by increasing the value by 50%. The ingestion dose factor is not modified.

Internal dose factors for radionuclides absorbed through the skin can be calculated from the numbers given in Table 7 by dividing the ingestion dose factor by the gut-to-body-fluid transfer fraction (f1). This is somewhat inexact because the material in the gut is wet and has a variety of chemicals secreted by the body to aid in the absorption of nutrients. In addition, the interior surface area of the small intestine is larger than the skin area of the entire body to aid in the absorption of nutrients.

For both soil and water in contact with the skin, the transfer from the skin to the body fluids is assumed to be proportional to the f1 parameter. The f1 transfer fraction thus cancels out of the calculation, and dermal contact becomes another ingestion dose.

Contaminated Soil. Soil adheres to the skin, which is one reason people take showers. Typical soil adherence values range from 0.1 mg/cm^2 to 5 mg/cm^2. The adult body has a skin area of about 20,000 cm^2. The hands and arms have about 20% of the total area. A small fraction of the contamination present on the skin will be absorbed into the body through the skin. This fraction is assumed to be one percent of the f1 value. Table 20 summarizes the affected skin areas, soil adherence, and annual contact events for each of the exposure scenarios. The product of these factors gives the effective soil ingestion due to dermal contact. The values shown are small compared to the values for direct ingestion of soil presented in Tables 13 and 14. Hence the approach taken in DOE/RL-91-45 to neglect dermal absorption of radionuclides will be adopted in the ILAW PA also.

Contaminated Irrigation Water. Waterborne contaminants in contact with the skin may potentially be absorbed through the skin into the body fluids. The leading dermal contact events are showers and the sauna or sweat lodge. Since these expose the entire skin surface, the potential for significant absorption exists. However, contact time is limited to 15 minutes for showers and 1 hour for the sauna or sweat lodge. Based on typical values for the dermal absorption constant (0.001 cm/h or less) and the dermal absorption method described in PNNL-10523 (Section 2.2), it is concluded that effective intakes per shower or sauna are less than 20 cm^3. With up to 180 saunas per year, the annual ingestion intake increases by less than 1 percent. Therefore, the dermal absorption of radionuclides in irrigation water will not be explicitly included in the calculations for the ILAW PA.

Table 20. Effective Soil Ingestion Due to Dermal Contact With Soil.

	Intruder	Post-Intrusion Resident and Irrigated Farm	HSRAM Industrial	HSRAM Residential and Agricultural	NASR
Skin Surface Fraction	0.25	0.2	0.25	0.25	0.25
Soil Adherence, mg/cm^2	0.25	0.25	0.20	0.20	1.0
Contact Frequency, d/y	5	100	146	180	365
Effective Annual Ingestion, g/y	0.063	1.0	1.5	1.8	18

Notes:

The total skin surface area for an adult is 20,000 cm^2. It is assumed that 1% of the soil adhering to the skin is available for absorption into the body.

The effective annual ingestion is the product of the total skin area, the skin surface fraction, 1% of the soil adherence, and the contact frequency. The NASR has the greatest intake.

HSRAM - Hanford Site Risk Assessment Methodology
NASR - Native American Subsistence Resident

2.3 Animal Parameters

The animal parameters discussed here are those pertaining to the eventual concentration of radioactivity in animal products consumed as food, such as fish, milk, meat, poultry, and eggs. The equilibrium model used to represent various animals assumes that they take in radioactivity by inhalation, ingestion, and dermal absorption at a rate which changes slowly during the year. The concentration in the animal reaches a steady-state maximum related to the concentration in its environment. Note that the radiation doses received by the animals are assumed to be low enough to not affect their health or metabolism. The contaminant concentration in food products is proportional to the level of contamination in the animal's environment, particularly in the food it consumes. The constants of proportionality are called bioaccumulation factors, or transfer factors.

Not all animals have transfer factors developed for them. It is assumed that other aquatic animals such as bottom-dwelling fish, crustaceans and mollusks are consumed in minimal amounts. If a group of people is identified who consume significant quantities of these creatures then efforts will be made to quantify the transfer factors which would apply to them. Other land animals such as pigs or goats are assumed to have transfer factors which differ very little from cattle.

The contaminant concentration in cattle and poultry depends on the rate at which the contaminant is consumed. The cattle and poultry diets are discussed in the next section. The equilibrium transfer factors for these animals are discussed afterward.

2.3.1 General Animal Parameters

The daily intake rates assumed for cattle and poultry are listed in Table 21. These are from NUREG/CR-5512, Section 6.5.1. No distinction is made between the diets of poultry raised for food and egg-laying hens. For comparison with prior Hanford Site performance assessments, the default intake rates used by the GENII program (PNNL-6584) are also shown in Table 21. The water intake rates are the same for both. Note that the GENII program does not distinguish between the two types of stored feed (i.e. hay or grain), nor does it allow the animals to ingest soil directly.

To calculate the radionuclide concentrations in the animal foods, it is necessary to introduce a "dry-to-wet ratio". The "dry-to-wet ratio" is a unitless quantity measured as the ratio of the dry weight of the item to its wet weight. The "dry-to-wet ratio" for stored hay applies at the time of harvest. In practice the hay is dried before being fed to cattle. Thus the "dry-to-wet ratio" for sun-cured hay is reported as approximately 0.9, similar to stored grain. All of the wet weights shown on Table 21 are at the time of harvest or when the animal is grazing.

The intake rates found in NUREG/CR-5512 will be used in the current performance assessment. The principal reason for this change from prior Hanford performance assessments is the extra detail provided on the diet. Previous performance assessments relied on the GENII software, which is unable to accommodate this detail. The ILAW PA for the low-level waste glass form will utilize hand calculations that incorporate the added detail.

The exposure of special groups living near waste sites or near locations where the ground water enters the Columbia River would probably include the consumption of some type of native game animals. These animals could acquire radioactivity from drinking and grazing near locations were ground water enters the river. The larger examples of these, such as deer, would graze over a large area. Thus only a small portion of the deer would be contaminated. Similarly, the smaller animals might derive all of their nourishment from a contaminated area. However, such animals would have to be harvested from many locations over the course of a year. The average concentration from all such animals would be much lower due to the large forage area needed for hunting and gathering. It will be assumed that the game animals are contaminated at such a low level compared with the domesticated animals that the dose from game animals can be ignored.

Table 21. Animal Feed, Water, and Soil Intake Rates

Values from NUREG/CR-5512 for use in the ILAW PA							
Type of Feed	dry-to-wet ratio	Beef, kg/d		Milk, kg/d		Poultry, kg/d	
		dry	wet	dry	wet	dry	wet
Fresh Forage	0.22	3	14	8	36	0.0275	0.13
Stored Hay	0.22	6	27	6	29	0	0
Stored Grain	0.91	3	3	2	2	0.0825	0.09
Total Feed, kg/d:		12	44	16	67	0.110	0.22
Soil Ingestion Rate:		0.6 kg/d		0.8 kg/d		0.011 kg/d	
Drinking Water:		50 L/d		60 L/d		0.3 L/d	
Values from GENII (PNNL-6584) used in previous Hanford Site PAs							
Type of Feed	dry-to-wet ratio	Beef, kg/d		Milk, kg/d		Poultry, kg/d	
		dry	wet	dry	wet	dry	wet
Fresh Forage	0.20	10	51	8	41	0	0
Stored Hay	0.18	3	17	2	14	0.022	0.12
Stored Grain	NA	NA	NA	NA	NA	NA	NA
Total Feed, kg/d:		13	68	10	55	0.022	0.12
Soil Ingestion Rate:		NA		NA		NA	
Drinking Water:		50 L/d		60 L/d		0.3 L/d	

The wet weights are at the time of harvest or grazing. The GENII software does not distinguish between stored hay and stored grain. In addition, GENII does not consider ingestion of soil by grazing animals.

It should be noted that animals killed by native hunters would be more efficiently scavenged than common farm animals. Some of the internal organs would be eaten. The animal skins could be used for clothing, and larger bones could be used as tools or ceremonial items. The more extensive use of animal parts could increase the exposed person's radiation dose. Nevertheless, it will be assumed that this dose is small compared with that from farm animals.

2.3.2 Equilibrium Transfer Factors

The equilibrium transfer factors for cattle and poultry relate the rate of intake of a contaminant to the eventual steady-state concentration in meat or milk or eggs. These parameters are the ratio of the equilibrium concentration of a nuclide in the animal product to the daily intake by the animal. For beef, poultry and eggs the units are Ci/kg per Ci/d (equivlent to d/kg), while for milk the units are Ci/L(milk) per Ci/d (equivalent to d/L). Values obtained from NUREG/CR-5512 (1992) are listed in Table 22. Transfer factors for organs such as liver or brain are not available. Since some elements may be found in higher concentrations in these tissues, individuals who consume the organs would receive higher doses from the radioactive isotopes of the elements.

The concentration of waterborne contaminants in fish is assumed to be proportional to the concentration of the contaminant in the water environment of the fish. The constant of proportionality for fish is called a "bioaccumulation" factor. It is the average concentration of the contaminant in the edible portion of the fish divided by the concentration in the water. This parameter has units of L/kg. Values for fresh-water fish from NUREG/CR-5512 (1992) and PNWD-2023 (1994) are listed in Table 22 under the column labelled "Fish". The NUREG/CR-5512 values have been used in prior Hanford Site performance assessments. The Hanford Environmental Dose Reconstruction (HEDR) values are recently published and have not been used in prior performance assessments. There are only two bioaccumulation factors which are affected by the HEDR research. The first is for sodium (100 in NUREG/CR-5512 became 8) and neptunium (250 in NUREG/CR-5512 became 21). These are marked in Table 22.

Table 22. Transfer Factors for Cows, Chickens, and Fish

Element	Meat d/kg	Milk d/L	Poultry d/kg	Eggs d/kg	Fish L/kg	Atomic Number
H	0.010*	0.0082*	1.9*	2.1*	1	1
Be	0.001	9.0E-07	0.4	0.02	2	4
C	0.049*	0.0105*	4.2*	3.1*	4,600	6
Na	0.055	0.035	0.01	0.2	8*	11
Si	4.0E-05	0	0.2	0	1,000	14
Cl	0.08	0.015	0.03	2	50	17
K	0.02	0.007	0.4	0.7	1,000	19
Ti	0.03	0.01	0.004	0.003	100	22
V	0.0025	2.0E-05	0.2	0.8	200	23
Mn	0.0004	0.00035	0.05	0.065	400	25
Fe	0.02	0.00025	1.5	1.3	2,000	26

Table 22. Transfer Factors for Cows, Chickens, and Fish

Element	Meat d/kg	Milk d/L	Poultry d/kg	Eggs d/kg	Fish L/kg	Atomic Number
Co	0.02	0.002	0.5	0.1	330	27
Ni	0.006	0.001	0.001	0.1	100	28
Se	0.015	0.004	8.5	9.3	170	34
Rb	0.015	0.01	2	3	2,000	37
Sr	0.0003	0.0015	0.035	0.3	50	38
Y	0.0003	2.0E-05	0.01	0.002	25	39
Zr	0.0055	3.0E-05	0.000064	0.00019	200	40
Nb	0.25	0.02	0.00031	0.0013	200	41
Mo	0.006	0.0015	0.19	0.78	10	42
Tc	0.0085	0.01	0.03	3	15	43
Ru	0.002	6.0E-07	0.007	0.006	100	44
Pd	0.004	0.01	0.0003	0.004	10	46
Ag	0.003	0.02	0.5	0.5	2	47
Cd	0.00055	0.001	0.84	0.1	200	48
In	0.008	0.0001	0.3	0.8	100,000	49
Sn	0.08	0.001	0.2	0.8	3,000	50
Sb	0.001	0.0001	0.006	0.07	200	51
Te	0.015	0.0002	0.085	5.2	400	52
I	0.007	0.01	0.018	2.8	500	53
Cs	0.02	0.007	4.4	0.49	2,000	55
Ba	0.00015	0.00035	0.00081	1.5	200	56
Pm	0.005	2.0E-05	0.002	0.02	25	61
Sm	0.005	2.0E-05	0.004	0.007	25	62
Eu	0.005	2.0E-05	0.004	0.007	25	63
Gd	0.0035	2.0E-05	0.004	0.007	25	64
Ho	0.0045	2.0E-05	0.004	0.007	25	67
Re	0.008	0.0015	0.04	0.4	120	75

Table 22. Transfer Factors for Cows, Chickens, and Fish

Element	Meat d/kg	Milk d/L	Poultry d/kg	Eggs d/kg	Fish L/kg	Atomic Number
Tl	0.04	0.002	0.3	0.8	5,000	81
Pb	0.0003	0.00025	0.2	0.8	100	82
Bi	0.0004	0.0005	0.1	0.8	15	83
Po	0.0003	0.00035	0.9	7	500	84
Ra	0.00025	0.00045	0.03	2.0E-05	70	88
Ac	2.5E-05	2.0E-05	0.004	0.002	25	89
Th	6.0E-06	5.0E-06	0.004	0.002	100	90
Pa	1.0E-05	5.0E-06	0.004	0.002	11	91
U	0.0002	0.0006	1.2	0.99	50	92
Np	5.5E-05	5.0E-06	0.004	0.002	21*	93
Pu	5.0E-07	1.0E-07	0.00015	0.008	250	94
Am	3.5E-06	4.0E-07	0.0002	0.009	250	95
Cm	3.5E-06	2.0E-05	0.004	0.002	250	96
Bk	3.5E-06	4.0E-07	0.0002	0.009	50	97
Cf	0.005	7.5E-07	0.004	0.002	25	98

*Beef, milk, poultry, and egg transfer factors for H-3 and C-14 were computed from the equilibrium model described in the text. Fish bioaccumulation factors for sodium and neptunium are from PNWD-2023. Other transfer factors are from NUREG/CR-5512. Above transfer factors are based on the wet weights.

Transfer factors for tritium (H-3) and C-14 are computed from an equilibrium model. The ratio of radioactive H-3 (or C-14) to the non-radioactive hydrogen (or carbon) in the animal's diet is assumed to be reproduced in the food product. The equilibrium transfer factor is then the fraction of hydrogen (or carbon) in the food product divided by the daily intake of hydrogen (or carbon). The assumed element fractions are listed in Table 23 below. Values in this table were taken from NUREG/CR-5512.

Table 23. Hydrogen and Carbon Fractions for Equilibrium Models

Food Pathway Item	Hydrogen Fraction	Carbon Fraction
Garden Soil	0.022	0.03
Leafy Vegetables	0.10	0.09
Other Vegetables	0.10	0.09
Fruit	0.10	0.09
Grain	0.068	0.40
Fresh Forage	0.10	0.09
Stored Hay	0.10	0.09
Stored Grain	0.068	0.40
Beef	0.10	0.24
Milk	0.11	0.07
Poultry	0.10	0.20
Eggs	0.11	0.15

Notes: All fractions listed above are based on the wet weight of the item. All fractions are taken from NUREG/CR-5512, except for the hydrogen fraction in garden soil, which is calculated as the soil porosity (30%) times the density of water (1.0 kg/L) divided by the soil density (1.5 kg/L) times 9. Hydrogen fractions include organically bound hydrogen as well as water. The effective water fraction is the hydrogen fraction times 8.94, which is the ratio of molecular weights for water and hydrogen.

The bioaccumulation factors shown in Table 22 are used to estimate total population dose from fish consumption to people living near the Columbia River. The edible portion of fish is the muscle normally cooked and consumed. The rest of the fish is assumed to be discarded. If there are individuals who eat or otherwise use other parts of the fish they could receive additional dose.

Although not important for the ILAW PA, a subject requiring research is the equilibrium transfer factors for wild animals consuming native vegetation. These species may be "harvested" by humans for food. In addition, since standard uptake factors are for muscle tissue only, there would need to be organ-specific uptake factors for those internal organs which may be consumed by special groups of people.

2.4 Plant Parameters

Living plants supplying food for people fall into two broad categories, aquatic plants and terrestrial plants. It will be assumed that aquatic plants contribute very little to the typical human diet -- either directly or indirectly. If exceptions are identified then a suitable set of parameters and models for contaminant uptake by aquatic plants and subsequent consumptions by humans will be utilized. All plants eaten are assumed to be terrestrial rather than aquatic.

The calculation of radionuclide concentrations in living terrestrial plants uses three main routes, (1) root uptake, (2) resuspension to leaves (also called "rain splash"), and (3) direct deposition of irrigation water on foliage. Each of these will be considered separately below. The three uptake routes are then combined to obtain the total concentration in edible portions of plants.

2.4.1 Root Uptake

The model for root uptake of a contaminant into terrestrial plants assumes that the concentration in the edible portion is proportional to the concentration in the soil at the time of harvest. The constants of proportionality are known as the soil-to-plant concentration ratios. These concentration ratios are measured as the concentration of the dry produce item divided by the soil concentration. They have no units, since the soil and food items have the same mass-based concentration units, eg. pCi/kg.

Because the human consumption rates shown in Tables 13 and 14 are the wet weights, it is necessary to select suitable constants to convert from dry weight to wet weight. These constants are known as "dry-to-wet ratios". They are simply the dry weight of the food item divided by the wet weight of the item. The "dry-to-wet ratios" from three sources are listed in Table 24. The values chosen for the ILAW PA are from PNWD-2023 for leafy vegetables and NUREG/CR-5512 for the others. The chosen values for the ILAW PA appear in the last column of Table 24. The values under the "GENII" column have been used in prior Hanford Site performance assessments.

The GENII dry-to-wet ratios for grains differ greatly from the other collections. However, it has been assumed in prior performance assessments that grains would be unlikely to become contaminated in the intruder or irrigation scenarios. The intruder would probably not raise grains in his home garden, and the principal grain crop in this area (dry-land wheat) would not be irrigated. For the ILAW PA grains are included as contaminated vegetable intakes. The basis for this approach is that some grains (e.g. corn) are irrigated. In addition, the 25% contamination fraction incorporates the presence of non-irrigated grains (e.g. wheat) in the individual's diet.

Table 24. Dry-to-Wet Ratios for Vegetation Consumed by Humans

Type of Produce	GENII	ORNL-5786	ILAW PA
Leafy Vegetables	0.10	0.067	0.09
Other (protected)	0.25	0.222	0.25
Fruit (exposed)	0.18	0.126	0.18
Grains	0.18	0.888	0.91

ILAW PA values are from PNWD-2023 and NUREG/CR-5512.

Root uptake will be calculated using concentration ratios listed in Table 25. The ratios for four types of vegetables are given on this table. The definition of the four types were given in Section 2.2.3. Most of the values are from NUREG/CR-5512 (1992). The value for the iodine concentration ratio in leafy vegetables is from the more recent HEDR assessment (PNWD-2023 1994). The values for hydrogen were calculated using an equilibrium assumption. The ratio of tritium to hydrogen in the soil is assumed to be duplicated in the plant. Thus the effective soil-to-plant transfer factor is the hydrogen concentration in the plant divided by the hydrogen concentration in the soil and the dry-to-wet ratio for the plant.

Table 25. Transfer Factors for Garden Produce

Element	Plant/Soil Concentration Ratios				Atomic Number
	Leafy	Root	Fruit	Grain	
H	51*	18*	25*	3.4*	1
Be	0.01	0.0015	0.0015	0.0015	4
C	0.7	0.7	0.7	0.7	6
Na	0.075	0.055	0.055	0.055	11
Si	0.35	0.07	0.07	0.07	14
Cl	70	70	70	70	17
K	1.0	0.55	0.55	0.55	19
Ti	0.0055	0.003	0.003	0.003	22
V	0.0055	0.003	0.003	0.003	23
Mn	0.56	0.15	0.05	0.29	25
Fe	0.004	0.001	0.001	0.001	26

Table 25. Transfer Factors for Garden Produce

Element	Plant/Soil Concentration Ratios				Atomic Number
	Leafy	Root	Fruit	Grain	
Co	0.081	0.04	0.007	0.0037	27
Ni	0.28	0.06	0.06	0.03	28
Se	0.025	0.025	0.025	0.025	34
Rb	0.15	0.07	0.07	0.07	37
Sr	1.6	0.81	0.17	0.13	38
Y	0.015	0.006	0.006	0.006	39
Zr	0.002	0.0005	0.0005	0.0005	40
Nb	0.02	0.005	0.005	0.005	41
Mo	0.25	0.06	0.06	0.06	42
Tc	44	1.1	1.5	0.73	43
Ru	0.52	0.02	0.02	0.005	44
Pd	0.15	0.04	0.04	0.04	46
Ag	0.00027	0.0013	0.0008	0.1	47
Cd	0.55	0.15	0.15	0.15	48
In	0.004	0.0004	0.0004	0.0004	49
Sn	0.03	0.006	0.006	0.006	50
Sb	0.00013	0.00056	8.0E-05	0.03	51
Te	0.025	0.004	0.004	0.004	52
I	0.05*	0.05	0.05	0.05	53
Cs	0.13	0.049	0.22	0.026	55
Ba	0.15	0.015	0.015	0.015	56
Pm	0.01	0.004	0.004	0.004	61
Sm	0.01	0.004	0.004	0.004	62
Eu	0.01	0.004	0.004	0.004	63
Gd	0.01	0.004	0.004	0.004	64
Ho	0.01	0.004	0.004	0.004	67

Table 25. Transfer Factors for Garden Produce

Element	Plant/Soil Concentration Ratios				Atomic Number
	Leafy	Root	Fruit	Grain	
Re	1.5	0.35	0.35	0.35	75
Tl	0.004	0.0004	0.0004	0.0004	81
Pb	0.0058	0.0032	0.009	0.0047	82
Bi	0.035	0.005	0.005	0.005	83
Po	0.0025	0.009	0.0004	0.0004	84
Ra	0.075	0.0032	0.0061	0.0012	88
Ac	0.0035	0.00035	0.00035	0.00035	89
Th	0.0066	0.00012	0.000085	0.000034	90
Pa	0.0025	0.00025	0.00025	0.00025	91
U	0.017	0.014	0.004	0.0013	92
Np	0.013	0.0094	0.01	0.0027	93
Pu	0.00039	0.0002	0.000045	0.000026	94
Am	0.00058	0.00041	0.00025	0.000059	95
Cm	0.0003	0.00024	0.000015	0.000021	96
Bk	0.00058	0.00024	0.000015	0.000059	97
Cf	0.01	0.00024	0.000015	0.01	98

*Concentration ratios shown for hydrogen were calculated from the equilibrium model. The concentration ratio for iodine is from PNWD-2023. Other concentration ratios are from NUREG/CR-5512. The above transfer factors are based on the dry weights.

The Hanford Site is very dry and sandy, so that plant uptake factors would likely differ from the generic values used in literature reviews such as NUREG/CR-5512 and ORNL-5786. However, the preparation of the soil for a garden changes the properties of surface layer. The tilling, watering and addition of fertilizers and organic material produces soil which resembles the generic garden soil of NUREG/CR-5512 and ORNL-5786. It is therefore assumed that the concentration ratios found in these documents are adequate to describe plant uptakes in possible future gardens on the Hanford Site.

Groups of people gathering native vegetation for nourishment and other household needs may require special consideration. The soil-to-plant transfer factors could differ considerably from the values shown on Table 25. Soils deficient in some mineral will have much higher uptake factors for radionuclides which are chemically similar to what is missing. The converse is also true. In addition, the distribution of the contaminant in the native vegetation during the growth of the plant is important. For example, Native American Indians use various parts of the cattail over its growth stages (CTUIR 1995). However, the ILAW PA deals with localized areas of contaminated soil resulting from intrusion or irrigation with contaminated ground water. The transfer factors for native plant species is not needed because the contaminated portion is an insignificant part of the overall diet.

2.4.2 Rain Splash

The term "rain splash" refers to all the processes which cause soil to deposit on the surfaces of plants. It includes the transport of soil by the irrigation water, rain drops, and the wind. The standard model (NRC 1977) then includes a "translocation" factor which is the fraction of activity deposited on plant surfaces which ends up in the edible portions of the plant. There are two basic approaches to estimating the concentration in plants due to resuspension of contaminated soil. The standard approach begins with an estimate of the average air concentration and then computes the activity deposition rate on the plant. The other approach (NUREG/CR-5512 1992) simply treats rain splash in a manner similar to root uptake.

In NUREG/CR-5512 the amount of rain splash is characterized by a "mass loading" factor which is the ratio of foliage contamination due to rain splash divided by the concentration in the soil nearby. It is similar to the root uptake concentration ratio described in the previous section. The value recommended in NUREG/CR-5512, Section 6.5.2 is 0.1 Ci/kg (dry produce) per Ci/kg soil for all plant types. In addition, this value "includes consideration of translocation of activity in soil from plant surfaces to edible parts of the plant." The only other parameter used to estimate the actual plant concentration from rain splash is the dry-to-wet ratio.

The more commonly used approach begins with an average air concentration due to rain splash and computes a deposition rate on plant surfaces. The RESRAD program (Yu et al. 1993) has a default mass loading air concentration of 0.1 mg/m^3. The default value in GENII is 0.225 mg/m^3. Both of these use a deposition speed of 0.001 m/sec which is suitable for respirable particles. However, both of these assumptions lead to rain splash transfers which are two or three orders of magnitude below the experimental data referenced in NUREG/CR-5512.

For the ILAW PA the standard transport model will be used rather than the effective mass loading approach of NUREG/CR-5512. However, the average air concentration for rain splash will be 1 mg/m^3 with a deposition speed of 0.01 m/sec. These parameters lead to mass loading values which are consistent with the data reported in NUREG/CR-5512.

Other parameters which are part of the standard model for foliar deposition are the interception fraction, the crop yield (biomass), the translocation factor, the weathering half-life, and the growing period.

The interception fraction is the portion of the airborne contamination depositing in a unit area which initially attaches to vegetation. It includes the fraction of the ground surface which is covered by vegetation. Values for interception fraction for various crops are given in ORNL-5786. More recent publications described in PNNL-6584 will be used as the basis of the interception fractions for this performance assessment. The empirical relationship between interception fraction and standing biomass (dry weight) is shown below.

$$\text{Interception Fraction} = 1.0 - \text{Exp}[-(P)(\text{Dry Yield})] \quad (3)$$

The parameter P depends on the type of vegetation. For leafy vegetables, grains, grass and hay the measured value for P is 2.9 m^2/kg, while for fruits and other plants the measured value for P is 3.6 m^2/kg. The "Dry Yield" is the mass per unit area of the standing biomass at the time of harvest, adjusted for water content. The "Dry Yield" is calculated as the product of the dry-to-wet ratio and the crop yield (wet). Values for biomass and interception fraction are shown on the Table 26.

Table 26. Various Crop-Specific Parameters

Type of Produce	Dry-to-wet Ratio	Crop Yield kg(wet)/m^2	Interception Fraction[2]	Translocation Factor	Growing Period
Leafy Vegetables	0.09[1]	2.0	0.407	1.0	45 d
Other (protected)	0.25	2.0	0.835	0.1	90 d
Fruit (exposed)	0.18	3.0	0.857	0.1	90 d
Grains	0.91	0.8	0.371	0.1	90 d
Fresh Forage - Cow	0.22	1.5	0.616	1.0	30 d
Stored Hay - Cow	0.22	1.0	0.472	1.0	45 d
Stored Grain - Cow	0.91	1.0	0.472	0.1	90 d
Forage - Poultry	0.22	1.0	0.472	1.0	30 d
Grain - Poultry	0.91	1.0	0.472	0.1	90 d

[1]Value shown is from PNWD-2023. All other values are from NUREG/CR-5512 Section 6.5.7.
[2]Interception fractions are calculated using the formula described in the text (PNNL-6584 Section 4.7.4).

The translocation factor is the fraction of what deposits on the foliage that reaches the edible parts of the plant. The values are shown on Table 26 are widely used in calculations of this type (NRC 1977; PNNL-6584 1988; NUREG/CR-5512 1992) and will be used in the ILAW PA.

The weathering half-life is the time required for half the contamination initially deposited on plant foliage to be removed by the action of wind, rain and irrigation. The value chosen for all nuclides is 14 days, based on the recommendations of NRC (1977) and the review given in ORNL-5786.

The growing period is the time that a plant is subject to the mechanical action of weathering prior to be harvested. The growing period varies with crop type. It is the time needed to produce one crop. During the growing season more than one crop may be harvested.

2.4.3 Direct Deposition

The models for root uptake and rain splash contributions to growing plants depend only on the soil concentration at the time of harvest. Direct deposition is unique to overhead irrigation. It refers to the transfer of contamination from irrigation water to the foliage intercepting the water as it falls.

A key parameter to model the contamination of foliage by direct deposition is the interception fraction. The value recommended for all plant types by the NRC (1977) will be used, 0.25. This value is not well documented, but is widely used in other reviews (PNNL-6584 1988; NUREG/CR-5512 1992).

The other parameters determining plant concentrations exposed to contaminated irrigation water are the translocation factors, the weathering half-life, and the growing periods. The same parameters used for describing rain splash will also be used for direct deposition. The translocation factors and growing periods are shown on Table 26, while the weathering half-life is 14 days.

If a special group of people were using overhead irrigation to increase growth density and crop yield, then the same parameters used for the standard group would apply to them also. No special modeling would be required unless the group were using the crop in some manner which could produce more dose than simply eating it.

2.5 Soil Parameters

The soil parameters of interest are those pertaining to the delivery of radiation exposure to someone living over, or growing food crops in contaminated soil. The two main types of exposure are from external and internal sources. In addition, the internal exposure can be divided into inhalation and ingestion intakes. Each of these routes of exposure will be discussed below.

The principal effect of the soil on the external exposure received by someone living nearby is through the soil density, chemical composition, and roughness. As described in Section 2.2.2, the surface soil density is assumed to be 1.5 g/cc. The contamination of interest is distributed through the top 15 cm. The assumed composition is primarily silicon dioxide, with various additions, such as water. Over time the radioactive contaminants have been observed to migrate into deeper layers. The radioactive elements are affected by the average flow of water through the surface layer into deeper layers. Some elements, such as hydrogen and iodine are very soluble and leach from the surface layer in a few years. Other elements, such as cesium and plutonium hardly move at all.

The principal relationship between soil contamination and inhalation dose is through the ease with which contaminants in the soil become airborne. The presence of ground cover and moisture reduces the air concentration. Hand-tilling activities increase the air concentration. The gradual leaching of radioactive contamination to deeper layers of soil reduces the air concentration as well.

The principal relationship between soil contamination and ingestion dose is through the ease with which contaminants in the soil become incorporated in plant and animal produce. It is assumed that the effects of tilling and fertilizers lead to soils that are similar to those for which the concentration ratios shown in Table 25 were derived. The gradual leaching of radioactive contamination to deeper layers of soil (below the root zone) reduces the concentration in plant and animal products as well.

Soil-specific parameters related to leaching are the soil composition (sand, clay, silt and organic), the distribution coefficients, the density, porosity, and the water content. These parameters determine the rate at which radionuclides leach from the surface layer into deeper layers, the magnitude of the external dose rate factors, and the expected ratios of radioactive elements to non-radioactive elements in those cases where equilibrium models can be applied, namely, for tritium.

The composition of the surface layer is assumed to be sandy, where sandy is defined to have greater than 70 percent sand-sized particles. With few exceptions this is what lies near the surface of the entire Hanford Site. The soil-to-plant concentration ratios and distribution coefficients depend on this assumption. However, the preparation of the soil for a garden changes the properties of surface layer. The tilling, watering and addition of fertilizers and organic material produces soil which resembles the generic garden soil of NUREG/CR-5512. It is therefore assumed that the leaching coefficients found in this document is adequate to describe possible future gardens on the Hanford Site.

The distribution coefficients are taken from NUREG/CR-5512 (1992) and are listed in Table 27. The values in NUREG/CR-5512 were obtained from experiments using four different soil types (sand, loam, clay, and organic). The smallest distribution coefficients (representing the most mobile condition) was reported in NUREG/CR-5512. While this approach may underestimate soil concentrations, the effect of leaching from the surface layer during the growing season is small for most nuclides.

The thickness of the surface soil of interest in the dose calculations is the top 15 centimeters. This thickness represents typical cultivation depths for mechanical mixing of deposited activity. In addition, it represents typical root depths. This thickness has been used in all prior Hanford Site performance assessments.

The density and thickness of the affected surface layer determine the external dose rate factors discussed in Section 2.2.2, as well as the leaching coefficients computed for the surface layer. Leaching is the process by which contaminants migrate from the surface layer of soil into deeper layers below. The driving force behind the leaching process is the application of water to the soil. Leaching is treated as a removal rate constant giving the fraction of the material in the surface layer which is removed per unit of time. It is calculated using equation (4) shown below.

$$\lambda_s = \frac{P + I - E}{\theta\, d\, (1 + \rho/\theta\, K_d)} \qquad (4)$$

where,

- λ_s = average soil leaching coefficient, fraction removed from a soil layer of thickness "d" during the time that irrigation occurs.
- P = total precipitation, in centimeters, during the irrigation period. Over the period 1961 to 1990, the precipitation during the 6 month irrigation season (April to September) has been 5.23 cm (PNNL-12087).
- I = total irrigation, assumed to be 82.3 cm per year (32.4 inches/y). Nearly all of this is deposited during a 6 month period.
- E = total evapo-transpiration, in centimeters per year. Assumed to be 77.5 cm per year so that the total over-irrigation (P+I-E) is 10 cm/y. This over-irrigation assumption is consistent with PNWD-2023, which assumed that farmers over-irrigate by 10 percent.
- d = thickness of soil from which nuclides migrate, in centimeters. This is assumed to be 15 cm (5.9 inches).
- ρ = bulk density of the surface soil, in grams per cubic centimeter. The value normally used at Hanford is 1.5 g/cc.
- θ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.3 ml/cc is assumed. The irrigated soil is assumed to be nearly saturated with water.
- K_d= distribution coefficient in surface soil for an element, in milliliters per gram. Values from NUREG/CR-5512 are shown on Table 27.

The values assigned to the variables in the above equation were used in prior Hanford performance assessments. The annual irrigation total (82.3 cm/y) is based on the Specific Information on the Terrestrial Environment (SITE) database referenced ORNL-5786. The SITE database reports that a large percentage of the drier western states falls into the range from 70 to 85 cm/y. The values chosen in NUREG/CR-5512 is 76 cm/y, while the value more appropriate to Hanford is 82.3 cm/y (WHC-SD-WM-EE-004). The Hanford value is based on irrigation rates in the counties surrounding the site. Note that the amount of irrigation is assumed to be the same for all plant types including grains.

Leaching coefficients computed from the equation (4) are listed in Table 27. The numerator represents the excess water added each year. It is taken to be about 10 cm during the irrigation season based on the discussion in PNWD-2023.

Table 27. Leaching Factors for Garden Soil

Element	Leach per year	Kd	Atomic Number	Element	Leach per year	Kd	Atomic Number
H	2.22E+00	0	1	Sb	9.83E-03	45	51
Be	1.85E-03	240	4	Te	3.17E-03	140	52
C	6.44E-02	6.7	6	I	3.70E-01	1	53
Na	5.83E-03	76	11	Cs	1.64E-03	270	55
Si	1.47E-02	30	14	Ba	8.51E-03	52	56
Cl	2.34E-01	1.7	17	Pm	1.85E-03	240	61
K	2.44E-02	18	19	Sm	1.85E-03	240	62
Ti	4.44E-04	1000	22	Eu	1.85E-03	240	63
V	4.44E-04	1000	23	Gd	1.85E-03	240	64
Mn	8.85E-03	50	25	Ho	1.85E-03	240	67
Fe	2.77E-03	160	26	Re	3.13E-02	14	75
Co	7.38E-03	60	27	Tl	1.14E-03	390	81
Ni	1.11E-03	400	28	Pb	1.64E-03	270	82
Se	3.17E-03	140	34	Bi	3.70E-03	120	83
Rb	8.51E-03	52	37	Po	2.96E-03	150	84
Sr	2.92E-02	15	38	Ra	8.89E-04	500	88
Y	2.34E-03	190	39	Ac	1.06E-03	420	89
Zr	7.66E-04	580	40	Th	1.39E-04	3200	90
Nb	2.77E-03	160	41	Pa	8.71E-04	510	91
Mo	4.36E-02	10	42	U	2.92E-02	15	92
Tc	1.48E+00	0.1	43	Np	8.55E-02	5	93
Ru	8.05E-03	55	44	Pu	8.08E-04	550	94
Pd	8.51E-03	52	46	Am	2.34E-04	1900	95
Ag	4.93E-03	90	47	Cm	1.11E-04	4000	96
Cd	1.11E-02	40	48	Bk	2.34E-04	1900	97
In	1.14E-03	390	49	Cf	8.71E-04	510	98

Element	Leach per year	Kd	Atomic Number	Element	Leach per year	Kd	Atomic Number
Sn	3.41E-03	130	50				

Soil distribution coefficients are from NUREG/CR-5512. The leaching factors were calculated using Equation (4).

The soil moisture is used in the special equilibrium model for tritium. The tritium is chemically bound in a water molecule and thus goes with the water. The transfer from soil or irrigation water to vegetation is best described with an equilibrium model. The concentration of tritium in irrigation water, for example, is similar to the concentration in the water in the soil or a plant or the cow's milk. The soil hydrogen fraction is 0.022 kg hydrogen per kg soil. Thus the effective moisture content of the soil is calculated as shown below. The density of water is 1.0 kg/L.

$$(8.94 \text{ g } H_2O/\text{g } H_2)(0.022 \text{ kg } H_2/\text{kg soil})/(1.0 \text{ kg/L})=0.197 \text{ L } H_2O/\text{kg soil}$$

This value is consistent with the assumed value for the volumetric water content of soil (0.3 ml/cc) and its density (1.5 kg/L). Note that the value reported in NUREG/CR-5512 is 0.1 L/kg. A higher value is therefore being used in the ILAW PA, which leads to higher tritium concentrations in irrigated soil.

In the exposure scenario where the glass waste matrix is brought to the surface, it will be assumed that the glass is still largely unchanged from the time of disposal. Most of the radionuclides are assumed to remain in the glass brought to the surface. Leaching from the surface layer for the nuclides trapped in the glass will not be considered.

Because the expected irrigation application rate of 82.3 cm/year (32.4 inches/year) is applied over a minimum area of 2 hectare (5 acres), the total annual water need for the farmer is at least 1.7×10^7 liters. This value was assumed in prior Hanford performance assessments. The ability of a well to supply water at this rate must be confirmed before dose calculations based on it are carried out.

The Hanford Environmental Dose Reconstruction Project (HEDR) found the irrigation rate in the counties surrounding the Hanford Site ranged from 61 cm/y to 98 cm/y (PNWD-2023, Rev 1). This range leads to leaching coefficients that range from 0 to 2.5 times the chosen values. This range has little effect on the resulting doses for most nuclides because the leaching coefficients are generally small.

A two-part removal rate from the soil has been adopted for use in the ILAW PA. It is assumed that significant irrigation occurs during 6 months of the year. The rest of the year has very little water infiltration. During the no-irrigation period there is no leaching from the surface layer. The one exception is tritium. Tritium is removed from the surface layer during this period by evaporation. Since the natural precipitation normally is 10.69 cm water during the no-irrigation period, this is also the evaporation rate. Evaporation of tritiated water thus leads to the effective leaching coefficient shown below.

$$\lambda_{s,H3} = (10.69 \text{ cm/y})/(0.3 \text{ ml/cc})/(15 \text{ cm}) = 2.38 \text{ per year}$$

Natural precipitation acts to dilute contaminated irrigation water slightly. It adds water that is not contaminated. The formula below shows the dilution factors [i.e., I/(I+P)] used in these calculations during the irrigation season.

$$\text{Dilution Adjustment (individual)} = (82.3 \text{ cm})/(82.3 + 5.23 \text{ cm}) = 0.940$$

$$\text{Dilution Adjustment (population)} = (63.5 \text{ cm})/(63.5 + 5.23 \text{ cm}) = 0.924$$

3.0 MATHEMATICAL MODELS AND DOSE CALCULATIONS

The mathematical models used for the ILAW PA unit dose factors are described in this section. The selection of the various pathway parameters discussed in the previous section can be best understood through the formulas that apply the parameters. The presence of radioactive decay chains complicates this discussion, and the subsequent calculations. But the use of decay chains is necessary because some progeny nuclides are more significant than the parent nuclide.

To facilitate calculations with the large number of nuclides that may be found at the Hanford Site, the hand calculations were automated using commercial spreadsheet software. Spreadsheet calculations have been verified by hand calculations presented in Appendix A and Appendix B.

Doses to humans exposed to exhumed contamination or irrigation water include both internal and external radiation exposures. The internal dose comes from the inhalation of resuspended dust and the ingestion of contaminated water, soil, and foodstuffs. The external dose comes primarily from being near the contaminated soil. The sections below describe how the human dose is computed from the parameters of Section 2 together with standard models for estimating this dose. First, the time dependence of soil concentrations are presented. Second, the external and inhalation doses received from contaminated soil are described. Third, the concentrations and doses for various plant types are described. Finally, the concentrations and doses for animal products are described. The role of radioactive decay and daughter ingrowth is discussed in each section.

3.1 Time Dependence of Soil Concentrations

The soil concentrations are of two types. The first type of soil contamination results from drilling a hole through the waste site and spreading the contamination in a garden. In this case there is some initial concentration of a nuclide in the surface layer that decreases with time due to radioactive decay and leaching from the surface layer. The second type of soil concentration results from irrigating with contaminated water. In this case the contamination increases with time due to the added radioactivity. However, this increase is offset by radioactive decay and leaching from the surface layer.

In the description of progeny ingrowth, it will be assumed that only the parent nuclide is present initially. Each nuclide in the chain must be treated independently. This enables the calculation of unit dose factors for each of the principal nuclides in a decay chain. In the case of irrigation water, it is also assumed that the progeny are not accumulating in the water prior to irrigation. Only the parent nuclide is coming from the well and being deposited on the soil. In addition, it is assumed that the water concentration is constant during the year of irrigation. As before, this enables the calculation of unit dose factors for each of the principal nuclides in a decay chain.

The discussion below is divided into three parts. The first describes the decay of a nuclide and progeny ingrowth with time due to nuclear decay alone, i.e., without leaching or additions from contaminated irrigation water. The second part adds decay in the presence of leaching from the surface layer. The third includes irrigation with contaminated water. In all cases, the decay chains shown in Table 6 are used. The longest decay chain has just four members because decay times less than 1000 years are assumed.

3.1.1 Decay Without Leaching or Irrigation Deposition

The radioactive decay constants will be represented as λ_{1r}, λ_{2r}, λ_{3r}, λ_{4r}, and so forth until λ_{nr}, which is the last member of the chain. The leaching coefficients describing removal from the surface layer by water infiltration will be represented as λ_{1s}, λ_{2s}, λ_{3s}, λ_{4s}, and so forth. The sum of these the radioactive and leaching constants for a given nuclide will be represented as λ_1, λ_2, λ_3, λ_4, and so forth. In other words, λ_2 is defined by the equation $\lambda_2 = \lambda_{2r} + \lambda_{2s}$. Radioactive decay constants are computed by dividing the half life of the nuclide (Table 5) into the logarithm of 2 (Ln 2 = 0.69314718). Leaching coefficients are listed in Table 27.

The following demonstrates the general form of the customary decay chain formula to describe the ingrowth of the "nth" progeny from the first member of the chain. In other words, the only member of the chain with any activity to begin with is the first nuclide. The equations below describe the ingrowth of a specific progeny nuclide, the "nth" member of the chain in the absence of leaching and irrigation with contaminated water. These equations also describe the activity in contaminated vegetables or animal products after they are harvested.

$$C_{sn} = C_{s1}^{0} \left(\prod_{k=1}^{n-1} B_{k,k+1} \right) \left(\prod_{k=2}^{n} \lambda_{kr} \right) DR_{1n} \tag{5}$$

$$DR_{1n} = \sum_{k=1}^{n} \frac{e^{-\lambda_{kr} t}}{PD_{1,kr,n}} \tag{6}$$

where

$$PD_{1,kr,n} = \prod_{\substack{i=1 \\ i \neq k}}^{n} \left(\lambda_{ir} - \lambda_{kr}\right) \tag{7}$$

C_{s1}^{0} is the initial soil concentration of the first member of the chain. C_{sn} is the concentration of the "nth" member of the chain after the time "t" has elapsed. C_{sn} is assumed to be zero initially, and to increase with time. Both concentrations have units of Ci/kg.

The term $B_{k,k+1}$ is the fraction of decays of nuclide number "k" which produce nuclide number "k+1". $B_{k,k+1}$ is also known as the branching ratio for nuclear transition from k to k+1. Most branching ratios are simply 1.0. Non-unit branching ratios are given in Table 6.

The term DR_{1n} contains the time dependent functions for each nuclide in the chain from nuclide "1" down to nuclide "n". For convenience in writing the denominator, the product of decay constant differences is defined as shown in Equation (7).

The decay equations are presented as Equation (8) for the first four nuclides. In a four-step decay chain, nuclide 1 (the parent) decays to nuclide 2, which then decays to nuclide 3, which then decays to nuclide 4.

$$C_{s1} = C_{s1}^{0}\ \mathrm{Exp}(-\lambda_{1r}T) \tag{8}$$

$$C_{s2} = C_{s1}^{0}\ \lambda_{2r} \left\{ \mathrm{Exp}(-\lambda_{1r}T)/(\lambda_{2r}-\lambda_{1r}) + \mathrm{Exp}(-\lambda_{2r}T)/(\lambda_{1r}-\lambda_{2r}) \right\}$$

$$\begin{aligned} C_{s3} = C_{s1}^{0}\ \lambda_{2r}\lambda_{3r} \{ & \mathrm{Exp}(-\lambda_{1r}T)/[(\lambda_{2r}-\lambda_{1r}/(\lambda_{3r}-\lambda_{1r})] \\ & + \mathrm{Exp}(-\lambda_{2r}T)/[(\lambda_{1r}-\lambda_{2r})(\lambda_{3r}-\lambda_{2r})] + \mathrm{Exp}(-\lambda_{3r}T)/[(\lambda_{1r}-\lambda_{3r})(\lambda_{2r}-\lambda_{3r})] \} \end{aligned}$$

$$\begin{aligned} C_{s4} = C_{s1}^{0}\ \lambda_{2r}\lambda_{3r}\lambda_{4r} \{ & \mathrm{Exp}(-\lambda_{1r}T)/[(\lambda_{2r}-\lambda_{1r})(\lambda_{3r}-\lambda_{1r})(\lambda_{4r}-\lambda_{1r})] \\ & + \mathrm{Exp}(-\lambda_{2r}T)/[(\lambda_{1r}-\lambda_{2r})(\lambda_{3r}-\lambda_{2r})(\lambda_{4r}-\lambda_{2r})] \\ & + \mathrm{Exp}(-\lambda_{3r}T)/[(\lambda_{1r}-\lambda_{3r})(\lambda_{2r}-\lambda_{3r})(\lambda_{4r}-\lambda_{3r})] \\ & + \mathrm{Exp}(-\lambda_{4r}T)/[(\lambda_{1r}-\lambda_{4r})(\lambda_{2r}-\lambda_{4r})(\lambda_{3r}-\lambda_{4r})] \} \end{aligned}$$

where,

C_{s1}^{0} = initial concentration of nuclide 1 (i.e. at T=0), in Ci/kg. The initial concentrations of all other members of the chain are assumed to be zero.

$C_{s1}, C_{s2}, C_{s3}, C_{s4}$	=	concentration of nuclides 1, 2, 3, and 4 at time T, in Ci/kg.
$\lambda_{1r}, \lambda_{2r}, \lambda_{3r}, \lambda_{4r}$	=	radioactive decay constants for nuclides 1, 2, 3, and 4. Note that the decay constant is the natural logarithm of 2 divided by the half-life of the nuclide. Note also that the decay constants in a decay chain are all different so the denominators will never be zero.

3.1.2 Decay With Leaching but Without Irrigation Deposition

For the case where leaching from the surface layer is allowed, there is an additional removal mechanism, which has the effect of increasing the size of the removal terms. Leaching coefficients were discussed in Section 2.5 and are listed in Table 27. The addition of leaching only changes Equations (6) and (7) by replacing λ_k for λ_{kr}. For these equations the radioactive decay constant, in effect, increases. The new equations for decay with leaching are shown below as Equations (9), (10), and (11). Note that the product of radioactive decay constants in Equation (9) is unchanged from Equation (5).

$$C_{sn} = C^0_{s1} \left(\prod_{k=1}^{n-1} B_{k,k+1} \right) \left(\prod_{k=2}^{n} \lambda_{kr} \right) DS_{1n} \qquad (9)$$

$$DS_{1n} = \sum_{k=1}^{n} \frac{e^{-\lambda_k t}}{PD_{1,k,n}} \qquad (10)$$

where

$$PD_{1,k,n} = \prod_{\substack{i=1 \\ i \neq k}}^{n} \left(\lambda_i - \lambda_k \right) \qquad (11)$$

The term C^0_{s1} is the same as in Equation (5). It is the initial soil concentration of the parent nuclide in the chain. The $B_{k,k+1}$ terms are also the same as in Equation (5). The change in the definition of the time-dependent function DS_{1n} increases the exponents, so the decline in soil concentration is faster. Note that the subtractions in the $PD_{1,k,n}$ term do not eliminate the leaching factor. Therefore Equations (7) and (11) are not the same.

In the post-intrusion gardening scenario, the dose received during the first year is greatest for most nuclides. However, a few nuclides with long half lives, little leaching, and progeny with large unit dose factors, the dose in some later year may be the largest. This will be discussed when the post-intrusion unit dose factors are described. An additional consideration for the glass waste matrix is degradation of the glass leading to increased availability for plant uptake and resuspension into the air.

3.1.3 Decay With Leaching and Irrigation Deposition

The sources of contaminated irrigation water are either groundwater or Columbia River water. The instantaneous rate of addition of contamination to the soil is given by the equation below. The conversion factor shown in the equations changes centimeters of water applied to the soil to liters applied per square meter.

$$ID_p = C_w \, I \, (10 \text{ L m}^{-2} \text{ cm}^{-1}) / T_{irr}$$

where

ID_p = instantaneous activity deposition rate during the irrigation of areas growing plant type p, in curies per square meter per year (Ci y^{-1} m^{-2}).

C_w = irrigation water concentration, in curies per liter (Ci/L). This concentration is assumed to be constant (no decay) during the 6 month application period.

I = irrigation water applied to plants during the irrigation period. For the maximum individual cases, this value is 82.3 cm. For the population dose, this value was lowered to 63.5 cm due to less irrigation in humid areas along the Columbia River (Kincaid 1993).

T_{irr} = irrigation period in years. The value 0.5 yr is used since the irrigation is assumed to take place 6 months per year.

The instantaneous rate of increase in the soil concentration is computed from Equation (12) below.

$$ID_{s1}^{0} = ID_p / (\rho \, d) \qquad (12)$$

where

ID_{s1}^{0} = instantaneous rate of increase in the soil concentration during the irrigation season, in curies per kilogram per year.

ID_p = instantaneous activity deposition rate during the irrigation of soils growing plant type p, in curies per square meter per year (Ci y^{-1} m^{-2}).

ρ = bulk density of the surface soil, in grams per cubic centimeter. The value normally used in Hanford Site PA work is 1.5 g/cc.

d = thickness of soil from which nuclides migrate, in centimeters. This is assumed to be 15 cm (5.9 inches).

Using contaminated irrigation water, the concentration of radioactivity in the surface layer of soil increases with time. The equations to represent this turn out to be the time integral of Equations (9), (10), and (11). This activity accumulation is shown in Equations (13) and (14), below. Equation (11), which defines $PD_{1,k,n}$, is not affected by the integration. The term ID^{0}_{s1} is the rate at which the concentration of the parent nuclide increases due to irrigation deposition. Note that irrigation is assumed for a 6 month period, followed by 6 months in which the precipitation essentially matches the evapo-transpiration, so that the leaching coefficients during the last 6 months are zero. Note the addition of the irrigation time (t) to the equation to make the DI decay term a unitless fraction representing accumulation in the soil of contaminants that decay or are leached from the surface layer. At the end of the irrigation period, $t=T_{irr}$.

$$C_{sn} = t \cdot ID^{0}_{s1} \left(\prod_{k=1}^{n-1} B_{k,k+1} \right) \left(\prod_{k=2}^{n} \lambda_{kr} \right) DI_{1n} \qquad (13)$$

$$DI_{1n} = \sum_{k=1}^{n} \frac{1 - e^{-\lambda_k t}}{\lambda_k t \, PD_{1,k,n}} \qquad (14)$$

Equations (5), (6), and (7) apply to soil with no leaching at all. Whatever water falls on the soil evaporates without forcing contamination through the surface layer into deeper layers. The key to represent this ordinary decay is the term DR_{1n}. Equations (9), (10), and (11) apply to soil with some leaching taking place. This might be due to excess natural precipitation or irrigation with uncontaminated water. The key to represent this decay with leaching is the term DS_{1n}. Equations (13) and (14) apply to soil being irrigated with contaminated water. Leaching from the surface layer is also occurring. The key to represent this combination of decay, leaching, and accumulation is the term DI_{1n}. These key terms will be used in the next section to describe the soil concentration after many years of irrigation with contaminated water. The soil concentration after 50 years of irrigation with a constant nuclide concentration can be computed for evaluation purposes.

One exception to the above is for tritium in the irrigation water applied to the soil. An equilibrium approach is used. The tritium concentration in the soil moisture is assumed to equal the tritium concentration in the applied irrigation water, adjusted for natural precipitation. This is calculated using the formula below.

$$C_{s,H3} = 8.94 \, F_{Hs} \, C_{w,H3} \, I/(I+P) \qquad (15)$$

where

$C_{s,H3}$ = concentration of tritium in the surface soil, in curies per kilogram.

8.94 = factor to convert the hydrogen weight fraction into a water fraction. It comes from the ratio of molecular weights for hydrogen (2.0159 g/gmole) and water (18.0153 g/gmole).

F_{Hs} = fraction of hydrogen in garden soil, 0.022 g hydrogen per gram of soil (from Table 23).

$C_{w,H3}$ = concentration of tritium in the irrigation water, in pCi/L.

I = total irrigation water applied to the soil during the irrigation season, 82.3 cm/y (63.5 cm/y for the population).

P = total natural precipitation water reaching the soil during the irrigation period, 5.23 cm/y (PNNL-12087).

The ratio I/(I+P) incorporates the dilution of contaminated irrigation water with natural precipitation. The values chosen for "I" and "P"lead to dilution ratio of 94%.

3.1.4 Activity Concentration at the End of the First Year

To describe the concentration of a nuclide in the soil at the end of the first year, one must combine the equations of the previous section into the physically allowable sequences. During the first 6 months of the year irrigation takes place. The leaching coefficients are as shown in Table 27. Then the irrigation ceases and the precipitation rate is assumed to match the evapo-transpiration rate, so that the leaching factors are all zero. During the second half of the year there is only radioactive decay.

Initial Soil Contamination. In the post-intrusion garden scenario, for the first member of a decay chain, the soil concentration at the end of the year is the initial concentration multiplied by factors for decay and leaching during the irrigation season followed by simple decay during the remainder of the year. This is shown in Equation (16) below. The Y_{11} term is introduced to simplify later equations.

$$C_{s1}(1) = C^0_{s1} \cdot DS_{11} \cdot DR_{11} = C^0_{s1} \cdot Y_{11} \tag{16}$$

In general, the term $C_{sn}(Ti)$ is the soil concentration of the "nth" member of the decay chain after Ti years. As before, C^0_{s1} is the initial soil concentration of the first member of the chain. The DS_{11} factor applies for the first 6 months. The DR_{11} factor controls the second 6 months. The DS_{11} and DR_{11} terms are normally preceded by factors for branching ratios and products of decay constants. However, for the first member of the chain, these terms are 1.

The first daughter of nuclide "1" is produced during the irrigation period and then decays during the rest of the year. It also is produced from the decay of the parent nuclide that is present at the end of the irrigation season. This is shown in Equation (17) below. The term BP_{12} contains the branching ratio and product of decay constants found in Equations 5 and 9.

$$C_{s2}(1) = C^0_{s1} \cdot BP_{12} \cdot (DS_{12} \cdot DR_{22} + DS_{11} \cdot DR_{12}) = C^0_{s1} \cdot BP_{12} \cdot Y_{12} \tag{17}$$

The concentration of the third and fourth nuclides in the chain at the end of the first year is calculated using Equation (18) below. Longer chains are computed in a similar fashion. Note that all possible decay paths must be considered. This leads to as many terms as there are members in the decay chain.

$$
\begin{aligned}
C_{s3}(1) &= C^0_{s1} \cdot BP_{13} \cdot (DS_{13} \cdot DR_{33} + DS_{12} \cdot DR_{23} + DS_{11} \cdot DR_{13}) \\
&= C^0_{s1} \cdot BP_{13} \cdot Y_{13} \\
C_{s4}(1) &= C^0_{s1} \cdot BP_{14} \cdot (DS_{14} \cdot DR_{44} + DS_{13} \cdot DR_{34} + DS_{12} \cdot DR_{24} + DS_{11} \cdot DR_{14}) \\
&= C^0_{s1} \cdot BP_{14} \cdot Y_{14}
\end{aligned}
\qquad (18)
$$

Irrigation. In the irrigation scenarios, for the first member of the chain, the concentration at the end of the year is the product of the accumulated activity at the end of the irrigation season and the decay factor resulting from decay without irrigation or leaching for the remainder of the year. This is shown in Equation (19) below. Note the similarity between Equations (16) and (19). This will be seen again in the next few equations.

$$C_{s1}(1) = T_{irr} \cdot ID^0_{s1} \cdot DI_{11} \cdot DR_{11} \qquad (19)$$

In general, the term $C_{sn}(Ti)$ is the soil concentration of the "nth" member of the decay chain after Ti years. As before, ID^0_{s1} is the instantaneous rate of increase in the soil concentration for the first member of the chain. The DI and DR terms are normally preceded by factors for branching ratios and products of decay constants. However, for the first member of the chain, these terms are 1.

The first daughter of nuclide "1" is produced during the irrigation period and then decays during the rest of the year. It also is produced from the decay of the parent nuclide that is present at the end of the irrigation season. This is shown in Equation (20) below. Note that the assumed amount of the daughter in the irrigation water is zero. The term BP_{12} contains the branching ratio and product of decay constants found in Equations (9) and (13).

$$C_{s2}(1) = T_{irr} \cdot ID^0_{s1} \cdot BP_{12} \cdot (DI_{12} \cdot DR_{22} + DI_{11} \cdot DR_{12}) \qquad (20)$$

The concentration of the third and fourth nuclides in the chain at the end of the first year is calculated using Equation (21) below. Longer chains are computed in a similar fashion. Note that all possible decay paths must be considered. This leads to as many terms as there are members in the decay chain, as shown below.

$$C_{s3}(1) = T_{irr} \cdot ID^{0}_{s1} \cdot BP_{13} \cdot (DI_{13} \cdot DR_{33} + DI_{12} \cdot DR_{23} + DI_{11} \cdot DR_{13})$$
$$C_{s4}(1) = T_{irr} \cdot ID^{0}_{s1} \cdot BP_{14} \cdot (DI_{14} \cdot DR_{44} + DI_{13} \cdot DR_{34} + DI_{12} \cdot DR_{24} + DI_{11} \cdot DR_{14}) \quad (21)$$

In practice, it is better to calculate the decay factors for each nuclide, since these are unitless fractions whose value is near 1.0 for nuclides with long half lives. The calculation of media concentrations and dose can be carried out ignoring decay. A decay factor can then be added.

3.1.5 Soil Concentration after Many Years of Irrigation

After the first year of irrigation, there is residual contamination which must be taken into account when computing the total activity at the end of the year under consideration. The activity after N years is the sum of (1) the activity after (N-1) years decaying for 1 year, plus (2) the activity which normally accumulates during the year. Note that the residual activity from (N-1) years of prior irrigation is first subjected to decay with leaching during the first portion of the year and then decay without leaching for the remainder (Y_{11}). As a reminder, it is assumed that the water concentration of the parent nuclide remains constant and that none of the progeny nuclides accumulate in the water. This permits separate unit dose factors for each of the principal nuclides in a decay chain. The concentration of progeny nuclides in the irrigation water will be determined by the release and transport codes.

For the first member of the decay chain, the soil concentration at the end of N years is shown in Equation (22). The Y and Z terms are introduced to simplify later equations. The Z term is analogous to an exponential term in the usual decay equations. Equation (22) applies to scenarios in which irrigation with contaminated water occurs.

$$\begin{aligned} C_{s1}(N) &= C_{s1}(N\text{-}1) \cdot Y_{11} + C_{s1}(1) \\ &= C_{s1}(1) \cdot (1 - Y^{N}_{11})/(1 - Y_{11}) = C_{s1}(1) \cdot Z_{1} \end{aligned} \quad (22)$$

where, $Z_1 = (1 - Y^{N}_{11})/(1 - Y_{11})$

The activity concentration of the first daughter after N years of accumulation and decay is shown below. The soil concentration after N years is the sum of (1) the activity added during the Nth year and the activity present at the end of N-1 years after one more year of leaching and decay.

The YZ combination term shown in Equation (23) is introduced to simplify later equations. The YZ term has a form similar to that of the standard decay equations. The product of decay constants represented as the PD term in Equations (6), (10) and (14) has a reversed order compared to these equations.

$$
\begin{aligned}
C_{s2}(N) &= C_{s1}(N\text{-}1)\cdot BP_{12}\cdot Y_{12} + C_{s2}(N\text{-}1)\cdot Y_{22} + C_{s2}(1) \\
&= C_{s2}(1)\cdot Z_2 + C_{s1}(1)\cdot BP_{12}\cdot Y_{12}\cdot(Z_1 - Z_2)/(Y_{11} - Y_{22}) \\
&= C_{s2}(1)\cdot Z_2 + C_{s1}(1)\cdot BP_{12}\cdot YZ_{12}
\end{aligned}
\tag{23}
$$

The activity concentration of the third member of the decay chain after N years of accumulation and decay is shown below.

$$
\begin{aligned}
C_{s3}(N) &= C_{s1}(N\text{-}1)\cdot BP_{13}\cdot Y_{13} + C_{s2}(N\text{-}1)\cdot BP_{23}\cdot Y_{23} + C_{s3}(N\text{-}1)\cdot Y_{33} + C_{s3}(1) \\
&= C_{s3}(1)\cdot Z_3 + C_{s2}(1)\cdot BP_{23}\cdot Y_{23}\cdot(Z_2 - Z_3)/(Y_{22} - Y_{33}) + \\
&\quad C_{s1}(1)\cdot BP_{13}\cdot Y_{13}\cdot(Z_1 - Z_3)/(Y_{11} - Y_{33}) + \\
&\quad C_{s1}(1)\cdot BP_{13}\cdot Y_{12}\cdot Y_{23}\cdot\{Z_1/[(Y_{11} - Y_{22})(Y_{11} - Y_{33})] + \\
&\quad Z_2/[(Y_{22} - Y_{11})(Y_{22} - Y_{33})] + Z_3/[(Y_{33} - Y_{11})(Y_{33} - Y_{22})]\} \\
&= C_{s3}(1)\cdot Z_3 + C_{s2}(1)\cdot BP_{23}\cdot YZ_{23} + C_{s1}(1)\cdot BP_{13}\cdot[YZ_{13} + YZ_{123}]
\end{aligned}
\tag{24}
$$

The activity concentration of the fourth member of the decay chain after N years of accumulation and decay is shown below.

$$
\begin{aligned}
C_{s4}(N) &= C_{s1}(N\text{-}1)\cdot BP_{14}\cdot Y_{14} + C_{s2}(N\text{-}1)\cdot BP_{24}\cdot Y_{24} + C_{s3}(N\text{-}1)\cdot BP_{34}\cdot Y_{34} + \\
&\quad C_{s4}(N\text{-}1)\cdot Y_{44} + C_{s4}(1) \\
&= C_{s4}(1)\cdot Z_4 + C_{s3}(1)\cdot BP_{34}\cdot YZ_{34} + C_{s2}(1)\cdot BP_{24}\cdot[YZ_{24} + YZ_{234}] \\
&\quad C_{s1}(1)\cdot BP_{14}\cdot[YZ_{14} + YZ_{124} + YZ_{134} + YZ_{1234}]
\end{aligned}
\tag{25}
$$

where

$$
\begin{aligned}
YZ_{1234} = Y_{12}\cdot Y_{23}\cdot Y_{34}\cdot\{&Z_1/[(Y_{11} - Y_{22})(Y_{11} - Y_{33})(Y_{11} - Y_{44})] + \\
&Z_2/[(Y_{22} - Y_{11})(Y_{22} - Y_{33})(Y_{22} - Y_{44})] + \\
&Z_3/[(Y_{33} - Y_{11})(Y_{33} - Y_{22})(Y_{33} - Y_{44})] + \\
&Z_4/[(Y_{44} - Y_{11})(Y_{44} - Y_{22})(Y_{44} - Y_{33})]\}
\end{aligned}
$$

Fortunately, chains with more than 4 members do not need to be considered because the accumulation time is 50 years. For the nuclides of interest, four member chains will be adequate for 1000 years. There is a similarity between the above equations for decay and leaching of an initial soil contamination over time and the ordinary decay equations.

The initial soil contamination may be due to well-drilling or to irrigation with contaminated water in prior years. Thus irrigation calculations involving prior irrigation with contaminated water are calculated as the sum of an initial soil concentration case and an irrigation case. The initial soil concentration is computed according to the method shown in equations (22) through (25).

3.2 Emanation of Gaseous Nuclides from the Soil Surface

Two cases are described in the "No Infiltration Scenarios" of Table 2. The first is the "Offsite Farmer" who is downwind of the disposal site. The second is the "Onsite Resident" who lives in a dwelling affected by the gaseous emission. These scenarios are presented in more detail below. In addition, the two are compared to show that the offsite dose is always lower than the onsite dose.

The nuclides of concern for these emissions are H-3, C-14, Rn-220, and Rn-222. The H-3 is normally found as water and would be released as water vapor. The C-14 has been assumed to be bound to an organic compound. Presumably the organic compound could be volatile as well. The most likely carbon compound to be emitted is carbon dioxide. However, the inhalation dose factor for carbon dioxide is about 90 time smaller than for organically bound C-14. Finally, the inhalation dose from radon compounds depends on the ease with which the particulate progeny of the inert gas become attached to dust particles in the air, as well as the relative amounts of the short half life progeny. For this reason, the radon emission is limited to 20 pCi m^{-2} s^{-1} (HNF-EP-0826).

3.2.1 Effect on the Offsite Farmer

Radioactivity released into the air is carried by the wind to locations some distance from the emission source. As the airborne material travels it is diluted, so that the potential doses are lessened. However, the radioactive material may settle on crops and pastures, leading to ingestion pathway doses as well as the initial inhalation dose as the plume passes the receptor location. The inhalation dose to an individual downwind is calculated using the formula shown below.

$$H_{bt} = Q_{emit}\ X/Q'\ BR\ DF_{inh} \qquad (26)$$

where,

H_{bt} = inhalation dose at a downwind location, mrem

Q_{emit} = activity released into the air as a gas or respirable particles, Ci

X/Q' = air transport factor, 1.0E-4 s/m^3

BR = breathing rate, 2.64E-4 m^3/s

DF_{inh} = inhalation dose factor for a nuclide emanating from the ground surface, in mrem per pCi inhaled. Values are given in Table 8.

Because the emission from the ground surface is assumed to take place over the course of a year, the parameters in Equation (26) are chosen to represent the annual average. Thus the annual average breathing rate is 0.95 m^3/h, or 2.64E-4 m^3/s. In addition, the activity released into the air is the total released over the course of one year. Finally, the air transport factor (1.0E-4 s/m^3) is a bounding value for an annual emission (WHC-SD-WM-TI-616). It includes the normal variation in wind direction, wind speed, and atmospheric stability.

Inserting values for inhalation dose factor, and assuming a 1 Ci emission over the course of a year, leads to unit dose factors of 0.0025 mrem per Ci H-3, and 0.055 mrem per Ci C-14.

An additional method for estimating the offsite dose, that takes into account the ingestion pathways is the CAP88-PC software from EPA (402-B-92-001). The software predicts that the total doses are 0.0237 mrem per Ci H-3, and 1.32 mrem per Ci C-14. The program output is listed in Appendix C. Note that the air transport factors used by CAP88-PC was 7.98E-6 s/m³ because a distance of 1000 m was input. The doses reported by CAP88-PC were then adjusted upward by the ratio of air transport factors, namely, (1.0E-4)/(7.98E-6)=12.5 to give the values reported above. An additional difference with the simple inhalation dose method is the assumed chemical form of the carbon. In CAP88-PC the carbon is in the form of carbon dioxide, while in the simple inhalation calculation, the organic form is used. Although the organic form of carbon leads to larger inhalation doses, the ingestion pathways in CAP88-PC give most of the dose. It should be noted that the various consumption parameters in CAP88-PC are larger. For example the fraction of contaminated vegetables is 100% in CAP88-PC. The value of CAP88-PC is that is can be used to demonstrate compliance with the 10 mrem/y performance objective for airborne emissions.

3.2.2 Effect on the Onsite Resident

For modeling the effect of contaminants emanating from the soil into a ventilated building, the equilibrium air concentration is the product of the emanation rate (activity per unit area per unit time) and the floor area divided by the building ventilation rate (volume per unit time). The ratio of ventilation rate to floor area is characteristic of classes of building construction. Typical ratios are less than 0.003 m/s. The individual exposed to gaseous emanations from the disposal site is located in a ventilated dwelling. For a constant emanation rate with a constant ventilation rate, the concentration starts at zero and rises according to the formula shown below.

$$C = (C_{eq})\cdot\{1\text{-Exp}[-(F)(t)/(V)]\}$$
$$C_{eq} = (E)/(F/A) \qquad (27)$$

where,

C = time-dependent air concentration inside the building, Ci/m³

C_{eq} = steady-state (or equilibrium) air concentration, Ci/m³

E = contaminant emanation rate, Ci m^{-2} s^{-1}

A = building floor area, m²

F = building ventilation rate, m³/s

V = building volume, m³

The ratio F/A is characteristic of certain dwellings. Two examples are listed below.

Typical values will need to be established for dose calculation purposes. For radon, the DOE uses an emanation limit. For gases such as tritium (as water vapor) and carbon-14, a dose calculation can be performed.

house: $F/A = (10\ cfm)/(100\ ft^2) = 1/600\ ft/s = 5.08E\text{-}4\ m/s$

office: $F/A = (100\ cfm)/(200\ ft^2) = 1/120\ ft/s = 2.54E\text{-}3\ m/s$

Using the smaller value to maximize the equilibrium air concentration, and assuming a unit emanation rate (1 pCi $m^{-2}\ s^{-1}$) leads to an equilibrium air concentration of 2000 pCi/m^3, or 2 pCi/L in the dirt-floor house.

The inhalation dose received by exposure to radionuclides emanating from the soil into a dwelling is the product of the steady-state air concentration, the volume of air inhaled during the year, and the inhalation dose factor as shown in Equation (28). Any decay factor is expected to be nearly one, since the nuclides that contribute to this pathway (tritium, C-14, Rn-220 and Rn-222) are expected to see very little change in the emanation rate due to radioactive decay.

$$H_{be} = Q_{ab}\ C_{eq}\ D_{inh}\ T_{inh} \tag{28}$$

where

- H_{be} = inhalation dose from the emanation of gaseous nuclides during one year, in mrem.
- Q_{ab} = quantity of air inhaled by the person while in the dwelling, in m^3/y. The value used is 6170 m^3/y based on the sleeping and indoor data in Table 17.
- C_{eq} = steady-state concentration of gaseous nuclides in the dwelling, in pCi/L.
- D_{inh} = inhalation dose factor for a nuclide, in mrem per pCi inhaled. Values are given in Table 8.
- T_{inh} = inhalation exposure time of the individual, 1 y.

For H-3 and C-14, the inhalation doses are calculated as shown below. They are based on a unit emanation rate, 1 pCi $m^{-2}\ s^{-1}$.

H-3: $(6170\ m^3/y)(2000\ pCi/m^3)(9.60E\text{-}8\ mrem/pCi)(1\ y) = 1.18\ mrem$

C-14: $(6170\ m^3/y)(2000\ pCi/m^3)(2.09E\text{-}6\ mrem/pCi)(1\ y) = 25.8\ mrem$

3.2.3 Comparison of Offsite and Onsite Doses

A basic difference between the two dose calculations is the input radioactivity. For the offsite dose calculation, the total released into the air during one year must be estimated. For the onsite dose calculation, the rate at which activity enters the air per unit area of floor space is needed. To put the two on a comparable level, assume the ground surface directly above the waste site has a surface area of 31,690 m^2. A uniform emanation rate of 1 pCi m^{-2} s^{-1} for one year will release 1 Ci of activity into the air.

$$(1 \text{ pCi m}^{-2} \text{ s}^{-1})(31{,}690 \text{ m}^2)(3.156\text{x}10^7 \text{ s/y})(1 \text{ y}) = 1 \text{ Ci}$$

Because the offsite dose is smaller than the onsite dose for unit emission rates (Table 28), the waste site area needs to be increased to raise the offsite dose, which depends on the total emitted during the year. Table 28 shows the calculated doses and required disposal site area for the two doses to be equal. Because the disposal site surface area will be significantly less than a square kilometer (1.0E+6 m^2), the onsite dose will always be greater than the offsite dose.

Table 28. Comparison of Onsite and Offsite Doses.

Volatile Nuclide	Onsite Resident (per pCi m^{-2} s^{-1})	Offsite Farmer (per Ci released)	Disposal Facility Surface Area
H-3	1.18 mrem	0.0237 mrem	1.58E+6 m^2
C-14	25.8 mrem	1.32 mrem	1.08E+6 m^2

Disposal Site Area is calculated as the Onsite dose multiplied by 31,690 m^2 and divided by the Offsite dose.

3.3 External and Inhalation Dose

The inhalation dose that is received by exposure to airborne water during showering or a sauna or under ambient conditions is simply the product of the volume of water inhaled during the year, the water concentration, and the inhalation dose factor as shown in equation (29). No consideration of radioactive decay or progeny ingrowth is needed, because the water concentration is assumed to be constant during the year, and no progeny are allowed to accumulate in the water.

$$H_{bw} = Q_{wb}\, C_w\, D_{inh}\, T_{inh} \tag{29}$$

where

H_{bw} = inhalation dose from airborne moisture during one year, in mrem.

Q_{wb} = quantity of contaminated water inhaled by the person while in the shower or sauna, in L/y. Values are given in Table 18.

C_w = concentration of a nuclide in the contaminated water, in pCi/L.

D_{inh} = inhalation dose factor for a nuclide, in mrem per pCi inhaled. Values are given in Table 8.

T_{inh} = inhalation exposure time of the individual, 1 y.

The external and inhalation dose due to exposure to contaminated soil are accumulated over the course of a year for all exposure scenarios except the waste intruder (driller). The amount accumulated per day depends on the soil concentration on that day. The external dose rate and the inhalation dose rate are proportional to the soil concentration. The total accumulated over the year is proportional to the time integral of the soil concentration. The external dose and inhalation doses are shown in equation (30). To obtain the total dose from the parent nuclide it is necessary to include the contributions from each progeny nuclide. Hence the sum over nuclides in a decay chain. Note that radioactive decay is not considered for the waste intruder because the exposure time is so brief (5 days) compared to the half lives of the nuclides selected for analysis.

$$H_{xs} = \sum_{i=1}^{n} \int_0^{1\,y} \rho\, d\, C_{si}\, D_{ext,i}\, dT$$

$$H_{bs} = \sum_{i=1}^{n} \int_0^{1\,y} M_{sb}\, C_{si}\, D_{inh,i}\, dT \qquad (30)$$

where

H_{xs} = external dose accumulated during the year from one radionuclide and its progeny due to radioactivity in the soil, mrem

H_{bs} = inhalation dose accumulated during the year from one radionuclide and its progeny due to radioactivity in the soil, mrem

I = index over the decay chain. I=1 refers to the first member, or parent nuclide; I=2 refers to the second member of the decay chain; I=3 refers to the third member; I=4 refers to the fourth member.

ρ = bulk density of the surface soil, in grams per cubic centimeter. The value normally used in Hanford Site PA work is 1.5 g/cc.

d = thickness of soil from which nuclides migrate, in centimeters. This is assumed to be 15 cm (5.9 inches).

C_{si} = time-dependent soil concentration of the ith nuclide during the year, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil.

$D_{ext,i}$ = external dose rate factor for exposure to radiation from nuclide "I" in contaminated soil, in mrem/h per Ci/m². Values are given in Table 10.

M_{sb} = mass of soil inhaled annually by the individual, in mg/y. Values are discussed in Section 2.2.4.

$D_{inh,i}$ = inhalation dose factor for nuclide "I", in mrem per pCi inhaled. Values are given in Table 8.

The only term in the integrals with any time dependence is the soil concentration. Thus the accumulated dose at time T is the time integral of the activity equations. These integrations are simply the integral of each exponential. Each of the exponential terms in the decay equations (6) and (10), namely, Exp(-λT), are replaced with the time integral shown in Equation (31). Note that the integral of the DS term in equation (10) is the same as the DI term in equation (14).

$$\text{Time Integral} = \int_0^T \text{Exp}(-\lambda t)\, dt = \left[1 - \text{Exp}(-\lambda T)\right]/\lambda \tag{31}$$

If the product λT is less than 0.0002, a loss of numeric accuracy is experienced. To overcome this, the integral in equation (31) is replaced with the equivalent polynomial to improve the numeric precision of the calculation. The polynomial used is shown in equation (32).

$$[1 - \text{Exp}(-\lambda T)]/\lambda = T \cdot [1 - \lambda T/2 + (\lambda T)^2/6 - (\lambda T)^3/24] \tag{32}$$

Notice that if the product λT is very small, the time integral approaches the decay period. For this reason, the time integral of the decay equation is sometimes referred to as an effective time period. In effect, it is a particular time period adjusted for radioactive decay. To consistently work with unitless decay periods, all time integrals are divided by the integration period. Thus the integration period must be made a factor in the calculation.

For the irrigated farm scenario, the concentration of nuclides in the soil increases with time due to the activity accumulating in the soil as shown in equation (14). The soil concentration follows the time integral formula of equations (31) and (32). The accumulated intake or dose at time T is the time integral of the equation (14). In other words, each exponential term in the decay equation (10), namely, Exp(-λT) is replaced with its second integral, shown in equation (33).

$$\text{Second Integral} = [\lambda T - 1 + \text{Exp}(-\lambda T)]/\lambda^2 \tag{33}$$

If the product λT is less than 0.001, a loss of numeric accuracy is experienced. To overcome this, the integral in equation (33) is replaced with the equivalent polynomial to improve the numeric precision of the calculation. The polynomial used is shown in equation (34).

$$[\lambda T - 1 + Exp(-\lambda T)]/\lambda^2 = T^2 \cdot [1 - \lambda T/3 + (\lambda T)^2/12 - (\lambda T)^3/60]/2 \qquad (34)$$

Notice that if the product λT is very small, the time integral in equations (33) and (34) approaches the decay period squared. Again, to only work with unitless decay factors, the second integral is divided by the integration period squared. This time must then be made a factor in the dose equation.

Using the two-part irrigation model, the dose accumulated during the first 6 months depends only on the DS or DI integration. The dose during the second 6 months (without irrigation) depends only on the DR integration. This idea is summarized in the equations below. Equation (35) shows the time integral of equations (16) through (18) for an initial soil contamination (e.g. the post-intrusion garden), while equation (36) shows the time integral of equations (19) through (21) for irrigation with contaminated water. Constant factors have been omitted to simplify the equations. In both equations the first integral represents the dose from the nth member of the decay chain during the first 6 months. During the first 6 months the only source of this nuclide is the decay of the parent nuclide. After 6 months of decay and ingrowth, each member of the decay chain will be present in the soil. Thus the second time integral on the right has contributions from decay of the parent as well as decay of the other members of the chain.

Initial Soil Contamination: (from Equation 16)

$$\int_0^{1y} Y_{1n}(T)\,dT = \int_0^{T_{irr}} DS_{1n}(T)\,dT + \sum_{k=1}^{n} DS_{1k}(T_{irr}) \int_0^{T_{no}} DR_{kn}(T)\,dT$$

$$\int_0^{1y} Y_{1n}(T)\,dT = T_{irr} \cdot DS_{1n}(T_{irr}) + T_{no} \sum_{k=1}^{n} DS_{1k}(T_{irr}) \cdot DR_{kn}(T_{no}) \qquad (35)$$

Irrigation with Contaminated Water: (from Equation 19)

$$\int_0^{1y} C_{s1}\,dT = \int_0^{T_{irr}} DI_{1n}(T)\,dT + \sum_{k=1}^{n} DI_{1k}(T_{irr}) \int_0^{T_{no}} DR_{kn}(T)\,dT$$

$$\int_0^{1y} C_{s1}\,dT = T_{irr} \cdot DI_{1n}(T_{irr}) + T_{no} \sum_{k=1}^{n} DI_{1k}(T_{irr}) \cdot DR_{kn}(T_{no}) \qquad (36)$$

The above equations show the decay factors that represent each integral. Additional terms needed in later calculations are defined below. Note that the integration period becomes a factor in the equation because the decay factors are designed to be unitless quantities between 0 and 1.

$$\int_0^{T_{irr}} D_S(T)\,dT = T_{irr}\,\bar{D}_S(T_{irr}) \qquad \int_0^{T_{no}} D_R(T)\,dT = T_{no}\,\bar{D}_R(T_{no})$$

$$\int_0^{T_{irr}} D_I(T)\,dT = T_{irr}\,\bar{D}_I(T_{irr}) \qquad T_{no} = 1y - T_{irr} \tag{37}$$

$$\int_0^{T_{veg}} D_R(T)\,dT = T_{veg}\,\bar{D}_R(T_{veg}) \qquad \int_0^{T_{beef}} D_R(T)\,dT = T_{beef}\,\bar{D}_R(T_{beef})$$

note that

T_{irr} = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

T_{no} = interval during which no irrigation takes place, $T_{no} = 1y - T_{irr}$

T_{veg} = consumption period for garden produce, assumed to be 90 days

T_{beef} = consumption period for beef after slaughter, assumed to be 120 days.

3.4 Ingestion Dose

Human ingestion dose comes from the pathways discussed earlier, such as contaminated drinking water, trace intakes of soil, vegetables grown on contaminated soil, and animal products. Each of these is discussed below. The basic dose calculation is the product of three factors, (1) the quantity consumed, (2) the radionuclide concentration in what is consumed, and (3) the ingestion dose factor. The addition of radioactive decay and progeny ingrowth is discussed with each pathway.

3.4.1 Soil and Water Ingestion

The ingestion dose from drinking water is shown in equation (38). The drinking water has no progeny. The concentration of each nuclide in a chain is treated separately.

$$H_{ew} = Q_{we}\,C_w\,D_{ing}\,T_{ing} \tag{38}$$

where

H_{ew} = ingestion dose from drinking water, in mrem.

Q_{we} = quantity of contaminated drinking water ingested by the person, in L/y. See Tables 13 and 14 for values.

C_w = concentration of a nuclide in the contaminated water, in pCi/L.

D_{ing} = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table 7.

T_{ing} = ingestion exposure time of the individual, 1 y.

The ingestion dose from the intake of trace amounts of soil is shown in equation (39). The soil concentration does include leaching, decay and progeny ingrowth. Because the soil is consumed in small amounts during the year, the total dose is represented as the time integral of the daily intake. As before, the time integral must accommodate the change in infiltration rates during the year, just as was done for the inhalation and external doses using equations (35) and (36).

$$H_{es} = \sum_{i=1}^{n} \int_{0}^{1\,y} M_{se}\, C_{si}\, D_{ing,i}\, dT \qquad (39)$$

where

H_{es} = ingestion dose accumulated during the year from one radionuclide and its progeny due to radioactivity in the soil, mrem

I = index over the decay chain. I=1 refers to the first member, or parent nuclide; I=2 refers to the second member of the decay chain; I=3 refers to the third member; I=4 refers to the fourth member.

M_{se} = mass of soil ingested annually by the individual, in mg/y.

C_{si} = time-dependent soil concentration of the ith nuclide during the year, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil.

$D_{ing,i}$ = ingestion dose factor for nuclide "I", in mrem per pCi ingested. Values are given in Table 7.

3.4.2 Garden Produce

The ingestion dose from garden produce grown in contaminated soil is the product of the quantity of vegetables eaten, the concentration of radioactivity in the vegetables, and the ingestion dose factor. The ingestion dose factors are given in Table 7. Quantities eaten are given in Tables 13 and 14. The calculation of radionuclide concentrations in living plants uses three main routes, (1) root uptake, (2) resuspension to leaves (also called "rain splash"), and (3) direct deposition of irrigation water on foliage. Each of these will be considered separately below. The three uptake routes are then combined to obtain the total ingestion dose from the garden produce.

The equations presented below apply to both garden produce and cattle feed in the sense that the quantity eaten and the ingestion dose factor can be removed to give the nuclide concentration in the cattle feed. These concentrations are needed to calculate dose from ingestion of contaminated animal products.

The garden produce intakes are based on the two situations. The first applies to leafy vegetables. It is assumed that leafy vegetables are produced more-or-less continuously during the growing season. They are consumed shortly after being collected. Thus the continuous model uses a time integral to represent the accumulated dose from leafy vegetables during the growing season. It is further assumed that leafy vegetables are not raised after the growing season has ended. Any leafy vegetables consumed after the growing seasons ends are assumed to have been imported from uncontaminated areas. The 25% of a person's diet that comes from contaminated sources is then assumed to be 50% during the irrigation period and 0% during the remainder of the year.

The second garden produce model applies to the other types of garden produce. These foods are assumed to be grown and harvested twice during the growing season. The plant concentration depends on the soil concentration at the time of harvest. For an initial soil contamination (e.g. post-intrusion garden or prior irrigation) this time is taken to be midway through the irrigation season. For the irrigation scenarios harvest is assumed to occur at the end of the irrigation season. Because these foods may be stored and eaten over a period of time, radioactive decay during the storage and consumption periods needs to be taken into account. The amount of radioactive contamination eaten during the consumption period is the time integral of the ordinary decay equations (5) through (7). The average consumption period for non-leafy vegetables is taken to be 90 days. Some products do not keep well, and have shorter consumption periods. Others keep very well and have longer consumption periods. The value selected for the ILAW PA (90 days) simplifies the calculations in that all non-leafy vegetables have the same period. Note that for long half life nuclides the actual value has no effect on the final doses.

Root uptake is calculated using concentration ratios. These ratios are listed in Table 25. The ingestion dose from garden produce due to root uptake into the various types of vegetation is described with equation (40). The first equation shows the continuous model for leafy vegetables. Note that the integral is over half the year so the assumed annual intake from garden must be adjusted upward to compensate. Hence the ratio (1 y)/(T_{irr}). The second equation shows the harvest model for the other vegetables. In both equations the sum over radionuclides in a decay chain is needed to obtain the total dose from the parent nuclide.

$$H_{epr}(\text{leafy}) = \sum_{i=1}^{n} \frac{1\,y}{T_{irr}} \int_0^{T_{irr}} R_p\, B_{pi}\, Q_{vp}\, C_{si}\, D_{ing,i}\, dT$$

(40)

$$H_{epr}(\text{others}) = \sum_{i=1}^{n} R_p\, B_{pi}\, Q_{vp}\, C_{si}\, IDR_i(T_{veg})\, D_{ing,i}\, T_{ing}$$

where

H_{epr} = ingestion dose from plant type p due to root uptake, in mrem.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

R^p = dry to wet ratio for plant type p. See Table 24 for values.

B_{pi} = soil to plant concentration ratio, as Ci/kg dry weight of vegetables to Ci/kg of soil. See Table 25 for values.

Q_{vp} = quantity of plant type p eaten by the person, in kg/y. See Tables 13 and 14 for values.

C_{si} = soil concentration of the ith nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season. In the second equation it is the soil concentration at the time of harvest.

T_{irr} = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

IDR_i = decay factor that accounts for radioactive decay of the ith nuclide during the consumption of garden produce

T_{veg} = consumption period for garden produce, assumed to be 90 days

T_{ing} = ingestion exposure time of the individual, 1 y.

$D_{ing,i}$ = ingestion dose factor for nuclide "I", in mrem per pCi ingested. Values are given in Table 7.

The resuspension of dust by wind, or water drops splashing soil onto the foliage leads to some contamination of the edible portion of the plant. The ingestion dose from this source of contamination is calculated using equation (41). The first equation shows the continuous model for leafy vegetables. Note that the integral is over half the year so the assumed annual intake from garden must be adjusted upward to compensate. Hence the ratio (1 y)/(T_{irr}). The second equation shows the harvest model for the other vegetables. Note the sum over radionuclides in a decay chain to obtain the total dose from the parent nuclide.

$$H_{epf}(leafy) = \sum_{i=1}^{n} \frac{1\,y}{T_{irr}} \int_0^{T_{irr}} R^a V_d \frac{F_{fp} F_{tp} T_w}{Y_p} Q_{vp} C_{si} D_{ing,i} \, dT$$

$$H_{epf}(others) = \sum_{i=1}^{n} R^a V_d \frac{F_{fp} F_{tp} T_w}{Y_p} Q_{vp} C_{si} IDR_i(T_{veg}) D_{ing,i} T_{ing} \qquad (41)$$

where

H_{epf} = ingestion dose from plant type p due to resuspension of contaminated soil onto plant surfaces (rain splash), in mrem.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

R^a = average concentration of soil in the air near the foliage due to rain splash, 1.0 mg/m^3. See Section 2.4.2 for further discussion.

V_d = diffusion attachment speed, or ground deposition speed that represents rain splash soil, 0.01 m/s or 864 m/d. See Section 2.4.2 for further discussion.

F_{fp} = interception fraction for plant type p. The fraction of what falls to the earth that lands on the plant. Computed using equation (3). Values are listed in Table 26.

F_{tp} = translocation factor, i.e. the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table 26.

T_w = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table 29.

Y_p = harvest yield of crop type p, in kg/m^2 (wet weight). Also called the standing biomass. Values are listed in Table 26.

Q_{vp} = quantity of plant type p eaten by the person during the year, in kg/y. See Tables 13 and 14 for values.

C_{si} = time-dependent soil concentration of the ith nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season. In the second equation it is the soil concentration at the time of harvest.

T_{irr} = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

IDR_i = decay factor that accounts for radioactive decay of the ith nuclide during the consumption of garden produce

T_{veg} = consumption period for garden produce, assumed to be 90 days

T_{ing} = ingestion exposure time of the individual, 1 y.

$D_{ing,i}$ = ingestion dose factor for nuclide "I", in mrem per pCi ingested. Values are given in Table 7.

One effect of wind, rain, and irrigation is to remove deposited contamination from plant surfaces. This effect is included using a weathering term shown in equation (42). Values for the effective growing period are only slightly affected by the radioactive half life of the isotope for the long half lives shown in Table 5. Therefore, the decay effects were not considered (λ_w=0). Values for T_w are given in Table 29 for the growing periods shown in Table 26.

$$T_w = \{ 1 - Exp[-(\lambda_w + \lambda_r)T_p^f] \} / (\lambda_w + \lambda_r) \qquad (42)$$

where

T_w = effective exposure period for foliar deposition, in days. Values are shown in Table 29.

λ_w = weathering removal coefficient, 0.0495105 per day, or 18.0713 per year, which corresponds to a 14 day half time.

λ_r = radioactive decay constant, namely, the natural logarithm of 2 divided by the radioactive decay half life in days. Values are listed in Table 5.

T_p^f = exposure time of the plant type p to the airborne contamination depositing on the foliage, in days (also called growing period). Values are shown in Table 26.

The previous two avenues by which contamination reaches the edible portions of the plants apply only to activity which is present in the soil. This section discusses direct deposition of contaminants in irrigation water onto the foliage. The ingestion dose due to radioactivity in the edible portion of the plants due to direct deposition on foliage is given in equation (43).

Table 29. Effective Exposure Times for Foliar Deposition

Growing Period	T_w
30 days	15.6 days
45 days	18.0 days
90 days	20.0 days

The effective exposure times are computed assuming radioactive decay is negligible for the nuclides of Table 5.

$$H_{epd}(leafy) = ID_p \frac{0.25\, F_{tp}\, T_w}{Y_p} Q_{vp}\, D_{ing}\, T_{ing}$$

$$H_{epd}(others) = \sum_{i=1}^{n} ID_p \frac{0.25\, F_{tp}\, T_w}{Y_p} Q_{vp}\, IDR_i(T_{veg})\, D_{ing,i}\, T_{ing} \qquad (43)$$

where

H_{epd} = ingestion dose from plant type p due to deposition of a nuclide in contaminated irrigation water onto plant surfaces, in mrem.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

ID_p = instantaneous activity deposition rate due to irrigation of soils growing plant type p, in Ci/yr/m². Only the parent nuclide is present. Any progeny nuclides are assumed to be absent.

0.25 = interception fraction for contaminants in irrigation water. The fraction of what falls to the earth that lands on the plant.

F_{tp} = translocation factor, i.e. the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table 26.

T_w = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table 29.

Y_p = harvest yield of crop type p, in kg/m² (wet weight). Also called the standing biomass. Values are listed in Table 26.

Q_{vp} = quantity of plant type p eaten by the person during the year, in kg/y. See Tables 13 and 14 for values.

IDR_i = decay factor that accounts for radioactive decay during the consumption of garden produce

T_{veg} = consumption period for garden produce, assumed to be 90 days

T_{ing} = ingestion exposure time of the individual, 1 y.

$D_{ing,i}$ = ingestion dose factor for the ith nuclide, in mrem per pCi ingested. Values are given in Table 7.

The ingestion dose from garden produce due to direct deposition depends on the rate at which water is applied. In the previous two pathways, root uptake and rain splash, the determining factor is the total amount of water (and thus activity) applied to the soil. A summary of the essential calculation and the decay corrections is presented in Table 30.

Table 30. Summary of Ingestion Dose from Garden Produce

Essential Dose Calculation for an Initial Soil Contamination	
Root Uptake:	$R_p\, B_p\, C_s\, Q_{vp}\, D_{ing}\, T_{ing}$
Rain Splash:	$R^a\, V_d\, F_{fp}\, (F_{tp}\, T_w\, /Y_p)\, C_s\, Q_{vp}\, D_{ing}\, T_{ing}$
Correction for Radioactive Decay and Progeny Ingrowth	
Leafy Vegetables:	$IDS(T_{irr})$
Other Vegetables, Fruit, and Grain:	$DS(T_h) \cdot IDR(T_{veg})$
Essential Dose Calculation for Irrigation with Contaminated Water	

Root Uptake:	$R_p\, B_p\, C_s\, Q_{vp}\, D_{ing}\, T_{ing}$
Rain Splash:	$R^a\, V_d\, F_{fp}\, (F_{tp}\, T_w / Y_p)\, C_s\, Q_{vp}\, D_{ing}\, T_{ing}$
Direct Deposition:	$ID_p\, (0.25)\, (F_{tp}\, T_w / Y_p)\, Q_{vp}\, D_{ing}\, T_{ing}$
Correction for Radioactive Decay and Progeny Ingrowth	
Leafy Vegetables:	Root Uptake & Splash: $IDI(T_{irr})$ Direct Deposition: no decay
Other Vegetables, Fruit, and Grain:	Root Uptake & Splash: $DI(T_{irr})\cdot IDR(T_{veg})$ Direct Deposition: $IDR(T_{veg})$

Notes: Leafy vegetables are consumed continuously during growing season (T_{irr}) only. Other produce is harvested and consumed over a period of time (T_{veg}). The decay factors are unitless fractions shown in Equation (37). Progeny ingrowth is computed using the method shown in Section 3.1.4.

Explanation of Symbols Used in Table 30.

B_p = soil to plant concentration ratio, as Ci/kg dry weight of vegetables to Ci/kg of soil. See Table 25 for values.

C_s = soil concentration of a nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season.

D_{ing} = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table 7.

F_{fp} = interception fraction for plant type p. The fraction of what falls to the earth that lands on the plant. Computed using equation (3). Values are listed in Table 26.

F_{tp} = translocation factor, i.e. the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table 26.

ID_p = instantaneous activity deposition rate due to irrigation of soils growing plant type p, in Ci/yr/m².

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

Q_{vp} = quantity of plant type p eaten by the person during the year, in kg/y. See Tables 13 and 14 for values.

R^a = average concentration of soil in the air near the foliage due to rain splash, 1.0 mg/m³. See Section 2.4.2 for further discussion.

R_p = dry to wet ratio for plant type p. See Table 24 for values.

T_h = time at which harvest occurs. For initial soil contaminations, harvest is assumed to occur halfway through the growing season, $T_h = T_{irr}/2$. For irrigation with contaminated water, the harvest occurs at the end of the irrigation season to maximize the soil contamination.

T_{ing} = ingestion exposure time of the individual, 1 y.

T_{irr} = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

T_{veg} = consumption period for garden produce, assumed to be 90 days

T_w = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table 29.

V_d = diffusion attachment speed, or ground deposition speed that represents rain splash soil, 0.01 m/s or 864 m/d. See Section 2.4.2 for further discussion.

Y_p = harvest yield of crop type p, in kg/m² (wet weight). Also called the standing biomass. Values are listed in Table 26.

The one special case nuclide is tritium in contaminated irrigation water. Tritium present in an initial soil contamination is handled using the same method as any other nuclide. The soil-to-plant concentration ratio shown in Table 25 is used. Tritium in irrigation water leads to an equilibrium situation in which the concentration of tritium in the water is reproduced throughout the plant. Since the equilibrium is established rather quickly, the decay corrections are simpler than for other nuclides. The calculation of dose from tritium in irrigation water is shown in Equation (44) below. Note that the tritium model assumes that loss of tritium by evaporation of water from soil or plants is not important.

$$H_{epH}(\text{leafy}) = \frac{I\,C_{w,H3}}{I+P}(8.94\,F_{Hp})\,Q_{vp}\,D_{ing,H3}\,T_{ing}$$

$$H_{epH}(\text{others}) = \frac{I\,C_{w,H3}}{I+P}(8.94\,F_{Hp})\,Q_{vp}\,DR(T_{veg})\,D_{ing,H3}\,T_{ing} \tag{44}$$

where

H_{epH} = ingestion dose from plant type p due to tritium (H-3) in the irrigation water, in mrem.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

I = total irrigation water applied to the soil during the irrigation season, 82.3 cm/y (63.5 cm/y for populations).

$C_{w,H3}$ = concentration of tritium in the irrigation water, in pCi/L.

P = total natural precipitation water applied to the soil during the irrigation period, 5.23 cm/y (PNNL-12087).

F_{Hp} = fraction of hydrogen in plant type p. Values are listed in Table 23. The factor of 8.94 converts the hydrogen fraction to an effective water fraction that includes organically bound hydrogen.

Q_{vp} = quantity of plant type p eaten by the person during the year, in kg/y. See Tables 13 and 14 for values.

IDR = decay factor that accounts for radioactive decay during the consumption of garden produce

T_{veg} = consumption period for garden produce, assumed to be 90 days

T_{ing} = ingestion exposure time of the individual, 1 y.

$D_{ing,H3}$ = ingestion dose factor for tritium, in mrem per pCi ingested. Value is given in Table 7.

3.4.3 Animal Products Eaten

The simplest animal product to evaluate is fish. The dose from fish consumption is shown in equation (45). It is the product of the quantity of fish consumed during the year, the concentration in the fish, and the ingestion dose factor. The fish harvested is consumed over the next few days, so there is no need to correct for radioactive decay and progeny ingrowth.

$$H_{ef} = Q_{fe}\, C_w\, B_f\, D_{ing}\, T_{ing} \qquad (45)$$

where

H_{ef} = ingestion dose from contaminated fish, in mrem.

Q_{fe} = quantity of contaminated fish consumed by the person during the year, in kg/y. See Tables 13 and 14 for values.

C_w = concentration of a nuclide in the contaminated water, in pCi/L.

B_f = bioaccumulation factor in fish, in L/kg. It is the ratio of the contamination in the edible parts of the fish to the concentration in the water. Values are shown in Table 22.

T_{ing} = ingestion exposure time of the individual, 1 y

D_{ing} = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table 7.

The ingestion dose from foods obtained from land animals is computed using equilibrium transfer factors shown in Table 22. These relate the total radioactive material ingested by the animal each day to the concentration in the animal product consumed by a person. The total diet of the animal must be taken into account. The animal may drink contaminated water, ingest contaminated soil, graze on contaminated grass and be fed stored material that is also contaminated. Each of these will be presented in turn. The total ingestion dose from animal products is the sum of these.

Just as with garden produce there is a continuous production model and a harvest model in which the animal is slaughtered for later consumption. The beef cattle model illustrates the latter, while the milk cow illustrates the former. The chicken (meat) and egg are treated as continuous because these are produced at regular intervals during the year and then consumed shortly thereafter.

The ingestion dose from contaminated water consumed by the animal is shown in equation (46). Because the progeny nuclides are not allowed to form in the water supply, the dose from each nuclide in a chain will be calculated separately. When the beef cattle is slaughtered (i.e. harvested), there is a large quantity of beef available. This food is then consumed over a period of time during which radioactive decay and progeny ingrowth occurs. The quantity of contaminated beef consumed during the year is from Tables 13 and 14. These values have already been adjusted for the fraction of the year that contaminated beef is consumed. Hence, the factor (T_{ing}/T_{beef}) is included.

$$H_{eqw}(beef) = \sum_{i=1}^{n} \int_0^{T_{beef}} Q_{wq}\, C_w\, F_{qi}\, Q_{aq} \left(\frac{T_{ing}}{T_{beef}} \right) D_{ing,i}\, DR_i\, dT$$

$$H_{eqw}(others) = Q_{wq}\, C_w\, F_q\, Q_{aq}\, D_{ing}\, T_{ing} \qquad (46)$$

where

- H_{eqw} = ingestion dose from animal product q due to contaminated drinking water, in mrem.
- q = index for animal products. There are 4 types of animal products, beef, milk, poultry, and eggs.
- Q_{wq} = quantity of contaminated drinking water ingested by the animal associated with animal product q each day, in L/d. See Table 21 for values.
- C_w = concentration of the parent nuclide in a decay chain in the contaminated water, in pCi/L. The progeny nuclide concentrations are assumed to be zero in the water.
- F_{qi} = equilibrium transfer factor for animal product q for the ith nuclide in a decay chain, in d/kg (or d/L for milk). Values are given in Table 22. F_q is the transfer factor of the first nuclide.
- Q_{aq} = quantity of animal product q consumed by the person during the year, in kg/y (or L/y for milk). See Tables 13 and 14 for values.

T_{beef} = consumption period for beef cattle, assumed to be 120 days

T_{ing} = ingestion exposure time of the individual, 1 y

$D_{ing,i}$ = ingestion dose factor for the ith nuclide in a decay chain, in mrem per pCi ingested. Values are given in Table 7. D_{ing} is the ingestion dose factor of the first nuclide in the chain.

The other contributors to the overall contamination of an animal product are summarized in Table 31. For the case of an initial soil contamination, the two components are vegetable foods consumed by the animal and the soil ingestion shown in Table 21. The animal foods are contaminated by root uptake and rain splash. There are three main kinds of food: fresh fodder (grass), stored hay (grass that is harvested and stored), and stored feed (grain that is harvested and stored). For the case of irrigation with contaminated water, additional components are direct deposition on the animal foods, and direct ingestion of the irrigation water.

Table 31. Summary of Ingestion Dose from Animal Products

Essential Dose Calculation for an Initial Soil Contamination. The activity intake rates are computed using the formulas below. These are converted to annual dose equivalent by means of the factor, $F_q Q_{aq} D_{ing} T_{ing}$.	
Trace Soil Ingestion:	$C_s Q_{sq}$
Fodder -- Root Uptake:	$R_p B_p C_s Q_{pq}$
Fodder -- Rain Splash:	$R^a V_d F_{fp} (F_{tp} T_w / Y_p) C_s Q_{pq}$
Correction for Radioactive Decay and Progeny Ingrowth -- Beef	
Soil Ingestion and Fresh Grass:	$DS(T_h) \cdot IDR(T_{beef})$
Stored Hay (grass) and Stored Grain:	$DS(T_h) \cdot DR(T_s) \cdot IDR(T_{beef})$
Correction for Radioactive Decay and Progeny Ingrowth -- Milk, Poultry, Eggs	
Soil Ingestion and Fresh Grass:	$[T_{irr} \cdot IDS(T_{irr}) + T_{no} \cdot DS(T_{irr}) \cdot IDR(T_{no})]/T_{ing}$
Stored Hay (grass) and Stored Grain:	$DS(T_h) \cdot DR(T_s) \cdot IDR(T_{an})$

Essential Dose Calculation for Irrigation with Contaminated Water. The activity intake rates are computed using the formulas below. These are converted to annual dose equivalent by means of the factor, $F_q\, Q_{aq}\, D_{ing}\, T_{ing}$.	
Trace Soil Ingestion:	$C_s\, Q_{sq}$
Fodder -- Root Uptake:	$R_p\, B_p\, C_s\, Q_{pq}$
Fodder -- Rain Splash:	$R^a\, V_d\, F_{fp}\, (F_{tp}\, T_w\, /Y_p)\, C_s\, Q_{pq}$
Fodder -- Direct Deposition:	$ID_p\, (0.25)\, (F_{tp}\, T_w\, /Y_p)\, Q_{pq}$
Drinking Water Ingestion:	$C_w\, Q_{wq}$
Correction for Radioactive Decay and Progeny Ingrowth -- Beef	
Trace Soil Ingestion:	$DI(T_{irr}) \cdot IDR(T_{beef})$
Fresh Grass:	Root & Splash: $DI(T_{irr}) \cdot IDR(T_{beef})$ Direct Deposition: $IDR(T_{beef})$
Stored Hay and Grain:	Root & Splash: $DI(T_{irr}) \cdot DR(T_s) \cdot IDR(T_{beef})$ Direct Deposition: $DR(T_s) \cdot IDR(T_{beef})$
Drinking Water:	$IDR(T_{beef})$
Correction for Radioactive Decay and Progeny Ingrowth -- Milk, Poultry, Eggs	
Trace Soil Ingestion:	$[T_{irr} \cdot IDI(T_{irr}) + T_{no} \cdot DI(T_{irr}) \cdot IDR(T_{no})]/T_{ing}$
Fresh Grass:	Root Uptake & Rain Splash: $[T_{irr} \cdot IDI(T_{irr}) + T_{no} \cdot DI(T_{irr}) \cdot IDR(T_{no})]/T_{ing}$ Direct Deposition: no decay
Stored Hay and Grain:	Root & Splash: $DI(T_{irr}) \cdot DR(T_s) \cdot IDR(T_{an})$ Direct Deposition: $DR(T_s) \cdot IDR(T_{an})$
Drinking Water:	no decay

Notes: Beef is harvested and consumed over a period of time. Milk, poultry, and eggs are consumed continuously during the year. The decay factors are unitless fractions shown in Equation (37). Progeny ingrowth is computed using the method shown in Section 3.1.4.

Explanation of Symbols Used in Table 31.

B_p = soil to plant concentration ratio, as Ci/kg dry weight of vegetables to Ci/kg of soil. See Table 25 for values.

C_s = soil concentration of a nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season.

C_w = concentration of a nuclide in the contaminated water, in pCi/L. Any progeny nuclide concentrations are assumed to be zero.

D_{ing} = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table 7.

F_q = equilibrium transfer factor for animal product q for a nuclide, in d/kg (or d/L for milk). Values are given in Table 22.

F_{fp} = interception fraction for plant type p. The fraction of what falls to the earth that lands on the plant. Computed using equation (3). Values are listed in Table 26.

F_{tp} = translocation factor, i.e. the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table 26.

ID_p = instantaneous activity deposition rate due to irrigation of soils growing plant type p, in $Ci/yr/m^2$.

p = index for animal fodder. There are 3 types of animal fodder, fresh grass, stored hay, and stored grain.

q = index for animal products. There are 4 types of animal products, beef, milk, poultry, and eggs.

Q_{aq} = quantity of animal product q eaten by the person during the year, in kg/y (or L/y for milk). See Tables 13 and 14 for values.

Q_{pq} = quantity of fodder type p eaten by the animal during the year, in kg/y. See Table 21 for values.

Q_{sq} = quantity of contaminated soil ingested by the animal associated with animal product q each day, in kg/d. See Table 21 for values.

Q_{wq} = quantity of contaminated drinking water ingested by the animal associated with animal product q each day, in L/d. See Table 21 for values.

R^a = average concentration of soil in the air near the foliage due to rain splash, 1.0 mg/m^3. See Section 2.4.2 for further discussion.

R_p = dry to wet ratio for plant type p. See Table 23 for values.

T_{an} = time period over which stored hay and grain are consumed by the milk cow and chickens. Assumed to be the same as T_{veg}, 90 d.

T_{beef} = consumption period for beef cattle, assumed to be 120 days.

T_h = time at which harvest occurs. For initial soil contaminations, harvest is assumed to occur halfway through the growing season, $T_h = T_{irr}/2$. For irrigation with contaminated water, the harvest occurs at the end of the irrigation season to maximize the soil contamination.

T_{ing} = ingestion exposure time of the individual, 1 y.

T_{irr} = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site. T_{no} = 1y - T_{irr}

T_s = storage time for the stored feed (hay and grain), 90 d.

T_w = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table 29.

V_d = diffusion attachment speed, or ground deposition speed that represents rain splash soil, 0.01 m/s or 864 m/d. See Section 2.4.2 for further discussion.

Y_p = harvest yield of crop type p, in kg/m² (wet weight). Also called the standing biomass. Values are listed in Table 25.

The one special case nuclide is tritium in contaminated irrigation water. Tritium present in an initial soil contamination is handled using the same method as any other nuclide. The equilibrium transfer factors shown in Table 22 are used. Tritium in irrigation water leads to an equilibrium situation in which the concentration of tritium in the water is reproduced throughout the animal product. Since the equilibrium is established rather quickly, the decay corrections are simpler than for other nuclides. The calculation of dose from tritium in irrigation water is shown in Table 32 below. Note that the tritium model assumes that loss of tritium by evaporation of water from soil or plants is not important.

Table 32. Ingestion Dose from Animal Products from Tritium

Essential Dose Calculation for Irrigation with Contaminated Water. The activity intake rates are computed using the formulas below. These are converted to annual dose equivalent by means of the factor, $C_{w,H3}\, F_q\, Q_{aq}\, D_{ing,H3}\, T_{ing}$.	
Trace Soil Ingestion:	$8.94\, F_{Hs}\, I/(I+P)\, Q_{sq}$
Fodder -- Root Uptake:	$8.94\, F_{Hp}\, I/(I+P)\, Q_{pq}$
Drinking Water Ingestion:	Q_{wq}
Correction for Radioactive Decay and Progeny Ingrowth -- Beef	
Trace Soil Ingestion:	$IDR(T_{beef})$
Fresh Grass:	$IDR(T_{beef})$
Stored Hay and Grain:	$DR(T_s) \cdot IDR(T_{beef})$
Drinking Water:	$IDR(T_{beef})$
Correction for Radioactive Decay and Progeny Ingrowth -- Milk, Poultry, Eggs	
Trace Soil Ingestion:	$[T_{irr} + T_{no} \cdot IDR(T_{no})]/T_{ing}$
Fresh Grass:	$[T_{irr} + T_{no} \cdot IDR(T_{no})]/T_{ing}$
Stored Hay and Grain:	$DR(T_s) \cdot IDR(T_{an})$
Drinking Water:	no decay

Notes: Beef is harvested and consumed over a period of time. Milk, poultry, and eggs are consumed continuously during the year. The decay factors are unitless fractions shown in Equation (37). Progeny ingrowth is computed using the method shown in Section 3.1.4.

Explanation of Symbols Used in Table 32.

$C_{w,H3}$ = concentration of tritium (H-3) in the irrigation water, in pCi/L.

$D_{ing,H3}$ = ingestion dose factor for tritium, in mrem per pCi ingested. Value is given in Table 7.

F_q = equilibrium transfer factor for animal product q for tritium, in d/kg (or d/L for milk). Value is given in Table 22.

F_{Hs} = fraction of hydrogen in garden soil. The value used is listed in Table 23. The factor of 8.94 converts the hydrogen fraction to an effective water fraction that includes organically bound hydrogen.

F_{Hp} = fraction of hydrogen in plant type p. Values are listed in Table 23. The factor of 8.94 converts the hydrogen fraction to an effective water fraction that includes organically bound hydrogen.

I = total irrigation water applied to the soil during the irrigation season, 82.3 cm/y (63.5 for populations).

p = index for animal fodder. There are 3 types of animal fodder, fresh grass, stored hay, and stored grain.

P = total natural precipitation water reaching the surface soil during the irrigation period, 5.23 cm/y (PNNL-12087).

q = index for animal products. There are 4 types of animal products, beef, milk, poultry, and eggs.

Q_{aq} = quantity of animal product q eaten by the person during the year, in kg/y (or L/y for milk). See Tables 13 and 14 for values.

Q_{pq} = quantity of fodder type p eaten by the animal during the year, in kg/y. See Table 21 for values.

Q_{sq} = quantity of contaminated soil ingested by the animal associated with animal product q each day, in kg/d. See Table 21 for values.

Q_{wq} = quantity of contaminated drinking water ingested by the animal associated with animal product q each day, in L/d. See Table 21 for values.

T_{an} = time period over which stored hay and grain are consumed by the milk cow and chickens. Assumed to be the same as T_{veg}, 90 d.

T_{beef} = consumption period for beef cattle, assumed to be 120 days.

T_{ing} = ingestion exposure time of the individual, 1 y.

T_{irr} = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site. T_{no} = 1y - T_{irr}

T_s = storage time for the stored feed (hay and grain), 90 d.

4.0 SCENARIO DOSE FACTORS

The tables in this section provide unit dose factors for each exposure scenario. The intrusion scenarios (no water infiltration) are given in Tables 33 and 34. The ground water scenarios are given in Tables 35 to 39. The population dose from use of contaminated drinking water is given in Table 40. Finally, Table 41 provides a comparison of the total dose to the drinking water dose for each scenario. The dose from the drinking water is the largest contributor for most nuclides.

The intrusion scenarios separate the external and internal doses to facilitate calculation of doses for an exhumed waste matrix that retains a portion of the radioactivity in a form that is not able to produce inhalation or ingestion doses (i.e., pieces of glass). The external dose depends only the amount exhumed. The internal dose also depends on the fraction that has decomposed and is available to produce inhalation and ingestion doses.

The irrigation scenarios are bounded by the NASR (Table 39). The next largest dose factors are for the HSRAM Agricultural and All Pathways Farmer (Tables 37 and 38). The traditional All Pathways Farmer doses are generally lower than those for the HSRAM Agricultural. Exceptions are for Gd-152, Ac-227, Th-229, Th-230, Th-232, and U-232, largely due to the strong inhalation dose component.

The comparison ratios in Table 41 are the total dose divided by the drinking water dose for each of the irrigation scenarios. The HSRAM Industrial scenario is not listed in Table 41 because the largest ratio was for Gd-152 (1.13). All other nuclide ratios were less than 1.06.

As indicated in DOE M 435.1-1 Chapter IV, the use of representative exposure scenarios is desired to avoid overly conservative assumptions. Thus the Post-Intrusion Resident (Table 34) should be used for evaluating compliance with the performance objectives for intruders. In addition, the All Pathways Farmer (Table 38) should be used for the groundwater performance objectives.

To bound the uncertainties associated with the various scenario parameters, the Native American Subsistence Residence case was created. Unit dose factors for this individual should be used to indicate an upper bound on the potential doses resulting from ground water contamination.

Table 33. No Water Infiltration Case: Intruder

Nuclide	External	Internal	Ingest	Inhale
H-3	0.00	1.44E-03	1.42E-03	2.05E-05
Be-10	2.15E-01	1.79E-01	1.04E-01	7.55E-02
C-14	2.73E-03	4.69E-02	4.64E-02	4.46E-04
Na-22	2.39E+03	2.57E-01	2.56E-01	1.63E-03
Si-32+D	2.28E+00	4.64E-01	2.44E-01	2.20E-01
Cl-36	4.64E-01	7.20E-02	6.73E-02	4.67E-03
K-40	1.73E+02	4.16E-01	4.13E-01	2.65E-03
Ti-44+D	2.40E+03	6.43E-01	5.47E-01	9.64E-02
V-49	0.00	1.44E-03	1.36E-03	7.36E-05
Mn-54	9.08E+02	6.30E-02	6.16E-02	1.43E-03

Table 33. No Water Infiltration Case: Intruder

Nuclide	External	Internal	Ingest	Inhale
Fe-55	0.00	1.41E-02	1.35E-02	5.74E-04
Co-60	2.75E+03	6.44E-01	5.98E-01	4.67E-02
Ni-59	0.00	4.95E-03	4.67E-03	2.82E-04
Ni-63	0.00	1.35E-02	1.28E-02	6.61E-04
Se-79	3.78E-03	1.95E-01	1.93E-01	2.10E-03
Rb-87	2.85E-02	1.10E-01	1.09E-01	6.89E-04
Sr-90+D	4.68E+00	3.45E+00	3.40E+00	5.29E-02
Zr-93	0.00	1.05E-01	3.69E-02	6.85E-02
Nb-91	2.30E+00	1.78E-02	1.16E-02	6.23E-03
Nb-93m	2.11E-02	1.78E-02	1.16E-02	6.23E-03
Nb-94	1.72E+03	2.47E-01	1.59E-01	8.83E-02
Mo-93	1.20E-01	3.61E-02	3.00E-02	6.06E-03
Tc-99	2.54E-02	3.42E-02	3.24E-02	1.78E-03
Ru-106+D	2.33E+02	7.11E-01	6.09E-01	1.02E-01
Pd-107	0.00	6.04E-03	3.31E-03	2.73E-03
Ag-108m+D	1.75E+03	2.30E-01	1.69E-01	6.04E-02
Cd-109	2.99E+00	3.15E-01	2.91E-01	2.43E-02
Cd-113m	1.30E-01	3.90E+00	3.58E+00	3.26E-01
In-115	8.04E-02	4.31E+00	3.51E+00	7.98E-01
Sn-121m+D	4.28E-01	5.25E-02	5.00E-02	2.54E-03
Sn-126+D	2.14E+03	4.90E-01	4.69E-01	2.15E-02
Sb-125	4.48E+02	6.50E-02	6.24E-02	2.60E-03
Te-125m	3.07E+00	8.31E-02	8.16E-02	1.56E-03
I-129	2.63E+00	6.17E+00	6.13E+00	3.71E-02
Cs-134	1.70E+03	1.64E+00	1.63E+00	9.88E-03
Cs-135	7.76E-03	1.58E-01	1.57E-01	9.71E-04
Cs-137+D	6.12E+02	1.12E+00	1.11E+00	6.81E-03
Ba-133	3.74E+02	7.72E-02	7.56E-02	1.67E-03
Pm-147	1.01E-02	3.17E-02	2.33E-02	8.36E-03

Table 33. No Water Infiltration Case: Intruder

Nuclide	External	Internal	Ingest	Inhale
Sm-147	0.00	2.00E+01	4.11E+00	1.59E+01
Sm-151	2.00E-04	1.50E-02	8.64E-03	6.40E-03
Eu-150	1.58E+03	1.99E-01	1.41E-01	5.72E-02
Eu-152	1.22E+03	1.91E-01	1.44E-01	4.71E-02
Eu-154	1.34E+03	2.73E-01	2.12E-01	6.10E-02
Eu-155	3.70E+01	4.28E-02	3.40E-02	8.83E-03
Gd-152	0.00	5.54E+01	3.58E+00	5.18E+01
Ho-166m	1.86E+03	3.44E-01	1.79E-01	1.65E-01
Re-187	0.00	2.23E-04	2.11E-04	1.16E-05
Tl-204	8.16E-01	7.52E-02	7.47E-02	5.14E-04
Pb-205	1.43E-03	3.71E-02	3.62E-02	8.36E-04
Pb-210+D	1.20E+00	1.22E+02	1.19E+02	2.94E+00
Bi-207	1.64E+03	1.26E-01	1.22E-01	4.27E-03
Po-209	3.58E+00	5.54E+01	5.29E+01	2.52E+00
Po-210	9.28E-03	4.42E+01	4.22E+01	2.01E+00
Ra-226+D	1.91E+03	3.14E+01	2.96E+01	1.83E+00
Ra-228+D	1.05E+03	3.31E+01	3.20E+01	1.08E+00
Ac-227+D	3.84E+02	1.76E+03	3.29E+02	1.43E+03
Th-228+D	1.68E+03	9.16E+01	1.80E+01	7.36E+01
Th-229+D	2.99E+02	5.50E+02	8.96E+01	4.61E+02
Th-230	2.42E-01	8.17E+01	1.22E+01	6.95E+01
Th-232	1.05E-01	4.11E+02	6.07E+01	3.50E+02
Pa-231	3.64E+01	5.09E+02	2.36E+02	2.73E+02
U-232	1.81E-01	1.70E+02	2.91E+01	1.41E+02
U-233	2.74E-01	3.52E+01	6.42E+00	2.88E+01
U-234	8.12E-02	3.44E+01	6.29E+00	2.82E+01
U-235+D	1.50E+02	3.22E+01	5.93E+00	2.62E+01
U-236	4.32E-02	3.26E+01	5.98E+00	2.67E+01
U-238+D	2.41E+01	3.11E+01	5.96E+00	2.52E+01

Table 33. No Water Infiltration Case: Intruder

Nuclide	External	Internal	Ingest	Inhale
Np-237+D	2.11E+02	2.14E+02	9.87E+01	1.15E+02
Pu-236	4.56E-02	5.69E+01	2.60E+01	3.09E+01
Pu-238	3.06E-02	1.55E+02	7.11E+01	8.36E+01
Pu-239	5.76E-02	1.70E+02	7.87E+01	9.15E+01
Pu-240	2.97E-02	1.70E+02	7.87E+01	9.15E+01
Pu-241+D	3.78E-03	3.28E+00	1.52E+00	1.76E+00
Pu-242	2.60E-02	1.62E+02	7.47E+01	8.77E+01
Pu-244+D	3.62E+02	1.60E+02	7.38E+01	8.60E+01
Am-241	8.88E+00	1.76E+02	8.09E+01	9.47E+01
Am-242m+D	1.33E+01	1.69E+02	7.82E+01	9.09E+01
Am-243+D	1.77E+02	1.75E+02	8.07E+01	9.39E+01
Cm-242	3.44E-02	6.25E+00	2.56E+00	3.69E+00
Cm-243	1.14E+02	1.21E+02	5.58E+01	6.55E+01
Cm-244	2.56E-02	9.78E+01	4.49E+01	5.29E+01
Cm-245	6.84E+01	1.80E+02	8.31E+01	9.71E+01
Cm-246	2.36E-02	1.78E+02	8.22E+01	9.62E+01
Cm-247+D	3.50E+02	1.64E+02	7.60E+01	8.83E+01
Cm-248	1.78E-02	6.54E+02	3.02E+02	3.52E+02
Cm-250+D	3.42E+02	3.73E+03	1.73E+03	2.01E+03
Bk-247	8.56E+01	2.27E+02	1.04E+02	1.22E+02
Cf-248	2.53E-02	1.82E+01	7.42E+00	1.08E+01
Cf-249	3.48E+02	2.28E+02	1.05E+02	1.23E+02
Cf-250	2.40E-02	1.03E+02	4.73E+01	5.59E+01
Cf-251	1.05E+02	2.33E+02	1.08E+02	1.25E+02
Cf-252	3.56E-02	5.75E+01	2.40E+01	3.35E+01

Units are mrem per Ci exhumed.
The "Internal" column is the sum of the "Inhale" and "Ingest" columns. External and internal doses are separated because the glass waste matrix will prevent a portion of the exhumed activity from contributing to the internal dose.

Table 34. No Water Infiltration Case: Post-Intrusion Resident

Nuclide	External	Internal	Garden	Ingest	Inhale
H-3	0.00	1.46E+02	1.46E+02	2.37E-02	5.58E-04
Be-10	2.41E+00	1.65E+01	8.21E+00	3.78E+00	4.50E+00
C-14	3.00E-02	7.20E+02	7.19E+02	1.65E+00	2.60E-02
Na-22	2.36E+04	3.05E+02	2.97E+02	8.17E+00	8.54E-02
Si-32+D	2.55E+01	4.39E+02	4.17E+02	8.86E+00	1.30E+01
Cl-36	4.78E+00	9.96E+04	9.96E+04	2.25E+00	2.56E-01
K-40	1.93E+03	5.16E+03	5.15E+03	1.49E+01	1.56E-01
Ti-44+D	2.68E+04	8.57E+01	6.02E+01	1.98E+01	5.71E+00
V-49	0.00	1.54E-01	1.16E-01	3.50E-02	3.09E-03
Mn-54	6.98E+03	2.64E+02	2.62E+02	1.54E+00	5.83E-02
Fe-55	0.00	1.28E+00	8.15E-01	4.34E-01	3.02E-02
Co-60	2.89E+04	1.86E+02	1.63E+02	2.04E+01	2.61E+00
Ni-59	0.00	4.68E+00	4.49E+00	1.70E-01	1.68E-02
Ni-63	0.00	1.28E+01	1.23E+01	4.66E-01	3.93E-02
Se-79	4.24E-02	1.24E+02	1.16E+02	7.05E+00	1.25E-01
Rb-87	3.20E-01	1.83E+02	1.79E+02	3.98E+00	4.10E-02
Sr-90+D	5.15E+01	2.00E+04	1.98E+04	1.21E+02	3.09E+00
Zr-93	5.03E-03	7.48E+00	2.03E+00	1.36E+00	4.09E+00
Nb-91	2.58E+01	2.65E+00	1.86E+00	4.23E-01	3.71E-01
Nb-93m	2.32E-01	2.61E+00	1.83E+00	4.14E-01	3.64E-01
Nb-94	1.93E+04	3.64E+01	2.54E+01	5.79E+00	5.27E+00
Mo-93	1.33E+00	4.47E+01	4.33E+01	1.09E+00	3.64E-01
Tc-99	1.69E-01	7.93E+02	7.92E+02	7.01E-01	6.28E-02
Ru-106+D	1.90E+03	2.29E+02	2.08E+02	1.61E+01	4.39E+00
Pd-107	0.00	3.52E+00	3.24E+00	1.20E-01	1.62E-01
Ag-108m+D	1.96E+04	3.02E+02	2.92E+02	6.15E+00	3.59E+00
Cd-109	2.58E+01	8.55E+02	8.45E+02	8.16E+00	1.11E+00
Cd-113m	1.42E+00	1.26E+04	1.24E+04	1.27E+02	1.89E+01
In-115	9.04E-01	3.61E+02	1.85E+02	1.28E+02	4.76E+01

Table 34. No Water Infiltration Case: Post-Intrusion Resident

Nuclide	External	Internal	Garden	Ingest	Inhale
Sn-121m+D	4.78E+00	1.12E+01	9.24E+00	1.81E+00	1.50E-01
Sn-126+D	2.41E+04	1.05E+02	8.71E+01	1.71E+01	1.28E+00
Sb-125	4.44E+03	3.57E+01	3.31E+01	2.48E+00	1.52E-01
Te-125m	7.80E+00	3.40E+00	2.71E+00	6.73E-01	2.10E-02
I-129	2.58E+01	6.70E+03	6.50E+03	1.95E+02	1.93E+00
Cs-134	1.62E+04	1.60E+03	1.55E+03	5.05E+01	5.00E-01
Cs-135	8.72E-02	1.75E+02	1.69E+02	5.73E+00	5.79E-02
Cs-137+D	6.80E+03	1.23E+03	1.19E+03	4.01E+01	4.01E-01
Ba-133	4.06E+03	3.43E+01	3.16E+01	2.66E+00	9.59E-02
Pm-147	1.00E-01	4.04E+00	2.85E+00	7.48E-01	4.38E-01
Sm-147	0.00	1.65E+03	5.52E+02	1.50E+02	9.51E+02
Sm-151	2.24E-03	1.85E+00	1.16E+00	3.14E-01	3.80E-01
Eu-150	1.76E+04	2.73E+01	1.89E+01	5.11E+00	3.38E+00
Eu-152	1.34E+04	2.69E+01	1.90E+01	5.12E+00	2.74E+00
Eu-154	1.44E+04	3.87E+01	2.77E+01	7.44E+00	3.50E+00
Eu-155	3.86E+02	5.97E+00	4.33E+00	1.15E+00	4.90E-01
Gd-152	0.00	3.70E+03	4.81E+02	1.30E+02	3.09E+03
Ho-166m	2.09E+04	4.05E+01	2.41E+01	6.54E+00	9.83E+00
Re-187	0.00	1.75E+00	1.74E+00	7.62E-03	6.85E-04
Tl-204	8.38E+00	6.22E+00	3.71E+00	2.49E+00	2.80E-02
Pb-205	1.61E-02	6.82E+00	5.45E+00	1.32E+00	4.99E-02
Pb-210+D	1.33E+01	2.47E+04	1.94E+04	5.11E+03	2.37E+02
Bi-207	1.83E+04	2.46E+01	2.00E+01	4.39E+00	2.52E-01
Po-209	4.01E+01	6.40E+03	4.33E+03	1.92E+03	1.50E+02
Po-210	4.79E-02	2.61E+03	1.85E+03	7.07E+02	5.49E+01
Ra-226+D	2.15E+04	4.79E+03	3.52E+03	1.15E+03	1.13E+02
Ra-228+D	1.40E+04	5.48E+03	3.54E+03	1.20E+03	7.40E+02
Ac-227+D	4.25E+03	1.13E+05	1.68E+04	1.18E+04	8.42E+04
Th-228+D	1.59E+04	4.97E+03	7.37E+02	5.52E+02	3.69E+03

Table 34. No Water Infiltration Case: Post-Intrusion Resident

Nuclide	External	Internal	Garden	Ingest	Inhale
Th-229+D	3.35E+03	3.49E+04	4.13E+03	3.27E+03	2.75E+04
Th-230	7.38E+00	5.16E+03	5.62E+02	4.45E+02	4.15E+03
Th-232	8.06E+02	2.61E+04	2.94E+03	2.29E+03	2.09E+04
Pa-231	4.78E+02	3.81E+04	1.17E+04	8.78E+03	1.76E+04
U-232	3.01E+03	1.38E+04	3.73E+03	1.15E+03	8.96E+03
U-233	3.21E+00	2.74E+03	8.05E+02	2.32E+02	1.70E+03
U-234	9.04E-01	2.68E+03	7.88E+02	2.27E+02	1.66E+03
U-235+D	1.66E+03	2.51E+03	7.44E+02	2.14E+02	1.55E+03
U-236	4.81E-01	2.54E+03	7.49E+02	2.16E+02	1.57E+03
U-238+D	2.61E+02	2.45E+03	7.46E+02	2.15E+02	1.49E+03
Np-237+D	2.30E+03	2.39E+04	1.38E+04	3.49E+03	6.66E+03
Pu-236	1.02E+01	3.60E+03	1.07E+03	8.49E+02	1.68E+03
Pu-238	3.43E-01	1.07E+04	3.11E+03	2.58E+03	4.97E+03
Pu-239	6.48E-01	1.18E+04	3.45E+03	2.87E+03	5.46E+03
Pu-240	3.34E-01	1.18E+04	3.45E+03	2.87E+03	5.46E+03
Pu-241+D	1.19E-01	2.31E+02	6.77E+01	5.66E+01	1.07E+02
Pu-242	2.92E-01	1.12E+04	3.28E+03	2.72E+03	5.23E+03
Pu-244+D	4.07E+03	1.11E+04	3.24E+03	2.69E+03	5.13E+03
Am-241	9.98E+01	1.23E+04	3.69E+03	2.95E+03	5.65E+03
Am-242m+D	1.47E+02	1.20E+04	3.60E+03	2.89E+03	5.51E+03
Am-243+D	1.99E+03	1.22E+04	3.68E+03	2.94E+03	5.60E+03
Cm-242	1.97E-01	2.52E+02	7.39E+01	5.39E+01	1.24E+02
Cm-243	1.27E+03	8.30E+03	2.43E+03	2.01E+03	3.86E+03
Cm-244	2.82E-01	6.65E+03	1.94E+03	1.61E+03	3.10E+03
Cm-245	7.69E+02	1.25E+04	3.65E+03	3.03E+03	5.80E+03
Cm-246	2.65E-01	1.23E+04	3.60E+03	3.00E+03	5.74E+03
Cm-247+D	3.93E+03	1.14E+04	3.33E+03	2.77E+03	5.27E+03
Cm-248	2.00E-01	4.53E+04	1.33E+04	1.10E+04	2.10E+04
Cm-250+D	3.85E+03	2.58E+05	7.57E+04	6.30E+04	1.20E+05

Table 34. No Water Infiltration Case: Post-Intrusion Resident

Nuclide	External	Internal	Garden	Ingest	Inhale
Bk-247	9.63E+02	1.58E+04	4.66E+03	3.81E+03	7.31E+03
Cf-248	2.04E-01	1.95E+03	1.24E+03	2.14E+02	4.99E+02
Cf-249	3.91E+03	3.38E+04	2.27E+04	3.84E+03	7.34E+03
Cf-250	2.63E-01	1.49E+04	1.00E+04	1.68E+03	3.25E+03
Cf-251	1.18E+03	3.46E+04	2.32E+04	3.93E+03	7.48E+03
Cf-252	3.53E-01	7.23E+03	4.70E+03	7.70E+02	1.76E+03

Units are mrem per Ci exhumed.
The "Internal" column is the sum of the "Garden", "Inhale", and "Ingest" columns. External and internal doses are separated because the glass waste matrix will prevent a portion of the exhumed activity from contributing to the internal dose.

Table 35. Low Water Infiltration Case: HSRAM Industrial

Nuclide	Total	Ingest	Inhale
H-3	1.62E-05	1.60E-05	2.02E-07
Be-10	1.17E-03	1.17E-03	7.43E-06
C-14	5.23E-04	5.23E-04	4.39E-08
Na-22	2.88E-03	2.88E-03	1.61E-07
Si-32+D	2.77E-03	2.75E-03	2.16E-05
Cl-36	7.58E-04	7.58E-04	4.60E-07
K-40	4.65E-03	4.65E-03	2.60E-07
Ti-44+D	6.16E-03	6.15E-03	9.49E-06
V-49	1.54E-05	1.54E-05	7.25E-09
Mn-54	6.93E-04	6.93E-04	1.41E-07
Fe-55	1.52E-04	1.52E-04	5.65E-08
Co-60	6.73E-03	6.73E-03	4.60E-06
Ni-59	5.25E-05	5.25E-05	2.77E-08
Ni-63	1.44E-04	1.44E-04	6.51E-08
Se-79	2.18E-03	2.18E-03	2.07E-07
Rb-87	1.23E-03	1.23E-03	6.78E-08
Sr-90+D	3.83E-02	3.83E-02	5.21E-06
Zr-93	4.22E-04	4.15E-04	6.74E-06
Nb-91	1.31E-04	1.31E-04	6.13E-07
Nb-93m	1.31E-04	1.31E-04	6.13E-07
Nb-94	1.79E-03	1.79E-03	8.69E-06
Mo-93	3.38E-04	3.38E-04	5.96E-07
Tc-99	3.65E-04	3.65E-04	1.75E-07
Ru-106+D	6.86E-03	6.85E-03	1.00E-05
Pd-107	3.75E-05	3.73E-05	2.69E-07
Ag-108m+D	1.91E-03	1.91E-03	5.94E-06
Cd-109	3.28E-03	3.28E-03	2.39E-06
Cd-113m	4.03E-02	4.03E-02	3.21E-05
In-115	3.96E-02	3.95E-02	7.85E-05

Table 35. Low Water Infiltration Case: HSRAM Industrial

Nuclide	Total	Ingest	Inhale
Sn-121m+D	5.63E-04	5.63E-04	2.50E-07
Sn-126+D	5.28E-03	5.28E-03	2.12E-06
Sb-125	7.03E-04	7.03E-04	2.56E-07
Te-125m	9.18E-04	9.18E-04	1.53E-07
I-129	6.90E-02	6.90E-02	3.65E-06
Cs-134	1.83E-02	1.83E-02	9.72E-07
Cs-135	1.77E-03	1.77E-03	9.56E-08
Cs-137+D	1.25E-02	1.25E-02	6.70E-07
Ba-133	8.50E-04	8.50E-04	1.64E-07
Pm-147	2.63E-04	2.63E-04	8.23E-07
Sm-147	4.78E-02	4.63E-02	1.57E-03
Sm-151	9.79E-05	9.73E-05	6.30E-07
Eu-150	1.60E-03	1.59E-03	5.63E-06
Eu-152	1.62E-03	1.62E-03	4.64E-06
Eu-154	2.39E-03	2.39E-03	6.01E-06
Eu-155	3.83E-04	3.83E-04	8.69E-07
Gd-152	4.54E-02	4.03E-02	5.10E-03
Ho-166m	2.03E-03	2.02E-03	1.62E-05
Re-187	2.38E-06	2.38E-06	1.14E-09
Tl-204	8.40E-04	8.40E-04	5.06E-08
Pb-205	4.08E-04	4.08E-04	8.23E-08
Pb-210+D	1.34E+00	1.34E+00	2.90E-04
Bi-207	1.37E-03	1.37E-03	4.20E-07
Po-209	5.95E-01	5.95E-01	2.48E-04
Po-210	4.75E-01	4.75E-01	1.97E-04
Ra-226+D	3.33E-01	3.33E-01	1.81E-04
Ra-228+D	3.60E-01	3.60E-01	1.07E-04
Ac-227+D	3.84E+00	3.70E+00	1.41E-01
Th-228+D	2.10E-01	2.03E-01	7.25E-03

Table 35. Low Water Infiltration Case: HSRAM Industrial

Nuclide	Total	Ingest	Inhale
Th-229+D	1.05E+00	1.01E+00	4.54E-02
Th-230	1.44E-01	1.37E-01	6.85E-03
Th-232	7.17E-01	6.83E-01	3.44E-02
Pa-231	2.68E+00	2.65E+00	2.69E-02
U-232	3.41E-01	3.28E-01	1.38E-02
U-233	7.51E-02	7.23E-02	2.84E-03
U-234	7.35E-02	7.08E-02	2.77E-03
U-235+D	6.93E-02	6.68E-02	2.58E-03
U-236	6.99E-02	6.73E-02	2.63E-03
U-238+D	6.95E-02	6.70E-02	2.48E-03
Np-237+D	1.12E+00	1.11E+00	1.13E-02
Pu-236	2.96E-01	2.93E-01	3.05E-03
Pu-238	8.08E-01	8.00E-01	8.23E-03
Pu-239	8.94E-01	8.85E-01	9.01E-03
Pu-240	8.94E-01	8.85E-01	9.01E-03
Pu-241+D	1.73E-02	1.71E-02	1.73E-04
Pu-242	8.49E-01	8.40E-01	8.63E-03
Pu-244+D	8.38E-01	8.30E-01	8.46E-03
Am-241	9.19E-01	9.10E-01	9.32E-03
Am-242m+D	8.89E-01	8.80E-01	8.95E-03
Am-243+D	9.17E-01	9.08E-01	9.24E-03
Cm-242	2.91E-02	2.88E-02	3.63E-04
Cm-243	6.34E-01	6.28E-01	6.45E-03
Cm-244	5.10E-01	5.05E-01	5.21E-03
Cm-245	9.45E-01	9.35E-01	9.56E-03
Cm-246	9.34E-01	9.25E-01	9.47E-03
Cm-247+D	8.64E-01	8.55E-01	8.69E-03
Cm-248	3.43E+00	3.40E+00	3.47E-02
Cm-250+D	1.96E+01	1.94E+01	1.97E-01

Table 35. Low Water Infiltration Case: HSRAM Industrial

Nuclide	Total	Ingest	Inhale
Bk-247	1.19E+00	1.18E+00	1.21E-02
Cf-248	8.46E-02	8.35E-02	1.06E-03
Cf-249	1.20E+00	1.19E+00	1.21E-02
Cf-250	5.38E-01	5.33E-01	5.50E-03
Cf-251	1.22E+00	1.21E+00	1.23E-02
Cf-252	2.73E-01	2.70E-01	3.30E-03

Units are mrem per pCi/L in the ground water.
The "Total" column is the sum of the "Ingest" and "Inhale" columns.

Table 36. Low Water Infiltration Case: HSRAM Residential

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
H-3	4.92E-05	4.67E-05	2.13E-06	2.98E-07	0.00
Be-10	3.89E-03	3.40E-03	4.79E-04	1.13E-05	2.32E-06
C-14	1.84E-03	1.53E-03	3.14E-04	6.69E-08	2.91E-08
Na-22	3.29E-02	8.40E-03	1.20E-03	2.44E-07	2.33E-02
Si-32+D	9.27E-03	8.03E-03	1.18E-03	3.30E-05	2.46E-05
Cl-36	1.64E-02	2.21E-03	1.42E-02	7.00E-07	4.77E-06
K-40	1.81E-02	1.36E-02	2.62E-03	3.97E-07	1.86E-03
Ti-44+D	4.63E-02	1.80E-02	2.53E-03	1.45E-05	2.58E-02
V-49	5.08E-05	4.48E-05	5.96E-06	1.10E-08	0.00
Mn-54	9.61E-03	2.02E-03	3.01E-04	2.13E-07	7.29E-03
Fe-55	5.04E-04	4.43E-04	6.11E-05	8.58E-08	0.00
Co-60	5.06E-02	1.96E-02	2.75E-03	7.00E-06	2.82E-02
Ni-59	1.75E-04	1.53E-04	2.22E-05	4.22E-08	0.00
Ni-63	4.82E-04	4.21E-04	6.08E-05	9.92E-08	0.00
Se-79	7.26E-03	6.35E-03	9.08E-04	3.15E-07	4.08E-08
Rb-87	4.12E-03	3.59E-03	5.29E-04	1.03E-07	3.08E-07
Sr-90+D	1.30E-01	1.12E-01	1.83E-02	7.93E-06	4.98E-05
Zr-93	1.39E-03	1.21E-03	1.71E-04	1.03E-05	3.77E-09
Nb-91	4.61E-04	3.81E-04	5.38E-05	9.34E-07	2.48E-05
Nb-93m	4.36E-04	3.81E-04	5.36E-05	9.34E-07	2.24E-07
Nb-94	2.45E-02	5.21E-03	7.36E-04	1.32E-05	1.85E-02
Mo-93	1.13E-03	9.86E-04	1.45E-04	9.09E-07	1.28E-06
Tc-99	1.31E-03	1.07E-03	2.44E-04	2.64E-07	2.02E-07
Ru-106+D	2.47E-02	2.00E-02	2.69E-03	1.52E-05	1.96E-03
Pd-107	1.25E-04	1.09E-04	1.57E-05	4.10E-07	0.00
Ag-108m+D	2.52E-02	5.56E-03	8.19E-04	9.06E-06	1.88E-02
Cd-109	1.10E-02	9.56E-03	1.40E-03	3.63E-06	2.63E-05
Cd-113m	1.36E-01	1.18E-01	1.81E-02	4.89E-05	1.37E-06

Table 36. Low Water Infiltration Case: HSRAM Residential

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
In-115	1.32E-01	1.15E-01	1.62E-02	1.20E-04	8.69E-07
Sn-121m+D	1.88E-03	1.64E-03	2.32E-04	3.81E-07	4.60E-06
Sn-126+D	4.07E-02	1.54E-02	2.18E-03	3.23E-06	2.32E-02
Sb-125	6.76E-03	2.05E-03	3.08E-04	3.90E-07	4.40E-03
Te-125m	2.97E-03	2.68E-03	2.84E-04	2.28E-07	9.67E-06
I-129	2.31E-01	2.01E-01	2.92E-02	5.55E-06	2.62E-05
Cs-134	7.72E-02	5.35E-02	7.59E-03	1.48E-06	1.61E-02
Cs-135	5.92E-03	5.16E-03	7.54E-04	1.46E-07	8.39E-08
Cs-137+D	4.84E-02	3.65E-02	5.32E-03	1.02E-06	6.56E-03
Ba-133	6.77E-03	2.48E-03	3.51E-04	2.50E-07	3.94E-03
Pm-147	8.74E-04	7.67E-04	1.06E-04	1.25E-06	9.89E-08
Sm-147	1.56E-01	1.35E-01	1.90E-02	2.39E-03	0.00
Sm-151	3.25E-04	2.84E-04	4.00E-05	9.60E-07	2.15E-09
Eu-150	2.23E-02	4.64E-03	6.54E-04	8.57E-06	1.70E-02
Eu-152	1.83E-02	4.73E-03	6.64E-04	7.07E-06	1.29E-02
Eu-154	2.20E-02	6.97E-03	9.77E-04	9.14E-06	1.40E-02
Eu-155	1.65E-03	1.12E-03	1.56E-04	1.32E-06	3.77E-04
Gd-152	1.42E-01	1.18E-01	1.66E-02	7.78E-03	0.00
Ho-166m	2.68E-02	5.89E-03	8.31E-04	2.47E-05	2.01E-02
Re-187	8.16E-06	6.94E-06	1.21E-06	1.74E-09	0.00
Tl-204	2.80E-03	2.45E-03	3.40E-04	7.70E-08	8.22E-06
Pb-205	1.36E-03	1.19E-03	1.68E-04	1.25E-07	1.55E-08
Pb-210+D	4.50E+00	3.92E+00	5.76E-01	4.46E-04	1.29E-05
Bi-207	2.22E-02	4.00E-03	5.64E-04	6.40E-07	1.76E-02
Po-209	1.98E+00	1.74E+00	2.44E-01	3.78E-04	3.86E-05
Po-210	1.56E+00	1.39E+00	1.71E-01	2.96E-04	5.39E-08
Ra-226+D	1.13E+00	9.71E-01	1.38E-01	2.75E-04	2.07E-02
Ra-228+D	1.21E+00	1.05E+00	1.49E-01	2.05E-04	1.31E-02
Ac-227+D	1.25E+01	1.08E+01	1.52E+00	2.15E-01	4.10E-03

Table 36. Low Water Infiltration Case: HSRAM Residential

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Th-228+D	7.00E-01	5.92E-01	8.10E-02	1.10E-02	1.58E-02
Th-229+D	3.43E+00	2.94E+00	4.14E-01	6.91E-02	3.22E-03
Th-230	4.67E-01	4.00E-01	5.63E-02	1.04E-02	6.10E-06
Th-232	2.33E+00	1.99E+00	2.82E-01	5.25E-02	5.91E-04
Pa-231	8.87E+00	7.74E+00	1.09E+00	4.10E-02	4.45E-04
U-232	1.12E+00	9.56E-01	1.37E-01	2.11E-02	2.31E-03
U-233	2.45E-01	2.11E-01	2.97E-02	4.32E-03	3.07E-06
U-234	2.40E-01	2.07E-01	2.91E-02	4.22E-03	8.72E-07
U-235+D	2.28E-01	1.95E-01	2.75E-02	3.94E-03	1.61E-03
U-236	2.28E-01	1.96E-01	2.77E-02	4.00E-03	4.64E-07
U-238+D	2.27E-01	1.96E-01	2.76E-02	3.78E-03	2.52E-04
Np-237+D	3.72E+00	3.24E+00	4.57E-01	1.73E-02	2.24E-03
Pu-236	9.77E-01	8.54E-01	1.18E-01	4.63E-03	6.45E-06
Pu-238	2.68E+00	2.34E+00	3.28E-01	1.25E-02	3.30E-07
Pu-239	2.96E+00	2.58E+00	3.63E-01	1.37E-02	6.23E-07
Pu-240	2.96E+00	2.58E+00	3.63E-01	1.37E-02	3.21E-07
Pu-241+D	5.73E-02	5.00E-02	7.05E-03	2.64E-04	9.84E-08
Pu-242	2.81E+00	2.45E+00	3.45E-01	1.32E-02	2.81E-07
Pu-244+D	2.78E+00	2.42E+00	3.41E-01	1.29E-02	3.91E-03
Am-241	3.05E+00	2.66E+00	3.74E-01	1.42E-02	9.60E-05
Am-242m+D	2.95E+00	2.57E+00	3.62E-01	1.36E-02	1.42E-04
Am-243+D	3.04E+00	2.65E+00	3.73E-01	1.41E-02	1.91E-03
Cm-242	9.52E-02	8.40E-02	1.07E-02	5.47E-04	2.18E-07
Cm-243	2.10E+00	1.83E+00	2.57E-01	9.82E-03	1.23E-03
Cm-244	1.69E+00	1.47E+00	2.07E-01	7.93E-03	2.72E-07
Cm-245	3.13E+00	2.73E+00	3.84E-01	1.46E-02	7.40E-04
Cm-246	3.10E+00	2.70E+00	3.80E-01	1.44E-02	2.55E-07
Cm-247+D	2.86E+00	2.50E+00	3.51E-01	1.32E-02	3.78E-03
Cm-248	1.14E+01	9.93E+00	1.40E+00	5.28E-02	1.92E-07

Table 36. Low Water Infiltration Case: HSRAM Residential

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Cm-250+D	6.50E+01	5.67E+01	7.98E+00	3.01E-01	3.70E-03
Bk-247	3.93E+00	3.43E+00	4.83E-01	1.84E-02	9.25E-04
Cf-248	2.79E-01	2.44E-01	3.31E-02	1.61E-03	2.10E-07
Cf-249	3.97E+00	3.46E+00	4.89E-01	1.85E-02	3.76E-03
Cf-250	1.78E+00	1.55E+00	2.19E-01	8.38E-03	2.55E-07
Cf-251	4.06E+00	3.54E+00	5.00E-01	1.88E-02	1.13E-03
Cf-252	9.03E-01	7.88E-01	1.09E-01	5.01E-03	3.49E-07

Units are mrem per pCi/L in the ground water.

Table 37. Low Water Infiltration Case: HSRAM Agricultural

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
H-3	5.73E-05	4.67E-05	1.03E-05	2.98E-07	0.00
Be-10	3.99E-03	3.40E-03	5.79E-04	1.13E-05	2.32E-06
C-14	6.44E-03	1.53E-03	4.92E-03	6.69E-08	2.91E-08
Na-22	8.82E-02	8.40E-03	5.65E-02	2.44E-07	2.33E-02
Si-32+D	9.30E-03	8.03E-03	1.22E-03	3.30E-05	2.46E-05
Cl-36	5.81E-02	2.21E-03	5.59E-02	7.00E-07	4.77E-06
K-40	4.09E-02	1.36E-02	2.55E-02	3.97E-07	1.86E-03
Ti-44+D	8.79E-02	1.80E-02	4.41E-02	1.45E-05	2.58E-02
V-49	5.31E-05	4.48E-05	8.25E-06	1.10E-08	0.00
Mn-54	9.73E-03	2.02E-03	4.18E-04	2.13E-07	7.29E-03
Fe-55	7.20E-04	4.43E-04	2.77E-04	8.58E-08	0.00
Co-60	6.57E-02	1.96E-02	1.79E-02	7.00E-06	2.82E-02
Ni-59	2.22E-04	1.53E-04	6.90E-05	4.22E-08	0.00
Ni-63	6.11E-04	4.21E-04	1.89E-04	9.92E-08	0.00
Se-79	1.44E-02	6.35E-03	8.10E-03	3.15E-07	4.08E-08
Rb-87	1.14E-02	3.59E-03	7.78E-03	1.03E-07	3.08E-07
Sr-90+D	1.60E-01	1.12E-01	4.81E-02	7.93E-06	4.98E-05
Zr-93	1.60E-03	1.21E-03	3.74E-04	1.03E-05	3.77E-09
Nb-91	3.91E-03	3.81E-04	3.50E-03	9.34E-07	2.48E-05
Nb-93m	3.84E-03	3.81E-04	3.46E-03	9.34E-07	2.24E-07
Nb-94	7.17E-02	5.21E-03	4.79E-02	1.32E-05	1.85E-02
Mo-93	1.56E-03	9.86E-04	5.72E-04	9.09E-07	1.28E-06
Tc-99	5.83E-03	1.07E-03	4.77E-03	2.64E-07	2.02E-07
Ru-106+D	2.54E-02	2.00E-02	3.44E-03	1.52E-05	1.95E-03
Pd-107	3.13E-04	1.09E-04	2.04E-04	4.10E-07	0.00
Ag-108m+D	4.37E-02	5.56E-03	1.93E-02	9.06E-06	1.88E-02
Cd-109	1.27E-02	9.56E-03	3.06E-03	3.63E-06	2.63E-05
Cd-113m	1.58E-01	1.18E-01	4.06E-02	4.89E-05	1.37E-06

Table 37. Low Water Infiltration Case: HSRAM Agricultural

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
In-115	1.55E-01	1.15E-01	4.00E-02	1.20E-04	8.69E-07
Sn-121m+D	5.19E-03	1.64E-03	3.54E-03	3.81E-07	4.60E-06
Sn-126+D	7.19E-02	1.54E-02	3.33E-02	3.23E-06	2.32E-02
Sb-125	6.99E-03	2.05E-03	5.35E-04	3.90E-07	4.40E-03
Te-125m	3.28E-03	2.68E-03	5.96E-04	2.28E-07	9.67E-06
I-129	5.92E-01	2.01E-01	3.90E-01	5.55E-06	2.62E-05
Cs-134	1.60E-01	5.35E-02	9.07E-02	1.48E-06	1.61E-02
Cs-135	1.46E-02	5.16E-03	9.42E-03	1.46E-07	8.39E-08
Cs-137+D	1.09E-01	3.65E-02	6.63E-02	1.02E-06	6.56E-03
Ba-133	6.92E-03	2.48E-03	5.00E-04	2.50E-07	3.94E-03
Pm-147	9.57E-04	7.67E-04	1.89E-04	1.25E-06	9.89E-08
Sm-147	1.73E-01	1.35E-01	3.51E-02	2.39E-03	0.00
Sm-151	3.59E-04	2.84E-04	7.38E-05	9.60E-07	2.15E-09
Eu-150	2.28E-02	4.64E-03	1.20E-03	8.57E-06	1.70E-02
Eu-152	1.89E-02	4.73E-03	1.22E-03	7.07E-06	1.29E-02
Eu-154	2.28E-02	6.97E-03	1.79E-03	9.14E-06	1.40E-02
Eu-155	1.78E-03	1.12E-03	2.84E-04	1.32E-06	3.77E-04
Gd-152	1.52E-01	1.18E-01	2.65E-02	7.78E-03	0.00
Ho-166m	2.74E-02	5.89E-03	1.46E-03	2.47E-05	2.01E-02
Re-187	1.13E-05	6.94E-06	4.39E-06	1.74E-09	0.00
Tl-204	5.72E-03	2.45E-03	3.26E-03	7.70E-08	8.22E-06
Pb-205	1.42E-03	1.19E-03	2.28E-04	1.25E-07	1.55E-08
Pb-210+D	4.72E+00	3.92E+00	8.00E-01	4.46E-04	1.29E-05
Bi-207	2.26E-02	4.00E-03	9.31E-04	6.40E-07	1.76E-02
Po-209	2.12E+00	1.74E+00	3.80E-01	3.78E-04	3.86E-05
Po-210	1.64E+00	1.39E+00	2.52E-01	2.96E-04	5.39E-08
Ra-226+D	1.21E+00	9.71E-01	2.17E-01	2.75E-04	2.07E-02
Ra-228+D	1.30E+00	1.05E+00	2.31E-01	2.05E-04	1.31E-02
Ac-227+D	1.26E+01	1.08E+01	1.56E+00	2.15E-01	4.10E-03

Table 37. Low Water Infiltration Case: HSRAM Agricultural

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Th-228+D	7.00E-01	5.92E-01	8.15E-02	1.10E-02	1.58E-02
Th-229+D	3.43E+00	2.94E+00	4.17E-01	6.91E-02	3.22E-03
Th-230	4.67E-01	4.00E-01	5.67E-02	1.04E-02	6.10E-06
Th-232	2.33E+00	1.99E+00	2.86E-01	5.25E-02	5.91E-04
Pa-231	8.88E+00	7.74E+00	1.10E+00	4.10E-02	4.45E-04
U-232	1.23E+00	9.56E-01	2.52E-01	2.11E-02	2.31E-03
U-233	2.71E-01	2.11E-01	5.53E-02	4.32E-03	3.07E-06
U-234	2.65E-01	2.07E-01	5.41E-02	4.22E-03	8.72E-07
U-235+D	2.52E-01	1.95E-01	5.10E-02	3.94E-03	1.61E-03
U-236	2.52E-01	1.96E-01	5.14E-02	4.00E-03	4.64E-07
U-238+D	2.51E-01	1.96E-01	5.12E-02	3.78E-03	2.52E-04
Np-237+D	3.72E+00	3.24E+00	4.64E-01	1.73E-02	2.24E-03
Pu-236	9.77E-01	8.54E-01	1.18E-01	4.63E-03	6.45E-06
Pu-238	2.68E+00	2.34E+00	3.28E-01	1.25E-02	3.30E-07
Pu-239	2.96E+00	2.58E+00	3.64E-01	1.37E-02	6.23E-07
Pu-240	2.96E+00	2.58E+00	3.64E-01	1.37E-02	3.21E-07
Pu-241+D	5.73E-02	5.00E-02	7.05E-03	2.64E-04	9.84E-08
Pu-242	2.81E+00	2.45E+00	3.45E-01	1.32E-02	2.81E-07
Pu-244+D	2.78E+00	2.42E+00	3.41E-01	1.29E-02	3.91E-03
Am-241	3.05E+00	2.66E+00	3.74E-01	1.42E-02	9.60E-05
Am-242m+D	2.95E+00	2.57E+00	3.63E-01	1.36E-02	1.42E-04
Am-243+D	3.04E+00	2.65E+00	3.73E-01	1.41E-02	1.91E-03
Cm-242	9.54E-02	8.40E-02	1.09E-02	5.47E-04	2.18E-07
Cm-243	2.11E+00	1.83E+00	2.63E-01	9.82E-03	1.23E-03
Cm-244	1.69E+00	1.47E+00	2.12E-01	7.93E-03	2.72E-07
Cm-245	3.14E+00	2.73E+00	3.93E-01	1.46E-02	7.40E-04
Cm-246	3.10E+00	2.70E+00	3.89E-01	1.44E-02	2.55E-07
Cm-247+D	2.87E+00	2.50E+00	3.60E-01	1.32E-02	3.78E-03
Cm-248	1.14E+01	9.93E+00	1.43E+00	5.28E-02	1.92E-07

Table 37. Low Water Infiltration Case: HSRAM Agricultural

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Cm-250+D	6.52E+01	5.67E+01	8.17E+00	3.01E-01	3.70E-03
Bk-247	3.93E+00	3.43E+00	4.83E-01	1.84E-02	9.25E-04
Cf-248	3.01E-01	2.44E-01	5.51E-02	1.61E-03	2.10E-07
Cf-249	4.37E+00	3.46E+00	8.90E-01	1.85E-02	3.76E-03
Cf-250	1.96E+00	1.55E+00	3.96E-01	8.38E-03	2.55E-07
Cf-251	4.47E+00	3.54E+00	9.11E-01	1.88E-02	1.13E-03
Cf-252	9.86E-01	7.88E-01	1.93E-01	5.01E-03	3.49E-07

Units are mrem per pCi/L in the ground water.

Table 38. Low Water Infiltration Case: All Pathways Farmer

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
H-3	4.58E-05	3.46E-05	7.04E-06	4.18E-06	0.00
Be-10	3.19E-03	2.52E-03	6.42E-04	3.03E-05	1.37E-06
C-14	4.67E-03	1.13E-03	3.54E-03	1.79E-07	1.71E-08
Na-22	5.21E-02	6.21E-03	3.22E-02	6.54E-07	1.37E-02
Si-32+D	7.42E-03	5.94E-03	1.38E-03	8.81E-05	1.44E-05
Cl-36	4.81E-02	1.64E-03	4.65E-02	1.87E-06	2.80E-06
K-40	2.83E-02	1.00E-02	1.72E-02	1.06E-06	1.10E-03
Ti-44+D	5.70E-02	1.33E-02	2.85E-02	3.87E-05	1.52E-02
V-49	4.26E-05	3.32E-05	9.42E-06	2.94E-08	0.00
Mn-54	6.19E-03	1.50E-03	4.11E-04	5.71E-07	4.28E-03
Fe-55	6.05E-04	3.28E-04	2.77E-04	2.30E-07	0.00
Co-60	4.57E-02	1.45E-02	1.46E-02	1.87E-05	1.66E-02
Ni-59	1.71E-04	1.13E-04	5.80E-05	1.13E-07	0.00
Ni-63	4.71E-04	3.12E-04	1.59E-04	2.65E-07	0.00
Se-79	1.15E-02	4.70E-03	6.80E-03	8.42E-07	2.40E-08
Rb-87	7.50E-03	2.66E-03	4.84E-03	2.76E-07	1.81E-07
Sr-90+D	1.19E-01	8.26E-02	3.59E-02	2.12E-05	2.93E-05
Zr-93	1.30E-03	8.96E-04	3.81E-04	2.75E-05	2.22E-09
Nb-91	3.06E-03	2.82E-04	2.76E-03	2.50E-06	1.46E-05
Nb-93m	3.01E-03	2.82E-04	2.73E-03	2.50E-06	1.32E-07
Nb-94	5.26E-02	3.86E-03	3.78E-02	3.54E-05	1.09E-02
Mo-93	1.19E-03	7.29E-04	4.62E-04	2.43E-06	7.55E-07
Tc-99	3.54E-03	7.88E-04	2.75E-03	7.09E-07	1.19E-07
Ru-106+D	1.98E-02	1.48E-02	3.78E-03	4.06E-05	1.15E-03
Pd-107	1.93E-04	8.05E-05	1.11E-04	1.10E-06	0.00
Ag-108m+D	2.51E-02	4.11E-03	9.89E-03	2.42E-05	1.11E-02
Cd-109	9.60E-03	7.07E-03	2.50E-03	9.72E-06	1.54E-05
Cd-113m	1.20E-01	8.69E-02	3.29E-02	1.31E-04	8.06E-07

Table 38. Low Water Infiltration Case: All Pathways Farmer

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
In-115	1.27E-01	8.53E-02	4.17E-02	3.20E-04	5.11E-07
Sn-121m+D	4.54E-03	1.22E-03	3.32E-03	1.02E-06	2.71E-06
Sn-126+D	5.63E-02	1.14E-02	3.13E-02	8.64E-06	1.36E-02
Sb-125	4.66E-03	1.52E-03	5.55E-04	1.04E-06	2.58E-03
Te-125m	2.77E-03	1.98E-03	7.86E-04	6.16E-07	5.68E-06
I-129	3.77E-01	1.49E-01	2.27E-01	1.49E-05	1.54E-05
Cs-134	1.10E-01	3.96E-02	6.07E-02	3.95E-06	9.49E-03
Cs-135	1.01E-02	3.82E-03	6.32E-03	3.89E-07	4.93E-08
Cs-137+D	7.53E-02	2.70E-02	4.44E-02	2.73E-06	3.85E-03
Ba-133	4.68E-03	1.84E-03	5.29E-04	6.68E-07	2.32E-03
Pm-147	7.70E-04	5.67E-04	2.00E-04	3.35E-06	5.81E-08
Sm-147	1.43E-01	9.99E-02	3.69E-02	6.39E-03	0.00
Sm-151	2.90E-04	2.10E-04	7.75E-05	2.57E-06	1.26E-09
Eu-150	1.47E-02	3.43E-03	1.26E-03	2.29E-05	9.99E-03
Eu-152	1.24E-02	3.50E-03	1.28E-03	1.89E-05	7.60E-03
Eu-154	1.53E-02	5.16E-03	1.88E-03	2.45E-05	8.23E-03
Eu-155	1.35E-03	8.26E-04	2.97E-04	3.54E-06	2.22E-04
Gd-152	1.36E-01	8.69E-02	2.82E-02	2.08E-02	0.00
Ho-166m	1.78E-02	4.36E-03	1.54E-03	6.61E-05	1.18E-02
Re-187	8.74E-06	5.14E-06	3.60E-06	4.65E-09	0.00
Tl-204	4.66E-03	1.81E-03	2.84E-03	2.06E-07	4.83E-06
Pb-205	1.12E-03	8.80E-04	2.39E-04	3.35E-07	9.10E-09
Pb-210+D	3.74E+00	2.90E+00	8.37E-01	1.19E-03	7.56E-06
Bi-207	1.42E-02	2.96E-03	8.82E-04	1.71E-06	1.04E-02
Po-209	1.83E+00	1.29E+00	5.41E-01	1.01E-03	2.27E-05
Po-210	1.41E+00	1.03E+00	3.81E-01	7.98E-04	3.17E-08
Ra-226+D	9.29E-01	7.18E-01	1.97E-01	7.36E-04	1.22E-02
Ra-228+D	9.97E-01	7.78E-01	2.11E-01	5.02E-04	7.68E-03
Ac-227+D	1.03E+01	7.99E+00	1.75E+00	5.75E-01	2.41E-03

Table 38. Low Water Infiltration Case: All Pathways Farmer

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Th-228+D	5.69E-01	4.38E-01	9.23E-02	2.95E-02	9.31E-03
Th-229+D	2.83E+00	2.18E+00	4.72E-01	1.85E-01	1.89E-03
Th-230	3.88E-01	2.96E-01	6.42E-02	2.79E-02	3.59E-06
Th-232	1.94E+00	1.47E+00	3.23E-01	1.40E-01	3.47E-04
Pa-231	7.08E+00	5.72E+00	1.25E+00	1.10E-01	2.62E-04
U-232	1.00E+00	7.07E-01	2.35E-01	5.65E-02	1.36E-03
U-233	2.19E-01	1.56E-01	5.13E-02	1.16E-02	1.80E-06
U-234	2.14E-01	1.53E-01	5.03E-02	1.13E-02	5.13E-07
U-235+D	2.03E-01	1.44E-01	4.74E-02	1.05E-02	9.45E-04
U-236	2.04E-01	1.45E-01	4.78E-02	1.07E-02	2.73E-07
U-238+D	2.03E-01	1.45E-01	4.76E-02	1.01E-02	1.48E-04
Np-237+D	2.97E+00	2.40E+00	5.25E-01	4.62E-02	1.32E-03
Pu-236	7.79E-01	6.32E-01	1.34E-01	1.24E-02	3.79E-06
Pu-238	2.14E+00	1.73E+00	3.74E-01	3.35E-02	1.94E-07
Pu-239	2.36E+00	1.91E+00	4.13E-01	3.67E-02	3.66E-07
Pu-240	2.36E+00	1.91E+00	4.13E-01	3.67E-02	1.89E-07
Pu-241+D	4.57E-02	3.70E-02	8.02E-03	7.06E-04	5.79E-08
Pu-242	2.24E+00	1.81E+00	3.92E-01	3.52E-02	1.65E-07
Pu-244+D	2.22E+00	1.79E+00	3.88E-01	3.45E-02	2.30E-03
Am-241	2.43E+00	1.97E+00	4.25E-01	3.80E-02	5.64E-05
Am-242m+D	2.35E+00	1.90E+00	4.13E-01	3.65E-02	8.33E-05
Am-243+D	2.42E+00	1.96E+00	4.24E-01	3.77E-02	1.12E-03
Cm-242	7.58E-02	6.21E-02	1.23E-02	1.47E-03	1.28E-07
Cm-243	1.68E+00	1.36E+00	2.95E-01	2.63E-02	7.20E-04
Cm-244	1.35E+00	1.09E+00	2.37E-01	2.12E-02	1.60E-07
Cm-245	2.50E+00	2.02E+00	4.41E-01	3.89E-02	4.35E-04
Cm-246	2.47E+00	2.00E+00	4.36E-01	3.86E-02	1.50E-07
Cm-247+D	2.29E+00	1.85E+00	4.03E-01	3.54E-02	2.22E-03
Cm-248	9.09E+00	7.34E+00	1.60E+00	1.41E-01	1.13E-07

Table 38. Low Water Infiltration Case: All Pathways Farmer

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Cm-250+D	5.19E+01	4.20E+01	9.16E+00	8.04E-01	2.17E-03
Bk-247	3.14E+00	2.54E+00	5.49E-01	4.91E-02	5.44E-04
Cf-248	2.43E-01	1.80E-01	5.87E-02	4.32E-03	1.24E-07
Cf-249	3.55E+00	2.56E+00	9.41E-01	4.94E-02	2.21E-03
Cf-250	1.59E+00	1.15E+00	4.19E-01	2.24E-02	1.50E-07
Cf-251	3.63E+00	2.62E+00	9.63E-01	5.03E-02	6.66E-04
Cf-252	8.01E-01	5.83E-01	2.04E-01	1.34E-02	2.05E-07

Units are mrem per pCi/L in the ground water.

Table 39. Low Water Infiltration Case: Native American Subsistence Resident

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
H-3	1.03E-04	7.01E-05	2.79E-05	5.09E-06	0.00
Be-10	8.25E-03	5.10E-03	3.08E-03	6.44E-05	2.32E-06
C-14	1.34E-02	2.29E-03	1.11E-02	3.80E-07	2.91E-08
Na-22	1.52E-01	1.26E-02	1.17E-01	1.39E-06	2.33E-02
Si-32+D	1.95E-02	1.20E-02	7.21E-03	1.87E-04	2.46E-05
Cl-36	1.80E-01	3.32E-03	1.76E-01	3.98E-06	4.77E-06
K-40	8.37E-02	2.04E-02	6.15E-02	2.26E-06	1.86E-03
Ti-44+D	1.50E-01	2.69E-02	9.70E-02	8.23E-05	2.58E-02
V-49	1.09E-04	6.72E-05	4.12E-05	6.25E-08	0.00
Mn-54	1.24E-02	3.03E-03	2.08E-03	1.21E-06	7.28E-03
Fe-55	1.47E-03	6.65E-04	8.01E-04	4.89E-07	0.00
Co-60	1.04E-01	2.95E-02	4.61E-02	3.98E-05	2.82E-02
Ni-59	4.56E-04	2.30E-04	2.25E-04	2.40E-07	0.00
Ni-63	1.25E-03	6.32E-04	6.18E-04	5.64E-07	0.00
Se-79	3.10E-02	9.53E-03	2.15E-02	1.79E-06	4.08E-08
Rb-87	2.33E-02	5.39E-03	1.79E-02	5.88E-07	3.08E-07
Sr-90+D	3.38E-01	1.68E-01	1.71E-01	4.51E-05	4.98E-05
Zr-93	3.29E-03	1.82E-03	1.42E-03	5.84E-05	3.77E-09
Nb-91	7.63E-03	5.72E-04	7.03E-03	5.31E-06	2.48E-05
Nb-93m	7.52E-03	5.72E-04	6.95E-03	5.31E-06	2.24E-07
Nb-94	1.23E-01	7.82E-03	9.62E-02	7.53E-05	1.85E-02
Mo-93	3.22E-03	1.48E-03	1.73E-03	5.17E-06	1.28E-06
Tc-99	1.23E-02	1.60E-03	1.07E-02	1.51E-06	2.02E-07
Ru-106+D	4.96E-02	3.00E-02	1.76E-02	8.65E-05	1.96E-03
Pd-107	6.34E-04	1.63E-04	4.69E-04	2.33E-06	0.00
Ag-108m+D	6.91E-02	8.34E-03	4.19E-02	5.15E-05	1.88E-02
Cd-109	2.62E-02	1.43E-02	1.18E-02	2.07E-05	2.63E-05
Cd-113m	3.32E-01	1.76E-01	1.55E-01	2.78E-04	1.37E-06

Table 39. Low Water Infiltration Case: Native American Subsistence Resident

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
In-115	3.20E-01	1.73E-01	1.46E-01	6.81E-04	8.69E-07
Sn-121m+D	1.03E-02	2.46E-03	7.80E-03	2.17E-06	4.60E-06
Sn-126+D	1.20E-01	2.31E-02	7.34E-02	1.84E-05	2.32E-02
Sb-125	9.78E-03	3.08E-03	2.31E-03	2.22E-06	4.39E-03
Te-125m	6.70E-03	4.02E-03	2.67E-03	1.31E-06	9.67E-06
I-129	1.21E+00	3.02E-01	9.10E-01	3.16E-05	2.62E-05
Cs-134	3.06E-01	8.03E-02	2.10E-01	8.41E-06	1.61E-02
Cs-135	2.94E-02	7.74E-03	2.17E-02	8.28E-07	8.39E-08
Cs-137+D	2.14E-01	5.48E-02	1.53E-01	5.81E-06	6.56E-03
Ba-133	1.02E-02	3.72E-03	2.52E-03	1.42E-06	3.94E-03
Pm-147	1.95E-03	1.15E-03	7.97E-04	7.12E-06	9.89E-08
Sm-147	3.62E-01	2.03E-01	1.45E-01	1.36E-02	0.00
Sm-151	7.37E-04	4.26E-04	3.06E-04	5.46E-06	2.15E-09
Eu-150	2.90E-02	6.96E-03	4.99E-03	4.88E-05	1.70E-02
Eu-152	2.51E-02	7.10E-03	5.06E-03	4.02E-05	1.29E-02
Eu-154	3.19E-02	1.05E-02	7.43E-03	5.20E-05	1.40E-02
Eu-155	3.24E-03	1.68E-03	1.18E-03	7.53E-06	3.77E-04
Gd-152	3.39E-01	1.76E-01	1.19E-01	4.42E-02	0.00
Ho-166m	3.53E-02	8.84E-03	6.22E-03	1.41E-04	2.01E-02
Re-187	2.42E-05	1.04E-05	1.37E-05	9.90E-09	0.00
Tl-204	1.14E-02	3.68E-03	7.75E-03	4.38E-07	8.22E-06
Pb-205	2.94E-03	1.78E-03	1.16E-03	7.13E-07	1.55E-08
Pb-210+D	9.91E+00	5.88E+00	4.03E+00	2.52E-03	1.29E-05
Bi-207	2.78E-02	6.00E-03	4.22E-03	3.64E-06	1.76E-02
Po-209	4.72E+00	2.61E+00	2.12E+00	2.15E-03	3.86E-05
Po-210	3.55E+00	2.08E+00	1.47E+00	1.70E-03	5.39E-08
Ra-226+D	2.47E+00	1.46E+00	9.88E-01	1.57E-03	2.07E-02
Ra-228+D	2.65E+00	1.58E+00	1.06E+00	1.05E-03	1.31E-02
Ac-227+D	2.66E+01	1.62E+01	9.20E+00	1.22E+00	4.10E-03

Table 39. Low Water Infiltration Case: Native American Subsistence Resident

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Th-228+D	1.45E+00	8.88E-01	4.87E-01	6.27E-02	1.58E-02
Th-229+D	7.30E+00	4.41E+00	2.49E+00	3.93E-01	3.22E-03
Th-230	9.99E-01	6.00E-01	3.39E-01	5.93E-02	6.10E-06
Th-232	4.99E+00	2.99E+00	1.70E+00	2.98E-01	5.91E-04
Pa-231	1.84E+01	1.16E+01	6.59E+00	2.33E-01	4.45E-04
U-232	2.64E+00	1.43E+00	1.08E+00	1.20E-01	2.31E-03
U-233	5.77E-01	3.16E-01	2.36E-01	2.46E-02	3.07E-06
U-234	5.65E-01	3.10E-01	2.31E-01	2.40E-02	8.72E-07
U-235+D	5.34E-01	2.92E-01	2.18E-01	2.24E-02	1.61E-03
U-236	5.37E-01	2.95E-01	2.20E-01	2.27E-02	4.64E-07
U-238+D	5.34E-01	2.93E-01	2.19E-01	2.15E-02	2.52E-04
Np-237+D	7.73E+00	4.86E+00	2.76E+00	9.83E-02	2.24E-03
Pu-236	2.02E+00	1.28E+00	7.10E-01	2.64E-02	6.45E-06
Pu-238	5.55E+00	3.50E+00	1.98E+00	7.13E-02	3.30E-07
Pu-239	6.14E+00	3.88E+00	2.19E+00	7.81E-02	6.23E-07
Pu-240	6.14E+00	3.88E+00	2.19E+00	7.81E-02	3.21E-07
Pu-241+D	1.19E-01	7.50E-02	4.24E-02	1.50E-03	9.84E-08
Pu-242	5.83E+00	3.68E+00	2.08E+00	7.48E-02	2.81E-07
Pu-244+D	5.76E+00	3.64E+00	2.05E+00	7.33E-02	3.91E-03
Am-241	6.32E+00	3.99E+00	2.25E+00	8.08E-02	9.60E-05
Am-242m+D	6.11E+00	3.85E+00	2.18E+00	7.75E-02	1.42E-04
Am-243+D	6.30E+00	3.97E+00	2.24E+00	8.01E-02	1.91E-03
Cm-242	1.94E-01	1.26E-01	6.45E-02	3.13E-03	2.18E-07
Cm-243	4.36E+00	2.75E+00	1.56E+00	5.59E-02	1.23E-03
Cm-244	3.51E+00	2.21E+00	1.25E+00	4.51E-02	2.72E-07
Cm-245	6.51E+00	4.10E+00	2.33E+00	8.28E-02	7.40E-04
Cm-246	6.44E+00	4.05E+00	2.30E+00	8.21E-02	2.55E-07
Cm-247+D	5.95E+00	3.74E+00	2.13E+00	7.53E-02	3.78E-03
Cm-248	2.37E+01	1.49E+01	8.46E+00	3.00E-01	1.92E-07

Table 39. Low Water Infiltration Case: Native American Subsistence Resident

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Cm-250+D	1.35E+02	8.51E+01	4.84E+01	1.71E+00	3.70E-03
Bk-247	8.16E+00	5.15E+00	2.90E+00	1.04E-01	9.25E-04
Cf-248	6.16E-01	3.66E-01	2.41E-01	9.20E-03	2.10E-07
Cf-249	9.01E+00	5.19E+00	3.71E+00	1.05E-01	3.76E-03
Cf-250	4.04E+00	2.33E+00	1.66E+00	4.77E-02	2.55E-07
Cf-251	9.22E+00	5.31E+00	3.80E+00	1.07E-01	1.13E-03
Cf-252	2.03E+00	1.18E+00	8.17E-01	2.85E-02	3.49E-07

Units are mrem per pCi/L in the ground water.

Table 40. Low Water Infiltration Case: Columbia River Population

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
H-3	2.29E-01	1.73E-01	3.48E-02	2.09E-02	0.00
Be-10	1.52E+01	1.26E+01	2.48E+00	1.50E-01	5.60E-03
C-14	1.95E+01	5.64E+00	1.39E+01	8.87E-04	7.02E-05
Na-22	2.14E+02	3.11E+01	1.26E+02	3.25E-03	5.63E+01
Si-32+D	3.55E+01	2.97E+01	5.33E+00	4.37E-01	5.92E-02
Cl-36	1.88E+02	8.18E+00	1.80E+02	9.29E-03	1.15E-02
K-40	1.22E+02	5.02E+01	6.72E+01	5.26E-03	4.49E+00
Ti-44+D	2.40E+02	6.64E+01	1.12E+02	1.92E-01	6.23E+01
V-49	2.03E-01	1.66E-01	3.66E-02	1.46E-04	0.00
Mn-54	2.66E+01	7.48E+00	1.59E+00	2.84E-03	1.76E+01
Fe-55	2.72E+00	1.64E+00	1.08E+00	1.14E-03	0.00
Co-60	1.98E+02	7.26E+01	5.72E+01	9.29E-02	6.81E+01
Ni-59	7.93E-01	5.67E-01	2.26E-01	5.60E-04	0.00
Ni-63	2.18E+00	1.56E+00	6.20E-01	1.32E-03	0.00
Se-79	5.03E+01	2.35E+01	2.68E+01	4.18E-03	9.85E-05
Rb-87	3.23E+01	1.33E+01	1.90E+01	1.37E-03	7.43E-04
Sr-90+D	5.53E+02	4.13E+02	1.39E+02	1.05E-01	1.20E-01
Zr-93	6.10E+00	4.48E+00	1.48E+00	1.36E-01	9.10E-06
Nb-91	1.23E+01	1.41E+00	1.08E+01	1.24E-02	5.98E-02
Nb-93m	1.21E+01	1.41E+00	1.07E+01	1.24E-02	5.42E-04
Nb-94	2.13E+02	1.93E+01	1.48E+02	1.76E-01	4.47E+01
Mo-93	5.46E+00	3.65E+00	1.80E+00	1.21E-02	3.10E-03
Tc-99	1.46E+01	3.94E+00	1.07E+01	3.53E-03	4.87E-04
Ru-106+D	9.36E+01	7.40E+01	1.47E+01	2.02E-01	4.72E+00
Pd-107	8.43E-01	4.02E-01	4.35E-01	5.43E-03	0.00
Ag-108m+D	1.05E+02	2.06E+01	3.87E+01	1.20E-01	4.55E+01
Cd-109	4.52E+01	3.54E+01	9.74E+00	4.83E-02	6.34E-02
Cd-113m	5.63E+02	4.35E+02	1.28E+02	6.49E-01	3.31E-03

Table 40. Low Water Infiltration Case: Columbia River Population

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
In-115	5.91E+02	4.27E+02	1.63E+02	1.59E+00	2.10E-03
Sn-121m+D	1.91E+01	6.08E+00	1.31E+01	5.05E-03	1.11E-02
Sn-126+D	2.36E+02	5.70E+01	1.23E+02	4.29E-02	5.59E+01
Sb-125	2.03E+01	7.59E+00	2.15E+00	5.18E-03	1.06E+01
Te-125m	1.30E+01	9.91E+00	3.11E+00	3.07E-03	2.33E-02
I-129	1.64E+03	7.45E+02	8.91E+02	7.38E-02	6.32E-02
Cs-134	4.75E+02	1.98E+02	2.38E+02	1.96E-02	3.89E+01
Cs-135	4.39E+01	1.91E+01	2.48E+01	1.93E-03	2.02E-04
Cs-137+D	3.25E+02	1.35E+02	1.74E+02	1.35E-02	1.58E+01
Ba-133	2.07E+01	9.18E+00	2.06E+00	3.31E-03	9.51E+00
Pm-147	3.63E+00	2.84E+00	7.76E-01	1.66E-02	2.39E-04
Sm-147	6.75E+02	5.00E+02	1.43E+02	3.17E+01	0.00
Sm-151	1.36E+00	1.05E+00	3.01E-01	1.27E-02	5.19E-06
Eu-150	6.32E+01	1.72E+01	4.91E+00	1.14E-01	4.10E+01
Eu-152	5.38E+01	1.75E+01	4.98E+00	9.38E-02	3.12E+01
Eu-154	6.70E+01	2.58E+01	7.29E+00	1.21E-01	3.38E+01
Eu-155	6.21E+00	4.13E+00	1.15E+00	1.76E-02	9.11E-01
Gd-152	6.47E+02	4.35E+02	1.09E+02	1.03E+02	0.00
Ho-166m	7.65E+01	2.18E+01	6.00E+00	3.28E-01	4.84E+01
Re-187	3.97E-02	2.57E-02	1.40E-02	2.31E-05	0.00
Tl-204	2.02E+01	9.07E+00	1.11E+01	1.02E-03	1.98E-02
Pb-205	5.33E+00	4.40E+00	9.28E-01	1.66E-03	3.74E-05
Pb-210+D	1.78E+04	1.45E+04	3.25E+03	5.87E+00	3.10E-02
Bi-207	6.07E+01	1.48E+01	3.43E+00	8.49E-03	4.25E+01
Po-209	8.56E+03	6.43E+03	2.13E+03	5.01E+00	9.31E-02
Po-210	6.63E+03	5.13E+03	1.50E+03	3.97E+00	1.30E-04
Ra-226+D	4.41E+03	3.59E+03	7.64E+02	3.65E+00	4.99E+01
Ra-228+D	4.74E+03	3.89E+03	8.16E+02	2.34E+00	3.15E+01
Ac-227+D	4.96E+04	4.00E+04	6.74E+03	2.85E+03	9.90E+00

Table 40. Low Water Infiltration Case: Columbia River Population

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Th-228+D	2.73E+03	2.19E+03	3.56E+02	1.46E+02	3.82E+01
Th-229+D	1.36E+04	1.09E+04	1.82E+03	9.17E+02	7.78E+00
Th-230	1.87E+03	1.48E+03	2.48E+02	1.38E+02	1.47E-02
Th-232	9.31E+03	7.37E+03	1.24E+03	6.96E+02	1.42E+00
Pa-231	3.40E+04	2.86E+04	4.81E+03	5.44E+02	1.07E+00
U-232	4.74E+03	3.54E+03	9.16E+02	2.80E+02	5.58E+00
U-233	1.04E+03	7.80E+02	2.00E+02	5.73E+01	7.40E-03
U-234	1.02E+03	7.64E+02	1.96E+02	5.60E+01	2.11E-03
U-235+D	9.62E+02	7.21E+02	1.85E+02	5.22E+01	3.88E+00
U-236	9.65E+02	7.26E+02	1.86E+02	5.30E+01	1.12E-03
U-238+D	9.60E+02	7.24E+02	1.85E+02	5.01E+01	6.09E-01
Np-237+D	1.42E+04	1.20E+04	2.03E+03	2.29E+02	5.41E+00
Pu-236	3.74E+03	3.16E+03	5.18E+02	6.15E+01	1.56E-02
Pu-238	1.02E+04	8.64E+03	1.44E+03	1.66E+02	7.96E-04
Pu-239	1.13E+04	9.56E+03	1.60E+03	1.82E+02	1.50E-03
Pu-240	1.13E+04	9.56E+03	1.60E+03	1.82E+02	7.75E-04
Pu-241+D	2.19E+02	1.85E+02	3.10E+01	3.50E+00	2.38E-04
Pu-242	1.08E+04	9.07E+03	1.51E+03	1.74E+02	6.77E-04
Pu-244+D	1.06E+04	8.96E+03	1.50E+03	1.71E+02	9.43E+00
Am-241	1.17E+04	9.83E+03	1.64E+03	1.88E+02	2.32E-01
Am-242m+D	1.13E+04	9.50E+03	1.59E+03	1.81E+02	3.42E-01
Am-243+D	1.16E+04	9.80E+03	1.64E+03	1.87E+02	4.61E+00
Cm-242	3.65E+02	3.11E+02	4.73E+01	7.31E+00	5.25E-04
Cm-243	8.05E+03	6.78E+03	1.14E+03	1.30E+02	2.96E+00
Cm-244	6.48E+03	5.45E+03	9.16E+02	1.05E+02	6.57E-04
Cm-245	1.20E+04	1.01E+04	1.70E+03	1.93E+02	1.78E+00
Cm-246	1.19E+04	9.99E+03	1.68E+03	1.91E+02	6.15E-04
Cm-247+D	1.10E+04	9.23E+03	1.56E+03	1.76E+02	9.12E+00
Cm-248	4.36E+04	3.67E+04	6.19E+03	7.00E+02	4.64E-04

Table 40. Low Water Infiltration Case: Columbia River Population

Nuclide	Total	Ingest (Drink)	Ingest (Other)	Inhale	External
Cm-250+D	2.49E+05	2.10E+05	3.54E+04	3.99E+03	8.92E+00
Bk-247	1.51E+04	1.27E+04	2.12E+03	2.44E+02	2.23E+00
Cf-248	1.15E+03	9.02E+02	2.28E+02	2.15E+01	5.07E-04
Cf-249	1.67E+04	1.28E+04	3.66E+03	2.45E+02	9.08E+00
Cf-250	7.49E+03	5.75E+03	1.63E+03	1.11E+02	6.14E-04
Cf-251	1.71E+04	1.31E+04	3.74E+03	2.50E+02	2.73E+00
Cf-252	3.78E+03	2.92E+03	7.95E+02	6.66E+01	8.41E-04

Units are person-rem per pCi/L in the Columbia River.

Table 41. Ratio of Total Dose to Drinking Water Dose

Nuclide	Residential	Agricultural	All Pathways	NASR	Population
H-3	1.05	1.23	1.32	1.47	1.32
Be-10	1.14	1.17	1.27	1.62	1.21
C-14	1.21	4.22	4.14	5.87	3.46
Na-22	3.92	10.51	8.39	12.11	6.88
Si-32+D	1.15	1.16	1.25	1.62	1.20
Cl-36	7.42	26.27	29.41	54.13	22.98
K-40	1.33	3.01	2.82	4.11	2.43
Ti-44+D	2.58	4.89	4.29	5.56	3.62
V-49	1.13	1.18	1.29	1.61	1.22
Mn-54	4.75	4.81	4.14	4.09	3.56
Fe-55	1.14	1.63	1.84	2.21	1.66
Co-60	2.58	3.35	3.15	3.52	2.73
Ni-59	1.14	1.45	1.51	1.98	1.40
Ni-63	1.14	1.45	1.51	1.98	1.40
Se-79	1.14	2.27	2.45	3.25	2.14
Rb-87	1.15	3.17	2.82	4.32	2.43
Sr-90+D	1.16	1.43	1.43	2.02	1.34
Zr-93	1.15	1.32	1.46	1.81	1.36
Nb-91	1.21	10.26	10.86	13.35	8.75
Nb-93m	1.14	10.08	10.68	13.16	8.61
Nb-94	4.70	13.76	13.64	15.68	11.03
Mo-93	1.15	1.58	1.64	2.18	1.50
Tc-99	1.23	5.47	4.49	7.66	3.71
Ru-106+D	1.23	1.27	1.34	1.65	1.26
Pd-107	1.15	2.88	2.40	3.89	2.10
Ag-108m+D	4.54	7.86	6.10	8.29	5.10
Cd-109	1.15	1.32	1.36	1.83	1.28
Cd-113m	1.15	1.35	1.38	1.88	1.30

Table 41. Ratio of Total Dose to Drinking Water Dose

Nuclide	Residential	Agricultural	All Pathways	NASR	Population
In-115	1.14	1.35	1.49	1.85	1.39
Sn-121m+D	1.14	3.16	3.74	4.17	3.15
Sn-126+D	2.65	4.67	4.94	5.18	4.14
Sb-125	3.29	3.40	3.07	3.18	2.68
Te-125m	1.11	1.23	1.40	1.67	1.32
I-129	1.15	2.94	2.53	4.01	2.20
Cs-134	1.44	3.00	2.77	3.82	2.40
Cs-135	1.15	2.83	2.65	3.80	2.30
Cs-137+D	1.33	3.00	2.79	3.91	2.41
Ba-133	2.73	2.79	2.55	2.74	2.26
Pm-147	1.14	1.25	1.36	1.70	1.28
Sm-147	1.16	1.28	1.43	1.79	1.35
Sm-151	1.14	1.26	1.38	1.73	1.30
Eu-150	4.80	4.92	4.28	4.16	3.68
Eu-152	3.87	3.99	3.54	3.54	3.07
Eu-154	3.15	3.27	2.96	3.05	2.60
Eu-155	1.48	1.59	1.63	1.93	1.50
Gd-152	1.21	1.29	1.56	1.92	1.49
Ho-166m	4.55	4.66	4.08	3.99	3.51
Re-187	1.17	1.63	1.70	2.32	1.55
Tl-204	1.14	2.33	2.57	3.11	2.23
Pb-205	1.14	1.19	1.27	1.65	1.21
Pb-210+D	1.15	1.20	1.29	1.69	1.22
Bi-207	5.54	5.64	4.80	4.64	4.10
Po-209	1.14	1.22	1.42	1.81	1.33
Po-210	1.12	1.18	1.37	1.71	1.29
Ra-226+D	1.16	1.25	1.29	1.69	1.23
Ra-228+D	1.15	1.23	1.28	1.68	1.22
Ac-227+D	1.16	1.16	1.29	1.64	1.24

Table 41. Ratio of Total Dose to Drinking Water Dose

Nuclide	Residential	Agricultural	All Pathways	NASR	Population
Th-228+D	1.18	1.18	1.30	1.64	1.25
Th-229+D	1.17	1.17	1.30	1.66	1.25
Th-230	1.17	1.17	1.31	1.66	1.26
Th-232	1.17	1.17	1.31	1.67	1.26
Pa-231	1.15	1.15	1.24	1.59	1.19
U-232	1.17	1.29	1.41	1.84	1.34
U-233	1.16	1.28	1.40	1.82	1.33
U-234	1.16	1.28	1.40	1.82	1.33
U-235+D	1.17	1.29	1.41	1.83	1.33
U-236	1.16	1.28	1.40	1.82	1.33
U-238+D	1.16	1.28	1.40	1.82	1.33
Np-237+D	1.15	1.15	1.24	1.59	1.19
Pu-236	1.14	1.14	1.23	1.57	1.18
Pu-238	1.15	1.15	1.24	1.58	1.19
Pu-239	1.15	1.15	1.24	1.58	1.19
Pu-240	1.15	1.15	1.24	1.58	1.19
Pu-241+D	1.15	1.15	1.24	1.59	1.19
Pu-242	1.15	1.15	1.24	1.58	1.19
Pu-244+D	1.15	1.15	1.24	1.59	1.19
Am-241	1.15	1.15	1.24	1.58	1.19
Am-242m+D	1.15	1.15	1.24	1.59	1.19
Am-243+D	1.15	1.15	1.24	1.58	1.19
Cm-242	1.13	1.14	1.22	1.54	1.18
Cm-243	1.15	1.15	1.24	1.59	1.19
Cm-244	1.15	1.15	1.24	1.59	1.19
Cm-245	1.15	1.15	1.24	1.59	1.19
Cm-246	1.15	1.15	1.24	1.59	1.19
Cm-247+D	1.15	1.15	1.24	1.59	1.19
Cm-248	1.15	1.15	1.24	1.59	1.19

Table 41. Ratio of Total Dose to Drinking Water Dose

Nuclide	Residential	Agricultural	All Pathways	NASR	Population
Cm-250+D	1.15	1.15	1.24	1.59	1.19
Bk-247	1.15	1.15	1.24	1.58	1.19
Cf-248	1.14	1.23	1.35	1.68	1.28
Cf-249	1.15	1.26	1.39	1.74	1.31
Cf-250	1.15	1.26	1.38	1.73	1.30
Cf-251	1.15	1.26	1.39	1.74	1.31
Cf-252	1.14	1.25	1.37	1.71	1.30

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Appendix A.

Hand Calculations for Tritium

HAND CALCULATIONS FOR TRITIUM

A.1 No Water Infiltration Exposure Scenarios

Each of the exposure scenarios listed in Table 2 will be evaluated. The external exposures are not computed for tritium because the external dose rate factor for tritium is zero. Absorption through the skin is included in the inhalation dose factor for tritium.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

A.1.1 Offsite Farmer

Assume 1 curie H-3 is released into the air during the year. The bounding annual average air transport factor is 1.0E-04 s/m^3.

Inhalation Dose: From Table 28, 0.0237 mrem

A.1.2 Onsite Resident

Assume the H-3 emanation rate is 1 pCi/m^2/s. The average air concentration in a dwelling with an air exchange to floor area ratio of 5.0E-04 m/s is computed as shown below.

$$C_{eq} = (1\ \text{pCi/m}^2\text{/s})/(5.0\text{E-04 m/s}) = 2000\ \text{pCi/m}^3$$

The individual is present in his dwelling about 6966 h/y from Table 17. The total volume of air inhaled during this period is computed as shown below.

$$V_{air} = (2920\ \text{h/y})(0.45\ \text{m}^3\text{/h}) + (4046\ \text{h/y})(1.2\ \text{m}^3\text{/h}) = 6170\ \text{m}^3\text{/y}$$

Inhalation Dose:

$$(2000\ \text{pCi/m}^3)(6170\ \text{m}^3)(9.60\text{E-08 mrem/pCi}) = \underline{1.18\ \text{mrem}}$$

A.1.3 Intruder (Well Driller)

Assume 1 curie H-3 is exhumed from the well shaft during the 5 day operation. The soil is spread over an area of 100 m^2 so the average soil concentration is computed as shown below.

$$C_s = (1\ \text{Ci})(1\text{E12 pCi/Ci})/(100\ \text{m}^2)/(225\ \text{kg/m}^2) = 4.444\text{E+7 pCi/kg}$$

A mass loading approach is used, so that the driller inhales a total of 4.8 mg (4.8E-06 kg) of soil. He ingests a total of 500 mg (5.0E-4 kg) soil. The inhalation and ingestion dose calculations are shown below.

Inhalation Dose:

(4.8E-06 kg inhaled)(4.444E+7 pCi/kg)(9.60E-08 mrem/pCi) = 2.05E-05 mrem

Ingestion Dose:

(5.0E-04 kg ingested)(4.444E+7 pCi/kg)(6.40E-08 mrem/pCi) = 1.42E-03 mrem

External Dose:

(40 h)(4.444E+7 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²) = 0 mrem

Total Dose to Driller:

2.05E-05 + 1.42E-03 mrem = 1.44E-03 mrem per Ci exhumed

A.1.4 Post-Intrusion Resident (Gardener)

Assume 1 curie H-3 is exhumed from the well shaft and spread over an area of 200 m². The average soil concentration is computed as shown below.

C_s = (1 Ci)(1E12 pCi/Ci)/(200 m²)/(225 kg/m²) = 2.222E+7 pCi/kg

This concentration decreases with time due to leaching from the surface layer during the irrigation season and radioactive decay. Decay factors used in the dose calculations are computed below (Table 30).

λ_r = (0.69315)/(12.33 y) = 0.056216 y^{-1} $\quad$ λ_l = 2.22 y^{-1} (Table 27)
$\lambda_t = \lambda_r + \lambda_l$ = 2.27622 y^{-1}

$\lambda_t T_{irr}$ = (2.27622 y^{-1})(0.5 y) = 1.13811
$DS(T_{irr})$ = Exp(-1.13811) = 0.32042
$IDS(T_{irr})$ = [1 - Exp(-1.13811)]/(1.13811) = 0.59711

$\lambda_r T_{no}$ = (0.056216 y^{-1})(0.5 y) = 0.028108
$IDR(T_{no})$ = [1 - Exp(-0.028108)]/(0.028108) = 0.98608

$T_{irr} \cdot IDS(T_{irr}) + T_{no} \cdot DS(T_{irr}) \cdot IDR(T_{no})$ =
(0.5y)(0.59711) + (0.5y)(0.32042)(0.98608) = 0.45653 y

$DS(T_h)$ = Exp[-(2.27622 y^{-1})(0.25 y)] = 0.56606

$\lambda_r T_{veg}$ = (0.056216 y^{-1})(90 d)/(365.25 d/y) = 0.013852
$IDR(T_{veg})$ = [1 - Exp(-0.013852)]/(0.013852) = 0.99311

$DS(T_h) \cdot IDR(T_{veg}) = (0.56606)(0.99311) = 0.56216$

A mass loading approach is used, so that the resident inhales a total of 573 mg (5.73E-04 kg) of soil over the course of a year. He also ingests a total of 0.0365 kg soil during the year. The inhalation and ingestion doses from these sources are shown below.

Inhalation Dose: (resuspended soil)
(5.73E-4 kg/y)(2.222E+7 pCi/kg)(9.60E-8 mrem/pCi)(0.45653 y) = 5.58E-4 mrem

Ingestion Dose: (soil only)
(0.0365 kg)(2.222E+7 pCi/kg)(6.40E-8 mrem/pCi)(0.45653 y) = 0.0237 mrem

External Dose:
(900 h/y)(2.222E+7 pCi/kg)(225 kg/m^2)(0 mrem/h per Ci/m^2)(0.45653 y) = 0 mrem

The vegetable produce from the garden is contaminated by root uptake and rain splash. Doses from each are shown below. The contaminated food consumption rate is combined with the ingestion period (1 year) so that the column of consumption rates has units of kg rather than kg/y. The product of soil concentration and ingestion dose is combined into a single quantity to simplify the calculation.
(2.222E+7 pCi/kg)(6.40E-8 mrem/pCi)=1.4221 mrem/kg

Ingestion Dose: (root uptake only)
(1.4221 mrem/kg)(51)(0.09)(4.1 kg)(0.59711) = 16.0 mrem
(1.4221 mrem/kg)(18)(0.25)(13.9 kg)(0.56216) = 50.0 mrem
(1.4221 mrem/kg)(25)(0.18)(9.6 kg)(0.56216) = 34.5 mrem
(1.4221 mrem/kg)(3.4)(0.91)(18.5 kg)(0.56216) = 45.8 mrem
Total from root uptake: 146.3 mrem

Ingestion Dose: (rain splash only)
To simplify the calculation, the mass loading, ground deposition speed, soil concentration and ingestion dose factor are combined in a single factor.
(1 mg/m^3)(0.01 m/s)(1.4221 mrem/kg)(86,400 s/d) = 1.229E-3 mrem/d/m^2

(1.229E-3mrem/d/m^2)(18d)(0.407)(1.0)/(2.0kg/m^2)(4.1kg)(0.59711) = 0.0110mrem
(1.229E-3mrem/d/m^2)(20d)(0.835)(0.1)/(2.0kg/m^2)(13.9kg)(0.56216) = 0.0080mrem
(1.229E-3mrem/d/m^2)(20d)(0.857)(0.1)/(3.0kg/m^2)(9.6kg)(0.56216) = 0.0038mrem
(1.229E-3mrem/d/m^2)(20d)(0.371)(0.1)/(0.8kg/m^2)(18.5kg)(0.56216) = 0.0119mrem
Total from rain splash: 0.0347mrem

Total Dose to Gardener:
5.58E-04 + 0.0237 + 146.3 + 0.0347 mrem = 146 mrem per Ci exhumed

A.1.5 Post-Intrusion Resident (HSRAM Residential)

Assume 1 curie H-3 is exhumed from the well shaft and spread over an area of 200 m². The average soil concentration is computed as before. The same decay factors used for the Gardener also apply here. Doses from each pathway are shown below.

Inhalation Dose: (resuspended soil)
(3.65E-4 kg/y)(2.222E+7 pCi/kg)(9.60E-8 mrem/pCi)(0.45653 y) = 3.55E-4 mrem

Ingestion Dose: (soil only)
(0.0365 kg)(2.222E+7 pCi/kg)(6.40E-8 mrem/pCi)(0.45653 y) = 0.0237 mrem

External Dose:
(7008 h/y)(2.222E+7 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²)(0.45653 y) = 0 mrem

Ingestion Dose: (root uptake only)
(1.4221 mrem/kg)(51)(0.09)(3.7 kg)(0.59711) = 14.4 mrem
(1.4221 mrem/kg)(18)(0.25)(11.0 kg)(0.56216) = 39.6 mrem
(1.4221 mrem/kg)(25)(0.18)(15.3 kg)(0.56216) = 55.0 mrem
(1.4221 mrem/kg)(3.4)(0.91)(14.6 kg)(0.56216) = 36.1 mrem
Total from root uptake: 145.1 mrem

Ingestion Dose: (rain splash only)
(1.229E-3mrem/d/m²)(18d)(0.407)(1.0)/(2.0kg/m²)(3.7kg)(0.59711) = 0.0099mrem
(1.229E-3mrem/d/m²)(20d)(0.835)(0.1)/(2.0kg/m²)(11.0kg)(0.56216) = 0.0063mrem
(1.229E-3mrem/d/m²)(20d)(0.857)(0.1)/(3.0kg/m²)(15.3kg)(0.56216) = 0.0060mrem
(1.229E-3mrem/d/m²)(20d)(0.371)(0.1)/(0.8kg/m²)(14.6kg)(0.56216) = 0.0094mrem
Total from rain splash: 0.0317mrem

Total Dose to HSRAM Residential:
3.55E-04 + 0.0237 + 145.1 + 0.0317 mrem = 145 mrem per Ci exhumed

A.2 Low Water Infiltration Exposure Scenarios

Each of the exposure scenarios listed in Table 4 will be evaluated. The external exposures are not computed for tritium because the external dose rate factor for tritium is zero. Absorption through the skin is included in the inhalation dose factor for tritium. The main dose pathway in every case is the drinking water pathway.

It will be assumed in each exposure scenario that the well water concentration is 1 pCi/L. Thus the doses computed are per pCi/L.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

A.2.1 Industrial (HSRAM)

The worker inhales 2.1 L/y during routine showering and ingests 250 L/y of drinking water (untreated). The soil pathways do not apply because the soil is not contaminated.

Inhalation Dose: (showering)
(2.1 L/y)(1 pCi/L)(9.60E-08 mrem/pCi)(1 y) = 2.02E-7 mrem

Ingestion Dose: (drinking)
(250 L/y)(1 pCi/L)(6.40E-08 mrem/pCi)(1 y) = 1.60E-5 mrem

Total Dose to Industrial Worker:
2.02E-7 + 1.60E-5 mrem = 1.62E-5 mrem per pCi/L

A.2.2 Residential (HSRAM)

The soil concentration decreases with time due to leaching from the surface layer during the irrigation season and radioactive decay. Decay factors used in the dose calculations are computed below (Table 30). Equilibrium model assumptions lead to somewhat different decay factors than in the no-infiltration cases.

$\lambda_r T_{no}$ = (0.056216 y^{-1})(0.5 y) = 0.028108
$IDR(T_{no})$ = [1 - Exp(-0.028108)]/(0.028108) = 0.98608

$T_{irr} + T_{no} \cdot IDR(T_{no})$ = (0.5y) + (0.5y)(0.98608) = 0.99304 y

$\lambda_r T_{veg}$ = (0.056216 y^{-1})(90 d)/(365.25 d/y) = 0.013852
$IDR(T_{veg})$ = [1 - Exp(-0.013852)]/(0.013852) = 0.99311

Inhalation of well water during showers amounts to 3.1 L/y. Inhalation of resuspended soil amounts to 365 mg (3.65E-04 kg) of soil over the course of a year. The individual also ingests a total of 0.0365 kg soil and 730 L water during the year. The soil concentration is based on the soil moisture having the same tritium concentration as the well water (adjusted for natural precipitation by Equation 15). The soil concentration and the resulting inhalation and ingestion doses from the soil and water are shown below.

$C_{s,H3}$ = (8.94)(0.022)(1 pCi/L)(82.3 cm)/(82.3 + 5.23 cm)/(1 kg/L)
$C_{s,H3}$ = 0.1849 pCi/kg

Inhalation Dose: (showering)
(3.1 L/y)(1 pCi/L)(9.60E-08 mrem/pCi)(1 y) = 2.98E-7 mrem

Inhalation Dose: (resuspended soil)

(3.65E-4 kg/y)(0.1849 pCi/kg)(9.60E-8 mrem/pCi)(0.99304 y) = 6.43E-12 mrem

Ingestion Dose: (drinking)

(730 L/y)(1 pCi/L)(6.40E-08 mrem/pCi)(1 y) = 4.67E-5 mrem

Ingestion Dose: (soil)

(0.0365 kg/y)(0.1849 pCi/kg)(6.40E-8 mrem/pCi)(0.99304 y) = 4.29E-10 mrem

External Dose:

(7008 h/y)(0.1849 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²)(0.99304 y) = 0 mrem

The vegetable produce contamination is based on the plant moisture having the same tritium concentration as the well water (adjusted for natural precipitation by Equation 15). The contaminated food consumption rate is combined with the ingestion period (1 year) so that the column of consumption rates has units of kg rather than kg/y. The product of plant water concentration and ingestion dose factor is combined into a single quantity to simplify the calculation.

(0.94)(1 pCi/L)(6.40E-8 mrem/pCi)=6.016E-8 mrem/L

The factors 0.894 L/kg and 0.6079 L/kg in the calculations below are the volume of water per kilogram of plant. They are calculated from the hydrogen fractions shown in Table 23 multiplied by 8.94 kg water per kg hydrogen, and divided by the density of water, 1.0 kg/L.

Ingestion Dose: (garden produce)

(6.016E-8 mrem/L)(0.894 L/kg)(3.7 kg)(1.00) = 1.99E-7 mrem
(6.016E-8 mrem/L)(0.894 L/kg)(11.0 kg)(0.99311) = 5.88E-7 mrem
(6.016E-8 mrem/L)(0.894 L/kg)(15.3 kg)(0.99311) = 8.17E-7 mrem
(6.016E-8 mrem/L)(0.6079L/kg)(14.6 kg)(0.99311) = 5.30E-7 mrem
Total from garden produce: 2.13E-6 mrem

Total Dose to Resident:

2.98E-7+6.43E-12+4.67E-5+4.29E-10+2.13E-6 mrem = 4.92E-5 mrem per pCi/L

A.2.3 Agricultural (HSRAM)

Both inhalation doses as well as the ingestion doses for drinking water, soil, and garden produce are the same as the HSRAM Residential case. They are listed below.

Inhalation Dose: (showering)

(3.1 L/y)(1 pCi/L)(9.60E-08 mrem/pCi)(1 y) = 2.98E-7 mrem

Inhalation Dose: (resuspended soil)

(3.65E-4 kg/y)(0.1849 pCi/kg)(9.60E-8 mrem/pCi)(0.99304 y) = 6.43E-12 mrem

Ingestion Dose: (drinking)

(730 L/y)(1 pCi/L)(6.40E-08 mrem/pCi)(1 y) = 4.67E-5 mrem

Ingestion Dose: (soil)

(0.0365 kg/y)(0.1849 pCi/kg)(6.40E-8 mrem/pCi)(0.99304 y) = 4.29E-10 mrem

External Dose:

(7008 h/y)(0.1849 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²)(0.99304 y) = 0 mrem

Ingestion Dose: (garden produce)

Total from garden produce: 2.13E-6 mrem

Total from the above pathways = 4.915E-05 mrem

The agricultural scenario adds the dose from animal products that are contaminated by ingestion of well water, contaminated fodder and soil. The decay factors are based on Table 32 and are shown below.

$\lambda_r T_s = (0.056216\ y^{-1})(90\ d)/365.25\ d/y) = 0.013852$
$DR(T_s) = Exp(-0.013852) = 0.98624$

$\lambda_r T_{beef} = (0.056216\ y^{-1})(120\ d)/(365.25\ d/y) = 0.018469$
$IDR(T_{beef}) = [1 - Exp(-0.018469)]/(0.018469) = 0.99082$

$DR(T_s) \cdot IDR(T_{beef}) = (0.98624)(0.99082) = 0.97719$

$\lambda_r T_{an} = (0.056216\ y^{-1})(90\ d)/(365.25\ d/y) = 0.013852$
$IDR(T_{an}) = [1 - Exp(-0.013852)]/(0.013852) = 0.99311$

$DR(T_s) \cdot IDR(T_{an}) = (0.98624)(0.99311) = 0.97944$

$\lambda_r T_{no} = (0.056216\ y^{-1})(0.5\ y) = 0.028108$
$IDR(T_{no}) = [1 - Exp(-0.028108)]/(0.028108) = 0.98608$

$T_{irr} + T_{no} \cdot IDR(T_{no}) = (0.5y) + (0.5y)(0.98608) = 0.99304\ y$

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the annual amount consumed by the individual, the ingestion dose factor, the equilibrium transfer factor, the water concentration, and the ingestion period.

Ingestion Dose: (beef)

(21.9 kg/y)(6.40E-8 mrem/pCi)(0.01 d/kg)(1 pCi/L)(1 y) = 1.402E-8 mrem·d/L

(1.402E-8 mrem·d/L)(0.94)(0.894 L/kg)(14 kg/d grass)(0.99082) = 1.63E-7 mrem

(1.402E-8 mrem·d/L)(0.94)(0.894 L/kg)(27 kg/d hay)(0.97719) = 3.11E-7 mrem
(1.402E-8 mrem·d/L)(0.94)(0.6079L/kg)(3 kg/d grain)(0.97719) = 2.35E-8 mrem
(1.402E-8 mrem·d/L)(0.94)(0.1967L/kg)(0.6 kg/d soil)(0.99082) = 1.54E-9 mrem
(1.402E-8 mrem·d/L)(1.00) (50 L/d water)(0.99082) = 6.95E-7 mrem
Total from beef: 1.19E-6 mrem

<u>Ingestion Dose:</u> (milk)
(110 L/y)(6.40E-8 mrem/pCi)(0.0082 d/L)(1 pCi/L)(1 y) = 5.773E-8 mrem·d/L

(5.773E-8 mrem·d/L)(0.94)(0.894 L/kg)(36 kg/d grass)(0.99304) = 1.73E-6 mrem
(5.773E-8 mrem·d/L)(0.94)(0.894 L/kg)(29 kg/d hay)(0.97944) = 1.38E-6 mrem
(5.773E-8 mrem·d/L)(0.94)(0.6079L/kg)(2 kg/d grain)(0.97944) = 6.46E-8 mrem
(5.773E-8 mrem·d/L)(0.94)(0.1967L/kg)(0.8 kg/d soil)(0.99304) = 8.48E-9 mrem
(5.773E-8 mrem·d/L)(1.00)(60 L/d water)(1.00) = 3.46E-6 mrem
Total from milk: 6.65E-6 mrem

<u>Ingestion Dose:</u> (poultry)
(5.5 kg/y)(6.40E-8 mrem/pCi)(1.9 d/kg)(1 pCi/L)(1 y) = 6.688E-7 mrem·d/L

(6.688E-7 mrem·d/L)(0.94)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 7.26E-8 mrem
(6.688E-7 mrem·d/L)(0.94)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 mrem
(6.688E-7 mrem·d/L)(0.94)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 3.37E-8 mrem
(6.688E-7 mrem·d/L)(0.94)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 1.35E-9 mrem
(6.688E-7 mrem·d/L)(1.00)(0.3 L/d water)(1.00) = 2.01E-7 mrem
Total from poultry: 3.08E-7 mrem

<u>Total Dose to HSRAM Agricultural:</u>
4.915E-5+1.19E-6+6.65E-6+3.08E-7 mrem = <u>5.73E-5 mrem per pCi/L</u>

A.2.4 All Pathways

The doses for each pathway are calculated in the same manner as the HSRAM Agricultural case except most of the exposure parameters are different. The revised doses are listed below.

<u>Inhalation Dose:</u> (showering and ambient humidity)
(4.5+39 L/y)(1 pCi/L)(9.60E-08 mrem/pCi)(1 y) = 4.18E-6 mrem

<u>Inhalation Dose:</u> (resuspended soil)
(5.73E-4 kg/y)(0.1849 pCi/kg)(9.60E-8 mrem/pCi)(0.99304 y) = 1.01E-11 mrem

<u>Ingestion Dose:</u> (drinking)
(540 L/y)(1 pCi/L)(6.40E-08 mrem/pCi)(1 y) = 3.46E-5 mrem

<u>Ingestion Dose:</u> (soil)

(0.0365 kg/y)(0.1849 pCi/kg)(6.40E-8 mrem/pCi)(0.99304 y) = 4.29E-10 mrem

<u>External Dose:</u>

(4120 h/y)(0.1849 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²)(0.99304 y) = 0 mrem

<u>Ingestion Dose:</u> (garden produce)

(6.016E-8 mrem/L)(0.894 L/kg)(4.1 kg)(1.00) = 2.21E-7 mrem
(6.016E-8 mrem/L)(0.894 L/kg)(13.9 kg)(0.99311) = 7.42E-7 mrem
(6.016E-8 mrem/L)(0.894 L/kg)(9.6 kg)(0.99311) = 5.13E-7 mrem
(6.016E-8 mrem/L)(0.6079L/kg)(18.5 kg)(0.99311) = 6.72E-7 mrem
Total from garden produce: 2.15E-6 mrem

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the annual amount consumed by the individual, the ingestion dose factor, the equilibrium transfer factor, the water concentration, and the ingestion period.

<u>Ingestion Dose:</u> (beef)

(21 kg/y)(6.40E-8 mrem/pCi)(0.01 d/kg)(1 pCi/L)(1 y) = 1.344E-8 mrem·d/L

(1.344E-8 mrem·d/L)(0.94)(0.894 L/kg)(14 kg/d grass)(0.99082) = 1.57E-7 mrem
(1.344E-8 mrem·d/L)(0.94)(0.894 L/kg)(27 kg/d hay)(0.97719) = 2.98E-7 mrem
(1.344E-8 mrem·d/L)(0.94)(0.6079L/kg)(3 kg/d grain)(0.97719) = 2.25E-8 mrem
(1.344E-8 mrem·d/L)(0.94)(0.1967L/kg)(0.6 kg/d soil)(0.99082) = 1.48E-9 mrem
(1.344E-8 mrem·d/L)(1.00)(50 L/d water)(0.99082) = 6.66E-7 mrem
Total from beef: 1.14E-6 mrem

<u>Ingestion Dose:</u> (milk)

(51.7 L/y)(6.40E-8 mrem/pCi)(0.0082 d/L)(1 pCi/L)(1 y) = 2.713E-8 mrem·d/L

(2.713E-8 mrem·d/L)(0.94)(0.894 L/kg)(36 kg/d grass)(0.99304) = 8.15E-7 mrem
(2.713E-8 mrem·d/L)(0.94)(0.894 L/kg)(29 kg/d hay)(0.97944) = 6.48E-7 mrem
(2.713E-8 mrem·d/L)(0.94)(0.6079L/kg)(2 kg/d grain)(0.97944) = 3.04E-8 mrem
(2.713E-8 mrem·d/L)(0.94)(0.1967L/kg)(0.8 kg/d soil)(0.99304) = 3.99E-9 mrem
(2.713E-8 mrem·d/L)(1.00)(60 L/d water)(1.00) = 1.63E-6 mrem
Total from milk: 3.12E-6 mrem

<u>Ingestion Dose:</u> (poultry)

(5.3 kg/y)(6.40E-8 mrem/pCi)(1.9 d/kg)(1 pCi/L)(1 y) = 6.445E-7 mrem·d/L

(6.445E-7 mrem·d/L)(0.94)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 6.99E-8 mrem
(6.445E-7 mrem·d/L)(0.94)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 mrem
(6.445E-7 mrem·d/L)(0.94)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 3.25E-8 mrem
(6.445E-7 mrem·d/L)(0.94)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 1.30E-9 mrem
(6.445E-7 mrem·d/L)(1.00)(0.3 L/d water)(1.00) = 1.93E-7 mrem

Total from poultry: 2.97E-7 mrem

Ingestion Dose: (eggs)

(5.3 kg/y)(6.40E-8 mrem/pCi)(2.1 d/kg)(1 pCi/L)(1 y) = 7.123E-7 mrem·d/L

(7.123E-7 mrem·d/L)(0.94)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 7.73E-8 mrem
(7.123E-7 mrem·d/L)(0.94)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 mrem
(7.123E-7 mrem·d/L)(0.94)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 3.59E-8 mrem
(7.123E-7 mrem·d/L)(0.94)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 1.44E-9 mrem
(7.123E-7 mrem·d/L)(1.00)(0.3 L/d water)(1.00) = 2.14E-7 mrem
Total from eggs: 3.28E-7 mrem

Total of all animal pathways = 4.89E-6 mrem

Total Dose from All Pathways:

4.18E-6+1.01E-11+3.46E-5+4.29E-10+2.15E-6+4.89E-6 mrem
= 4.58E-5 mrem per pCi/L

A.2.5 Native American Subsistence Resident

The doses for each pathway are calculated in the same manner as the HSRAM Agricultural case except that the exposure parameters are larger. The revised doses are listed below.

Inhalation Dose: (sweat lodge and ambient humidity)

(14+39 L/y)(1 pCi/L)(9.60E-08 mrem/pCi)(1 y) = 5.09E-6 mrem

Inhalation Dose: (resuspended soil)

(1.095E-3 kg/y)(0.1849 pCi/kg)(9.60E-8 mrem/pCi)(0.99304 y) = 1.93E-11 mrem

Ingestion Dose: (drinking)

(1095 L/y)(1 pCi/L)(6.40E-08 mrem/pCi)(1 y) = 7.01E-5 mrem

Ingestion Dose: (soil)

(0.0730 kg/y)(0.1849 pCi/kg)(6.40E-8 mrem/pCi)(0.99304 y) = 8.58E-10 mrem

External Dose:

(7008 h/y)(0.1849 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²)(0.99304 y) = 0 mrem

Ingestion Dose: (garden produce)

(6.016E-8 mrem/L)(0.894 L/kg)(20 kg)(1.00) = 1.08E-6 mrem
(6.016E-8 mrem/L)(0.894 L/kg)(67 kg)(0.99311) = 3.58E-6 mrem
(6.016E-8 mrem/L)(0.894 L/kg)(46 kg)(0.99311) = 2.46E-6 mrem
(6.016E-8 mrem/L)(0.6079L/kg)(108kg)(0.99311) = 3.92E-6 mrem
Total from garden produce: 1.10E-5 mrem

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the annual amount consumed by the individual, the ingestion dose factor, the equilibrium transfer factor, the water concentration, and the ingestion period.

Ingestion Dose: (beef)

(42 kg/y)(6.40E-8 mrem/pCi)(0.01 d/kg)(1 pCi/L)(1 y) = 2.688E-8 mrem·d/L

(2.688E-8 mrem·d/L)(0.94)(0.894 L/kg)(14 kg/d grass)(0.99082) = 3.13E-7 mrem
(2.688E-8 mrem·d/L)(0.94)(0.894 L/kg)(27 kg/d hay)(0.97719) = 5.96E-7 mrem
(2.688E-8 mrem·d/L)(0.94)(0.6079L/kg)(3 kg/d grain)(0.97719) = 4.50E-8 mrem
(2.688E-8 mrem·d/L)(0.94)(0.1967L/kg)(0.6 kg/d soil)(0.99082) = 2.95E-9 mrem
(2.688E-8 mrem·d/L)(1.00)(50 L/d water)(0.99082) = 1.33E-6 mrem
Total from beef: 2.29E-6 mrem

Ingestion Dose: (milk)

(219 L/y)(6.40E-8 mrem/pCi)(0.0082 d/L)(1 pCi/L)(1 y) = 1.149E-7 mrem·d/L

(1.149E-7 mrem·d/L)(0.94)(0.894 L/kg)(36 kg/d grass)(0.99304) = 3.45E-6 mrem
(1.149E-7 mrem·d/L)(0.94)(0.894 L/kg)(29 kg/d hay)(0.97944) = 2.74E-6 mrem
(1.149E-7 mrem·d/L)(0.94)(0.6079L/kg)(2 kg/d grain)(0.97944) = 1.29E-7 mrem
(1.149E-7 mrem·d/L)(0.94)(0.1967L/kg)(0.8 kg/d soil)(0.99304) = 1.69E-8 mrem
(1.149E-7 mrem·d/L)(1.00)(60 L/d water)(1.00) = 6.89E-6 mrem
Total from milk: 1.32E-5 mrem

Ingestion Dose: (poultry)

(11 kg/y)(6.40E-8 mrem/pCi)(1.9 d/kg)(1 pCi/L)(1 y) = 1.338E-6 mrem·d/L

(1.338E-6 mrem·d/L)(0.94)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 1.45E-7 mrem
(1.338E-6 mrem·d/L)(0.94)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 mrem
(1.338E-6 mrem·d/L)(0.94)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 6.74E-8 mrem
(1.338E-6 mrem·d/L)(0.94)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 2.70E-9 mrem
(1.338E-6 mrem·d/L)(1.00)(0.3 L/d water)(1.00) = 4.01E-7 mrem
Total from poultry: 6.17E-7 mrem

Ingestion Dose: (eggs)

(11 kg/y)(6.40E-8 mrem/pCi)(2.1 d/kg)(1 pCi/L)(1 y) = 1.478E-6 mrem·d/L

(1.478E-6 mrem·d/L)(0.94)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 1.60E-7 mrem
(1.478E-6 mrem·d/L)(0.94)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 mrem
(1.478E-6 mrem·d/L)(0.94)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 7.44E-8 mrem
(1.478E-6 mrem·d/L)(0.94)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 2.99E-9 mrem
(1.478E-6 mrem·d/L)(1.00)(0.3 L/d water)(1.00) = 4.43E-7 mrem
Total from eggs: 6.81E-7 mrem

Total of all animal pathways = 1.68E-5 mrem

Total Dose for the NASR:

5.09E-6+1.93E-11+7.01E-5+8.58E-10+1.10E-5+1.68E-5 mrem
= 1.03E-4 mrem per pCi/L

A.2.6 Columbia River Population

The collective doses for each pathway are calculated in the same manner as the All Pathways Irrigator case scaled up for a population of 5 million, with a lower irrigation rate, and reduced by a factor of 1000 to convert from mrem to rem. The inhalation and ingestion doses are adjusted for the population and unit conversion as shown below. The new soil concentration is shown also.

Inhalation: (9.60E-8 mrem/pCi)(5.0E+6)(0.001 rem/mrem) = 4.80E-4 rem/pCi
Ingestion: (6.40E-8 mrem/pCi)(5.0E+6)(0.001 rem/mrem) = 3.20E-4 rem/pCi

$C_{s,H3}$ = (8.94)(0.022)(1 pCi/L)(63.5 cm)/(63.5 + 5.23 cm)/(1 kg/L)
$C_{s,H3}$ = 0.1817 pCi/kg

Inhalation Dose: (showering and ambient humidity)
(4.5+39 L/y)(1 pCi/L)(4.80E-4 rem/pCi)(1 y) = 2.09E-2 rem

Inhalation Dose: (resuspended soil)
(4.16E-4 kg/y)(0.1817 pCi/kg)(4.80E-4 rem/pCi)(0.99304 y) = 3.60E-8 rem

Ingestion Dose: (drinking)
(540 L/y)(1 pCi/L)(3.20E-4 rem/pCi)(1 y) = 0.1728 rem

Ingestion Dose: (soil)
(0.0365 kg/y)(0.1817 pCi/kg)(3.20E-4 rem/pCi)(0.99304 y) = 2.11E-6 rem

External Dose:
(4383 h/y)(0.1817 pCi/kg)(225 kg/m²)(0 mrem/h per Ci/m²)(0.99304 y) = 0 mrem

With a lower irrigation rate, the irrigation dilution factor changes to become (63.5 cm)/(63.5+5.23cm)=0.924. The common factor used in the garden produce calculation is shown below.

(0.924)(1 pCi/L)(3.20E-4 rem/pCi)=2.957E-4 rem/L

Ingestion Dose: (garden produce)
(2.957E-4 rem/L)(0.894 L/kg)(4.1 kg)(1.00) = 1.08E-3 rem
(2.957E-4 rem/L)(0.894 L/kg)(13.9 kg)(0.99311) = 3.65E-3 rem
(2.957E-4 rem/L)(0.894 L/kg)(9.6 kg)(0.99311) = 2.52E-3 rem

(2.957E-4 rem/L)(0.6079L/kg)(18.5 kg)(0.99311) = 3.30E-3 rem
Total from garden produce: 1.06E-2 rem

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the annual amount consumed by the individual, the ingestion dose factor, the equilibrium transfer factor, the water concentration, and the ingestion period.

Ingestion Dose: (beef)
(21 kg/y)(3.20E-4 rem/pCi)(0.01 d/kg)(1 pCi/L)(1 y) = 6.720E-5 rem·d/L

(6.720E-5 rem·d/L)(0.924)(0.894 L/kg)(14 kg/d grass)(0.99082) = 7.70E-4 rem
(6.720E-5 rem·d/L)(0.924)(0.894 L/kg)(27 kg/d hay)(0.97719) = 1.46E-3 rem
(6.720E-5 rem·d/L)(0.924)(0.6079L/kg)(3 kg/d grain)(0.97719) = 1.11E-4 rem
(6.720E-5 rem·d/L)(0.924)(0.1967L/kg)(0.6 kg/d soil)(0.99082) = 7.26E-6 rem
(6.720E-5 rem·d/L)(1.00)(50 L/d water)(0.99082) = 3.33E-3 rem
Total from beef: 5.68E-3 rem

Ingestion Dose: (milk)
(51.7 L/y)(3.20E-4 rem/pCi)(0.0082 d/L)(1 pCi/L)(1 y) = 1.357E-4 rem·d/L

(1.357E-4 rem·d/L)(0.924)(0.894 L/kg)(36 kg/d grass)(0.99304) = 4.01E-3 rem
(1.357E-4 rem·d/L)(0.924)(0.894 L/kg)(29 kg/d hay)(0.97944) = 3.18E-3 rem
(1.357E-4 rem·d/L)(0.924)(0.6079L/kg)(2 kg/d grain)(0.97944) = 1.49E-4 rem
(1.357E-4 rem·d/L)(0.924)(0.1967L/kg)(0.8 kg/d soil)(0.99304) = 1.96E-5 rem
(1.357E-4 rem·d/L)(1.00)(60 L/d water)(1.00) = 8.14E-3 rem
Total from milk: 1.55E-2 rem

Ingestion Dose: (poultry)
(5.3 kg/y)(3.20E-4 rem/pCi)(1.9 d/kg)(1 pCi/L)(1 y) = 3.222E-3 rem·d/L

(3.445E-3 rem·d/L)(0.924)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 3.44E-4 rem
(3.222E-3 rem·d/L)(0.924)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 rem
(3.222E-3 rem·d/L)(0.924)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 1.60E-4 rem
(3.222E-3 rem·d/L)(0.924)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 6.40E-6 rem
(3.222E-3 rem·d/L)(1.00)(0.3 L/d water)(1.00) = 9.67E-4 rem
Total from poultry: 1.48E-3 rem

Ingestion Dose: (eggs)
(5.3 kg/y)(3.20E-4 rem/pCi)(2.1 d/kg)(1 pCi/L)(1 y) = 3.562E-3 rem·d/L

(3.562E-3 rem·d/L)(0.924)(0.894 L/kg)(0.13 kg/d grass)(0.99304) = 3.80E-4 rem
(3.562E-3 rem·d/L)(0.924)(0.894 L/kg)(0.0 kg/d hay)(0.97944) = 0.0 rem
(3.562E-3 rem·d/L)(0.924)(0.6079L/kg)(0.09 kg/d grain)(0.97944) = 1.76E-4 rem
(3.562E-3 rem·d/L)(0.924)(0.1967L/kg)(0.011 kg/d soil)(0.99304) = 7.07E-6 rem

(3.562E-3 rem·d/L)(1.00)(0.3 L/d water)(1.00) = 1.07E-3 rem
Total from eggs: 1.63E-3 rem

Ingestion Dose: (fish)
(0.003 kg/y)(1 L/kg)(1 pCi/L)(3.20E-4 rem/pCi)(1 y) = 9.60E-7 rem

Total of all animal pathways = 2.43E-2 rem

Total Collective Dose to the Population:
2.09E-2 + 3.60E-8 + 0.1728 + 2.11E-6 + 1.06E-2 + 2.43E-2 rem
= 0.229 person-rem per pCi/L

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Appendix B.

Hand Calculations for Carbon-14

HAND CALCULATIONS FOR CARBON-14

B.1 No Water Infiltration -- Post-Intrusion Resident

Only two of the exposure scenarios listed in Table 2 will be evaluated, the post-intrusion gardener and the all-pathways irrigator. These two exercise all of the relevant calculations. The other scenarios are very similar to previous calculations with tritium, or are very similar to the calculations shown for C-14.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

It will be assumed that 1 curie C-14 is exhumed from the well shaft and spread over an area of 200 m². The average soil concentration is computed as shown below.

C_s = (1 Ci)(1E12 pCi/Ci)/(200 m²)/(225 kg/m²) = 2.222E+7 pCi/kg

This concentration decreases with time due to leaching from the surface layer during the irrigation season and radioactive decay. Decay factors used in the dose calculations are computed below (see Table 30).

λ_r = (0.69315)/(5730 y) = 1.210E-4 y^{-1} λ_l = 0.0644 y^{-1} (Table 27)
$\lambda_t = \lambda_r + \lambda_l$ = 0.064521 y^{-1}

$\lambda_t T_{irr}$ = (0.064521 y^{-1})(0.5 y) = 0.032261
$DS(T_{irr})$ = Exp(-0.032261) = 0.96825
$IDS(T_{irr})$ = [1 - Exp(-0.032261)]/(0.032261) = 0.98404

$\lambda_r T_{no}$ = (1.21E-4 y^{-1})(0.5 y) = 6.05E-5
$IDR(T_{no})$ = [1 - Exp(-6.05E-5)]/(6.05E-5) = 0.99997

$T_{irr} \cdot IDS(T_{irr}) + T_{no} \cdot DS(T_{irr}) \cdot IDR(T_{no})$ =
(0.5y)(0.98404) + (0.5y)(0.96825)(0.99997) = 0.97613 y

$DS(T_h)$ = Exp[-(0.064521 y^{-1})(0.25 y)] = 0.98400

$\lambda_r T_{veg}$ = (1.21E-4 y^{-1})(90 d)/(365.25 d/y) = 2.98E-5
$IDR(T_{veg})$ = [1 - Exp(-2.98E-5)]/(2.98E-5) = 0.99999

$DS(T_h) \cdot IDR(T_{veg})$ = (0.98400)(0.99999) = 0.98399

A mass loading approach is used, so that the resident inhales a total of 573 mg, or 5.73E-

04 kg (Table 17) of soil over the course of a year. He also ingests a total of 0.0365 kg soil (Table 13) during the year. The inhalation and ingestion doses from these sources are shown below. Note that the C-14 internal dose factors for inhalation and ingestion are the same.

Inhalation Dose: (resuspended soil)

(5.73E-4 kg/y)(2.222E+7 pCi/kg)(2.09E-6 mrem/pCi)(0.97613 y) = 0.0260 mrem

Ingestion Dose: (soil only)

(0.0365 kg)(2.222E+7 pCi/kg)(2.09E-6 mrem/pCi)(0.97613 y) = 1.65 mrem

External dose is computed from the external dose rate factor for C-14, the soil concentration and the exposure time (900 h from Section 2.2.5). A modified form of the soil concentration is used to simplify the calculation. This is shown below.

External Dose:

(900 h/y)(1 Ci)/(200 m^2)(6.82E-3 mrem/h per Ci/m^2)(0.97613 y) = 0.0300 mrem

The vegetable produce from the garden is contaminated by root uptake and rain splash. Doses from each are shown below. The contaminated food consumption rate is combined with the ingestion period (1 year) so that the column of consumption rates has units of kg rather than kg/y. The product of soil concentration and ingestion dose is combined into a single quantity to simplify the calculation.

(2.222E+7 pCi/kg)(2.09E-6 mrem/pCi)=46.44 mrem/kg

Ingestion Dose: (root uptake only)

(46.44 mrem/kg)(0.7)(0.09)(4.1 kg)(0.98404) = 11.8 mrem
(46.44 mrem/kg)(0.7)(0.25)(13.9 kg)(0.98399) = 111.2 mrem
(46.44 mrem/kg)(0.7)(0.18)(9.6 kg)(0.98399) = 55.3 mrem
(46.44 mrem/kg)(0.7)(0.91)(18.5 kg)(0.98399) = 538.5 mrem
Total from root uptake: 716.7 mrem

Ingestion Dose: (rain splash only)

To simplify the calculation, the mass loading, ground deposition speed, soil concentration and ingestion dose factor are combined in a single factor.

(1 mg/m^3)(0.01 m/s)(46.44 mrem/kg)(86,400 s/d) = 0.04012 mrem/d/m^2

(0.04012mrem/d/m^2)(18d)(0.407)(1.0)/(2.0kg/m^2)(4.1kg)(0.98404) = 0.593mrem
(0.04012mrem/d/m^2)(20d)(0.835)(0.1)/(2.0kg/m^2)(13.9kg)(0.98399) = 0.458mrem
(0.04012mrem/d/m^2)(20d)(0.857)(0.1)/(3.0kg/m^2)(9.6kg)(0.98399) = 0.217mrem
(0.04012mrem/d/m^2)(20d)(0.371)(0.1)/(0.8kg/m^2)(18.5kg)(0.98399) = 0.677mrem
Total from rain splash: 1.945mrem

Total Dose to Gardener:

0.0260 + 1.65 + 0.0298 + 716.7 + 1.945 mrem = 720 mrem per Ci exhumed

B.2 Low Water Infiltration -- All Pathways Farmer

It will be assumed in each exposure scenario that the well water concentration is 1 pCi/L. Thus the doses computed are per pCi/L. The main dose pathway in every case is the drinking water pathway.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

Inhalation of well water during showers amounts to 0.045 L/y (Table 18). Inhalation of evaporated well water under ambient conditions amounts to 0.39 L/y. The individual ingests a total of 540 L/y of drinking water (Table 13). The doses from these pathways are shown below. Because the ground water comes from the well and is ingested or inhaled shortly after, no decay factors are needed.

Inhalation Dose: (showering and ambient humidity)

(0.046+0.039 L/y)(1 pCi/L)(2.09E-06 mrem/pCi)(1 y) = 1.76E-7 mrem

Ingestion Dose: (drinking)

(540 L/y)(1 pCi/L)(2.09E-06 mrem/pCi)(1 y) = 1.13E-3 mrem

The soil concentration at the end of the year (apart from decay corrections) is based on 82.3 cm of irrigation water applied to the garden and pasture (Section 2.5). The soil concentration is shown below in two units. Both are used in the calculations that follow.

C_s = (82.3 cm/y)(10,000 cm^2/m^2)(0.001 L/cm^3)(1 pCi/L) = 823 pCi/m^2

or

C_s = (823 pCi/m^2)/(225 kg/m^2) = 3.6578 pCi/kg

The soil concentration decreases with time due to leaching from the surface layer during the irrigation season and radioactive decay. Additional decay factors used in the dose calculations for the all pathways irrigation scenario are shown below (see Tables 30 and 31).

$\lambda_t T_{irr}$ = (0.064521 y^{-1})(0.5 y) = 0.032261

$DI(T_{irr})$ = [1 - Exp(-0.032261)]/(0.032261) = 0.98404

$IDI(T_{irr})$ = [0.032261 - 1 + Exp(-0.032261)]/$(0.032261)^2$ = 0.49471

$T_{irr} \cdot IDI(T_{irr}) + T_{no} \cdot DI(T_{irr}) \cdot IDR(T_{no})$ =

(0.5y)(0.49471) + (0.5y)(0.98404)(0.99997) = 0.73936 y

$\lambda_r T_{veg}$ = (1.21E-4 y^{-1})(90 d)/(365.25 d/y) = 2.98E-5

$IDR(T_{veg})$ = [1 - Exp(-2.98E-5)]/(2.98E-5) = 0.99999

$DI(T_{irr})\cdot IDR(T_{veg})$ = (0.98404)(0.99999) = 0.98403

$\lambda_r T_{beef}$ = (1.21E-4 y^{-1})(120 d)/(365.25 d/y) = 3.98E-5
$IDR(T_{beef})$ = [1 - Exp(-3.98E-5)]/(3.98E-5) = 0.99998

$DI(T_{irr})\cdot IDR(T_{beef})$ = (0.98404)(0.99998) = 0.98402

$DR(T_s)$ = Exp[-(1.21E-4 y^{-1})(90 d)/(365.25 d/y)] = 0.99997

$DR(T_s)\cdot IDR(T_{beef})$ = (0.99997)(0.99998) = 0.99995

$DI(T_{irr})\cdot DR(T_s)\cdot IDR(T_{beef})$ = (0.98404)(0.99997)(0.99998) = 0.98399

$\lambda_r T_{an}$ = (1.21E-4 y^{-1})(90 d)/(365.25 d/y) = 2.98E-5
$IDR(T_{an})$ = [1 - Exp(-2.98E-5)]/(2.98E-5) = 0.99999

$DI(T_{irr})\cdot DR(T_s)\cdot IDR(T_{an})$ = (0.98404)(0.99997)(0.99999) = 0.98400

$DR(T_s)\cdot IDR(T_{an})$ = (0.99997)(0.99999) = 0.99996

Inhalation of resuspended soil amounts to 573 mg (5.73E-04 kg) of soil over the course of a year. The individual also ingests a total of 0.0365 kg soil during the year. The time of exposure to external radiation is 4120 h/y. The inhalation, ingestion, and external doses from the soil are shown below.

Inhalation Dose: (resuspended soil)
(5.73E-4 kg/y)(3.6578 pCi/kg)(2.09E-6 mrem/pCi)(0.73936 y) = 3.24E-9 mrem

Ingestion Dose: (soil)
(0.0365 kg/y)(3.6578 pCi/kg)(2.09E-6 mrem/pCi)(0.73936 y) = 2.06E-7 mrem

External Dose:
(4120 h/y)(8.23E-10 Ci/m²)(6.82E-3 mrem/h per Ci/m²)(0.73936 y) = 1.71E-8 mrem

The vegetable produce contamination is calculated as shown below. The contaminated food consumption rate is combined with the ingestion period (1 year) so that the column of consumption rates has units of kg rather than kg/y. The product of the soil concentration and the ingestion dose factor is computed below and used in the calculations to simplify the equations.
(3.6578 pCi/kg)(2.09E-6 mrem/pCi)=7.645E-6 mrem/kg

Separate dry-to-wet ratios and consumption amounts are needed for each plant type. The soil-to-plant concentration ratio is 0.7 for all plant types (Table 25). The ingestion doses from root uptake and rain splash are shown below.

Ingestion Dose -- Garden Produce: (root uptake only)

(7.645E-6 mrem/kg)(0.7)(0.09)(4.1 kg)(0.49471) = 9.77E-7 mrem
(7.645E-6 mrem/kg)(0.7)(0.25)(13.9 kg)(0.98403) = 1.83E-5 mrem
(7.645E-6 mrem/kg)(0.7)(0.18)(9.6 kg)(0.98403) = 9.10E-6 mrem
(7.645E-6 mrem/kg)(0.7)(0.91)(18.5 kg)(0.98403) = 8.87E-5 mrem
Total from root uptake: 1.17E-4 mrem

Ingestion Dose -- Garden Produce: (rain splash only)

To simplify the calculation, the mass loading, ground deposition speed, soil concentration and ingestion dose factor are combined in a single factor.

(1 mg/m^3)(0.01 m/s)(7.645E-6 mrem/kg)(86,400 s/d) = 6.605E-9 mrem/d/m^2

(6.605E-9mrem/d/m^2)(18d)(0.407)(1.0)/(2.0kg/m^2)(4.1kg)(0.49471)=4.91E-8mrem
(6.605E-9mrem/d/m^2)(20d)(0.835)(0.1)/(2.0kg/m^2)(13.9kg)(0.98403)=7.54E-8mrem
(6.605E-9mrem/d/m^2)(20d)(0.857)(0.1)/(3.0kg/m^2)(9.6kg)(0.98403)=3.56E-8mrem
(6.605E-9mrem/d/m^2)(20d)(0.371)(0.1)/(0.8kg/m^2)(18.5kg)(0.98403)=1.12E-7mrem
Total from rain splash: 2.72E-7mrem

Ingestion Dose -- Garden Produce: (direct deposition)

To simplify the calculation, the activity addition rate and ingestion dose factor are soil concentration and ingestion dose factor are combined in a single factor.

(823 pCi/m^2)/(0.5 y)/(365.25 d/y)(2.09E-6 mrem/pCi) = 9.419E-6 mrem/d/m^2

(9.419E-6mrem/d/m^2)(18d)(0.25)(1.0)/(2.0kg/m^2)(4.1kg)(1.00)=8.69E-5mrem
(9.419E-6mrem/d/m^2)(20d)(0.25)(0.1)/(2.0kg/m^2)(13.9kg)(0.99999)=3.27E-5mrem
(9.419E-6mrem/d/m^2)(20d)(0.25)(0.1)/(3.0kg/m^2)(9.6kg)(0.99999)=1.51E-5mrem
(9.419E-6mrem/d/m^2)(20d)(0.25)(0.1)/(0.8kg/m^2)(18.5kg)(0.99999)=1.09E-4mrem
Total from direct deposition: 2.44E-4mrem

Total Dose from Garden Produce:

1.17E-4 + 2.72E-7 + 2.44E-4 mrem = 3.61E-4 mrem

The animal pathways add the dose from animal products that are contaminated by ingestion of well water, contaminated fodder and soil. The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the annual amount consumed by the individual, the ingestion dose factor, the equilibrium transfer factor, the water concentration, and the ingestion period.

Common Factor for Beef:

(0.049 d/kg)(21 kg/y)(2.09E-6 mrem/pCi)(1 y) = 2.151E-6 mrem·d/pCi

Ingestion Dose from Beef: (drinking water ingestion)

(2.151E-6 mrem·d/pCi)(50 L/d)(1 pCi/L)(0.99998) = 1.08E-4 mrem

Ingestion Dose from Beef: (soil ingestion)

(2.151E-6 mrem·d/pCi)(0.6 kg/d)(3.6578 pCi/kg)(0.98402) = 4.65E-6 mrem

Ingestion Dose from Beef: (root uptake into feed)

(2.151E-6 mrem·d/pCi)(3.6578 pCi/kg) = 7.868E-6 mrem·d/kg

(7.868E-6 mrem·d/kg)(0.7)(0.22)(14 kg/d grass)(0.98402) = 1.67E-5 mrem
(7.868E-6 mrem·d/kg)(0.7)(0.22)(27 kg/d hay)(0.98399) = 3.22E-5 mrem
(7.868E-6 mrem·d/kg)(0.7)(0.91)(3 kg/d grain)(0.98399) = 1.48E-5 mrem
Total from root uptake: 6.37E-5 mrem

Ingestion Dose from Beef: (rain splash onto feed)

(1 mg/m³)(0.01 m/s)(7.868E-6 mrem·d/kg)(86,400 s/d) = 6.798E-9 mrem/m²

(6.798E-9mrem/m²)(15.6d)(0.616)(1.0)/(1.5kg/m²)(14kg/d)(0.98402)=6.00E-7mrem
(6.798E-9mrem/m²)(18.0d)(0.472)(1.0)/(1.0kg/m²)(27kg/d)(0.98399)=1.53E-6mrem
(6.798E-9mrem/m²)(20.0d)(0.472)(0.1)/(1.0kg/m²)(3kg/d)(0.98399)=1.89E-8mrem
Total from rain splash: 2.15E-6mrem

Ingestion Dose from Beef: (direct deposition onto feed)

To simplify the calculation, the activity addition rate and ingestion dose factor are soil concentration and ingestion dose factor are combined in a single factor.

(823 pCi/m²)/(0.5 y)/(365.25 d/y)(2.151E-6 mrem·d/pCi) = 9.693E-6 mrem/m²

(9.693E-6mrem/d/m²)(15.6d)(0.25)(1.0)/(1.5kg/m²)(14kg/d)(0.99998)=3.53E-4mrem
(9.693E-6mrem/d/m²)(18.0d)(0.25)(1.0)/(1.0kg/m²)(27kg/d)(0.99995)=1.18E-3mrem
(9.693E-6mrem/d/m²)(20.0d)(0.25)(0.1)/(1.0kg/m²)(3kg/d)(0.99995)=1.45E-5mrem
Total from direct deposition: 1.54E-3mrem

Total Dose from Beef: 1.72E-3 mrem

Common Factor for Milk:

(0.0105 d/L)(51.7 L/y)(2.09E-6 mrem/pCi)(1 y) = 1.135E-6 mrem·d/pCi

Ingestion Dose from Milk: (drinking water ingestion)

(1.135E-6 mrem·d/pCi)(60 L/d)(1 pCi/L) = 6.81E-5 mrem

Ingestion Dose from Milk: (soil ingestion)

(1.135E-6 mrem·d/pCi)(0.8 kg/d)(3.6578 pCi/kg)(0.73936) = 2.46E-6 mrem

Ingestion Dose from Milk: (root uptake into feed)

(1.135E-6 mrem·d/pCi)(3.6578 pCi/kg) = 4.152E-6 mrem·d/kg

(4.152E-6 mrem·d/kg)(0.7)(0.22)(36 kg/d grass)(0.73936) = 1.70E-5 mrem

(4.152E-6 mrem·d/kg)(0.7)(0.22)(29 kg/d hay)(0.98400) = 1.82E-5 mrem
(4.152E-6 mrem·d/kg)(0.7)(0.91)(2 kg/d grain)(0.98400) = 5.21E-6 mrem
Total from root uptake: 4.05E-5 mrem

Ingestion Dose from Milk: (rain splash onto feed)
(1 mg/m³)(0.01 m/s)(4.152E-6 mrem·d/kg)(86,400 s/d) = 3.587E-9 mrem/m²

(3.587E-9mrem/m²)(15.6d)(0.616)(1.0)/(1.5kg/m²)(36kg/d)(0.73936)=6.12E-7mrem
(3.587E-9mrem/m²)(18.0d)(0.472)(1.0)/(1.0kg/m²)(29kg/d)(0.98400)=8.70E-7mrem
(3.587E-9mrem/m²)(20.0d)(0.472)(0.1)/(1.0kg/m²)(2kg/d)(0.98400)=6.66E-9mrem
Total from rain splash: 1.49E-6mrem

Ingestion Dose from Milk: (direct deposition onto feed)
To simplify the calculation, the activity addition rate and ingestion dose factor are soil concentration and ingestion dose factor are combined in a single factor.
(823 pCi/m²)/(0.5 y)/(365.25 d/y)(1.135E-6 mrem·d/pCi) = 5.115E-6 mrem/m²

(5.115E-6mrem/m²)(15.6d)(0.25)(1.0)/(1.5kg/m²)(36kg/d)(1.00)=4.79E-4mrem
(5.115E-6mrem/m²)(18.0d)(0.25)(1.0)/(1.0kg/m²)(29kg/d)(0.99996)=6.67E-4mrem
(5.115E-6mrem/m²)(20.0d)(0.25)(0.1)/(1.0kg/m²)(2kg/d)(0.99996)=5.11E-6mrem
Total from direct deposition: 1.15E-3mrem

Total Dose from Milk: 1.26E-3 mrem

Common Factor for Poultry:
(4.2 d/kg)(5.3 kg/y)(2.09E-6 mrem/pCi)(1 y) = 4.652E-5 mrem·d/pCi

Ingestion Dose from Poultry: (drinking water ingestion)
(4.652E-5 mrem·d/pCi)(0.3 L/d)(1 pCi/L) = 1.40E-5 mrem

Ingestion Dose from Poultry: (soil ingestion)
(4.652E-5 mrem·d/pCi)(0.011 kg/d)(3.6578 pCi/kg)(0.73936) = 1.38E-6 mrem

Ingestion Dose from Poultry: (root uptake into feed)
(4.652E-5 mrem·d/pCi)(3.6578 pCi/kg) = 1.702E-4 mrem·d/kg

(1.702E-4 mrem·d/kg)(0.7)(0.22)(0.13 kg/d grass)(0.73936) = 2.52E-6 mrem
(1.702E-4 mrem·d/kg)(0.7)(0.22)(0.0 kg/d hay)(0.98400) = 0.0 mrem
(1.702E-4 mrem·d/kg)(0.7)(0.91)(0.09 kg/d grain)(0.98400) = 9.60E-6 mrem
Total from root uptake: 4.05E-5 mrem

Ingestion Dose from Poultry: (rain splash onto feed)

$$(1\ mg/m^3)(0.01\ m/s)(1.702E\text{-}4\ mrem\cdot d/kg)(86{,}400\ s/d) = 1.471E\text{-}7\ mrem/m^2$$

$(1.471E\text{-}7mrem/m^2)(15.6d)(0.616)(1.)/(1.5kg/m^2)(.13kg/d)(0.73936)=9.06E\text{-}8mrem$
$(1.471E\text{-}7mrem/m^2)(18.0d)(0.472)(1.)/(1.0kg/m^2)(.0\ kg/d)(0.98400)=0.0\ \ mrem$
$(1.471E\text{-}7mrem/m^2)(20.0d)(0.472)(.1)/(1.0kg/m^2)(.09kg/d)(0.98400)=1.23E\text{-}8mrem$

Total from rain splash: 1.03E-7mrem

Ingestion Dose from Poultry: (direct deposition onto feed)

To simplify the calculation, the activity addition rate and ingestion dose factor are soil concentration and ingestion dose factor are combined in a single factor.

$$(823\ pCi/m^2)/(0.5\ y)/(365.25\ d/y)(4.652E\text{-}5\ mrem\cdot d/pCi) = 2.096E\text{-}4\ mrem/m^2$$

$(2.096E\text{-}4mrem/m^2)(15.6d)(0.25)(1.)/(1.5kg/m^2)(.13kg/d)(1.00\ \ )=7.08E\text{-}5mrem$
$(2.096E\text{-}4mrem/m^2)(18.0d)(0.25)(1.)/(1.0kg/m^2)(0.0kg/d)(0.99996)=0.0\ \ mrem$
$(2.096E\text{-}4mrem/m^2)(20.0d)(0.25)(.1)/(1.0kg/m^2)(.09kg/d)(0.99996)=9.43E\text{-}6mrem$

Total from direct deposition: 8.03E-5mrem

Total Dose from Poultry: 1.08E-4 mrem

Common Factor for Eggs:

$$(3.1\ d/kg)(5.3\ kg/y)(2.09E\text{-}6\ mrem/pCi)(1\ y) = 3.434E\text{-}5\ mrem\cdot d/pCi$$

Ingestion Dose from Eggs: (drinking water ingestion)

$$(3.434E\text{-}5\ mrem\cdot d/pCi)(0.3\ L/d)(1\ pCi/L) = 1.03E\text{-}5\ mrem$$

Ingestion Dose from Eggs: (soil ingestion)

$$(3.434E\text{-}5\ mrem\cdot d/pCi)(0.011\ kg/d)(3.6578\ pCi/kg)(0.73936) = 1.02E\text{-}6\ mrem$$

Ingestion Dose from Eggs: (root uptake into feed)

$$(3.434E\text{-}5\ mrem\cdot d/pCi)(3.6578\ pCi/kg) = 1.256E\text{-}4\ mrem\cdot d/kg$$

$(1.256E\text{-}4\ mrem\cdot d/kg)(0.7)(0.22)(0.13\ kg/d\ grass)(0.73936) = 1.86E\text{-}6\ mrem$
$(1.256E\text{-}4\ mrem\cdot d/kg)(0.7)(0.22)(0.0\ \ kg/d\ hay\ \ )(0.98400) = 0.0\ \ \ mrem$
$(1.256E\text{-}4\ mrem\cdot d/kg)(0.7)(0.91)(0.09\ kg/d\ grain)(0.98400) = 7.09E\text{-}6\ mrem$

Total from root uptake: 8.94E-6 mrem

Ingestion Dose from Eggs: (rain splash onto feed)

$$(1\ mg/m^3)(0.01\ m/s)(1.256E\text{-}4\ mrem\cdot d/kg)(86{,}400\ s/d) = 1.085E\text{-}7\ mrem/m^2$$

$(1.085E\text{-}7mrem/m^2)(15.6d)(0.616)(1.)/(1.5kg/m^2)(.13kg/d)(0.73936)=6.68E\text{-}8mrem$
$(1.085E\text{-}7mrem/m^2)(18.0d)(0.472)(1.)/(1.0kg/m^2)(.0\ kg/d)(0.98400)=0.0\ \ mrem$
$(1.085E\text{-}7mrem/m^2)(20.0d)(0.472)(.1)/(1.0kg/m^2)(.09kg/d)(0.98400)=9.07E\text{-}9mrem$

Total from rain splash: 7.59E-8mrem

Ingestion Dose from Eggs: (direct deposition onto feed)

To simplify the calculation, the activity addition rate and ingestion dose factor are soil concentration and ingestion dose factor are combined in a single factor.

$$(823\ pCi/m^2)/(0.5\ y)/(365.25\ d/y)(3.434E\text{-}5\ mrem\cdot d/pCi) = 1.548E\text{-}4\ mrem/m^2$$

$$(1.548E\text{-}4mrem/m^2)(15.6d)(0.25)(1.)/(1.5kg/m^2)(.13kg/d)(1.00\quad)=5.23E\text{-}5mrem$$
$$(1.548E\text{-}4mrem/m^2)(18.0d)(0.25)(1.)/(1.0kg/m^2)(0.0kg/d)(0.99996)=0.0\quad mrem$$
$$(1.548E\text{-}4mrem/m^2)(20.0d)(0.25)(.1)/(1.0kg/m^2)(.09kg/d)(0.99996)=6.97E\text{-}6mrem$$

Total from direct deposition: 5.93E-5mrem

Total Dose from Eggs: 7.96E-5 mrem

Total of All Animal Pathways = 3.17E-3 mrem

Total Dose from All Pathways:

1.76E-7 + 1.13E-3 + 3.24E-9 + 2.06E-7 + 1.70E-8 + 3.61E-4 + 3.17E-3 mrem
= 4.67E-3 mrem per pCi/L

Appendix C.

Output from CAP88-PC for H-3 and Carbon-14

OUTPUT FROM CAP88-PC FOR H-3 AND CARBON-14

From the SYNOPSIS report, the worst-case wind direction was east southeast (ESE). From the CHI/Q TABLE report, the air transport factor for this direction is 7.980E-6 s/m^3. From the SUMMARY report, the effective dose equivalent for H-3 is 0.00189 mrem, and for C-14 0.105 mrem.

At a location where the air transport factor is 1.0E-4 s/m^3, the CAP88-PC dose is computed as shown below. These values are listed in Table 28.

H-3: (0.00189 mrem)(1.0E-4 s/m^3)/(7.98E-6 s/m^3) = 0.0237 mrem

C-14: (0.105 mrem)(1.0E-4 s/m^3)/(7.98E-6 s/m^3) = 1.32 mrem

The EPA default parameter file was used as input to the CAP88-PC calculations rather than the Hanford-specific parameter file.

C A P 8 8 - P C

Version 1.00

Clean Air Act Assessment Package - 1988

S Y N O P S I S   R E P O R T

Non-Radon Individual Assessment
Nov 30, 1999   7:45 am

Facility: Various Cases
Address:
City: Richland
State: WA   Zip: 99352

Effective Dose Equivalent
(mrem/year)

1.07E-01

At This Location: 1000 Meters East Southeast
Source Category:
Source Type: Stack
Emission Year: 1996

Comments:

Dataset Name: ILAW PA
Dataset Date: Nov 30, 1999   7:45 am
Wind File: WNDFILES\HB-200E.WND

Nov 30, 1999 7:45 am
SYNOPSIS

Page 1

MAXIMALLY EXPOSED INDIVIDUAL

Location Of The Individual: 1000 Meters East Southeast

Lifetime Fatal Cancer Risk: 2.61E-06

ORGAN DOSE EQUIVALENT SUMMARY

Organ	Dose Equivalent (mrem/y)
GONADS	4.68E-02
BREAST	1.19E-01
R MAR	2.08E-01
LUNGS	5.64E-02
THYROID	5.61E-02
ENDOST	4.32E-01
RMNDR	1.02E-01
EFFEC	1.07E-01

Nov 30, 1999 7:45 am
SYNOPSIS

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RADIONUCLIDE EMISSIONS DURING THE YEAR 1996

Nuclide	Class	Size	Source #1 Ci/y	TOTAL Ci/y
H-3	*	0.00	1.0E+00	1.0E+00
C-14	*	0.00	1.0E+00	1.0E+00

SITE INFORMATION

Temperature:	12 degrees C
Precipitation:	17 cm/y
Mixing Height:	1000 m

Nov 30, 1999 7:45 am
SYNOPSIS

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SOURCE INFORMATION

Source Number: 1

Stack Height (m): 1.00
Diameter (m): 0.10

Plume Rise Pasquill Cat:	A	B	C	D	E	F	G
Zero:	0.00	0.00	0.00	0.00	0.00	0.00	0.00

AGRICULTURAL DATA

	Vegetable	Milk	Meat
Fraction Home Produced:	1.000	1.000	1.000
Fraction From Assessment Area:	0.000	0.000	0.000
Fraction Imported:	0.000	0.000	0.000

Food Arrays were not generated for this run.
Default Values used.

DISTANCES USED FOR MAXIMUM INDIVIDUAL ASSESSMENT

1000

C A P 8 8 - P C

Version 1.00

Clean Air Act Assessment Package - 1988

D O S E   A N D   R I S K   E Q U I V A L E N T   S U M M A R I E S

Non-Radon Individual Assessment
Nov 30, 1999   7:45 am

Facility: Various Cases
Address:
City: Richland
State: WA   Zip: 99352

Source Category:
Source Type: Stack
Emission Year: 1996

Comments:

Dataset Name: ILAW PA
Dataset Date: Nov 30, 1999   7:45 am
Wind File: WNDFILES\HB-200E.WND

Nov 30, 1999   7:45 am
SUMMARY

Page 1

ORGAN DOSE EQUIVALENT SUMMARY

Organ	Selected Individual (mrem/y)
GONADS	4.68E-02
BREAST	1.19E-01
R MAR	2.08E-01
LUNGS	5.64E-02
THYROID	5.61E-02
ENDOST	4.32E-01
RMNDR	1.02E-01
EFFEC	1.07E-01

PATHWAY EFFECTIVE DOSE EQUIVALENT SUMMARY

Pathway	Selected Individual (mrem/y)
INGESTION	1.06E-01
INHALATION	2.82E-04
AIR IMMERSION	0.00E+00
GROUND SURFACE	0.00E+00
INTERNAL	1.07E-01
EXTERNAL	0.00E+00
TOTAL	1.07E-01

Nov 30, 1999 7:45 am
SUMMARY

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NUCLIDE EFFECTIVE DOSE EQUIVALENT SUMMARY

Nuclide	Selected Individual (mrem/y)
H-3	1.89E-03
C-14	1.05E-01
TOTAL	1.07E-01

Nov 30, 1999 7:45 am
SUMMARY

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CANCER RISK SUMMARY

Cancer	Selected Individual Total Lifetime Fatal Cancer Risk
LEUKEMIA	6.60E-07
BONE	7.65E-08
THYROID	2.55E-08
BREAST	4.67E-07
LUNG	2.80E-07
STOMACH	2.48E-07
BOWEL	1.26E-07
LIVER	2.70E-07
PANCREAS	1.67E-07
URINARY	8.36E-08
OTHER	2.04E-07
TOTAL	2.61E-06

PATHWAY RISK SUMMARY

Pathway	Selected Individual Total Lifetime Fatal Cancer Risk
INGESTION	2.60E-06
INHALATION	7.62E-09
AIR IMMERSION	0.00E+00
GROUND SURFACE	0.00E+00
INTERNAL	2.61E-06
EXTERNAL	0.00E+00
TOTAL	2.61E-06

Nov 30, 1999 7:45 am
SUMMARY

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NUCLIDE RISK SUMMARY

Nuclide	Selected Individual Total Lifetime Fatal Cancer Risk
H-3	5.12E-08
C-14	2.56E-06
TOTAL	2.61E-06

Nov 30, 1999 7:45 am
SUMMARY

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INDIVIDUAL EFFECTIVE DOSE EQUIVALENT RATE (mrem/y)
(All Radionuclides and Pathways)

	Distance (m)
Direction	1000
N	3.2E-02
NNW	4.3E-02
NW	4.2E-02
WNW	3.4E-02
W	2.7E-02
WSW	2.0E-02
SW	2.1E-02
SSW	1.9E-02
S	2.4E-02
SSE	3.1E-02
SE	6.2E-02
ESE	1.1E-01
E	7.5E-02
ENE	4.3E-02
NE	3.1E-02
NNE	2.6E-02

Nov 30, 1999 7:45 am
SUMMARY

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INDIVIDUAL LIFETIME RISK (deaths)
(All Radionuclides and Pathways)

	Distance (m)
Direction	1000
N	7.9E-07
NNW	1.0E-06
NW	1.0E-06
WNW	8.2E-07
W	6.6E-07
WSW	5.0E-07
SW	5.2E-07
SSW	4.8E-07
S	5.8E-07
SSE	7.6E-07
SE	1.5E-06
ESE	2.6E-06
E	1.8E-06
ENE	1.1E-06
NE	7.6E-07
NNE	6.4E-07

C A P 8 8 - P C

Version 1.00

Clean Air Act Assessment Package - 1988

C H I / Q   T A B L E S

Non-Radon Individual Assessment
Nov 30, 1999   7:45 am

Facility: Various Cases
Address:
City: Richland
State: WA   Zip: 99352

Source Category:
Source Type: Stack
Emission Year: 1996

Comments:

Dataset Name: ILAW PA
Dataset Date: Nov 30, 1999   7:45 am
Wind File: WNDFILES\HB-200E.WND

Nov 30, 1999 7:45 am
CHIQ

Page 1

GROUND-LEVEL CHI/Q VALUES FOR H-3
CHI/Q TOWARD INDICATED DIRECTION (SEC/CUBIC METER)

Distance (meters)

Dir	1000
N	2.429E-06
NNW	3.192E-06
NW	3.166E-06
WNW	2.521E-06
W	2.025E-06
WSW	1.524E-06
SW	1.595E-06
SSW	1.455E-06
S	1.784E-06
SSE	2.326E-06
SE	4.672E-06
ESE	7.980E-06
E	5.598E-06
ENE	3.251E-06
NE	2.330E-06
NNE	1.946E-06

Nov 30, 1999 7:45 am
CHIQ

Page 2

GROUND-LEVEL CHI/Q VALUES FOR C-14
CHI/Q TOWARD INDICATED DIRECTION (SEC/CUBIC METER)

Distance (meters)

Dir	1000
N	2.429E-06
NNW	3.192E-06
NW	3.166E-06
WNW	2.521E-06
W	2.025E-06
WSW	1.524E-06
SW	1.595E-06
SSW	1.455E-06
S	1.784E-06
SSE	2.326E-06
SE	4.672E-06
ESE	7.980E-06
E	5.598E-06
ENE	3.251E-06
NE	2.330E-06
NNE	1.946E-06

Appendix D.

Quality Assurance Considerations

Quality Assurance Considerations

For analysis of data and calculations in this report, a peer review procedure was established and followed. The peer reviewers were selected based on their experience and knowledge of specific subject areas. The internal peer review was provided per Fluor Daniel Northwest (FDNW) internal procedures. PNNL provided the Hanford Environmental Dose Overview (HEDOP) technical review for this report.

Example hand calculations are provided in Appendices A and B to illustrate in detail the methods used. Reviewer checklists are attached.

PEER REVIEW CHECKLIST

Document Reviewed: Exposure Scenarios and Unit Dose Factors for the Hanford Immobilized Low-Activity Tank Waste Performance Assessment

Scope of Review:

Yes	No	N/A	
[ ]	[ ]	[ ]	Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
[ ]	[ ]	[ ]	Problem completely defined.
[ ]	[ ]	[ ]	Accident scenarios developed in a clear and logical manner.
[ ]	[ ]	[ ]	Necessary assumptions explicitly stated and supported.
[ ]	[ ]	[ ]	Computer codes and data files documented.
[ ]	[ ]	[ ]	Data used in calculations explicitly stated in document.
[ ]	[ ]	[ ]	Data checked for consistency with original source information as applicable.
[ ]	[ ]	[ ]	Mathematical derivations checked including dimensional consistency of results.
[ ]	[ ]	[ ]	Models appropriate and used within range of validity or use outside range of established validity justified.
[ ]	[ ]	[ ]	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
[ ]	[ ]	[ ]	Software input correct and consistent with document reviewed.
[ ]	[ ]	[ ]	Software output consistent with input and with results reported in document reviewed.
[ ]	[ ]	[ ]	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
[ ]	[ ]	[ ]	Safety margins consistent with good engineering practices.
[ ]	[ ]	[ ]	Conclusions consistent with analytical results and applicable limits.
[ ]	[ ]	[ ]	Results and conclusions address all points required in the problem statement.
[ ]	[ ]	[ ]	Format consistent with appropriate NRC Regulatory Guide or other standards
[ ]	[ ]	[ ]	Review calculations, comments, and/or notes are attached.

[ ] [ ] Document approved.

Peer Reviewer: Harvey J. Goldberg, PhD CHP

Signature Date

HEDOP REVIEW CHECKLIST

Document Reviewed: Exposure Scenarios and Unit Dose Factors for the Hanford Immobilized Low-Activity Tank Waste Performance Assessment

Scope of Review:

Yes	No*	N/A		
[ ]	[ ]	[ ]	1.	A detailed technical review and approval of the environmental transport and dose calculation portion of the analysis has been performed and documented.
[ ]	[ ]	[ ]	2.	Detailed technical review(s) and approval(s) of scenario and release determinations have been performed and documented.
[ ]	[ ]	[ ]	3.	HEDOP-approved code(s) were used.
[ ]	[ ]	[ ]	4.	Receptor locations were selected according to HEDOP recommendations.
[ ]	[ ]	[ ]	5.	All applicable environmental pathways and code options were included and are appropriate for the calculations.
[ ]	[ ]	[ ]	6.	Hanford site data were used.
[ ]	[ ]	[ ]	7.	Model adjustments external to the computer program were justified and performed correctly.
[ ]	[ ]	[ ]	8.	The analysis is consistent with HEDOP recommendations.
[ ]		[ ]	9.	Supporting notes, calculations, comments, comment resolutions, or other information is attached. (Use the "Page 1 of X" page numbering format and sign and date each added page.)
[ ]	**[ ]**		**10.**	**Approval is granted on behalf of the Hanford Environmental Dose Overview Panel.**

*All "No" responses must be explained. The use of nonstandard methods must be justified.

HEDOP Reviewer:

____
Signature   Date

COMMENTS (add additional signed and dated pages if necessary):