6.0 Occupational Environmental Dose

In the context of reconstructing doses for Atomic Weapons employees, Occupational Environmental Dose includes doses due to

- direct, exernal irradiation from material in process, in storage, in transit, and from radioactive contamination on surfaces, in soil and water, and in plumes of radioactive material
- internal irradiation due to intakes of fugitive radioactive material through inhalation, ingestion, dermal contact with radioactive material, and through wounds. Generally, dermal contact and wound entry are assumed to be negligible in the absence of information to the contrary.

6.1 Environmental External Irradiation

Typically, energy employees who were not categorized as radiation workers were not monitored using personal dosimeters. However, the work environment for these employees was often routinely monitored using area dosimeters or periodically monitored using survey instrumentation to measure the "background" environmental radiation levels. At many of these facilities, routine monitoring stations have recorded the average photon dose in a general area or at the plant boundaries. At several DOE facilities, radioactive emissions from plant stacks have been known to significantly increase the "background" radiation levels on the plant site. In general the dose from increased background is rather low.

6.1.1 During Operations

Direct, external irradiation of people on site can occur from material in process, in storage, in transit, and from radioactive contamination on surfaces, in soil and water, and in plumes of radioactive material. Uranium metal emits beta particles (electrons) and to a lesser extent, photon radiation primarily in the form of bremsstrahlung X-rays but with some gamma emissions (e.g., the 186 keV photon from ^{235}U). Neutron radiation (from spontaneous fission) is negligible, even for massive quantities of uranium (based on neutron production calculated by Sources4 (Wilson et al. 1999)).

During operations, environmental doses were much smaller than those occurring in the actual refining portions of the facility, so these doses would be significant only for workers who spent little time in the high-dose portions of the facility. For these workers, the exposure scenario is spending eight hours per working day in an area with a low level of airborne contamination and a low level of contamination deposited on the floor. To estimate external doses resulting from these two pathways, dose factors are provided in Table 3.9 and Table 3.10. The dose reconstructor should refer to ORAUT-OTIB-0005, Rev. 02 PC-1 (ORAUT 2006) to determine which of the tabulated organ dose rates should be used for any particular ICD code.

Notice that the dose quantity calculated for this conversion factor is exposure, in units of milliRoentgen. For this particular conversion factor, 50.5% of the exposure is associated with photons with energies below 30 keV; 28.5% is from photons with energies between 30 keV and 250 keV, and the remaining 21.0% is for photons with energies greater than 250 keV.

The dose reconstructor should refer to ORAUT-OTIB-0005, Rev. 02 PC-1 (ORAUT 2006) to determine which of the tabulated organ dose rates should be used for any particular ICD code.

The environmental external dose received by a worker exposed to contaminated air and walking on contaminated ground can be found by multiplying the dose factors by the contamination levels, assuming a number of hours of exposure per workday. This analysis assumes that during plant operation, the worker away from the main operation area is exposed to a uranium concentration in air of 7 dpm/m^3. This level corresponds to 0.1 MAC, and is consistent with general area air sampling results for positions on the factory floor away from uranium milling operations. (The results from metal working facilities are used for uranium refining operations until better data are found.) Air sampling results for three plants, American Machine and Foundry, Medart, and Allegheny Ludlum were examined, comparing air samples at the highest concentration areas to air samples at the lowest concentration areas during the same operation. For 11 different cases, the ratio of the low to high concentration ranged from 0.002 to 0.029, with all but two of those ratios below 0.01. Thus it would be reasonable to use a ratio of 0.01 for areas that are further away from the heavy operations, which non-operational areas of the facility would be. In similarity with the generic TBD for metal operations, we assume that a heavy operation would produce a daily-weighted air concentration of 10 MAC at the operator's position, so ratioing this by 0.01 gives a value of 0.1 MAC or 7 dpm/m^3 in the non-operational areas of the plant.

For the surface contamination, it is assumed that the uranium deposited on the floor with a deposition velocity of 0.00075 m/s for a period of one year without cleanup, then remained at that level of contamination for the duration of operations. This would be a contamination level of 1.65×10^5 dpm/m^2. The worker exposure is estimated as daily doses for 40-, 44-, and 48-hour workweeks. Using these assumptions, the daily doses can be calculated, and they are presented in Table 6.1

Table 6.1. Dose rate from submersion in uranium dust and standing on uranium contaminated surfaces.

Hours worked per week	Submersion Dose Rate(mrem/d)	Contaminated Surface Dose Rate(mrem/d)	Total Dose Rate (mrem/d)
40	2.08E-07	3.15E-04	3.15E-04
44	2.29E-07	3.46E-04	3.47E-04
48	2.50E-07	3.78E-04	3.78E-04

6.1.2 After Operations and Initial Decontamination and Before FUSRAP Remediation

Workers at a facility that is no longer performing AWE work may also be inhaling uranium from residual contamination. If measurements of the contamination are not available for this time period, the intake presented in the previous section can be used as an estimate of the external doses from this dose pathway.

6.1.3 After FUSRAP Remediation

At the conclusion of remediation, exit surveys, such as FUSRAP reports can be used to estimate external dose rates. If no exit surveys are available, external doses can be estimated using the doses presented in Section 6.1.1.

6.2 Environmental Internal Dose Due to Inhalation and Ingestion of Radioactive Material

At several DOE facilities, radioactive emissions from plant stacks have been known to significantly increase the "background" radiation levels on the plant site. The estimate of 7 dpm/m^3 used in Section 6.1.1 can be assumed for the contamination level. Ingestion intakes were found using the equation

$I_{IMBA} = 3.062 \times 10^{-5} Ah$ as discussed in Section 8.5.3. Table 6.2 gives the intakes, both from inhalation and ingestion, for these conditions.

6.2.1 During Operations

Radioactive material aerosolized by various industrial processes in uranium refining can be released deliberately or inadvertently to the environment, producing uranium aerosols in the environs of the site.

An estimate of the intake from the inhalation pathway can be estimated assuming an airborne contamination level, a breathing rate, and daily exposure period. The estimate of 1 dpm/m^3 can be assumed for the contamination level. A breathing rate of 9.6 m^3/d includes an exposure period of 8 hours per day. A conversion factor of 2.22 dpm/pCi must also be employed, to give a daily intake of 4.4 pCi/d of uranium.

Table 6.2. Environmental daily intakes to workers in non-operational areas of the plant.

Hours worked per week	Daily Intake from Inhalation (pCi/d)	Daily Intake from Ingestion (pCi/d)
40	20.7	0.429
44	22.8	0.472
48	24.9	0.514

6.2.2 After Operations and Initial Decontamination and Before FUSRAP Remediation

Workers at a facility that is no longer performing AWE work may also be inhaling uranium from residual contamination. If measurements of the contamination are not available for this time period, the intake presented in the previous section can be used as an estimate of the internal doses from this dose pathway.

6.2.3 After FUSRAP Remediation

At the conclusion of remediation, exit surveys should be available to form a basis for intakes. If no exit surveys are available, intakes can be estimated as identical to that given in Section 6.2.1.

6.3 Summary of Environmental Irradiation

Environmental doses and intakes for generic sites are summarized in Table 6.3. Each site's stages correspond to dates given in the Appendix for that site. (Site stages are described in Section 4.11). Intakes must be adjusted for a 2,400, a 2,200, or a 2,000-hour work year by date as specified in Section 3.10 of Battelle-TIB-5000 (Strom 2006).

Default environmental dose assumptions for a generic uranium refining site during Stage 1 are shown in Table 6.3. All doses are lognormally distributed.

Table 6.3. Default environmental dose assumptions for a generic uranium refining site during Stage 1. All doses are lognormally distributed with a GSD of 5.

Type of exposure; radiation type, energy, quantity, units, [geometry]	48-h work week	44-h work week	40-h work week

External irradiation, photons, 30<E≤250 keV, Hp(10) rem/y, AP geometry	3.78E-4 mrem/d	3.47E-4 mrem/d	3.15E-4 mrem/d
365-day average daily chronic inhalation intake of Type M or Type S ^{234}U, pCi/d	24.9 pCi/d	22.8 pCi/d	20.7 pCi/d
365-day average daily chronic ingestion intake of Type M or Type S ^{234}U, pCi/d	0.514 pCi/d	0.472 pCi/d	0.429 pCi/d

Table 6.4. Default environmental dose assumptions for a generic uranium refining site during Stage 2. All doses are lognormally distributed.

Type of exposure; radiation type, energy, quantity, units, [geometry]	48-h work week	44-h work week	40-h work week
External irradiation, photons, 30<E≤250 keV, Hp(10) rem/y, AP geometry	NA	NA	3.15E-4 mrem/d
365-day average daily chronic inhalation intake of Type M or Type S ^{234}U, pCi/d	NA	NA	20.7 pCi/d
365-day average daily chronic ingestion intake of Type M or Type S ^{234}U, pCi/d	NA	NA	0.429 pCi/d

Table 6.5. Default environmental dose assumptions for a generic uranium refining site during Stage 3. All doses are lognormally distributed.

Type of exposure; radiation type, energy, quantity, units, [geometry]	48-h work week	44-h work week	40-h work week
External irradiation, photons, 30<E≤250 keV, Hp(10) rem/y, AP geometry	NA	NA	3.15E-4 mrem/d
365-day average daily chronic inhalation intake of Type M or Type S ^{234}U, pCi/d	NA	NA	20.7 pCi/d
365-day average daily chronic ingestion intake of Type M or Type S ^{234}U, pCi/d	NA	NA	0.429 pCi/d

7.0 Occupational External Dose

Occupational external dose can arise from three sources; direct radiation from radioactive material in storage or in process, airborne radioactive material, and radioactive material on the surfaces of objects in a work area.

If the workers wore radiation dosimeters and that data are available then the dosimetry data should be used for all dose estimates.

Section 6.0 (Occupational Internal Dose) discusses the air concentrations of uranium dusts due to various processes. In some cases the work areas were quite dusty. High air concentrations would also result in high contamination levels. It is not known how often work areas were cleaned of dust. We assume that areas were cleaned on a weekly basis.

Film badge usage at AWE sites varied from plant to plant and over time. When film badge data for workers are available, these readings are the preferred indicator of the worker's whole body dose. In some cases there may be coworker dosimetry results available that can be used to estimate an unbadged worker's dose. When film badges were not issued, the worker's dose must be determined from plant conditions. This section contains information that can be used to estimate external doses to workers when no dosimetry data are available. The external dose rates presented in this section are those for typical conditions in the workplace described in this document. The appendices to this document will present site-specific information to provide more appropriate estimates where available. If site information is insufficient to estimate a dose to a worker, the information in this section can be used.

7.1 Radiation Doses

Workers at refining facilities may have been exposed to three types of radiation; beta radiation, gamma radiation, and neutron radiation. Detailed information on the dosimetry of uranium was described in Chapter 3.

7.1.1 Submersion in Contaminated Air

When workers are enveloped in a cloud of radioactive dust, they will receive a small amount of external dose. External dose rates from uranium and its radioactive progeny are shown in Table 3.9.

Notice that the dose quantity calculated for this conversion factor is exposure, in units of milliRoentgen. For this particular conversion factor, 50.5% of the exposure is associated with photons with energies below 30 keV; 28.5% is from photons with energies between 30 keV and 250 keV, and the remaining 21.0% is for photons with energies greater than 250 keV.

The dose reconstructor should refer to ORAUT-OTIB-0005, Rev. 02 PC-1 (ORAUT 2006) to determine which of the tabulated organ dose rates should be used for any particular ICD code.

7.1.2 Exposures from Contaminated Surfaces

When workers are working on a contaminated surface, they will receive a small amount of external dose. External dose rates from uranium and its radioactive progeny are shown in Table 3.9.

The doses were calculated using the computer code MicroShield version 6.02 (Grove Engineering 2003). The calculated dose rates are for natural uranium and include the dose contribution from the radioactive progeny of ^{238}U, ^{235}U, and ^{234}U. In accordance with (ORAUT 2005c) 100 days of radioactive progeny ingrowth was assumed for these calculations.

Notice that the dose quantity calculated for this conversion factor is exposure, in units of milliRoentgen. For this particular conversion factor, 50.5% of the exposure is associated with photons with energies below 30 keV; 28.5% is from photons with energies between 30 keV and 250 keV, and the remaining 21.0% is for photons with energies greater than 250 keV.

The dose reconstructor should refer to ORAUT-OTIB-0005, Rev. 02 PC-1 (ORAUT 2006) to determine which of the tabulated organ dose rates should be used for any particular ICD code.

The quantity of uranium on the floor surface can be obtained from floor survey (wipe) sample measurements. Most survey samples were based on a 100 cm^2 sample rather than a 1 meter squared sample, in this case the dose values in Table 3.10 should be divided by 10,000.

When measured floor contamination rates are not available the contamination on the floor may be estimated from measured air concentrations. The floor activity may be computed from the air concentrations following the method of ORAUT (2005c) (ORAUT-OTIB -0004, Rev 3, p 15). The level of surface contamination was determined by first calculating a terminal settling velocity for 5-μm activity mean aerodynamic diameter (AMAD) particles. The calculated terminal settling velocity was 0.00075 meters per second. It was assumed that the surface contamination level was due to 365 days of constant deposition from the constant air concentration to give a deposition factor of 2.37E4 meters. The floor contamination level is then estimated as Floor Concentration (dpm/m^2) = Air Concentration (dpm/m^3) × 2.37E4 meters. This method calculates the surface contamination over 1 m^2 and the dose factors in Table 6.1 should be used.

7.2 Process Specific Dose Rates

Two references were used to generate the process specific dose rates shown in this section. The first was the dose rate information presented by Christofano and Harris (1960). Their data were used primarily to estimate the dose rate due to submersion in a dust cloud and due to contamination on the floor. This paper has extensive air concentration data. The air concentration data are summarized in chapter 8.

External dose rates were extracted from the TBD for Mallinckrodt (ORAUT-TKBS-0005) (ORAUT, 2005a). To compute the daily doses from external sources of radiation it was necessary to estimate the exposure duration. This was accomplished by a crude time-and-motion estimate that was primarily an educated opinion of how much time was spent near the particular source in a day.

In the sections that follow, the external dose rate and durations are tabulated. The tabulated values are in terms of mR h^{-1}, the conversions to mrem h^{-1} are performed by the dose reconstruction spreadsheet.

Table 7.1. Process Specific Dose Rates for Uranium Refining at AWE Sites

Task	Duration (h/d)	Penetrating (mR/h)	Non-penetrating (hands) (mrem/h)	Non-penetrating (other) (mrem/h)	Reference
Ore Digestion					
High grade pitchblende ore, 45"	6	6.1			TKBS-0005 [230[5)]
High grade pitchblende ore, 6"	2		66		TKBS-0005 [230(8)]
High grade pitchblende ore, contact	2			100	TKBS-0005 [230(9)]
Total		36.6	132	200	
Solvent Extraction					
ether extraction tanks	3	3.1			TKBS-0005 [230(14)]
residue dryer	3			75	TKBS-0005 [230(15)]
Total		9.3	0	225	
Boildown and Denitration					
ether extraction tanks	3	3.1			TKBS-0005 [230(14)]
55 gal drum, 100 day, 1 m	8	3.10			Table 7.2
55 gal drum, 100 day, 1 cm	2	0.28			Table 7.2
55 gal drum, 100 day, 30 cm	2		4.50		Table 7.2
Total		11.55	9.00	2.65	
Oxide Reduction					
55 gal drum, 100 day, 1 m	8	0.28			Table 7.2
Handling U material	3		233.00	20.80	Table 3.4
Total		2.25	699.00	62.40	
Hydrofluorination					

Task	Duration (h/d)	Penetrating (mR/h)	Non-penetrating (hands) (mrem/h)	Non-penetrating (other) (mrem/h)	Reference
Handling U material	3		233.00	20.80	Table 1.3
55 gal drum, 100 day, 1 m	8	0.28			Table 5.6
Total		2.25	699.00	62.40	
Reduction to Metal					
Metal (average of all task dose rates)		13.5			TKBS-0005 [234(P4-Dosiimeters)]
loading bomb	2		53	53	TKBS-0005 [231(9)]
Contact with unchipped derby	2		116		TKBS-0005 [231(14)]
chipping - 1 ft	2			42	TKBS-0005 [231(15)]
Total 8		108	338	190	
Recasting					
Contact with cleaned crucible lid	1		155		TKBS-0005 [231(25)]
billets	1	180		180	TKBS-0005 [231(33)]
Recasting: chest high cleaning top	1			135	TKBS-0005 [231(26)]
Furnace tending	6	665		665	TKBS-0005 [234(P4-14)]
Total		4170.00	155.00	4305.00	
Fluorination					
55 gal drum, 100 day, 1 m	8	0.28			Table 7.2
Handling U material	2		233.00	20.80	Table 3.4
Total		2.25	466.00	41.60	
Scrap Recovery					
Handling U material	4		233	20.8	Table 3.4
55 gal drum, 100 day, 1 m	8	0.28			Table 7.2
Total		2.25	932.00	83.20	

Task	Duration (h/d)	Penetrating (mR/h)	Non-penetrating (hands) (mrem/h)	Non-penetrating (other) (mrem/h)	Reference
Drum Loading					
55 gal drum, 100 day, 1 m	8	0.28			Table 7.2
High grade pitchblende ore, 45"	1	6.1			TKBS-0005 [230(5)]
Total		8.35	0.00	0.00	

7.3 Drum Doses

Uranium compounds were kept in drums of various sizes. The dose rates from drums were calculated using MicroShield Version 5.01 for two different situations. The first set of calculations assumed that the time of decay was 100 days, which allows the ingrowth of uranium progeny which will increase the dose rate. The contents of the drums were modeled as soil at a density of 1.6 (FGR-12 (Eckerman and Ryman 1993)). This combination of density and elemental composition will result in exaggerated dose rates. The calculations did not account for Bremsstrahlung that may have been generated by the interactions of beta particles with the contents of the drum. Calculations performed by others (Glover 2006, Anderson and Hertel 2005) indicate that the dose rate due to Bremsstrahlung may be equal to the photon dose rate. Therefore, the values shown in Table 7.2 are twice the dose rate that was calculated for photons alone. The dose rates shown here should be combined with the dose conversion factors for the AP irradiation geometry. The dose rates from drums that contain pitchblend were derived from (ORAUT-TKBS-0005) (ORAUT, 2005).

Table 7.2 Dose rates from drums of uranium compounds

Drum Size (gal)	Dose Rates (mR/h)			
	1 cm	10 cm	30 cm	100 cm
100 day decay				
5	3.7	1.4	0.4	0.1
30	4.4	2.5	1.1	0.2
55	4.5	2.8	1.3	0.3
Equilibrium (pitchblende)				
5	80.52	29.85	8.64	1.25
30	107.68	59.25	25.03	4.72
55	112.88	68.12	32.11	6.77

7.4 Summary of External Doses Received by Workers During Operation

- The daily doses received by workers at a plant that handled uranium, according to the five pathways described in this section, are given in Table 7.3. Three of the dose pathways are mR/h and are converted to dose by the dose assignment spreadsheet. Dose reconstructors should assume that the entire photon dose from uranium is due to photons having the following energy bin structure: 50.5% of the exposure is associated with photons with energies below 30 keV; 28.5% is from photons with energies between 30 keV and 250 keV, and the remaining 21.0% is for photons with energies greater than 250 keV.

The “hands and forearms” and “other skin” pathways are doses at a skin depth of 0.07 mg/cm^2, caused by electrons with energies above 15 keV.

The daily dose rates shown in Table 7.3 have been adjusted so that the daily dose rates is for calendar days rather than working days. The dose reconstructor has to estimate only the number of calendar days that elapsed between the start and end of AWE employment to use this table.

Table 7.3. Summary external dose rates for uranium refining facilities

Operation	Job Title	Dose Pathway	Geometry	Daily dose parameters for external dose pathways (mR for penetrating radiation and mrem for nonpenetrating)					
				48-h week		44-h week		40-h week	
				Median	GSD	Median	GSD	Median	GSD
Ore Digestion	Operator	Submersion	ISO	4.58E-07	5.7	4.20E-07	5.7	3.81E-07	5.7
		Contaminated Floor	Underfoot Plane	2.47E-01	5.7	2.27E-01	5.7	2.06E-01	5.7
		Material handled	A-P	8.59E+00	5.0	7.88E+00	5.0	7.16E+00	5.0
		Non-penetrating hands	n/a	3.10E+01	5.0	2.84E+01	5.0	2.58E+01	5.0
		Non-penetrating, other skin	n/a	4.69E+01	5.0	4.30E+01	5.0	3.91E+01	5.0
	General Laborer	Submersion	ISO	2.29E-07	5.7	2.10E-07	5.7	1.91E-07	5.7
		Contaminated Floor	Underfoot Plane	1.24E-01	5.7	1.13E-01	5.7	1.03E-01	5.7
		Material handled	A-P	4.30E+00	5.0	3.94E+00	5.0	3.58E+00	5.0
		Non-penetrating hands	n/a	1.55E+01	5.0	1.42E+01	5.0	1.29E+01	5.0
		Non-penetrating, other skin	n/a	2.35E+01	5.0	2.15E+01	5.0	1.96E+01	5.0
	Supervisor	Submersion	ISO	1.14E-07	5.7	1.05E-07	5.7	9.53E-08	5.7
		Contaminated Floor	Underfoot Plane	6.18E-02	5.7	5.67E-02	5.7	5.15E-02	5.7
		Material handled	A-P	2.15E+00	5.0	1.97E+00	5.0	1.79E+00	5.0
		Non-penetrating hands	n/a	7.75E+00	5.0	7.10E+00	5.0	6.46E+00	5.0
		Non-penetrating, other skin	n/a	1.17E+01	5.0	1.08E+01	5.0	9.78E+00	5.0
	Clerical	Submersion	ISO	1.14E-08	5.7	1.05E-08	5.7	9.53E-09	5.7
		Contaminated Floor	Underfoot Plane	6.18E-03	5.7	5.67E-03	5.7	5.15E-03	5.7
		Material handled	A-P	2.15E-01	5.0	1.97E-01	5.0	1.79E-01	5.0
		Non-penetrating hands	n/a	7.75E-01	5.0	7.10E-01	5.0	6.46E-01	5.0
		Non-penetrating, other skin	n/a	1.17E+00	5.0	1.08E+00	5.0	9.78E-01	5.0
Solvent Extraction	Operator	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	2.18E+00	5.0	2.00E+00	5.0	1.82E+00	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	5.28E+01	5.0	4.84E+01	5.0	4.40E+01	5.0
	General Laborer	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	1.09E+00	5.0	1.00E+00	5.0	9.10E-01	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	2.64E+01	5.0	2.42E+01	5.0	2.20E+01	5.0
	Supervisor	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	5.46E-01	5.0	5.00E-01	5.0	4.55E-01	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	1.32E+01	5.0	1.21E+01	5.0	1.10E+01	5.0

Operation	Job Title	Dose Pathway	Geometry	Daily dose parameters for external dose pathways (mR for penetrating radiation and mrem for nonpenetrating)					
				48-h week		44-h week		40-h week	
				Median	GSD	Median	GSD	Median	GSD
	Clerical	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	5.46E-02	5.0	5.00E-02	5.0	4.55E-02	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	1.32E+00	5.0	1.21E+00	5.0	1.10E+00	5.0
Boildown and Denitration	Operator	Submersion	ISO	8.73E-07	2.3	8.00E-07	2.3	7.27E-07	2.3
		Contaminated Floor	Underfoot Plane	4.72E-01	2.3	4.32E-01	2.3	3.93E-01	2.3
		Material handled	A-P	2.71E+00	5.0	2.49E+00	5.0	2.26E+00	5.0
		Non-penetrating hands	n/a	2.11E+00	5.0	1.94E+00	5.0	1.76E+00	5.0
		Non-penetrating, other skin	n/a	6.22E-01	5.0	5.70E-01	5.0	5.18E-01	5.0
	General Laborer	Submersion	ISO	4.36E-07	2.3	4.00E-07	2.3	3.64E-07	2.3
		Contaminated Floor	Underfoot Plane	2.36E-01	2.3	2.16E-01	2.3	1.96E-01	2.3
		Material handled	A-P	1.36E+00	5.0	1.24E+00	5.0	1.13E+00	5.0
		Non-penetrating hands	n/a	1.06E+00	5.0	9.68E-01	5.0	8.80E-01	5.0
		Non-penetrating, other skin	n/a	3.11E-01	5.0	2.85E-01	5.0	2.59E-01	5.0
	Supervisor	Submersion	ISO	2.18E-07	2.3	2.00E-07	2.3	1.82E-07	2.3
		Contaminated Floor	Underfoot Plane	1.18E-01	2.3	1.08E-01	2.3	9.82E-02	2.3
		Material handled	A-P	6.78E-01	5.0	6.21E-01	5.0	5.65E-01	5.0
		Non-penetrating hands	n/a	5.28E-01	5.0	4.84E-01	5.0	4.40E-01	5.0
		Non-penetrating, other skin	n/a	1.56E-01	5.0	1.43E-01	5.0	1.30E-01	5.0
	Clerical	Submersion	ISO	2.18E-08	2.3	2.00E-08	2.3	1.82E-08	2.3
		Contaminated Floor	Underfoot Plane	1.18E-02	2.3	1.08E-02	2.3	9.82E-03	2.3
		Material handled	A-P	6.78E-02	5.0	6.21E-02	5.0	5.65E-02	5.0
		Non-penetrating hands	n/a	5.28E-02	5.0	4.84E-02	5.0	4.40E-02	5.0
		Non-penetrating, other skin	n/a	1.56E-02	5.0	1.43E-02	5.0	1.30E-02	5.0
	Operator	Submersion	ISO	2.50E-06	3.5	2.30E-06	3.5	2.09E-06	3.5
		Contaminated Floor	Underfoot Plane	1.35E+00	3.5	1.24E+00	3.5	1.13E+00	3.5
		Material handled	A-P	5.28E-01	5.0	4.84E-01	5.0	4.40E-01	5.0
		Non-penetrating hands	n/a	1.64E+02	5.0	1.50E+02	5.0	1.37E+02	5.0
		Non-penetrating, other skin	n/a	1.46E+01	5.0	1.34E+01	5.0	1.22E+01	5.0
	General Laborer	Submersion	ISO	1.25E-06	3.5	1.15E-06	3.5	1.04E-06	3.5
		Contaminated Floor	Underfoot Plane	6.77E-01	3.5	6.21E-01	3.5	5.64E-01	3.5
		Material handled	A-P	2.64E-01	5.0	2.42E-01	5.0	2.20E-01	5.0
		Non-penetrating hands	n/a	8.20E+01	5.0	7.52E+01	5.0	6.84E+01	5.0
		Non-penetrating, other skin	n/a	7.32E+00	5.0	6.71E+00	5.0	6.10E+00	5.0
	Supervisor	Submersion	ISO	6.26E-07	3.5	5.74E-07	3.5	5.22E-07	3.5
		Contaminated Floor	Underfoot Plane	3.38E-01	3.5	3.10E-01	3.5	2.82E-01	3.5
		Material handled	A-P	1.32E-01	5.0	1.21E-01	5.0	1.10E-01	5.0

Operation	Job Title	Dose Pathway	Geometry	Daily dose parameters for external dose pathways (mR for penetrating radiation and mrem for nonpenetrating)					
				48-h week		44-h week		40-h week	
				Median	GSD	Median	GSD	Median	GSD
Oxide Reduction		Non-penetrating hands	n/a	4.10E+01	5.0	3.76E+01	5.0	3.42E+01	5.0
		Non-penetrating, other skin	n/a	3.66E+00	5.0	3.36E+00	5.0	3.05E+00	5.0
	Clerical	Submersion	ISO	6.26E-08	3.5	5.74E-08	3.5	5.22E-08	3.5
		Contaminated Floor	Underfoot Plane	3.38E-02	3.5	3.10E-02	3.5	2.82E-02	3.5
		Material handled	A-P	1.32E-02	5.0	1.21E-02	5.0	1.10E-02	5.0
		Non-penetrating hands	n/a	4.10E+00	5.0	3.76E+00	5.0	3.42E+00	5.0
		Non-penetrating, other skin	n/a	3.66E-01	5.0	3.36E-01	5.0	3.05E-01	5.0
Hydrofluorination	Operator	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	5.28E-01	5.0	4.84E-01	5.0	4.40E-01	5.0
		Non-penetrating hands	n/a	1.64E+02	5.0	1.50E+02	5.0	1.37E+02	5.0
		Non-penetrating, other skin	n/a	1.46E+01	5.0	1.34E+01	5.0	1.22E+01	5.0
	General Laborer	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	2.64E-01	5.0	2.42E-01	5.0	2.20E-01	5.0
		Non-penetrating hands	n/a	8.20E+01	5.0	7.52E+01	5.0	6.84E+01	5.0
		Non-penetrating, other skin	n/a	7.32E+00	5.0	6.71E+00	5.0	6.10E+00	5.0
	Supervisor	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	1.32E-01	5.0	1.21E-01	5.0	1.10E-01	5.0
		Non-penetrating hands	n/a	4.10E+01	5.0	3.76E+01	5.0	3.42E+01	5.0
		Non-penetrating, other skin	n/a	3.66E+00	5.0	3.36E+00	5.0	3.05E+00	5.0
	Clerical	Submersion	ISO	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Contaminated Floor	Underfoot Plane	0.00E+00	1.0	0.00E+00	1.0	0.00E+00	1.0
		Material handled	A-P	1.32E-02	5.0	1.21E-02	5.0	1.10E-02	5.0
		Non-penetrating hands	n/a	4.10E+00	5.0	3.76E+00	5.0	3.42E+00	5.0
		Non-penetrating, other skin	n/a	3.66E-01	5.0	3.36E-01	5.0	3.05E-01	5.0
	Operator	Submersion	ISO	2.10E-06	4.5	1.92E-06	4.5	1.75E-06	4.5
		Contaminated Floor	Underfoot Plane	1.13E+00	4.5	1.04E+00	4.5	9.45E-01	4.5
		Material handled	A-P	2.54E+01	5.0	2.32E+01	5.0	2.11E+01	5.0
		Non-penetrating hands	n/a	7.93E+01	5.0	7.27E+01	5.0	6.61E+01	5.0
		Non-penetrating, other skin	n/a	4.46E+01	5.0	4.09E+01	5.0	3.72E+01	5.0
	General Laborer	Submersion	ISO	1.05E-06	4.5	9.62E-07	4.5	8.74E-07	4.5
		Contaminated Floor	Underfoot Plane	5.67E-01	4.5	5.20E-01	4.5	4.72E-01	4.5
		Material handled	A-P	1.27E+01	5.0	1.16E+01	5.0	1.06E+01	5.0
		Non-penetrating hands	n/a	3.97E+01	5.0	3.64E+01	5.0	3.31E+01	5.0
		Non-penetrating, other skin	n/a	2.23E+01	5.0	2.04E+01	5.0	1.86E+01	5.0
		Submersion	ISO	5.25E-07	4.5	4.81E-07	4.5	4.37E-07	4.5

Operation	Job Title	Dose Pathway	Geometry	Daily dose parameters for external dose pathways (mR for penetrating radiation and mrem for nonpenetrating)					
				48-h week		44-h week		40-h week	
				Median	GSD	Median	GSD	Median	GSD
Metal Reduction		Contaminated Floor	Underfoot Plane	2.83E-01	4.5	2.60E-01	4.5	2.36E-01	4.5
		Material handled	A-P	6.34E+00	5.0	5.81E+00	5.0	5.28E+00	5.0
		Non-penetrating hands	n/a	1.98E+01	5.0	1.82E+01	5.0	1.65E+01	5.0
		Non-penetrating, other skin	n/a	1.11E+01	5.0	1.02E+01	5.0	9.29E+00	5.0
	Clerical	Submersion	ISO	5.25E-08	4.5	4.81E-08	4.5	4.37E-08	4.5
		Contaminated Floor	Underfoot Plane	2.83E-02	4.5	2.60E-02	4.5	2.36E-02	4.5
		Material handled	A-P	6.34E-01	5.0	5.81E-01	5.0	5.28E-01	5.0
		Non-penetrating hands	n/a	1.98E+00	5.0	1.82E+00	5.0	1.65E+00	5.0
		Non-penetrating, other skin	n/a	1.11E+00	5.0	1.02E+00	5.0	9.29E-01	5.0
Recasting	Operator	Submersion	ISO	1.86E-06	2.1	1.71E-06	2.1	1.55E-06	2.1
		Contaminated Floor	Underfoot Plane	1.01E+00	2.1	9.22E-01	2.1	8.38E-01	2.1
		Material handled	A-P	9.79E+02	5.0	8.97E+02	5.0	8.16E+02	5.0
		Non-penetrating hands	n/a	3.64E+01	5.0	3.34E+01	5.0	3.03E+01	5.0
		Non-penetrating, other skin	n/a	1.01E+03	5.0	9.26E+02	5.0	8.42E+02	5.0
	General Laborer	Submersion	ISO	9.30E-07	2.1	8.53E-07	2.1	7.75E-07	2.1
		Contaminated Floor	Underfoot Plane	5.03E-01	2.1	4.61E-01	2.1	4.19E-01	2.1
		Material handled	A-P	4.89E+02	5.0	4.49E+02	5.0	4.08E+02	5.0
		Non-penetrating hands	n/a	1.82E+01	5.0	1.67E+01	5.0	1.52E+01	5.0
		Non-penetrating, other skin	n/a	5.05E+02	5.0	4.63E+02	5.0	4.21E+02	5.0
	Supervisor	Submersion	ISO	4.65E-07	2.1	4.26E-07	2.1	3.88E-07	2.1
		Contaminated Floor	Underfoot Plane	2.51E-01	2.1	2.30E-01	2.1	2.09E-01	2.1
		Material handled	A-P	2.45E+02	5.0	2.24E+02	5.0	2.04E+02	5.0
		Non-penetrating hands	n/a	9.10E+00	5.0	8.34E+00	5.0	7.58E+00	5.0
		Non-penetrating, other skin	n/a	2.53E+02	5.0	2.32E+02	5.0	2.11E+02	5.0
	Clerical	Submersion	ISO	4.65E-08	2.1	4.26E-08	2.1	3.88E-08	2.1
		Contaminated Floor	Underfoot Plane	2.51E-02	2.1	2.30E-02	2.1	2.09E-02	2.1
		Material handled	A-P	2.45E+01	5.0	2.24E+01	5.0	2.04E+01	5.0
		Non-penetrating hands	n/a	9.10E-01	5.0	8.34E-01	5.0	7.58E-01	5.0
		Non-penetrating, other skin	n/a	2.53E+01	5.0	2.32E+01	5.0	2.11E+01	5.0
	Operator	Submersion	ISO	2.27E-06	3.3	2.08E-06	3.3	1.90E-06	3.3
		Contaminated Floor	Underfoot Plane	1.23E+00	3.3	1.13E+00	3.3	1.02E+00	3.3
		Material handled	A-P	5.28E-01	5.0	4.84E-01	5.0	4.40E-01	5.0
		Non-penetrating hands	n/a	1.09E+02	5.0	1.00E+02	5.0	9.12E+01	5.0
		Non-penetrating, other skin	n/a	9.76E+00	5.0	8.95E+00	5.0	8.14E+00	5.0
	General	Submersion	ISO	1.14E-06	3.3	1.04E-06	3.3	9.48E-07	3.3
		Contaminated Floor	Underfoot Plane	6.15E-01	3.3	5.63E-01	3.3	5.12E-01	3.3
		Material handled	A-P	2.64E-01	5.0	2.42E-01	5.0	2.20E-01	5.0
		Non-penetrating hands	n/a	5.47E+01	5.0	5.01E+01	5.0	4.56E+01	5.0

Operation	Job Title	Dose Pathway	Geometry	Daily dose parameters for external dose pathways (mR for penetrating radiation and mrem for nonpenetrating)					
				48-h week		44-h week		40-h week	
				Median	GSD	Median	GSD	Median	GSD
Fluorination	Laborer	Non-penetrating, other skin	n/a	4.88E+00	5.0	4.48E+00	5.0	4.07E+00	5.0
	Supervisor	Submersion	ISO	5.69E-07	3.3	5.21E-07	3.3	4.74E-07	3.3
		Contaminated Floor	Underfoot Plane	3.07E-01	3.3	2.82E-01	3.3	2.56E-01	3.3
		Material handled	A-P	1.32E-01	5.0	1.21E-01	5.0	1.10E-01	5.0
		Non-penetrating hands	n/a	2.73E+01	5.0	2.51E+01	5.0	2.28E+01	5.0
		Non-penetrating, other skin	n/a	2.44E+00	5.0	2.24E+00	5.0	2.03E+00	5.0
	Clerical	Submersion	ISO	5.69E-08	3.3	5.21E-08	3.3	4.74E-08	3.3
		Contaminated Floor	Underfoot Plane	3.07E-02	3.3	2.82E-02	3.3	2.56E-02	3.3
		Material handled	A-P	1.32E-02	5.0	1.21E-02	5.0	1.10E-02	5.0
		Non-penetrating hands	n/a	2.73E+00	5.0	2.51E+00	5.0	2.28E+00	5.0
		Non-penetrating, other skin	n/a	2.44E-01	5.0	2.24E-01	5.0	2.03E-01	5.0
Scrap Recovery	Operator	Submersion	ISO	6.96E-07	5.0	6.38E-07	5.0	5.80E-07	5.0
		Contaminated Floor	Underfoot Plane	3.76E-01	5.0	3.45E-01	5.0	3.13E-01	5.0
		Material handled	A-P	5.28E-01	5.0	4.84E-01	5.0	4.40E-01	5.0
		Non-penetrating hands	n/a	2.19E+02	5.0	2.01E+02	5.0	1.82E+02	5.0
		Non-penetrating, other skin	n/a	1.95E+01	5.0	1.79E+01	5.0	1.63E+01	5.0
	General Laborer	Submersion	ISO	3.48E-07	5.0	3.19E-07	5.0	2.90E-07	5.0
		Contaminated Floor	Underfoot Plane	1.88E-01	5.0	1.72E-01	5.0	1.57E-01	5.0
		Material handled	A-P	2.64E-01	5.0	2.42E-01	5.0	2.20E-01	5.0
		Non-penetrating hands	n/a	1.09E+02	5.0	1.00E+02	5.0	9.12E+01	5.0
		Non-penetrating, other skin	n/a	9.76E+00	5.0	8.95E+00	5.0	8.14E+00	5.0
	Supervisor	Submersion	ISO	1.74E-07	5.0	1.59E-07	5.0	1.45E-07	5.0
		Contaminated Floor	Underfoot Plane	9.40E-02	5.0	8.62E-02	5.0	7.83E-02	5.0
		Material handled	A-P	1.32E-01	5.0	1.21E-01	5.0	1.10E-01	5.0
		Non-penetrating hands	n/a	5.47E+01	5.0	5.01E+01	5.0	4.56E+01	5.0
		Non-penetrating, other skin	n/a	4.88E+00	5.0	4.48E+00	5.0	4.07E+00	5.0
	Clerical	Submersion	ISO	1.74E-08	5.0	1.59E-08	5.0	1.45E-08	5.0
		Contaminated Floor	Underfoot Plane	9.40E-03	5.0	8.62E-03	5.0	7.83E-03	5.0
		Material handled	A-P	1.32E-02	5.0	1.21E-02	5.0	1.10E-02	5.0
		Non-penetrating hands	n/a	5.47E+00	5.0	5.01E+00	5.0	4.56E+00	5.0
		Non-penetrating, other skin	n/a	4.88E-01	5.0	4.48E-01	5.0	4.07E-01	5.0
	Operator	Submersion	ISO	3.56E-06	2.5	3.27E-06	2.5	2.97E-06	2.5
		Contaminated Floor	Underfoot Plane	1.93E+00	2.5	1.77E+00	2.5	1.60E+00	2.5
		Material handled	A-P	1.96E+00	5.0	1.80E+00	5.0	1.63E+00	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Submersion	ISO	1.78E-06	2.5	1.63E-06	2.5	1.48E-06	2.5
		Contaminated Floor	Underfoot Plane	9.63E-01	2.5	8.83E-01	2.5	8.02E-01	2.5

Operation	Job Title	Dose Pathway	Geometry	Daily dose parameters for external dose pathways (mR for penetrating radiation and mrem for nonpenetrating)					
				48-h week		44-h week		40-h week	
				Median	GSD	Median	GSD	Median	GSD
Drum Loading	General Laborer	Material handled	A-P	9.80E-01	5.0	8.98E-01	5.0	8.17E-01	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
	Supervisor	Submersion	ISO	8.91E-07	2.5	8.16E-07	2.5	7.42E-07	2.5
		Contaminated Floor	Underfoot Plane	4.81E-01	2.5	4.41E-01	2.5	4.01E-01	2.5
		Material handled	A-P	4.90E-01	5.0	4.49E-01	5.0	4.08E-01	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
	Clerical	Submersion	ISO	8.91E-08	2.5	8.16E-08	2.5	7.42E-08	2.5
		Contaminated Floor	Underfoot Plane	4.81E-02	2.5	4.41E-02	2.5	4.01E-02	2.5
		Material handled	A-P	4.90E-02	5.0	4.49E-02	5.0	4.08E-02	5.0
		Non-penetrating hands	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0
		Non-penetrating, other skin	n/a	0.00E+00	5.0	0.00E+00	5.0	0.00E+00	5.0

8.0 Occupational Internal Dose

In this section the internal dosimetry parameters are discussed. For each process, there is a table of internal dosimetry parameters – particle size and solubility information. The tabulated values are for reference only, the ICRP (1994) default values are to be used for all internal dose calculations (see Section 3.5.) Also included for each process is a table of default dust air concentrations that can be used to estimate intakes when site specific information is lacking.

8.1 Uranium Bioassay

Bioassays were performed on workers at many sites, and urinalysis was the most effective method of determining an individual worker's uranium intake. When bioassay data are available for individual workers, this should be the primary source of dose reconstruction for internal exposure.

8.2 Process Specific Uranium Air Sampling Data

The data shown in this section are from Chrostofano and Harris (1960).

8.2.1 Ore Digestion

Internal dosimetry parameters for dusts in ore digestion are shown in Table 8.1.

Table 8.1. Internal dosimetry parameters for ore digestion

Time Period	All times
Particle Parameters	5 micron AMAD; 8.3 g/cm^3
Input Material	U_3O_8
Output Material	U nitrate solution

Default air concentrations of U_3O_8 are shown in Table 8.2.

Table 8.2 Dust concentrations during digestion

	Dust Concentration, d/min/m^3					
	Ore d/m/m^3			Concentrate d/m/m^3		
Operations	min	max	average	min	max	average
BZ Reaming ore chute	350	8,000	1,000			
BZ drum dumping						
Uncontrolled			2,500	1,000	6,000	2,400
Ventilated				0	220	90
Remote				6	44	30
BZ lidding and delidding drums	600	1,700	1,200			
GA Digest area	6	330	150	0	75	30
GA Ore room	90	2,600	1,000			
Average daily exposure	7	350	110	17	100	40

The lognormal distributions parameters for digestion are shown in Table 8.3.

Table 8.3. Lognormal Distributions of dust concentrations during digestion

Operations	Dust Concentration, d/m/m^3			
	Ore d/m/m^3		Concentrate d/m/m^3	
	Median	GSD	Median	GSD
BZ Reaming ore chute	1673	0.357		
BZ drum dumping				
Uncontrolled	685	5	2449	0.960
Ventilated			25	5
Remote			16	3.409
BZ lidding and delidding drums	1010	1.412		
GA Digest area	44	11.364	8	5
GA Ore room	484	4.274		
Average daily exposure	49	4.939	41	0.941

8.2.2 Solvent Extraction

Internal dosimetry parameters for dusts during solvent extraction are shown in Table 8.4.

Table 8.4. Internal dosimetry parameters for solvent extraction

Time Period	All times
Particle Parameters	5 micron AMAD; 8.3 g/cm^3
Input Material	U nitrate solution$_8$
Output Material	U-nitrate solution

The airborne material is assumed to be U_3O_8. The air concentration table for solvent extraction is in development.

8.2.3 Boildown and Denitration

Internal dosimetry parameters for dusts of boildown and denitration are shown in Table 8.5.

Table 8.5. Denitration area information and parameters

Time Period	All times
Particle Parameters	5 micron AMAD; 7.3 g/cm^3
Input Material	U nitrate solution
Output Material	UO_3

Default air concentrations of dusts during denitration are shown in Table 8.6.

Table 8.6. Dust Concentrations During Denitration

Operations	Dust Concentration, d/min/m^3		
	min	max	average
GA denitration area	7	750	140
GA UO_3 packaging area	15	160	63
BZ Scrape and shovel UO_3 from pots	29,000	82,000	48,000

BZ Pneumatically empty UO_3 pot	70	1,800	560
BZ Pour UNH liquor into pots	45	63	56
Average weighted exposure up to 1949	4,200	32,000	15,000
Average weighted exposure since 1949	31	234	130

Table 8.7 shows lognormal distributions values for denitration operations.

Table 8.7 Lognormal Distributions of Dust Concentrations during denitration

Operations	Dust Concentration, d/min/m^3	
	Median	GSD
GA denitration area	72	3.733
GA UO_3 packaging area	49	1.654
BZ Scrape and shovel UO_3 from pots	48765	0.969
BZ Pneumatically empty UO_3 pot	355	2.489
BZ Pour UNH liquor into pots	53	1.106
Average weighted exposure up to 1949	11593	1.674
Average weighted exposure since 1949	85	2.330

8.2.4 Oxide Reduction

Internal dosimetry parameters for dusts found in oxide reduction are found in Table 8.8.

Table 8.8. Oxide reduction area information and parameters

Time Period	All times
Particle Parameters	5 micron AMAD; 7.3 g/cm^3 (UO_3), 10.96 g/cm^3 (UO_2)
Input Material	UO_3
Output Material	UO_2

The air concentrations of uranium for the three methods of UO_3 reduction are shown in Table 8.9. Note that the introduction of the continuous flow method (method 3) resulted in a significant reduction in the air concentration of powder to which the workers were exposed.

Table 8.9. Dust concentrations during oxide reduction

Operations	Dust Concentration, d/min/m^3		
	min	max	average
BZ Load UO_3 trays	3,200	61,000	26,000
BZ Load UO_3 horizontal reactor	70	240	170
BZ Load UO_3 multiple hearth furnace	160	2,700	1,400
BZ Unload UO_2 from trays	4,000	125,000	60,000
BZ Package UO_2 from trays	25,000	115,000	80,000
BZ Package UO_2 from multiple hearth	16,500	35,000	23,000

GA Tray furnace area	78	3,300	1,800
GA Multiple hearth furnace area	245	440	340
GA Horizontal reactor area	33	120	60
DWA Tray furnace operations	9,800	32,000	20,000
DWA Multiple hearth operations	31	4,200	700
DWA Horizontal reactor operations	45	234	140

Lognormal distribution parameters for oxide reductions are shown as Table 8.10.

Table 8.10. Lognormal Distributions of Dust Concentrations During Oxide Reduction.

Operation	Dust Concentration, d/min/m^3	
	Median	GSD
BZ Load UO_3 trays	13971	3.463
BZ Load UO_3 horizontal reactor	130	1.720
BZ Load UO_3 multiple hearth furnace	657	4.537
BZ Unload UO_2 from trays	22361	7.2
BZ Package UO_2 from trays	53619	2.226
BZ Package UO_2 from multiple hearth	24031	0.916
GA Tray furnace area	507	12.578
GA Multiple hearth furnace area	328	1.072
GA Horizontal reactor area	63	0.909
DWA Tray furnace operations	17709	1.276
DWA Multiple hearth operations	361	3.763
DWA Horizontal reactor operations	103	1.861

8.2.5 Hydrofluorination

Internal dosimetry parameters for hydrofluorination are shown in Table 8.11.

Table 8.11. Hydrofluorination area information and parameters

Time Period	All times
Particle Parameters	5 micron AMAD; 10.96 g/cm^3 (UO_2), 6.7 g/cm^3 (UF_4)
Input Material	UO_2
Output Material	UF_4

As with oxide reduction, more than one method was used for this process. In similarity to the Oxide reduction process, the first methods involved manually loading the reactant onto a tray, the tray was placed in a reactor, and after the reaction was complete the product was manually scooped out of the tray. The later method was a continuous process where the UO_2 was exposed to HF in a counter current process similar to that for oxide reduction. Default dust air concentrations for hydrofluorination are shown in Table 8.12.

Table 8.12. Dust concentrations during hydrofluorination

	Dust Concentration, d/min/m^3

Operations	Trays			Reactor		
	min	max	average	min	max	average
Weighted Average Exposures						
UO_2 loaders	260	8,900	3,300	-	-	-
Furnace Operator	50	1,200	500	30	40	30
UF_4 package	110	4,400	1,300	1	57	20
Breathing Zone operations						
Loading UO_2	730	15,000	5,000	-	-	-
Unload UF_4	400	53,000	14,000	-	-	-
Interchanging Trays	70	3,300	1,000	-	-	-
Package UF_4	500	115,000	23,000	10	390	110

The lognormal distribution parameters for hydrofluorination are shown in Table 8.13.

Table 8.13. Lognormal Distribution Parameters for Dust Concentrations During Hydrofluorination

Operations	Dust Concentration, d/min/m^3			
	Trays		Reactor	
	Median	GSD	Median	GSD
Weighted Average Exposures				
UO_2 loaders	1334	6.118	-	-
Furnace Operator	245	4.167	8	5
UF_4 package	696	3.492	8	7.081
Breathing Zone operations				
Loading UO_2	3309	2.283		
Unload UF_4	4604	9.245		
Interchanging Trays	481	4.329		
Package UF_4	7583	9.200	60	3.361

8.2.6 Reduction to Metal

Internal dosimetry parameters for reduction to metal are shown in Table 8.14.

Table 8.14. Metal reduction information and parameters

Time Period	All times
Particle Parameters	5 micron AMAD; 6.7 g/cm^3 (UF_4)
Input Material	UF_4
Output Material	U metal

The dust concentrations in air for the metal reduction process are shown in Table 8.15. The modification from manual handling and remote handling occurred between 1949 and 1951. The dose reconstructor is urged to determine if manual or remote handling occurred when the worker under consideration was working.

Table 8.15. Dust concentrations during metal reduction

Operations	Dust Concentration, d/min/m^3					
	Before Modification			Remote Handling		
	min	max	average	min	max	average
Bomb Preparation						
BZ Load bomb	700	320,000	90,000	1	220	45
BZ Jolting	12,000	110,000	50,000	10	200	36
GA Preparation Area	80	5,900	2,650	1	311	21
Weighted Ave. Exp.	300	2,300	875	7	130	30
Reduction Operations						
BZ Change bombs	300	2,700	1,200	0	144	27
GA Reduction furnace area	80	2,200	520	0	32	7
Weighted Ave. Exp.	130	970	300	7	20	11
Bomb Breakout						
BZ Clean and unload shell	370	5,000	1,600	0	146	43
BZ Chipping Derby	400	6,000	2,000	0	300	70
GA Breakout Area	26	2,100	530	0	75	25

Table 8.16 shows the lognormal distribution parameters for metal reduction.

Table 8.16. Lognormal Distributions of Parameters for Metal Reduction

Operations	Dust Concentration, d/min/m^3			
	Before Modification		Remote Handling	
	Median	GSD	Median	GSD
Bomb Preparation				
BZ Load bomb	24650	5	15	9.205
BZ Jolting	36332	1.894	10	5
GA Preparation Area	687	14.878	18	2.894
Weighted Ave. Exp.	240	5	8	5
Reduction Operations				
BZ Change bombs	900	1.778	7	5
GA Reduction furnace area	143	5	2	5
Weighted Ave. Exp.	82	5	3	5
Bomb Breakout				
BZ Clean and unload shell	438	5	12	5
BZ Chipping Derby	1549	1.667	19	5
GA Breakout Area	234	5.145	7	5

8.2.7 Recasting

Internal dosimetry parameters for recasting are shown in Table 8.17.

Table 8.17. Metal recasting information and parameters

Time Period	All times
Particle Parameters	5 micron AMAD; 6.7 g/cm^3 (UF_4)
Input Material	UF_4
Output Material	U metal

Default air concentrations of uranium dusts for recasting are shown in Table 8.18.

Table 8.18. Dust concentrations during recasting

Operations	Dust Concentration, d/min/m^3					
	Before 1951			After 1951		
	min	max	average	min	max	average
BZ Load crucible	28	2,700	1,050	64	870	250
GA Crucible loading area	6	77	25	5	87	32
Weighted Average – crucible loading	25	77	51	15	86	36
BZ Open furnace and clean furnace	20	77,000	32,000	130	4,600	2,100
BZ Remove crucible	6,600	10,000	8,400	800	1,700	1,300
GA Recasting furnace area	11	3,400	580	0	290	34
Weighted Average – recasting	110	4,100	1,100	11	83	47
GA Crucible burnout area	17	140	55	0	250	32
Weighted average – crucible burnout	25	100	50	7	360	70
BZ Billet removal	1,200	3,800	2,700	78	310	180
BZ Clean Billet with chisel	4,900	6,300	5,600	--	--	--
BZ Degrease and weigh billet	46	70	59	45	1,200	130
Weighted Average – billet cleaning	14	80	47	14	49	28
BZ Assemble crucible	56	2,800	1,300	12	270	81
BZ Clean crucible parts	160	360	250	92	1,000	320
GA Crucible assembly area	17	140	80	13	280	81
Weighted average – crucible assembly	100	540	360	31	81	55

Table 8.19 shows the lognormal distributions parameters for recasting.

Table 8.19. Lognormal Distributions of Parameters for Metal Recasting

Operations	Dust Concentration, d/min/m^3			
	Before 1951		After 1951	
	Median	GSD	Median	GSD
BZ Load crucible	275	14.583	69	5
GA Crucible loading area	7	5	21	2.354
Weighted Average – crucible loading	44	1.351	10	5
BZ Open furnace and clean furnace	8763	5	773	7.375
BZ Remove crucible	2300	5	1166	1.243
GA Recasting furnace area	193	8.995	9	5
Weighted Average – recasting	672	2.683	30	2.419
GA Crucible burnout area	15	5	9	5
Weighted average – crucible burnout	14	5	19	5
BZ Billet removal	2135	1.599	155	1.340
BZ Clean Billet with chisel	1534	5	-	-
BZ Degrease and weigh billet	57	1.081		
Weighted Average – billet cleaning	33	1.972	8	5
BZ Assemble crucible	396	10.788	57	2.025
BZ Clean crucible parts	68	5	88	5
GA Crucible assembly area	49	2.689	60	1.802
Weighted average – crucible assembly	232	2.4	50	1.205

8.2.8 Fluorination

Table 8.20. Fluorination information and parameters

Time Period	All times
Particle Parameters	5 micron AMAD; 6.7 g/cm^3 (UF_4);
Input Material	UF_4
Output Material	UF_6

Table 8.21. Dust concentrations during fluorination

Operations	Dust Concentration, d/min/m^3		
	min	max	average
Hex Loaders			
BZ Remove ash	1,000	14,000	5,800
BZ Loading tubes into furnace	400	26,000	8,200
BZ Connect line to receiver	1,000	35,000	2,100
DWA Hex loaders	670	7,300	2,600
Fluorination Operators			
GA Cell room and steam room	10	90	55

GA Fluorination area	210	7,500	1,500
DWA Fluorination Operators	150	5,600	1,100
Redistillation Operators			
BZ Make or break line connections	35	2,000	530
BZ Remove receivers	55	450	190
GA Distillation Area	66	1,300	450
DWA Still operators	65	910	350
Central Loaders			
BZ Dump UF_4 to central hopper	1,900	6,300	4,400
BZ Vacuum ash from tray	1,200	1,400	1,350
BZ Load UF_4 at central loading	190	370	240
GA Central loading room	100	430	220
DWA Central loaders	220	1,100	550

The lognormal distribution parameters for dust concentrations during fluorination are shown in Table 8.22.

Table 8.22. Lognormal Distributions of Parameters for Dust Concentrations During Fluorination

Operations	Dust Concentration, d/min/m^3	
	Median	GSD
Hex Loaders		
BZ Remove ash	3742	2.403
BZ Loading tubes into furnace	3225	6.465
BZ Connect line to receiver	575	5
DWA Hex loaders	2212	1.382
Fluorination Operators		
GA Cell room and steam room	30	3.361
GA Fluorination area	1255	1.429
DWA Fluorination Operators	624	3.103
Redistillation Operators		
BZ Make or break line connections	265	4.013
BZ Remove receivers	157	1.459
GA Distillation Area	293	2.360
DWA Still operators	243	2.071
Central Loaders		
BZ Dump UF_4 to central hopper	3460	1.617
BZ Vacuum ash from tray	1296	1.085
BZ Load UF_4 at central loading	66	5
GA Central loading room	60	5
DWA Central loaders	469	1.375

8.2.9 Scrap Recovery

Table 8.23. Dust concentrations during scrap recovery

Operations	Dust Concentration, d/min/m^3	
	Trays	Calciner
	average	average
Furnace operators’ average exposures up to 1952	3,000	--
Furnace operators’ average exposures since 1952	300	1,000
GA Furnace area	900	200
BZ Dump scrap into furnace	23,000	135,000
BZ Rake charge	2,500	2,000
BZ Remove material from furnace	7,500	4,000
Digest operator average exposure	2,500	2,000
Filtration operator average exposure	7,500	4,000
Digest operator average exposure	28	
Filtration operator average exposure	10	

The lognormal distribution parameters for scrap recovery are listed in Table 8.24.

Table 8.24 Lognormal Distributions of Parameters for Air Concentrations During Scrap Recovery

Operations	Dust Concentration, d/min/m^3			
	Trays		Trays	
	Median	GSD	Median	GSD
Furnace operators’ average exposures up to 1952	822	5	--	--
Furnace operators’ average exposures since 1952	82	5	274	5
GA Furnace area	246	5	55	5
BZ Dump scrap into furnace	6299	5	36971	5
BZ Rake charge	685	5	548	5
BZ Remove material from furnace	2054	5	1095	5
	median		GSD	
Digest operator average exposure	8		5	
Filtration operator average exposure	3		5	

8.2.10 Drum Transfer Operations

Several chemical forms of uranium were involved in drum transfer operations. The default internal dosimetry parameters to be used should be in agreement with the data in Table 3.12.

Table 8.25. Dust concentrations during drum transfer operations

Operations	Dust Concentration, $d/min/m^3$		
	min	max	average
BZ Fill uranyl nitrate drum	300	2,000	1,100
BZ Fill UO_3 drums from pots	31	29,000	600
BZ Fill UO_2 drums – manual	170	20,000	10,000
BZ Fill UO_2 drums – remote	26	950	220
BZ Fill UO_2 cartons	1,000	175,000	36,000
BZ Fill UO_2 cartons – manual	3,800	40,000	21,000
BZ Fill UO_2 cartons – remote	120	980	400
BZ Open UO_2 cartons for remote dump	3,300	31,000	11,000
Package UF_4			
BZ Weigh and seal full drum	110	115,000	21,000
BZ Adjust final drum weight	100	6,400	1,600
GA Packaging area before 1950	110	960	500
GA Packaging area since 1950	1	180	43

The lognormal distribution parameters for drum loading operations are shown in Table 8.26.

Table 8.26. Lognormal Distributions of Parameters for Drum Loading Operations.

Operations	Dust Concentration, $d/min/m^3$	
	median	GSD
BZ Fill uranyl nitrate drum	775	2.017
BZ Fill UO_3 drums from pots	164	5
BZ Fill UO_2 drums – manual	2739	5
BZ Fill UO_2 drums – remote	157	1.960
BZ Fill UO_2 cartons	13229	7.406
BZ Fill UO_2 cartons – manual	12329	2.901
BZ Fill UO_2 cartons - remote	110	5
BZ Open UO_2 cartons for remote dump	3012	5
Package UF_4		
BZ Weigh and seal full drum	5,751	5
BZ Adjust final drum weight	800	4.000
GA Packaging area before 1950	325	2.367
GA Packaging area since 1950	13	10.272

8.3 Resuspension During Periods with no Uranium Operations

There was a potential for internal exposure to resuspended material from the AEC work during non-AEC operations. To estimate exposure from resuspended materials, this analysis assumed that surfaces in the building became contaminated by deposition of uranium dust during the uranium operations. NIOSH

(2005) estimates that for uranium operations, a reasonable maximum time-weighted average air concentration would be 7000 dpm/m^3 during AEC operations.

The level of contamination was determined by multiplying the air concentration of 7000 dpm/m^3 (ORAUT-OTIB-0004) by the indoor deposition velocity and the assumed deposition time, which for uranium was 20 hr per operating day. The indoor deposition velocity is dependent on the physical properties of the room (air viscosity and density, turbulence, thermal gradients, surface geometry, etc.). It is also dependent on the physical properties of the aerosol particles (such as diameter, shape, and density). These characteristics are not known, so the terminal settling velocity was calculated for an aerosol with the default particle size distribution of 5-μm activity median aerodynamic diameter. The calculated terminal settling velocity was 7.5×10^{-4} m/s, which is within the range of deposition velocities (2.7×10^{-6} to 2.7×10^{-3} m/s) measured in various studies (NRC 2002a).

The calculated surface contamination level created from airborne dusts during a 1-year period of uranium metal-working operations would be 3.44×10^{7} pCi/m^2. This level of surface contamination assumes that all uranium deposited on the floor was present for the entire period of AEC operations. Therefore, using a resuspension factor of 1×10^{-6}/m (NRC 2002b), the air concentration due to resuspension would be 34.4 pCi/m^3.

The annual inhalation intake received from resuspension of deposited material, assuming 10-hour workdays and the worst-case air concentrations for a one-year metal-working operation would be 413 pCi/day.

8.4 Time-Dependent Air Concentration Data

The air concentration in refining plants varied with time. The following information was extracted from Strom (2006). Christofano and Harris (1960) showed that there was a large reduction over the years in time-weighted average air concentrations of uranium in various refining plants (Figure 1).

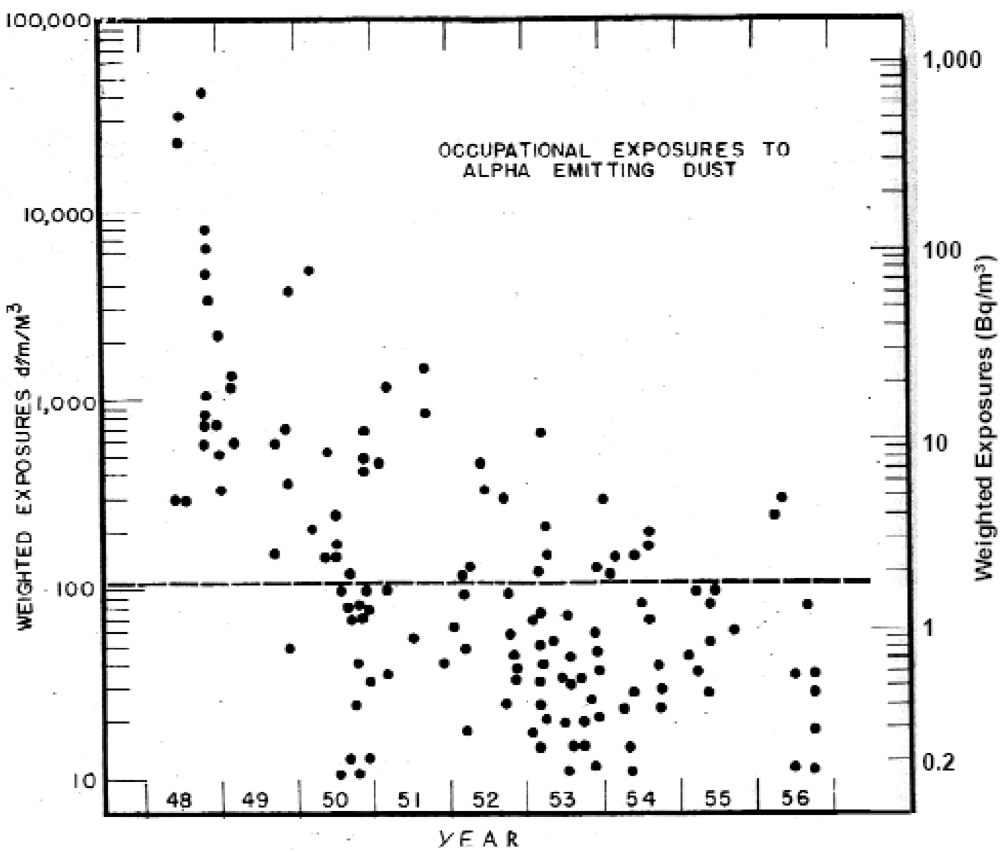

Figure 1. Data from Figure 1 of Christofano and Harris (1960) showing the decreasing trend in time-weighted average air concentrations of alpha-emitting dust.

The image in Figure 1 was digitized[1] and the data analyzed for each year. The average value (mean) was computed from the digitized data for each year, and a lognormal was fit to the data for each year by computing natural logs, averaging them, and taking their standard deviation as described in BTIB-5000. The geometric mean and geometric standard deviation (*GSD*) was calculated for each year, and an upper 95th percentile. These results are shown in Table 8.27 and Figure 2. Vertical bars are "times or divided by" one *GSD*.

[1] UnGraph V5, Biosoft, http://www.biosoft.com, PO Box 1013, Great Shelford, Cambridge, CB2 5WQ United Kingdom. tel: +44 1223 841700 fax: +44 1223 841802

Table 8.27. Results of digitizing data from **Figure 1**. All concentrations (columns 3-7 and 9) are in dpm/m^3

Year	No. Data Points	Mean	Standard Deviation	Geometric Mean	Geometric Mean ×*GSD*	Geometric Mean ÷*GSD*	*GSD*	Upper 95%ile
1948	17	7398	12417	2061	10792	393	5.24	31391
1949	9	964	1119	540	1902	153	3.52	4286
1950	25	349	951	101	434	24	4.29	1112
1951	8	521	569	219	1062	45	4.85	2940
1952	15	124	133	79	207	30	2.62	385
1953	31	71	121	40	102	16	2.53	186
1954	15	94	85	60	170	21	2.84	334
1955	8	63	27	57	91	36	1.58	122
1956	9	85	109	43	144	13	3.35	315
Total	137							

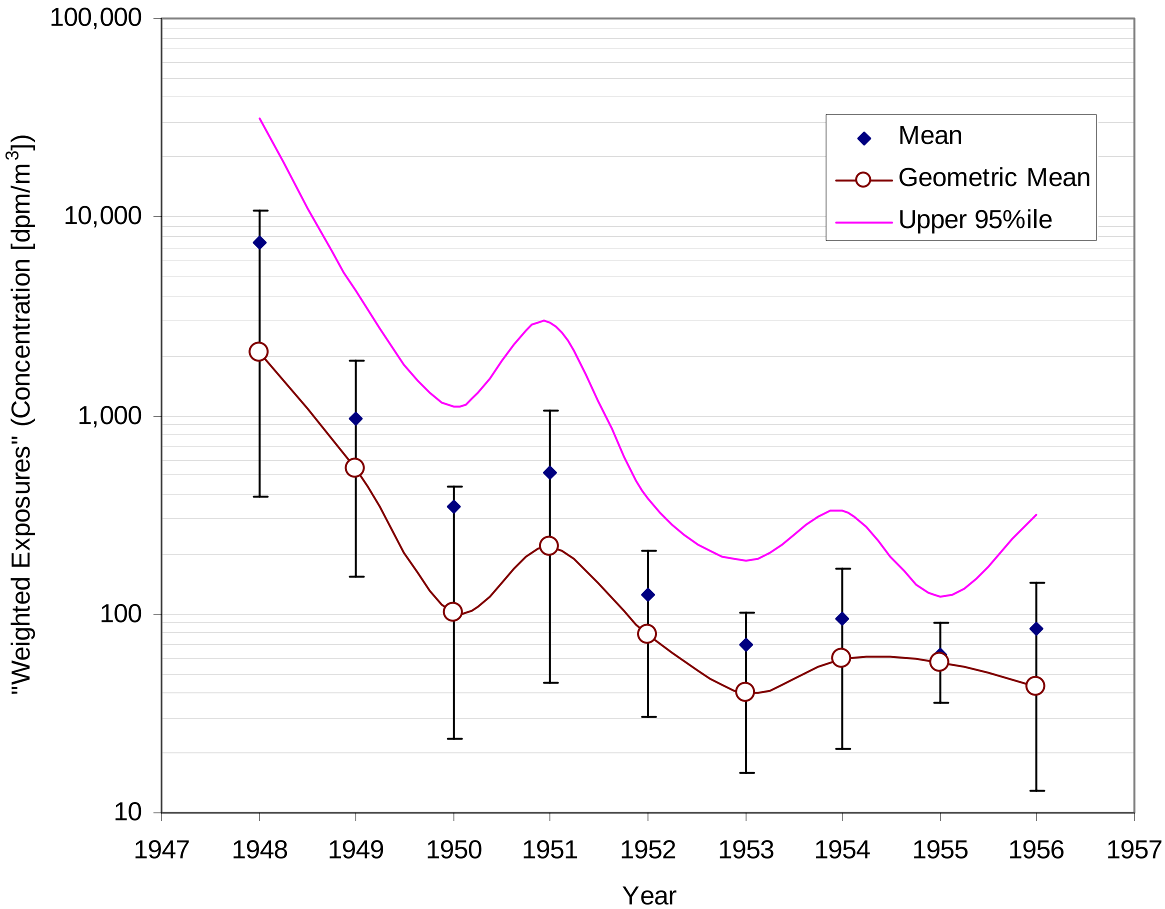

Figure 2. Analysis of time-weighted average air concentrations from Christofano and Harris (1960; Fig. 1). Variability bars are the geometric mean times or divided by one *GSD*.