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Acronyms and Abbreviations

ABRWH	Advisory Board on Radiation and Worker Health
AEC	Atomic Energy Commission
AMAD	Aerodynamic Median Aerosol Diameter
AP	anterior-posterior
AWE	Atomic Weapons Employer
BZ	breathing zone
CATI	Computer-Assisted Telephone Interview
CV	coefficient of variation
$d/m/m^3$	disintegrations per minute per cubic meter
DCF	dose conversion factor
DOL	Department of Labor
DR	dose reconstruction
DWA	daily weighted average
Dx	diagnosis
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
FGR-12	Federal Guidance Report 12
GA	general area
GSD	geometric standard deviation
HP	health physicist
ICD-9	International Classification of Diseases Revision 9
ICRP	International Commission on Radiological Protection
IH	industrial hygienist
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive Radioepidemiological Program
ISO	isotropic
keV	kiloelectronvolt
LAT	lateral
LOGNORM4	computer program
Max	maximum
MED	Manhattan Engineer District
MeV	megaelectronvolt
Min	minimum
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH Occupational Claims Tracking System
NORMSDIST()	standard Normal distribution function in Microsoft Excel
NORMSINV()	inverse standard Normal distribution function in Microsoft Excel
OCAS	Office of Compensation and Support
PA	posterior-anterior
ROT	rotational

SD	standard deviation (arithmetic)
SEC	Special Exposure Cohort
SQRI	Site Query Research Interface
TBD	Technical Basis Document
TIB	Technical Information Bulletin
TLD	thermoluminescent dosimeter
TLV®	Threshold Limit Value (® American Conference of Governmental Industrial Hygienists)
Tn	thoron (^{220}Rn)
TWA	time-weighted average
WLM	working level month (a unit of potential alpha energy concentration)

1.0 PURPOSE AND SCOPE

Technical Basis Documents and Site Profile Documents are general working documents that provide guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 (42 U.S.C. § 7384l(5)) and (12)).

This technical basis is established for the reconstruction of radiation doses of workers at Atomic Weapons Employer (AWE) sites which refined uranium under contract to the United States government from 1942 to 1958.

The two principal purposes of this technical basis document are (1) to provide information sufficient to enable dose reconstructors to estimate favorable to claimant doses for these workers on an individual basis under the provisions of the Energy Employees Occupational Illness Compensation Program Act (EEOICPA) and (2) to allow claimants, federal assessors, and others to understand the information sources and assumptions on which the dose estimations are based.

This document covers the generic aspects of uranium refining and the data are useful where no other dosimetry data exist. Site specific appendices are included that provide information that apply to only the identified site.

Employment at an AWE facility is categorized as either (1) during the contract period (*i.e.*, when the AWE was processing or producing material that emitted radiation and was used in the production of an atomic weapon), or (2) during the residual contamination period (*i.e.*, periods that NIOSH has determined there is the potential for significant residual contamination outside of the period in which weapons-related production occurred). For contract period employment, all occupationally-derived radiation exposures at the facility must be included in dose reconstructions. NIOSH does not consider the following exposures to be occupationally-derived:

- radiation from naturally occurring radon present in conventional structures; and
- radiation from diagnostic X-rays received in the treatment of work-related injuries.

For residual contamination period employment, only the radiation exposures defined in 42 U.S.C. § 7384n(c)(4) (*i.e.*, radiation doses received from DOE/AEC-related work) must be included in dose reconstructions. Radiation dose received from DOE/AEC-related work includes: (1) radiation from radon consistent with NIOSH's policies for including such radiation in the contract period; and, (2) medical screening X-rays, but not diagnostic X-rays for the treatment of work-related injuries. It should be noted that: (1) under subparagraph A of § 7384n(c)(4), radiation associated with the Naval Propulsion Program is specifically excluded from the employee's radiation dose; and, (2) under subparagraph B of this section, radiation from a source not covered by subparagraph A that cannot be reliably distinguished from radiation that is covered by subparagraph A is considered part of the employee's radiation dose. This site profile covers only exposures resulting from nuclear weapons-related work. Exposures resulting from non-weapons related work, if applicable, will be covered elsewhere.

2.0 INTRODUCTION

The Manhattan Engineer District (MED), the predecessor agency of the Atomic Energy Commission (AEC), asked various companies to assist in the production of uranium metal from ore. In most cases, no one contractor had experience in all aspects of the refining process and it was necessary to partition the refining process into several steps and apportion the steps among various chemical forms (Christofano and Harris 1960).

In this document, the context for interpretation of the existing records is established, along with the basis on which to determine missing doses for periods in which records do not exist.

Site specific appendices are also presented that may be used for dose reconstruction. Where gaps occur in site specific dosimetry information, the dosimetry data of the generic portion of the TBD should be used.

The primary reference for the generic portion of the TBD is Christofano and Harris (1960). The text and data tables were liberally borrowed from Christofano and Harris (1960) unless otherwise stated.

3.0 Uranium Dosimetry

This TBD discusses the radiation doses that could result from work at AWE refinery sites. Most refinery work was associated with the production of uranium metal from ore. There was, however, refining for thorium metal. This section describes the dosimetry of uranium.

3.1 Characteristics of Uranium

Uranium is a heavy metal. There are several isotopes of uranium and, depending on the process in question, uranium may have been enriched in some of the isotopes. Most AWE uranium refining sites were concerned with natural uranium.

All isotopes of uranium are radioactive and the decay progeny of uranium are also radioactive, forming a long decay chain. For the most part, the radioactive progeny of uranium were separated from uranium during the digestion and extraction phases. After those processes were completed only the uranium isotopes were present. But some ingrowth of uranium progeny does occur even after a short time (~100 days) with a dose rate that exceeds the dose rate from pure uranium.

It is important for the dose reconstructor to determine the source of the ore that was refined. For the purposes of this TBD, there were two types of ore; a high grade (high concentration of uranium in the mined ore) often refered to as pitchblend, and all other types of ore that were of lesser uranium concentration. The reason it is important to know the source of the ore is that the quantity of radioactive progeny in the ore would vary according to the source. The relative concentration of radioactive progeny might not vary, but the absolute quantity of the radioactive progeny would vary according to the concentration of uranium in the ore. The source of uranium is important for only the initial steps of the refining process. After the uranium has been extracted from ore, the dose rates from all uranium sources are identical. See Table 7.2 to obtain dose rates from drums that contain uranium. Table 3.8 lists measured dose rates from drums that contained pitchblend. Because it may not be known which ore was processed at a particular facility, the dose rates shown in the External Dosimetry section are for pitchblend ore.

Natural uranium consists of four isotopes, ^{234}U, ^{235}U, ^{236}U, and ^{238}U. The term enrichment refers to the extent to which the amount of ^{235}U has been increased relative to naturally occurring uranium. The relative amounts of each isotope for different enrichments were obtained from IMBA Expert – OCAS Edition and are listed in Table 3.1.

Table 3.1 Typical isotopic composition of uranium at different enrichments.

Enrichment	Isotope	Weight Fraction	Specific Activity		
			Bq/mg	pCi/mg	dpm/mg
Depleted	^{234}U	0.000010	2.31×10^{00}	$6.24\times10^{+01}$	$1.39\times10^{+02}$
	^{235}U	0.001991	1.59×10^{-01}	$4.30\times10^{+00}$	$9.55\times10^{+00}$
	^{236}U	0.000003	7.44×10^{-03}	2.01×10^{-01}	4.46×10^{-01}
	^{238}U	0.997996	$1.24\times10^{+01}$	$3.35\times10^{+02}$	$7.45\times10^{+02}$
	Total		$1.49\times10^{+01}$	$4.02\times10^{+02}$	$8.93\times10^{+02}$
Natural	^{234}U	0.000054	$1.24\times10^{+01}$	$3.35\times10^{+02}$	$7.44\times10^{+02}$
	^{235}U	0.007204	5.76×10^{-01}	$1.56\times10^{+01}$	$3.46\times10^{+01}$
	^{236}U	0.000000	$0.00\times10^{+00}$	$0.00\times10^{+00}$	$0.00\times10^{+00}$
	^{238}U	0.992742	$1.23\times10^{+01}$	$3.33\times10^{+02}$	$7.41\times10^{+02}$
	Total		$2.53\times10^{+01}$	$6.84\times10^{+02}$	$1.52\times10^{+03}$
Low Enrichment	^{234}U	0.000290	$6.70\times10^{+01}$	$1.81\times10^{+03}$	$4.02\times10^{+03}$
	^{235}U	0.034989	$2.80\times10^{+00}$	$7.56\times10^{+01}$	$1.68\times10^{+02}$
	^{236}U	0.000000	$0.00\times10^{+00}$	$0.00\times10^{+00}$	$0.00\times10^{+00}$
	^{238}U	0.964722	$1.20\times10^{+01}$	$3.24\times10^{+02}$	$7.20\times10^{+02}$
	Total		$8.18\times10^{+01}$	$2.21\times10^{+03}$	$4.91\times10^{+03}$
High Enrichment	^{234}U	0.010606	$2.45\times10^{+03}$	$6.62\times10^{+04}$	$1.47\times10^{+05}$
	^{235}U	0.934636	$7.47\times10^{+01}$	$2.02\times10^{+03}$	$4.48\times10^{+03}$
	^{236}U	0.002075	$4.97\times10^{+00}$	$1.34\times10^{+02}$	$2.98\times10^{+02}$
	^{238}U	0.052683	6.55×10^{-01}	$1.77\times10^{+01}$	$3.93\times10^{+01}$
	Total		$2.53\times10^{+03}$	$6.84\times10^{+04}$	$1.52\times10^{+05}$
Recycled	^{234}U	0.000082	$1.90\times10^{+01}$	$5.13\times10^{+02}$	$1.14\times10^{+03}$
	^{235}U	0.009700	7.76×10^{-01}	$2.10\times10^{+01}$	$4.65\times10^{+01}$
	^{236}U	0.000680	$1.63\times10^{+00}$	$4.40\times10^{+01}$	$9.77\times10^{+01}$
	^{238}U	0.989500	$1.23\times10^{+01}$	$3.33\times10^{+02}$	$7.38\times10^{+02}$
	Total		$3.37\times10^{+01}$	$9.10\times10^{+02}$	$5.03\times10^{+03}$

Table 3.1 includes a reference to recycled uranium. Recycled uranium is uranium that has been irradiated in a reactor and from which the plutonium has been extracted. Recycled uranium will contain ^{236}U, sparingly found in naturally occurring uranium, due to the processes in a reactor. Note that high enrichment uranium contains appreciable amounts of ^{236}U while low enriched uranium contains virtually no ^{236}U. The reason for this apparent discrepancy is that high enriched uranium is generally derived from recycled uranium and is commonly associated with weapons development whereas low enriched uranium is generally associated with the commercial fuel cycle where the feed material for enrichment is natural uranium.

For the time period from 1944 until 1952, all uranium used by the DOE (and predecessor agencies) was derived from natural sources because processes that recover uranium from spent fuel were not available (DOE/SO-0003, p 14)(DOE 2003).

There is the possibility that uranium processed in refineries after 1953 was recycled uranium or contained recycled uranium, so for these time periods, in the absence of definitive information about the origin of the processed uranium, it should be assumed that the uranium contains the contaminants listed in Table 3.2 of ORAUT-OTIB-0004, R3 (ORAUT 2005c). The appendices for each site should contain information concerning whether recycled uranium was present at the site.

Table 3.2. Assumed activity fraction (Bq contaminant/Bq uranium) of contaminants in recycled uranium.

Recycled Uranium Contaminant	Pu-239	Np-237	Tc-99	Th-232	Th-228
Activity fraction of contaminant in uranium	0.00246	0.00182	0.379	2.73E-06	2.73E-06
Contaminant in ppb of uranium	10	1,040	9,000	10,888	*

* assumes same activity as Th-232

3.2 Radiation Emissions

Natural uranium emits both beta particles (electrons) and photons (X-ray and gamma photons), as shown in Table 3.3, derived from Kocher (1981). The two primordial components of natural uranium are ^{238}U and ^{235}U, but some of their decay products grow into equilibrium quickly enough to be hazardous in processing metal.

Uranium-238 transitions by alpha decay to ^{234}Th, emitting traces of weakly penetrating ~ 13 keV L X-rays. However, ^{234}Th transitions primarily to 1.17-minute ^{234m}Pa, the metastable state of protactinium-234, which in turn transitions to ^{234}U with the emission of a 2.28-MeV beta particle in 98.6% of transitions (Kocher 1981). This relatively high-energy beta particle accounts for significant external dose rates to skin, lens of the eye, and to a certain extent to shallow portions of tissues such as thyroid, female breast and bone marrow. It also produces significant bremsstrahlung X-rays, primarily in the 30-250 keV energy range. The photons emitted from ^{234m}Pa are responsible for the external doses from uranium progeny. Because ^{234m}Pa is a decay product of ^{234}Th the dose rate due to ^{234m}Pa will decay with an effective half-life of 24.1 days. Dose rates from uranium compounds are presented in Sections 7.2 and 7.3.

Uranium-235 emits alpha particles and gamma photons in about 70% of its transitions, but occurs as 0.7200 atom % in natural uranium.

Like ^{238}U, ^{234}U emits alpha particles and traces of weakly penetrating L X-rays.

Table 3.3. Principal radiation emissions from natural uranium and its short-lived decay products that are of concern for external irradiation (not including bremsstrahlung)

Radionuclide	Half-life	Beta Energy (MeV Max)	Photon (x or γ) Energy (MeV)
^{238}U	4.468E+9 years	None	x: 0.013 (8.8%)
^{234}Th	24.1 days	0.096 (25%)	x: 0.013 (9.6%)
		0.189 (73%)	γ: 0.063 (3.8%)
			γ: 0.093 (5.4%)
^{234m}Pa	1.17 minutes	2.28 (98.6%)	γ: 0.765 (0.2%)
		~1.4 (1.4%)	γ: 1.001 (0.6%)
^{235}U	7.038E8 years	None	x: 0.013 (31%)
			x: 0.090-0.105 (9.3%)
			γ: 0.144 (10.5%)
			γ: 0.163 (4.7%)
			γ: 0.186 (54%)
			γ: 0.205 (4.7%)
^{231}Th	25.5 hours	0.206 (15%)	x: 0.013 (71%)
		0.288 (49%)	γ: 0.026 (14.7%)
		0.305 (35%)	γ: 0.084 (6.4%)
^{234}U	2.445E+5 years	None	x: 0.013 (10.5%)
			γ: 0.053 (0.2%)

3.3 External Dosimetry

External dosimetry refers to the radiation dose received from radioactive material that is outside the body. External doses can be associated with immersion in airborne radioactive material, accumulations of radioactive material associated with a particular process and radioactive material that contaminates the floor or other surfaces.

Nonpenetrating dose from natural uranium consists primarily of electrons with energies above 15 keV. For consistent presentation, exposure or dose is reported as:

- penetrating, assumed to be associated with photons 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, and
- nonpenetrating, assumed to be associated with photons of energies less than 30 keV or with electrons.

3.3.1 Electron Dosimetry

Uranium metal and compounds emit beta and electron radiation that can irradiate the skin, and to a more limited extent, the shallow organs of the body. Table 3.4, taken from DOE-STD-1136-2004 (DOE 2004) shows the measured beta surface dose rates from uranium metal and selected uranium compounds.

Table 3.4. Beta Surface Exposure Rates from Equilibrium Thickness of Uranium Metal and Compounds (DOE-STD-1136-2004)

Source	Beta Surface Exposure Rate, mrad h^{-1}
U-Nat metal slab	233
UO_2	207
UF_4	179
$UO_2(NO_3)_26H_20$	111
UO_3	204
U_3O_8	203
UO_2F_2	176
$Na_2U_2O_7$	167
a. Beta surface exposure rate in air through a polystyrene filter 7mg/cm^2 thick.	

The data shown in Table 3.4 show that the dose rates from uranium metal exceed the dose rates from other uranium compounds. However, the dose rates from uranium oxides and UF_4 are sufficiently similar in magnitude to the dose rates from uranium metal so that uranium metal dose rates can be assumed to be representative of the dose rates from all uranium compounds.

Nonpenetrating dose from natural uranium consists primarily of electrons with energies >15 keV. Skin doses to uranium refining workers can be estimated using the same methods used to calculate the dose from uranium metal. Skin doses (7 mg/cm^2) are estimated for two worker cases: the hands and forearms of a worker who handles uranium metal, and the other skin surfaces of a worker who handles the metal.

Assuming that an operator's hands are in contact with the uranium metal or compounds for 50% of the day would give a non-penetrating dose to the hands and forearms of 1.17 rad for a 10-hour workday (0.93 rad for an eight-hour workday). This dose estimate assumes that no gloves or protected clothing shielded the worker's hands and forearms, which may have been true for some of the earliest years of uranium metal-working, and is an assumption that is favorable to the claimant for other workers. These assumed dose rates are also favorable to claimants who worked at uranium refining facilities other than where metal reduction occurred.

For dose to other skin on the worker's body that is not in direct contact with uranium, but is nearby (for example, a worker's neck and face when the hands are in contact with metal), a dose relation can be used that estimates this dose to be 10 times the photon dose rate at 1-foot. This relation, based on a review of film badge data, is documented in ORAUT (2005e). The photon dose rate at 1 foot from a slab of uranium is 2.08 mrem/h (ORAUT-TKBS-0034) (ORAUT2005e), which would give a non-penetrating dose rate of 20.8 mrem/h using this relation. For a worker spending 50% of a 10-hour workday handling uranium, this would give a dose rate of 0.10 rad/d (0.083 rad/d for an eight-hour workday). This dose rate would be appropriate for areas of the skin other than the hands and forearms, and for tissues and organs near the body surface, including breast, penis, testes, skin and eye.

For a worker who does not directly handle uranium materials, the non-penetrating dose rate would usually be zero, but it could be argued that a worker who was very close to the uranium material without actually touching it may have been exposed to 0.10 rad/d of non-penetrating radiation, similar to the non-contact skin doses for a metal handler described in the previous paragraph.

3.3.2 Other Non-Penetrating

After 1952, small quantities of primarily alpha (Pu-239, Np-237, and Th-232/228) and beta (Tc-99) emitting radionuclides found their way into the uranium metal via recycling (see Table 3.2). Because of their primarily non-penetrating radiation types, relatively low activities, and relatively low external radiation hazard when compared to that of their uranium matrix, their contribution to dose is considered adequately addressed by the uranium external dose estimates. A quick check of the relative penetrating dose from an overestimate of recycled uranium contaminants in ground surface contamination shows that they contribute less than 1% to penetrating dose. The assumed non-penetrating doses from uranium in this document are sufficiently large to bound any small contribution from Tc-99.

3.3.3 Photon Dosimetry

- According to ORAUT-OTIB-0004, Rev. 3 (ORAUT 2005c) the majority of photons from natural uranium are in the 30 to 250 keV energy range. Calculations using the program MicroShield indicate that about 56% of the photon energy released from natural uranium is above 250 keV. Uranium, even when present as chemical compounds, provides considerable shielding of the lower energy photons and will tend to harden the spectrum, causing the majority of photons emitted from uranium, to have energies greater than 250 keV. While it is recognized that uranium sources will have a somewhat hardened photon spectrum, exposure to a thin layer of uranium on a surface will result in a larger fraction of exposure to lower energy photons. The analysis described above assumed workers were exposed to photon energies in the 30 to 250 keV range, which is favorable to claimants when considering both organ dose conversion factors and radiation effectiveness factors.

3.3.4 Neutron Dosimetry

There are two sources of neutrons. First, neutrons arise from (α-n) reactions, where the reactant is fluorine which occurs during the production of UF_4 and UF_6 and oxygen that is present in uranium oxides. Second, there is a small amount of spontaneous fission by uranium. Table 3.5 shows spontaneous fission and alpha-neutron yields for various uranium isotopes and ^{232}Th.

Table 3.5. Neutron yields from spontaneous fission and alpha-neutron reactions for oxides and fluorides.

Isotope	Spontaneous Fission Yield, n s^{-1} g^{-1}	Yield in Oxides, n s^{-1} g^{-1}	Yield in Fluorides, n s^{-1} g^{-1}
^{232}Th		2.2E-5	
^{232}U	1.3	1.49E4	2.6E+6
^{233}U	8.6E-4	4.8	7.0E+2
^{234}U	5.02E-3	3	5.8E+2
^{235}U	2.99E-4	7.1E-4	0.08
^{236}U	5.49E-3	2.4E-2	2.9
^{238}U	1.36E-2	8.3E-5	0.028
(DOE-STD-1136-2000)			

The production of neutrons by alpha-neutron interactions in uranium compounds will vary according to the light element involved in the interaction. Table 3.6, obtained from DOE-STD-1136-2004 (DOE 2004), shows the neutron yields for various light elements. The data in this table shows that, for the

compounds present in refineries, the greatest yield is from fluorine and the yield from oxygen compounds is two orders of magnitude less.

Table 3.6 Neutron yields for trace impurities in uranium

Element	Neutron Yield per 10^6 Alphas at 4.7 MeV (^{234}U)
Li	0.16 ± 0.04
Be	44. ± 4
B	12.4 ± 0.6
C	0.051 ± 0.002
O	0.040 ± 0.001
F	3.1 ± 0.3
Na	0.5 ± 0.5
Mg	0.42 ± 0.03
Al	0.13 ± 0.01
Si	0.028 ± 0.002
Cl	0.01 ± 0.01
(DOE-STD-1136-2004)	

An analysis of neutron dose rates from uranium and thorium oxides and fluorides was performed for the Mallinckrodt site (ORAUT-TKBS-0005) (ORAUT 2005a). The calculated neutron dose rates are shown in Table 3.7. The calculated neutron dose rates can then be compared to the measured dose rates from pitchblende ore, shown in Table 3.8. Pitchblende ore contains a very high concentration of U_3O_8. The measured dose rates from pitchblende ore were divided by 4.43 and 5.91 so that the measured and calculated dose rates would represent the dose rate from the same amount of U_3O_8. Comparison of the measured beta/photon dose rates and the calculated neutron dose rates show that the neutron dose rate is about 0.07% of the beta/photon dose rate and need not be included in dose rate calculations. For uranium metal, the neutron dose rate is even less important. The data in Table 3.5 show that the neutron emission rate due to spontaneous fission is much less than the neutron emission rate due to (alpha, n) reactions.

The calculated neutron dose rates from selected uranium compounds are shown in Table 3.7.

Table 3.7 Neutron dose rates and doses from alpha-neutron reaction sources

Form	Source	Target element(s)	Weight in container	Dose rate at 1 foot, rem/h	Dose Rate at 3 feet, rem/h
U3O8	U natural mix	O	100 lb	1.29E-07	1.44E-08
	U natural mix + daughters	O	100 lb	1.22E-07	3.67E-04
UO3, UO2	U natural mix	O	75 lb	9.71E-08	3.24E-05
	U natural mix + daughters	O	75 lb	8.27E-07	9.19E-08
UF4	U natural mix	F	75 lb	6.92E-06	7.69E-07
	U natural mix + daughters	F	75 lb	5.91E-05	6.57E-06
Na2U2O7 (soda salt)	U natural mix	O, Na	75 lb	2.61E-07	2.90E-08
	U natural mix + daughters	O, Na	75 lb	2.13E-06	2.37E-07

Data taken from Table 34 of ORAUT-TKBS-0005 (ORAUT 2005a)

In the alpha-neutron case, the neutron energy was taken as 1.5 MeV because it is the approximate maximum energy for Th-232, the other isotopes also emit neutrons in the range 1.0-2.0, and the flux-to-dose conversion factor varies slowly in this range.

The neutron dose rates of Table 3.7 can be compared with the measured beta/gamma dose rates for drums that contain pitchblende ore as shown in Table 3.8. Pitchblende ore contains a large fraction of U_3O_8 and allows comparison with the neutron dose rates in Table 3.7.

Table 3.8. Measured beta/gamma dose rates from containers of pitchblende ore.

Source Material	Exposure mrep/h or mR/h		
	443 lb	100 lb	75 lb
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 60”	2.4	0.55	0.41
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 45”	3.6	0.81	0.61
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 30”	7.1	1.6	1.2
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: contact	90	20	15
Data taken from Table 33 of ORAUT-TKBS-0005 (ORAUT 2005a) . The column labeled “443 lb” contains the actual measured dose rates. The column labeled “100 lb” contains dose rates that have been reduce by a factor of 4.43 so they can be compared with the neutron dose rates shown in Table 3.7.			

The data shown in Table 3.7 and Table 3.8 indicate that, for U_3O_8, the neutron dose rate is about 0.3% of the beta/gamma dose rate. This fraction is small enough to be neglected in dose calculations. The data in Table 3.5, indicate that, for uranium metal, the neutron dose rate will be an even smaller fraction of the total dose rate. Dose reconstructors may ignore the neutron dose rates for dose calculations involving uranium metal and compounds.

3.4 Source Terms for External Doses

External doses in uranium refining facilities typically arise from five different modes of exposure:

- Submersion in air contaminated with uranium dust,
- Exposure from contaminated surfaces,
- Exposure to electrons from the surface of the uranium, particularly if the uranium is metal,
- Exposure to photons from the surface of uranium, and
- Exposure to an annual diagnostic X-ray.

Exposures to diagnostic X-rays are discussed in Section 5.0. The other components of external dose are discussed in Sections 3.3.

3.4.1 Submersion in Contaminated Air and Exposure to Contaminated Surfaces

When workers are enveloped in a cloud of radioactive dust, they will receive a small amount of external dose. External exposure 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.

Table 3.9. Dose conversion factors and daily doses for external dose due to submersion in uranium-contaminated air.

External Dose Conversion factor		
Time since separation	(mR/h per dpm(α)/m^3)	(mR/d per dpm(α)/m^3)
100 d	2.46E-09	1.97E-08

3.4.2 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 3.10. 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.

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, 76.7% of the exposure is associated with photons with energies below 30 keV; 10.0% is from photons with energies between 30 keV and 250 keV, and the remaining 13.3% 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.

Table 3.10 Daily dose rates from natural uranium surface contamination (dpm total alpha activity) over 1 m^2.

Surface contamination dose conversion factors		
Time since separation	(mR/h per dpm(α)/m^2)	(mR/d per dpm(α)/m^2)
100 d	5.61E-10	4.49E-09

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. 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.

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 3.10 should be used. 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.

3.4.3 Exposures from Contaminated Soil

Workers at a facility that is no longer performing AWE work will also be exposed to radiation from residual contamination. If measurements of the contamination are not available for this time period, the doses presented in Table 3.11 can be used as an estimate of the external doses from this dose pathway.

Table 3.11. Dose rates from uranium activity in the soil.

Soil contamination dose conversion factor		
Time since separation	(mrem/h per g/cm^3)	(mrem/d per g/cm^3)
100 d	152.78	1222.22
15 y	152.85	1222.76

3.5 Internal Dosimetry

Internal dosimetry refers to the radiation dose received from radioactive material that is inside the body. Radioactive material can enter the body via inhalation of radioactive dusts, ingestion of radioactive dusts as may happen due to incidental hand to mouth transfers, and contaminated wounds. Internal doses for individuals can be estimated based on airborne concentrations of radioactive materials by using the computer code IMBA Expert OCAS Edition that implements the biokinetic models that have been developed by the International Commission on Radiological Protection (ICRP).

IMBA Expert also provides mechanisms for interpretation of bioassay data. Bioassay data can be of two kinds; in vivo bioassay and in vitro bioassay. In vivo bioassay consists of placing the person near radiation detectors that measure the amount of radiation that exits the body and based on the efficiency of the counting process the quantity of radioactive material in the body can be determined. In vitro bioassay consists of collecting the excreta (urine and feces) or breath of an individual who has had an intake of radioactive material and, by comparing the measured results with the results predicted by biokinetic models, the quantity of radioactive material that would be required to be in the body to produce the observed excretion is calculated.

Internal doses are influenced by several properties of the material that is taken into the body. Pertinent quantities include the particle size of the aerosol, the shape of individual particles in the aerosol, the density of the airborne material, and the solubility of the material.

During the refining process, uranium undergoes several chemical reactions and so there are several uranium compounds that may have become airborne during various processes. The impact of uranium forming compounds is that the specific activity of uranium metal, shown in Table 3.1 will be different than the specific activity of the compound. The specific activities of various compounds of natural uranium are shown in Table 3.12.

In the text of this TBD the chemical compound associated with each process will be identified.

Table 3.12. Some internal dosimetry related characteristics of uranium

Material	U weight Fraction	Density	Solubility Data		Specific Activity		
		g/cm^3	Type	f_1	Bq/mg	pCi/mg	dpm/mg
UO_2	0.881498	10.96	S	0.002	2.23E+01	6.03E+02	1.34E+03
UO_3	0.832190	7.29	M	0.02	2.11E+01	5.69E+02	1.26E+03
U_3O_8	0.848001	8.3	S	0.002	2.15E+01	5.80E+02	1.29E+03
UF_4	0.757999	6.7	M	0.02	1.92E+01	5.18E+02	1.15E+03
UF_6	0.676181	-	F	0.02	1.71E+01	4.63E+02	1.03E+03
$UO_2(NO_3)_2$	0.604077	-	F	0.02	1.53E+01	4.13E+02	9.18E+02
UO_2F_2	0.772760	-	F	0.02	1.96E+01	5.29E+02	1.17E+03
UCl_4	0.626656	4.87	M	0.02	1.59E+01	4.29E+02	9.53E+02

Unless specified otherwise, the characteristics of aerosols are:

- Particle Size is 5 micron AMAD
- Shape Factor is 1.5
- Density is 3
- Lung Solubility Type as given in Table 3.12
- Absorption factor f_1 as given in Table 3.12

The dose reconstructor should use the default values shown above. The default values of ICRP-66 (ICRP 1994) should be used. The density values shown in Table 3.12 are for reference only.

The intake of radioactive material via inhalation depends on the characteristics of the worker, that is their breathing rate and the extent to which they breath through the mouth. IMBA does not calculate intakes based on air concentrations, rather the dose reconstructor is required to calculate the intake from the breathing rate and the air concentration. Unless specified otherwise in the site specific guidance, the following worker characteristics should be assumed:

- Worker type: Light Worker
- Breathing Characteristics: Nasal Augmentor
- Breathing Rate: 1.2 m^3/h or 9.6 m^3/day (for an 8 h day)

The intake is the product of the breathing rate, shown above, and the air concentration. The generic air concentrations are listed in the Chapter 8. For some processes, the air concentration tables show a DWA and in those cases the Daily Weighted Average (DWA) (See Section 11) is the air concentration to use. If a DWA air concentration is not available then use the average daily exposure air concentration.

3.5.1 Inhalation

Inhaled uranium can have two sources:

- Uranium dust generated by plant operations. This source will dominate while the plant is operating.
- Uranium dust generated by resuspension of material on contaminated floors by casual foot traffic.

Specific information concerning these two sources are discussed in the internal dosimetry section.

3.5.2 Ingestion

In the case where inhalation intakes are calculated from air concentrations, ingestion intakes are also to be considered. NIOSH (2004) indicates that the ingestion rate, in terms of dpm for an 8-hour workday, can be estimated by multiplying the air concentration in dpm per cubic meter by a factor of 0.2. Adjusting for a 10-hour day, and converting dpm to pCi, the ingestion intake would be 0.114 times the inhalation intake.

4.0 Process Description

Refining consists of converting uranium in the form of U_3O_8 to either metal or UF_6. Nine processes were associated with the refining of uranium. They are:

- Ore digestion
- Solvent extraction
- Boildown and Denitration
- Oxide Reduction
- Hydrofluorination
- Reduction to Metal
- Recasting
- Fluorination
- Scrap Recovery

The industrial hygiene aspects of uranium refining varied over time. Initially, the process was spread over many facilities and there were few dust control measures in the plants. Packaging and transferring of materials between sites often involved some of the highest exposures. With time the processes were improved and organized into two parallel integrated DOE plants. The process descriptions are a summary of the information provided by Christofano and Harris (1960).

4.1 Ore Digestion

Ore digestion was the first step in the refining process. In this process hot uranium ore (often screened to 20 mesh powder - Christofano and Harris (1960)) or concentrate (without processing) was dissolved in hot concentrated nitric acid. Separate systems were maintained for hot ore and concentrate as the hot ore required shielding and some remote operation. In the hot ore process, piping became contaminated and produced significant amounts of background γ-radiation. If materials were added too rapidly, the violence of the reaction would flood the air with uranium-laden nitric fumes. Materials that could become airborne were dusts, mist, and nitric oxide fumes. These reactions were kept under a slight negative pressure through a nitric acid recovery system. Uncontrolled manual feeding operations had much higher exposures than contained and ventilated operations. Highest exposures were associated with the maintenance and cleaning of filters used to separate the dissolved uranium solution from the silica (sand). Later modification allowed the slurry containing sand to be fed into the solvent extraction process removing this high exposure task.

A byproduct from this process included radium cake (a barium sulfate precipitate) which was separated out by centrifuge. Drums of this material had high γ-radiation levels at their surface.

The uranium ore was a powder, often 20 mesh (Christofano and Harris (1960)). Twenty mesh powder has a diameter of 840 μm (Lide 1995, p 15-37). If 840 μm is assumed to be the upper 99%ile of the aerosol particle size distribution, the equations of ICRP-66 (ICRP 1994) would imply that the actual AMAD of the aerosol is about 54 μm. For this project dusts have an assumed particle size distribution of 5 micron AMAD.

4.2 Solvent Extraction

This process separates uranium nitrate from nitrates of other, undesirable metals including radioactive components. The uranium that exits the solvent extraction process is the purest form of uranium in the refining process because ingrowth of uranium progeny that occurs after this time will reduce the purity of uranium. The byproduct is called raffinate and may be concentrated and calcined to recover nitric acid or simply discarded – presenting a problem of waste storage. The process is continuous, enclosed and utilizes only liquids, and thus presents the least exposure of the refining processes. Ethyl ether was used early on and replaced by tributyl phosphate in kerosene. The uranium-bearing aqueous solution from the digestion process is fed into the top of the extraction column, while the organic solvent is fed into the bottom. The organic extract is then scrubbed with hot demineralized water in a similar column. The resulting dilute solution of highly purified uranium nitrate is the purest form of uranium in the refining process. From here on out contaminants are added by the process.

4.3 Boildown and Denitration

Denitration is the process of converting the extracted uranium nitrate to UO_3(orange oxide). The dilute solution of uranium nitrate is concentrated into uranyl nitrate hexahydrate (UNH) using multi-effect evaporators and boildown tanks. If metal is the desired end product, denitration is accomplished by controlled heating in gas-fired pots with continuous agitation. First water vapor is driven off, followed by oxides of nitrogen (into an acid recovery system), leaving uranium trioxide (UO_3). The UO_3 is dry and very dusty. Hand removal by shovel and scraping resulted in very high exposures (30,000-80,000 $d/m/m^3$). This method was later replaced by pneumatic conveyor which considerably reduced exposures (560 $d/m/m^3$). However, when improper heat regulation caused UO_3 to build on the pots, it had to be chopped out causing the same high exposures as manual removal. A continuous rotary kiln denitration process could be used if the product was to be UF_6, but introduced too much product variation for metal production. This process was used at Paducah and Oak Ridge. Even in these situations, with enclosures and ventilation, exposures in the remote control areas exceeded the maximum permissible exposure level and required air supplied respirators and rotation of personnel.

4.4 Oxide Reduction

The reduction of UO_3 to UO_2 first requires that the lumpy UO_3 be pulverized to a fine powder. It is then heated and hydrogen (H_2) is passed over it to form UO_2 and water vapor. Three methods were employed. Two batch methods heated the UO_3 in furnaces, one with the UO_3 spread thinly on copper trays and the other continuously agitating the UO_3 with rakes to assure contact with the H_2. The later, continuous method used screw flites (similar to helical screw conveyors) to move UO_3 through horizontal reactors with a counterflow of H_2. Off gases, which contained excess H_2, were burned. The continuous method produced a significant amount of uranium salts that had to be filtered from the burned hydrogen stream. High exposures were incurred in the batch operations feeding of UO_3 and bagging of the fine UO_2 powder. The continuous process reduced exposures by approximately two magnitudes. Manual bagging was done in this process only for special circumstances.

4.5 Hydrofluorination

Hydrofluorination was used to convert UO_2 to UF_4 (green salt). The process is similar to the oxide reduction process described previously, except that hydrogen fluoride (HF) is passed over the heated UO_2, with water vapor and excess HF collected by acid recovery units. In the batch mode, HF is passed over heated UO_2 in shallow trays on an open table. Later this table was enclosed and ventilated, reducing the

exposure by about 7 fold (from 10,000 d/m/m^3 to 1,500 d/m/m^3). Eventually a continuous method was employed using horizontal screw flite reactors identical to those used in the oxide reduction process. In some places UO_3 was converted directly to UF_4 by using a series of these reactors. Exposures during continuous processing are negligible, but cleaning and maintenance of the spiral flite reactors presents exposure problems.

UF_4 was then used as feedstock for two separate processes. The first process was for production of uranium metal. The second process was for the production of UF_6 which was used in the enrichment process.

Packaging of uranium powders has presented high exposure problems. High velocity local exhaust ventilation around the lip of the drum and total enclosure was tried. However, excessive airborne concentrations were still measured in the breathing zones of operators. In addition, empty drums after use remained sources of airborne exposure.

4.6 Reduction to Metal

Metal is obtained by thermite reduction of the fluoride salt with magnesium in refractory lined steel "bombs". The "bomb" is lined with a refractory material and then filled with a mixture of UF_4 and Mg chips. The bomb is sealed and heated to start an exothermic reaction that heats the uranium beyond its melting point. Uranium metal forms at the bottom of the bomb and a MgF slag floats to the top. After the reaction has run to completion, the bomb is opened and the metal is dislodged from the slag and refractory lining. This "breakout" task results in the greatest amount of dust for the metal production process.

4.7 Recasting

Metallic uranium produced by the thermite reaction contains impurities, mostly on the surface of the metal, that make the uranium unsuitable for reactor fuel. The metal was vacuum cast into shapes called metal derbies. Impurities in the original metal either were volatile and collected on the lid of the vacuum casting machine, or floated to the top of the derby. The top of the derby that contained impurities was sawed off and the derby was then ready for metal processing.

4.8 Fluorination

UF_6 is used in the process of enriching the ^{235}U content of uranium. UF_6 is produced from UF_4 by a process known as fluorination. The UF_6 product is a gas and can be distilled to remove impurities.

UF_6 is produced by passing a reactive gas, in this case anhydrous fluorine, over a bed of UF_4. As UF_6 is produced it evaporates and is carried away from the reaction.

Three fluorination methods were used. The first two methods differ only in the tasks to clean the reaction vessels.

For the first and earliest method, UF_4 was spread in shallow trays, sealed in reaction tubes and placed in a reactor furnace. The reaction was then allowed to run to completion with the evolution of UF_6 gas that was collected. The process is specific to uranium and so contaminates (ash) would remain in the reaction trays. The ash was brushed into a collection barrel. The ash contained ^{234}Th and ^{234m}Pa and the external dose rates in the vicinity of the collection drum approached 1R/h. The collection drums would be sealed and stored for about 6 months at which time the radionuclides in fresh ash would have decayed to ^{234}U

with a significantly lower dose rate. Eisenbug (1975) indicates that the dose to the hands from the ash could range from 2-3 rad/week. This dose rate is consistent with the dose rates shown in Table 7.1.

The second method was the same as the first method with the addition of a ventilated enclosure for the vacuum and brushing steps. This improvement reduced the radiation exposures of workers.

The third method was a vertical continuous reactor where the ash is collected in an ash pit and was automatically removed.

4.9 Scrap Recovery

Uranium was recovered from scrap. The nature of the scrap would vary from plant to plant and, in all likelihood, from batch to batch. The basic process was to dry the scrap and then calcine it either in trays or multiple hearth furnaces. Metallic uranium is burned to the oxide, generally U_3O_8, with the evolution of some fumes. The steps associated with the scrap recovery process are:

- Calcine the scrap in a furnace to convert metal and easily oxidized compounds to U_3O_8.
- Pulverize the oxidized material, digest it with acids, filter the material, and then treat the material with hydroxide to precipitate uranium.
- The precipitate is separated from the liquor and purified and concentrated into a diurinate salt which can be used as feedstock for the refinery.

4.10 Drum Transfer Operation

Purified uranium ore were transferred to the refining facilities in 55 gal drums (see picture in Christofano and Harris 1960, p79/443). Dose rates from drums of uranium ore are presented in Table 7.2. The dose rates due to neutrons from spontaneous fission are about 0.09% of the photon dose rates.

4.11 Three Distinct Stages of Site History

Site history can generally be divided into three distinct stages:

1. operations through and including cessation of operations and initial decontamination
2. the period following initial decontamination through and including FUSRAP decontamination
3. post-FUSRAP decontamination.

During operations (Stage 1), there may or may not have been personnel monitoring, air sampling, area surveys, and contamination monitoring, but this period may include monitored doses, unmonitored doses, and missed doses due to occupational medical exposures, environmental exposures, internal irradiation due to intakes in the workplace, and external irradiation due to radioactive material in the workplace and other AWE-associated radiation sources such as radiography equipment.

Generally, there was little or no monitoring of workers after initial decontamination (Stage 2). For this period of time, exposures to residual contamination include external irradiation and inhalation intakes of resuspended contamination. During Stage 2, there is no occupational internal or external irradiation due to AWE operations or occupational medical dose.

During Stage 3, after FUSRAP remediation, it is assumed that persons working on the site are exposed to environmental radiation at the limits allowed for a remediated site. During Stage 3, there is no occupational internal or external irradiation due to AWE operations or occupational medical dose.

Clearly, there are exceptions to the default three-stage history. Some sites may not have had any FUSRAP cleanup. Others may have been decontaminated several times.

5.0 Occupational Medical Dose

In many AWE facilities, workers received a pre-employment X-ray examination, and in many of these facilities, the X-ray was also administered annually to employees who worked with uranium. The "pre-employment" X-ray was often administered at the start of AEC operations. In the absence of site-specific information about medical X-rays required for employment, the assumption should be made that it was administered at the beginning of AEC operations (or at the beginning of a worker's employment) and annually during uranium processing. The exposure geometry was assumed to be posterior-anterior (PA) (NIOSH, 2002).

5.1 Chest X-Rays

Information to be used in dose reconstruction for the early years for which no specific information is available is provided in ORAUT-OTIB-0006, the dose reconstruction project technical information bulletin covering diagnostic x-ray procedures (ORAUT 2005d). ORAUT (2005d) should be referred to regarding the underlying bases, interpretation details, and a sample of a summary data table where actual beam data are known.

Doses for organs not listed in ICRP Publication 34 (ICRP 1982) but specified in the IREP code should be determined by analogy with anatomical location as indicated below. Analogues for IREP organs not included in ICRP 34.

Table 5.1 Anatomical locations, reference organs, and organ analogues for occupational X-rays

Anatomical location	ICRP 34 reference organ	IREP organ analogues
Thorax	Lung	Thymus Esophagus Stomach Bone surface Liver/gall bladder/spleen Remainder organs
Abdomen	Ovaries	Urinary/bladder Colon/rectum Uterus
Head and neck	Thyroid	Eye/Brain

As ORAUT (2003c) notes, for any individual entrance skin exposure (ESE) or derived organ dose, an uncertainty of ± 30% at the one sigma confidence level may be assumed; for further conservatism it may be appropriate to assume that errors are all positive and thus only the + 30% should be used.

5.2 Pelvic X-Rays

Guidance regarding pelvic x-ray examinations is available in Appendix A of ORAUT-OTIB-0006 (ORAUT 2005d). Note that pelvic X-rays would be applicable to only some workers, i.e. those working with fluorides; presumably this class would consist of workers involved with the UO_2-to-UF_4 and the

UF_4-to-derby processes, including workers who handled the hydrogen fluoride supply and storage functions.

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).

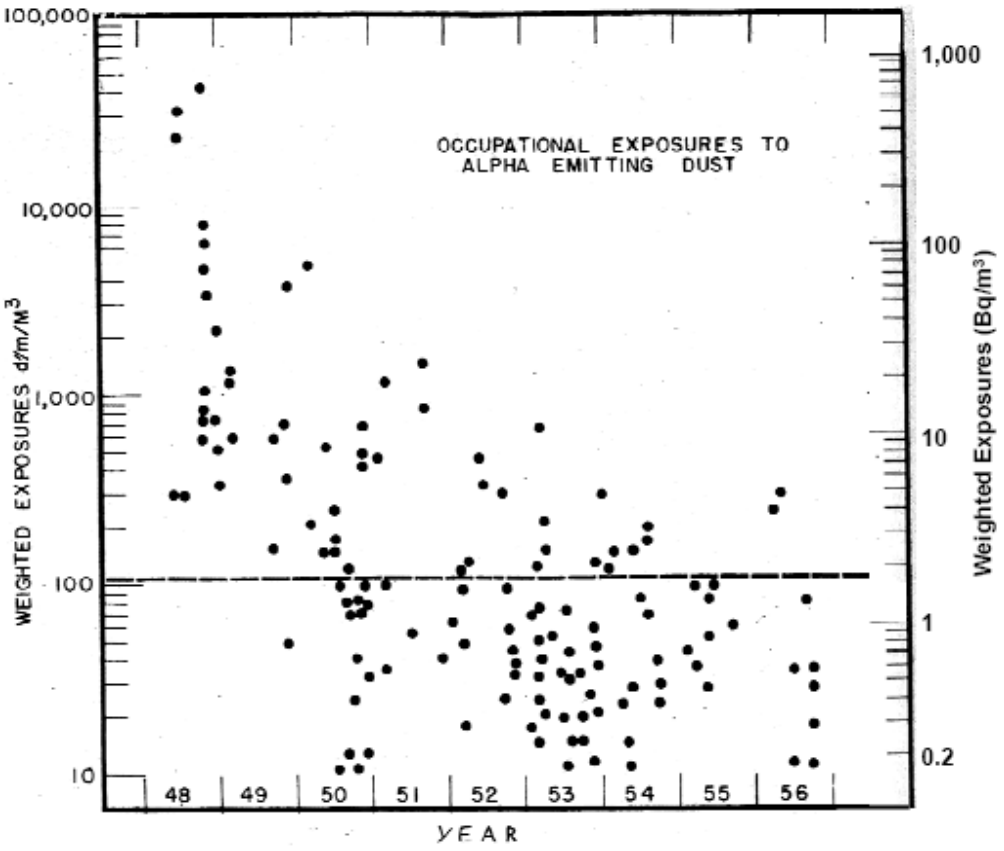

Figure 1. Data from Figure 1 of Christofano and Harris (1960) showing the decreasing trend in time-weighted average air concentrations of alpha-emitting dust.

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							

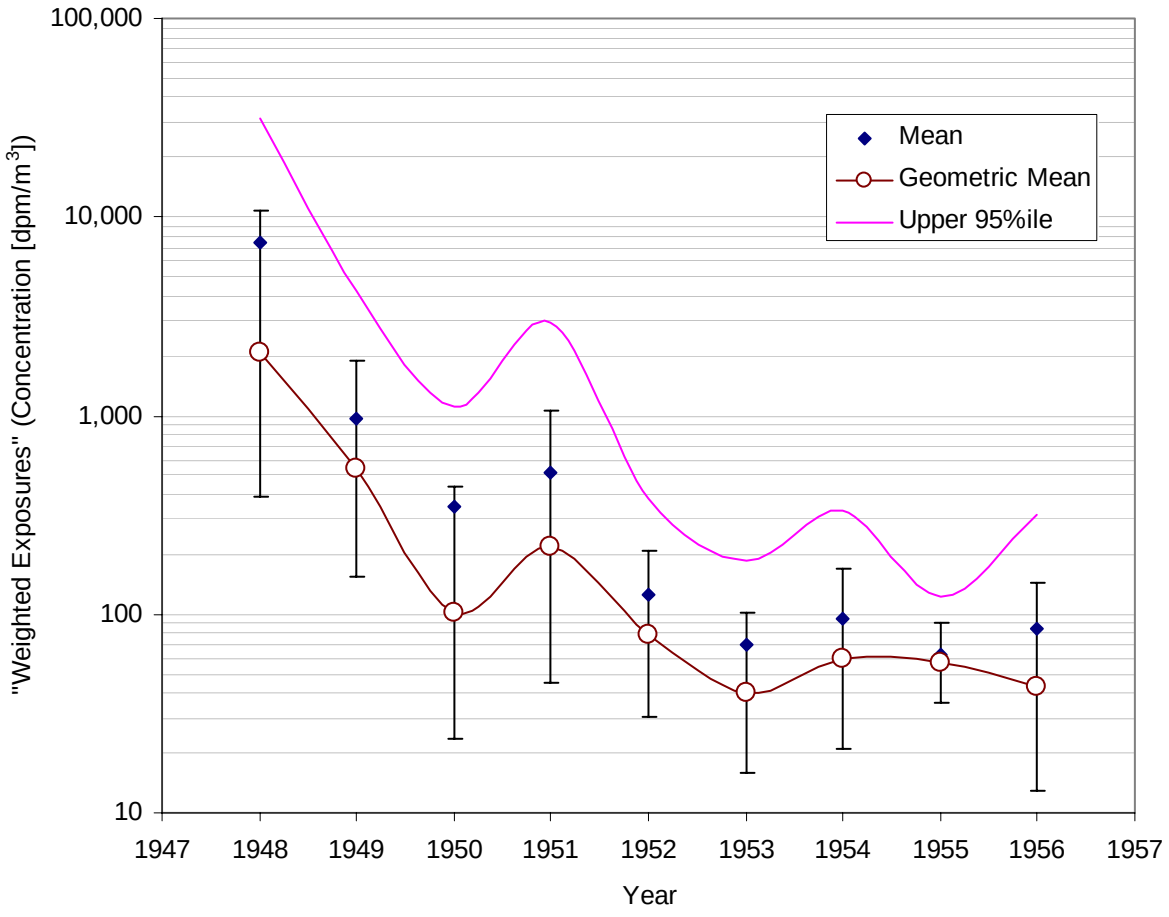

Figure 2. Analysis of time-weighted average air concentrations from Christofano and Harris (1960; Fig. 1). Variability bars are the geometric mean times or divided by one *GSD*.

Clearly, the mean concentration drops rapidly from 1948 through 1950, from 7,400 dpm/m^3 to 350 dpm/m^3 (a factor of over 20), as engineered workplace controls were installed at the dustiest locations. Alpha-emitting dust concentrations for the years 1953-1957 are roughly 100 times lower than they were in 1948.

The first difficulty in interpreting Table 8.27 is that it combines data from different processes, and we do not know which processes these are, that is, which are the dustiest or cleanest in a given year.

The second difficulty in interpreting the data in Table 8.27 and the analysis in Figure 2 is that data for the various processes may have been measured one or more times, and we do not know which times these were. So, while we know that workplace air became dramatically cleaner on the average, it is necessary to develop a defensible method to apply this knowledge to the tabulated values for the various operations that have been derived from the 1960 Christofano and Harris paper.

One approach to using these data would be to ignore process-specific information and use the upper 95th percentile value in a given year for all process workers, and the median value for non-process workers. This assumption may be favorable to the claimant, but it ignores information that can be used.

A preferred approach to using these data is to analyze all of the averages and create a year-specific scaling or correction factor for the tabulated values for the various operations that have been derived from the 1960 Christofano and Harris paper. The time-dependent correction factors that result from this method are shown in Figure 3. The average of these factors is 1.00, so that a worker who was present for all 9 years would have a predicted intake that is unchanged by the application of this method. In this sense, the time correction method is *unbiased*. A worker who was present only for 1948 would have a nearly 7-fold higher intake, while workers who were present after 1953 would have dramatically lower intakes. The 1948 value would be used for all years prior to 1948, and the 1956 value would be used for all years after 1956. These factors are presented in Table 8.28.

The annual intake is thus computed using

$$I_{\text{annual}} = (1.2\text{m}^3/\text{h}) \times (\text{actual or default hours per year}) \times (\text{process - specific concentration}) \times (\text{year - specific correction factor}), \quad 1$$

which is a modification of Eq. 21 in BTIB-5000 (Strom 2006).

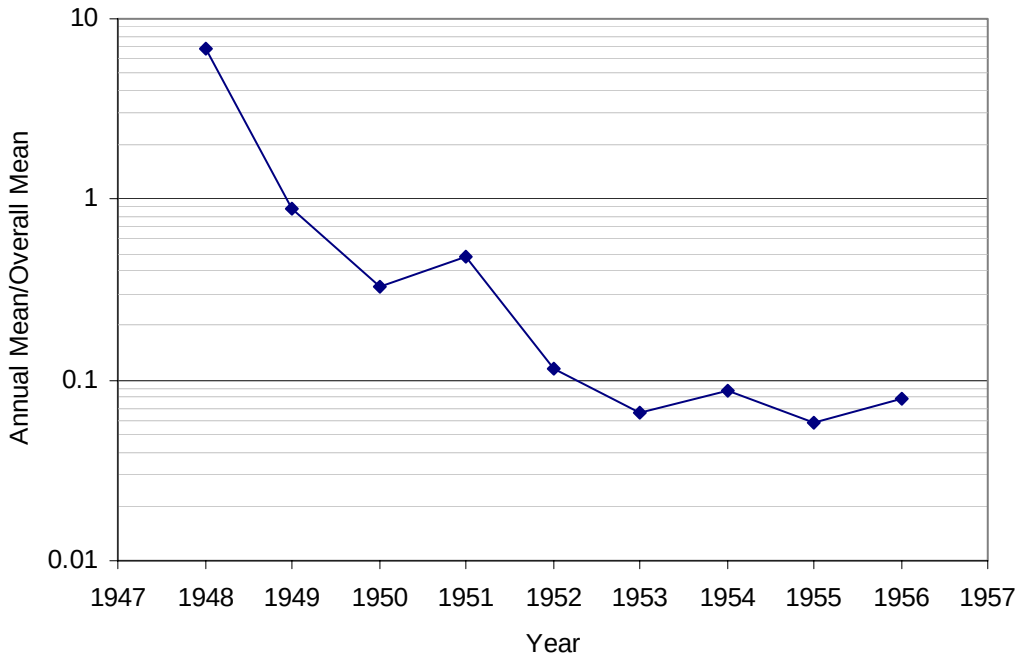

Figure 3. Use of year-specific correction factors to adjust air concentrations for processes over time.

Table 8.28. Year-specific correction factors for tabulated process-specific air concentrations, derived from analysis of Christofano and Harris (1960) Fig. 1.

Year	Year-Specific Correction Factor
1948 or before	6.89
1949	0.897
1950	0.325
1951	0.485
1952	0.116
1953	0.0656
1954	0.0875
1955	0.0582
1956 or after	0.0792
Average	1

The tabulated process-specific data reported by Christofano and Harris (1960) include measurements made over the duration of the survey. They state, “In substantially every case, the first survey conducted at any plant disclosed the highest exposures and the most recent measurements were lowest. In reporting occupational dust exposures, we have presented the range of exposures and also the numerical average of all such evaluations made during the 10 years from 1948 through 1957” (Christofano and Harris 1960, p.

77)[2]. The inclusion of measurements made at different times as ventilation and engineered controls improved means that some of the broader lognormal distributions include non-random variability due to temporal improvements in workplace controls, as well a component of random variability due to other factors such as process differences between plants and air sample representativeness. Using the year-specific correction factors to average air concentrations improves the precision of the estimates of air concentrations.

8.5 Summary

This section provides summary internal dosimetry information for the dose reconstructor.

8.5.1 Inhalation Intakes

The algorithm for populating this table was to use the TWA or DWA values for the operators who were assumed to be exposed the entire working day. General laborers were assumed to be exposed to 50% of the operators. Supervisors were assumed to be exposed for one-fourth of the working day. Clerical workers (who represent all other workers), were assumed to have intakes one-tenth that of a supervisor. The inhalation intake rate is the air concentration times the breathing rate for a light worker, 9.6 m^3/d. This intake rate is the actual daily intake rate experienced by the individual. Internal doses are calculated using the IMBA codes and, for chronic intakes, it is necessary to provide a daily intake rate that corresponds to intakes that occur even during times when the individual was not at work. The intake rate, from inhalation of known air concentrations, that accommodates the IMBA code is $I_{\text{IMBA}} = 3.288 \times 10^{-3} Ah$, where I_{IMBA} is the IMBA chronic intake in pCi/d, A is the air concentration (pCi/m^3) and h is the number of working hours in a year. If the measured air concentration has units of dpm/m^3 then divide the constant by 2.22 (dpm/pCi).

8.5.1.1 Stage 1: Operations

The daily inhalation intake rates for the operations phase of the plant are shown in Table 8.29. These intake rates have been calculated for use in the IMBA code, as described above.

[Solvent Extraction Data is Reserved]

Table 8.29. Intake rates for inhalation of uranium dusts during Stage 1 – Operations.

Operation	Job Title	Years	Inhalation Rates (pCi/d) for three work week durations.					
			48-h/week		44-h/week		40-h/week	
			median	GSD	median	GSD	median	GSD
Ore Digestion	Operator	All	1.74E+02	4.94	1.60E+02	4.94	1.45E+02	4.94
	general laborer		8.71E+01	4.94	7.98E+01	4.94	7.26E+01	4.94
	Supervisor		4.35E+01	4.94	3.99E+01	4.94	3.63E+01	4.94
	Clerical		4.35E+00	4.94	3.99E+00	4.94	3.63E+00	4.94
Solvent Extraction	Operator	start – 1949	N/A	N/A	N/A	N/A	N/A	N/A
	general laborer		N/A	N/A	N/A	N/A	N/A	N/A
	Supervisor		N/A	N/A	N/A	N/A	N/A	N/A
	Clerical		N/A	N/A	N/A	N/A	N/A	N/A
	Operator		N/A	N/A	N/A	N/A	N/A	N/A

[2] There are no data from 1957 in Figure 1, so this analysis goes only through 1956.

	general laborer	1950 - end	N/A	N/A	N/A	N/A	N/A	N/A
	Supervisor		N/A	N/A	N/A	N/A	N/A	N/A
	Clerical		N/A	N/A	N/A	N/A	N/A	N/A
Boildown and Denitration	Operator	Start – 1949	4.12E+04	1.67	3.78E+04	1.67	3.43E+04	1.67
	general laborer		2.06E+04	1.67	1.89E+04	1.67	1.72E+04	1.67
	Supervisor		1.03E+04	1.67	9.44E+03	1.67	8.59E+03	1.67
	Clerical		1.03E+03	1.67	9.44E+02	1.67	8.59E+02	1.67
	Operator	1950 – End	3.02E+02	2.33	2.77E+02	2.33	2.52E+02	2.33
	general laborer		1.51E+02	2.33	1.38E+02	2.33	1.26E+02	2.33
	Supervisor		7.55E+01	2.33	6.92E+01	2.33	6.29E+01	2.33
	Clerical		7.55E+00	2.33	6.92E+00	2.33	6.29E+00	2.33
Oxide Reduction: Tray Furnace Operations	Operator	All	6.29E+04	1.28	5.77E+04	1.28	5.25E+04	1.28
	general laborer		3.15E+04	1.28	2.89E+04	1.28	2.62E+04	1.28
	Supervisor		1.57E+04	1.28	1.44E+04	1.28	1.31E+04	1.28
	Clerical		1.57E+03	1.28	1.44E+03	1.28	1.31E+03	1.28
Oxide Reduction: Multiple Hearth Operations	Operator	All	1.28E+03	3.76	1.18E+03	3.76	1.07E+03	3.76
	general laborer		6.42E+02	3.76	5.88E+02	3.76	5.35E+02	3.76
	Supervisor		3.21E+02	3.76	2.94E+02	3.76	2.67E+02	3.76
	Clerical		3.21E+01	3.76	2.94E+01	3.76	2.67E+01	3.76
Oxide Reduction: Horizontal Reactor Operations	Operator	All	3.66E+02	1.86	3.36E+02	1.86	3.05E+02	1.86
	general laborer		1.83E+02	1.86	1.68E+02	1.86	1.53E+02	1.86
	Supervisor		9.15E+01	1.86	8.39E+01	1.86	7.63E+01	1.86
	Clerical		9.15E+00	1.86	8.39E+00	1.86	7.63E+00	1.86
Hydrofluorination: UO_2 Loaders (Trays)	Operator	All	4.74E+03	6.12	4.35E+03	6.12	3.95E+03	6.12
	general laborer		2.37E+03	6.12	2.17E+03	6.12	1.98E+03	6.12
	Supervisor		1.19E+03	6.12	1.09E+03	6.12	9.88E+02	6.12
	Clerical		1.19E+02	6.12	1.09E+02	6.12	9.88E+01	6.12
Hydrofluorination: Furnace Operator (Trays)	Operator	All	8.71E+02	4.17	7.98E+02	4.17	7.26E+02	4.17
	general laborer		4.35E+02	4.17	3.99E+02	4.17	3.63E+02	4.17
	Supervisor		2.18E+02	4.17	2.00E+02	4.17	1.81E+02	4.17
	Clerical		2.18E+01	4.17	2.00E+01	4.17	1.81E+01	4.17
Hydrofluorination: Package UF_4 (Trays)	Operator	All	2.47E+03	3.49	2.27E+03	3.49	2.06E+03	3.49
	general laborer		1.24E+03	3.49	1.13E+03	3.49	1.03E+03	3.49
	Supervisor		6.18E+02	3.49	5.67E+02	3.49	5.15E+02	3.49
	Clerical		6.18E+01	3.49	5.67E+01	3.49	5.15E+01	3.49
Hydrofluorination: Furnace Operator (Reactor)	Operator	All	1.07E+02	5.00	9.78E+01	5.00	8.89E+01	5.00
	general laborer		5.33E+01	5.00	4.89E+01	5.00	4.44E+01	5.00
	Supervisor		2.67E+01	5.00	2.44E+01	5.00	2.22E+01	5.00
	Clerical		2.67E+00	5.00	2.44E+00	5.00	2.22E+00	5.00
Hydrofluorination: Package UF_4 (Reactor)	Operator	All	2.84E+01	7.08	2.61E+01	7.08	2.37E+01	7.08
	general laborer		1.42E+01	7.08	1.30E+01	7.08	1.18E+01	7.08
	Supervisor		7.11E+00	7.08	6.52E+00	7.08	5.92E+00	7.08
	Clerical		7.11E-01	7.08	6.52E-01	7.08	5.92E-01	7.08
Metal Reduction: Bomb Preparation	Operator	Before 1952	8.53E+02	5.00	7.82E+02	5.00	7.11E+02	5.00
	general laborer		4.27E+02	5.00	3.91E+02	5.00	3.55E+02	5.00
	Supervisor		2.13E+02	5.00	1.96E+02	5.00	1.78E+02	5.00
	Clerical		2.13E+01	5.00	1.96E+01	5.00	1.78E+01	5.00

Metal Reduction: Reduction Operations	Operator	Before 1952	2.91E+02	5.00	2.67E+02	5.00	2.43E+02	5.00
	general laborer		1.46E+02	5.00	1.34E+02	5.00	1.21E+02	5.00
	Supervisor		7.29E+01	5.00	6.68E+01	5.00	6.07E+01	5.00
	Clerical		7.29E+00	5.00	6.68E+00	5.00	6.07E+00	5.00
Metal Reduction: Bomb Breakout	Operator	Before 1952	8.32E+02	5.00	7.62E+02	5.00	6.93E+02	5.00
	general laborer		4.16E+02	5.00	3.81E+02	5.00	3.47E+02	5.00
	Supervisor		2.08E+02	5.00	1.91E+02	5.00	1.73E+02	5.00
	Clerical		2.08E+01	5.00	1.91E+01	5.00	1.73E+01	5.00
Metal Reduction: Bomb Preparation	Operator	1952 and later	2.84E+01	5.00	2.61E+01	5.00	2.37E+01	5.00
	general laborer		1.42E+01	5.00	1.30E+01	5.00	1.18E+01	5.00
	Supervisor		7.11E+00	5.00	6.52E+00	5.00	5.92E+00	5.00
	Clerical		7.11E-01	5.00	6.52E-01	5.00	5.92E-01	5.00
Metal Reduction: Reduction Operations	Operator	1952 and later	1.07E+01	5.00	9.78E+00	5.00	8.89E+00	5.00
	general laborer		5.33E+00	5.00	4.89E+00	5.00	4.44E+00	5.00
	Supervisor		2.67E+00	5.00	2.44E+00	5.00	2.22E+00	5.00
	Clerical		2.67E-01	5.00	2.44E-01	5.00	2.22E-01	5.00
Metal Reduction: Bomb Breakout	Operator	1952 and later	2.49E+01	5.00	2.28E+01	5.00	2.07E+01	5.00
	general laborer		1.24E+01	5.00	1.14E+01	5.00	1.04E+01	5.00
	Supervisor		6.22E+00	5.00	5.70E+00	5.00	5.18E+00	5.00
	Clerical		6.22E-01	5.00	5.70E-01	5.00	5.18E-01	5.00
Recasting: Crucible Loading	Operator	Prior to 1951	1.56E+02	1.35	1.43E+02	1.35	1.30E+02	1.35
	general laborer		7.82E+01	1.35	7.17E+01	1.35	6.52E+01	1.35
	Supervisor		3.91E+01	1.35	3.58E+01	1.35	3.26E+01	1.35
	Clerical		3.91E+00	1.35	3.58E+00	1.35	3.26E+00	1.35
Recasting: Recasting	Operator	Prior to 1951	2.39E+03	2.68	2.19E+03	2.68	1.99E+03	2.68
	general laborer		1.19E+03	2.68	1.09E+03	2.68	9.95E+02	2.68
	Supervisor		5.97E+02	2.68	5.47E+02	2.68	4.98E+02	2.68
	Clerical		5.97E+01	2.68	5.47E+01	2.68	4.98E+01	2.68
Recasting: Crucible Burnout	Operator	Prior to 1951	4.98E+01	5.00	4.56E+01	5.00	4.15E+01	5.00
	general laborer		2.49E+01	5.00	2.28E+01	5.00	2.07E+01	5.00
	Supervisor		1.24E+01	5.00	1.14E+01	5.00	1.04E+01	5.00
	Clerical		1.24E+00	5.00	1.14E+00	5.00	1.04E+00	5.00
Recasting: Billet Cleaning	Operator	Prior to 1951	1.17E+02	1.97	1.08E+02	1.97	9.78E+01	1.97
	general laborer		5.87E+01	1.97	5.38E+01	1.97	4.89E+01	1.97
	Supervisor		2.93E+01	1.97	2.69E+01	1.97	2.44E+01	1.97
	Clerical		2.93E+00	1.97	2.69E+00	1.97	2.44E+00	1.97
Recasting: Crucible Assembly	Operator	Prior to 1951	8.25E+02	2.40	7.56E+02	2.40	6.87E+02	2.40
	general laborer		4.12E+02	2.40	3.78E+02	2.40	3.44E+02	2.40
	Supervisor		2.06E+02	2.40	1.89E+02	2.40	1.72E+02	2.40
	Clerical		2.06E+01	2.40	1.89E+01	2.40	1.72E+01	2.40
Recasting: Crucible Loading	Operator	1951 and later	3.55E+01	5.00	3.26E+01	5.00	2.96E+01	5.00
	general laborer		1.78E+01	5.00	1.63E+01	5.00	1.48E+01	5.00
	Supervisor		8.89E+00	5.00	8.15E+00	5.00	7.41E+00	5.00
	Clerical		8.89E-01	5.00	8.15E-01	5.00	7.41E-01	5.00
Recasting: Recasting	Operator	1951 and later	1.07E+02	2.42	9.78E+01	2.42	8.89E+01	2.42
	general laborer		5.33E+01	2.42	4.89E+01	2.42	4.44E+01	2.42
	Supervisor		2.67E+01	2.42	2.44E+01	2.42	2.22E+01	2.42
	Clerical		2.67E+00	2.42	2.44E+00	2.42	2.22E+00	2.42

Recasting: Crucible Burnout	Operator	1951 and later	3.20E+01	5.00	2.93E+01	5.00	2.67E+01	5.00
	general laborer		1.60E+01	5.00	1.47E+01	5.00	1.33E+01	5.00
	Supervisor		8.00E+00	5.00	7.33E+00	5.00	6.66E+00	5.00
	Clerical		8.00E-01	5.00	7.33E-01	5.00	6.66E-01	5.00
Recasting: Billet Cleaning	Operator	1951 and later	2.84E+01	5.00	2.61E+01	5.00	2.37E+01	5.00
	general laborer		1.42E+01	5.00	1.30E+01	5.00	1.18E+01	5.00
	Supervisor		7.11E+00	5.00	6.52E+00	5.00	5.92E+00	5.00
	Clerical		7.11E-01	5.00	6.52E-01	5.00	5.92E-01	5.00
Recasting: Crucible Assembly	Operator	1951 and later	1.78E+02	1.21	1.63E+02	1.21	1.48E+02	1.21
	general laborer		8.89E+01	1.21	8.15E+01	1.21	7.41E+01	1.21
	Supervisor		4.44E+01	1.21	4.07E+01	1.21	3.70E+01	1.21
	Clerical		4.44E+00	1.21	4.07E+00	1.21	3.70E+00	1.21
Fluorination: Hex Loaders	Operator	All	7.86E+03	1.38	7.21E+03	1.38	6.55E+03	1.38
	general laborer		3.93E+03	1.38	3.60E+03	1.38	3.28E+03	1.38
	Supervisor		1.97E+03	1.38	1.80E+03	1.38	1.64E+03	1.38
	Clerical		1.97E+02	1.38	1.80E+02	1.38	1.64E+02	1.38
Fluorination: Operators	Operator	All	2.22E+03	3.10	2.03E+03	3.10	1.85E+03	3.10
	general laborer		1.11E+03	3.10	1.02E+03	3.10	9.24E+02	3.10
	Supervisor		5.55E+02	3.10	5.08E+02	3.10	4.62E+02	3.10
	Clerical		5.55E+01	3.10	5.08E+01	3.10	4.62E+01	3.10
Fluorination: Still Operators	Operator	All	8.64E+02	2.07	7.92E+02	2.07	7.20E+02	2.07
	general laborer		4.32E+02	2.07	3.96E+02	2.07	3.60E+02	2.07
	Supervisor		2.16E+02	2.07	1.98E+02	2.07	1.80E+02	2.07
	Clerical		2.16E+01	2.07	1.98E+01	2.07	1.80E+01	2.07
Fluorination: Central Loaders	Operator	All	1.67E+03	1.38	1.53E+03	1.38	1.39E+03	1.38
	general laborer		8.34E+02	1.38	7.64E+02	1.38	6.95E+02	1.38
	Supervisor		4.17E+02	1.38	3.82E+02	1.38	3.47E+02	1.38
	Clerical		4.17E+01	1.38	3.82E+01	1.38	3.47E+01	1.38
Scrap Recovery: Furnace Operator (Trays)	Operator	1951 and earlier	2.92E+03	5.00	2.68E+03	5.00	2.43E+03	5.00
	general laborer		1.46E+03	5.00	1.34E+03	5.00	1.22E+03	5.00
	Supervisor		7.30E+02	5.00	6.70E+02	5.00	6.09E+02	5.00
	Clerical		7.30E+01	5.00	6.70E+01	5.00	6.09E+01	5.00
Scrap Recovery: Furnace Operator (Trays)	Operator	1952 and later	2.91E+02	5.00	2.67E+02	5.00	2.43E+02	5.00
	general laborer		1.46E+02	5.00	1.34E+02	5.00	1.21E+02	5.00
	Supervisor		7.29E+01	5.00	6.68E+01	5.00	6.07E+01	5.00
	Clerical		7.29E+00	5.00	6.68E+00	5.00	6.07E+00	5.00
Scrap Recovery: Furnace Operator (Calciner)	Operator	1952 and later	9.74E+02	5.00	8.93E+02	5.00	8.12E+02	5.00
	general laborer		4.87E+02	5.00	4.46E+02	5.00	4.06E+02	5.00
	Supervisor		2.43E+02	5.00	2.23E+02	5.00	2.03E+02	5.00
	Clerical		2.43E+01	5.00	2.23E+01	5.00	2.03E+01	5.00
Scrap Recovery: Digest Operator	Operator	All	2.84E+01	5.00	2.61E+01	5.00	2.37E+01	5.00
	general laborer		1.42E+01	5.00	1.30E+01	5.00	1.18E+01	5.00
	Supervisor		7.11E+00	5.00	6.52E+00	5.00	5.92E+00	5.00
	Clerical		7.11E-01	5.00	6.52E-01	5.00	5.92E-01	5.00
Scrap Recovery: Filtration Operator	Operator	All	1.07E+01	4.94	9.78E+00	4.94	8.89E+00	4.94
	general laborer		5.33E+00	4.94	4.89E+00	4.94	4.44E+00	4.94
	Supervisor		2.67E+00	4.94	2.44E+00	4.94	2.22E+00	4.94
	Clerical		2.67E-01	4.94	2.44E-01	4.94	2.22E-01	4.94

Drum Loading Operations	Operator	All	N/A	N/A	N/A	N/A	N/A	N/A
	general laborer		N/A	N/A	N/A	N/A	N/A	N/A
	Supervisor		N/A	N/A	N/A	N/A	N/A	N/A
	Clerical		N/A	N/A	N/A	N/A	N/A	N/A

8.5.2 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 following soon after the actual operations. To estimate exposure from resuspended materials, this analysis assumed that surfaces in the building became contaminated by deposition of uranium dust during operations similar to metal-working operations. NIOSH (2005) estimates that for uranium metal-working operations, a reasonable maximum time-weighted average air concentration would be 7000 dpm/m^3 (equal to 100 MAC) during AEC operations. The estimation of time-weighted average air concentrations for refining operations are still in preparation and therefore the metal working data will be used.

The level of contamination was determined by multiplying the air concentration of 7000 dpm/m^3 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 working operation, would be 413 pCi/day.

8.5.3 Ingestion Intakes

Ingestion Intakes are determined using the OCAS method (NIOSH 2004) and are shown in Table 8.30. Briefly, the daily ingestion rate from food contamination is given by $I = 0.0985A$, where I is the daily ingestion rate in pCi/d, A is the average air concentration (pCi/m^3). The ingestion rate I must be adjusted for the fact that IMBA assumes chronic intakes, even during weekends, and that the number of hours worked in a year changed over time (Strom 2006). The adjustments result in an IMBA chronic intake rate $I_{\text{IMBA}} = 3.373 \times 10^{-5} Ah$, where I_{IMBA} is the daily intake (pCi/d), A is the median air concentration (pCi/m^3), and h is the number of hours in a working year.

Making similar adjustments to Neton's (NIOSH 2004) equations for incidental hand-to-mouth ingestion the chronic IMBA daily intake rate is $I_{\text{IMBA}} = 3.425 \times 10^{-5} Ah$, where I_{IMBA} is the daily chronic intake rate (pCi/d), h is the number of hours in a work year, and A is the median dust concentration (pCi/m^3).

The total ingestion rate is the sum of the food contamination and incidental hand-to-mouth ingestion rates and is $I_{IMBA} = 6.798 \times 10^{-5} Ah$ where the variables are the same as previously defined.

Table 8.30. Intake rates for ingestion of uranium dusts during Stage 1 – Operations.

Operation	Job Title	Years	Ingestion Rates (pCi/d) for three work week durations.					
			48-h/week		48-h/week		48-h/week	
			median	GSD	median	GSD	median	GSD
Ore Digestion	Operator	All	1.79E+00	4.94	1.64E+00	4.94	1.49E+00	4.94
	general laborer		8.93E-01	4.94	8.18E-01	4.94	7.44E-01	4.94
	Supervisor		4.46E-01	4.94	4.09E-01	4.94	3.72E-01	4.94
	Clerical		4.46E-02	4.94	4.09E-02	4.94	3.72E-02	4.94
Solvent Extraction	Operator	start – 1949	N/A	N/A	N/A	N/A	N/A	N/A
	general laborer		N/A	N/A	N/A	N/A	N/A	N/A
	Supervisor		N/A	N/A	N/A	N/A	N/A	N/A
	Clerical		N/A	N/A	N/A	N/A	N/A	N/A
	Operator	1950 - end	N/A	N/A	N/A	N/A	N/A	N/A
	general laborer		N/A	N/A	N/A	N/A	N/A	N/A
	Supervisor		N/A	N/A	N/A	N/A	N/A	N/A
	Clerical		N/A	N/A	N/A	N/A	N/A	N/A
Boildown and Denitration	Operator	Start – 1949	4.22E+02	1.67	3.87E+02	1.67	3.52E+02	1.67
	general laborer		2.11E+02	1.67	1.94E+02	1.67	1.76E+02	1.67
	Supervisor		1.06E+02	1.67	9.68E+01	1.67	8.80E+01	1.67
	Clerical		1.06E+01	1.67	9.68E+00	1.67	8.80E+00	1.67
	Operator	1950 – End	3.10E+00	2.33	2.84E+00	2.33	2.58E+00	2.33
	general laborer		1.55E+00	2.33	1.42E+00	2.33	1.29E+00	2.33
	Supervisor		7.74E-01	2.33	7.10E-01	2.33	6.45E-01	2.33
	Clerical		7.74E-02	2.33	7.10E-02	2.33	6.45E-02	2.33
Oxide Reduction: Tray Furnace Operations	Operator	All	6.45E+02	1.28	5.91E+02	1.28	5.38E+02	1.28
	general laborer		3.23E+02	1.28	2.96E+02	1.28	2.69E+02	1.28
	Supervisor		1.61E+02	1.28	1.48E+02	1.28	1.34E+02	1.28
	Clerical		1.61E+01	1.28	1.48E+01	1.28	1.34E+01	1.28
Oxide Reduction: Multiple Hearth Operations	Operator	All	1.32E+01	3.76	1.21E+01	3.76	1.10E+01	3.76
	general laborer		6.58E+00	3.76	6.03E+00	3.76	5.48E+00	3.76
	Supervisor		3.29E+00	3.76	3.01E+00	3.76	2.74E+00	3.76
	Clerical		3.29E-01	3.76	3.01E-01	3.76	2.74E-01	3.76
Oxide Reduction: Horizontal Reactor Operations	Operator	All	3.75E+00	1.86	3.44E+00	1.86	3.13E+00	1.86
	general laborer		1.88E+00	1.86	1.72E+00	1.86	1.56E+00	1.86
	Supervisor		9.38E-01	1.86	8.60E-01	1.86	7.82E-01	1.86
	Clerical		9.38E-02	1.86	8.60E-02	1.86	7.82E-02	1.86
Hydrofluorination: UO_2 Loaders (Trays)	Operator	All	4.86E+01	6.12	4.46E+01	6.12	4.05E+01	6.12
	general laborer		2.43E+01	6.12	2.23E+01	6.12	2.03E+01	6.12
	Supervisor		1.22E+01	6.12	1.11E+01	6.12	1.01E+01	6.12
	Clerical		1.22E+00	6.12	1.11E+00	6.12	1.01E+00	6.12
Hydrofluorination: Furnace Operator (Trays)	Operator	All	8.93E+00	4.17	8.18E+00	4.17	7.44E+00	4.17
	general laborer		4.46E+00	4.17	4.09E+00	4.17	3.72E+00	4.17
	Supervisor		2.23E+00	4.17	2.05E+00	4.17	1.86E+00	4.17
	Clerical		2.23E-01	4.17	2.05E-01	4.17	1.86E-01	4.17

Hydrofluorination: Package UF_4 (Trays)	Operator	All	2.54E+01	3.49	2.32E+01	3.49	2.11E+01	3.49
	general laborer		1.27E+01	3.49	1.16E+01	3.49	1.06E+01	3.49
	Supervisor		6.34E+00	3.49	5.81E+00	3.49	5.28E+00	3.49
	Clerical		6.34E-01	3.49	5.81E-01	3.49	5.28E-01	3.49
Hydrofluorination: Furnace Operator (Reactor)	Operator	All	1.09E+00	5.00	1.00E+00	5.00	9.11E-01	5.00
	general laborer		5.46E-01	5.00	5.01E-01	5.00	4.55E-01	5.00
	Supervisor		2.73E-01	5.00	2.50E-01	5.00	2.28E-01	5.00
	Clerical		2.73E-02	5.00	2.50E-02	5.00	2.28E-02	5.00
Hydrofluorination: Package UF_4 (Reactor)	Operator	All	2.91E-01	7.08	2.67E-01	7.08	2.43E-01	7.08
	general laborer		1.46E-01	7.08	1.34E-01	7.08	1.21E-01	7.08
	Supervisor		7.29E-02	7.08	6.68E-02	7.08	6.07E-02	7.08
	Clerical		7.29E-03	7.08	6.68E-03	7.08	6.07E-03	7.08
Metal Reduction: Bomb Preparation	Operator	Before 1952	8.74E+00	5.00	8.02E+00	5.00	7.29E+00	5.00
	general laborer		4.37E+00	5.00	4.01E+00	5.00	3.64E+00	5.00
	Supervisor		2.19E+00	5.00	2.00E+00	5.00	1.82E+00	5.00
	Clerical		2.19E-01	5.00	2.00E-01	5.00	1.82E-01	5.00
Metal Reduction: Reduction Operations	Operator	Before 1952	2.99E+00	5.00	2.74E+00	5.00	2.49E+00	5.00
	general laborer		1.49E+00	5.00	1.37E+00	5.00	1.24E+00	5.00
	Supervisor		7.47E-01	5.00	6.85E-01	5.00	6.22E-01	5.00
	Clerical		7.47E-02	5.00	6.85E-02	5.00	6.22E-02	5.00
Metal Reduction: Bomb Breakout	Operator	Before 1952	8.53E+00	5.00	7.81E+00	5.00	7.10E+00	5.00
	general laborer		4.26E+00	5.00	3.91E+00	5.00	3.55E+00	5.00
	Supervisor		2.13E+00	5.00	1.95E+00	5.00	1.78E+00	5.00
	Clerical		2.13E-01	5.00	1.95E-01	5.00	1.78E-01	5.00
Metal Reduction: Bomb Preparation	Operator	1952 and later	2.91E-01	5.00	2.67E-01	5.00	2.43E-01	5.00
	general laborer		1.46E-01	5.00	1.34E-01	5.00	1.21E-01	5.00
	Supervisor		7.29E-02	5.00	6.68E-02	5.00	6.07E-02	5.00
	Clerical		7.29E-03	5.00	6.68E-03	5.00	6.07E-03	5.00
Metal Reduction: Reduction Operations	Operator	1952 and later	1.09E-01	5.00	1.00E-01	5.00	9.11E-02	5.00
	general laborer		5.46E-02	5.00	5.01E-02	5.00	4.55E-02	5.00
	Supervisor		2.73E-02	5.00	2.50E-02	5.00	2.28E-02	5.00
	Clerical		2.73E-03	5.00	2.50E-03	5.00	2.28E-03	5.00
Metal Reduction: Bomb Breakout	Operator	1952 and later	2.55E-01	5.00	2.34E-01	5.00	2.13E-01	5.00
	general laborer		1.28E-01	5.00	1.17E-01	5.00	1.06E-01	5.00
	Supervisor		6.38E-02	5.00	5.84E-02	5.00	5.31E-02	5.00
	Clerical		6.38E-03	5.00	5.84E-03	5.00	5.31E-03	5.00
Recasting: Crucible Loading	Operator	Prior to 1951	1.60E+00	1.35	1.47E+00	1.35	1.34E+00	1.35
	general laborer		8.02E-01	1.35	7.35E-01	1.35	6.68E-01	1.35
	Supervisor		4.01E-01	1.35	3.67E-01	1.35	3.34E-01	1.35
	Clerical		4.01E-02	1.35	3.67E-02	1.35	3.34E-02	1.35
Recasting: Recasting	Operator	Prior to 1951	2.45E+01	2.68	2.24E+01	2.68	2.04E+01	2.68
	general laborer		1.22E+01	2.68	1.12E+01	2.68	1.02E+01	2.68
	Supervisor		6.12E+00	2.68	5.61E+00	2.68	5.10E+00	2.68
	Clerical		6.12E-01	2.68	5.61E-01	2.68	5.10E-01	2.68
Recasting: Crucible Burnout	Operator	Prior to 1951	5.10E-01	5.00	4.68E-01	5.00	4.25E-01	5.00
	general laborer		2.55E-01	5.00	2.34E-01	5.00	2.13E-01	5.00
	Supervisor		1.28E-01	5.00	1.17E-01	5.00	1.06E-01	5.00
	Clerical		1.28E-02	5.00	1.17E-02	5.00	1.06E-02	5.00

Recasting: Billet Cleaning	Operator	Prior to 1951	1.20E+00	1.97	1.10E+00	1.97	1.00E+00	1.97
	general laborer		6.01E-01	1.97	5.51E-01	1.97	5.01E-01	1.97
	Supervisor		3.01E-01	1.97	2.76E-01	1.97	2.50E-01	1.97
	Clerical		3.01E-02	1.97	2.76E-02	1.97	2.50E-02	1.97
Recasting: Crucible Assembly	Operator	Prior to 1951	8.45E+00	2.40	7.75E+00	2.40	7.04E+00	2.40
	general laborer		4.23E+00	2.40	3.87E+00	2.40	3.52E+00	2.40
	Supervisor		2.11E+00	2.40	1.94E+00	2.40	1.76E+00	2.40
	Clerical		2.11E-01	2.40	1.94E-01	2.40	1.76E-01	2.40
Recasting: Crucible Loading	Operator	1951 and later	3.64E-01	5.00	3.34E-01	5.00	3.04E-01	5.00
	general laborer		1.82E-01	5.00	1.67E-01	5.00	1.52E-01	5.00
	Supervisor		9.11E-02	5.00	8.35E-02	5.00	7.59E-02	5.00
	Clerical		9.11E-03	5.00	8.35E-03	5.00	7.59E-03	5.00
Recasting: Recasting	Operator	1951 and later	1.09E+00	2.42	1.00E+00	2.42	9.11E-01	2.42
	general laborer		5.46E-01	2.42	5.01E-01	2.42	4.55E-01	2.42
	Supervisor		2.73E-01	2.42	2.50E-01	2.42	2.28E-01	2.42
	Clerical		2.73E-02	2.42	2.50E-02	2.42	2.28E-02	2.42
Recasting: Crucible Burnout	Operator	1951 and later	3.28E-01	5.00	3.01E-01	5.00	2.73E-01	5.00
	general laborer		1.64E-01	5.00	1.50E-01	5.00	1.37E-01	5.00
	Supervisor		8.20E-02	5.00	7.51E-02	5.00	6.83E-02	5.00
	Clerical		8.20E-03	5.00	7.51E-03	5.00	6.83E-03	5.00
Recasting: Billet Cleaning	Operator	1951 and later	2.91E-01	5.00	2.67E-01	5.00	2.43E-01	5.00
	general laborer		1.46E-01	5.00	1.34E-01	5.00	1.21E-01	5.00
	Supervisor		7.29E-02	5.00	6.68E-02	5.00	6.07E-02	5.00
	Clerical		7.29E-03	5.00	6.68E-03	5.00	6.07E-03	5.00
Recasting: Crucible Assembly	Operator	1951 and later	1.82E+00	1.21	1.67E+00	1.21	1.52E+00	1.21
	general laborer		9.11E-01	1.21	8.35E-01	1.21	7.59E-01	1.21
	Supervisor		4.55E-01	1.21	4.17E-01	1.21	3.80E-01	1.21
	Clerical		4.55E-02	1.21	4.17E-02	1.21	3.80E-02	1.21
Fluorination: Hex Loaders	Operator	All	8.06E+01	1.38	7.39E+01	1.38	6.72E+01	1.38
	general laborer		4.03E+01	1.38	3.69E+01	1.38	3.36E+01	1.38
	Supervisor		2.01E+01	1.38	1.85E+01	1.38	1.68E+01	1.38
	Clerical		2.01E+00	1.38	1.85E+00	1.38	1.68E+00	1.38
Fluorination: Operators	Operator	All	2.27E+01	3.10	2.08E+01	3.10	1.89E+01	3.10
	general laborer		1.14E+01	3.10	1.04E+01	3.10	9.47E+00	3.10
	Supervisor		5.68E+00	3.10	5.21E+00	3.10	4.74E+00	3.10
	Clerical		5.68E-01	3.10	5.21E-01	3.10	4.74E-01	3.10
Fluorination: Still Operators	Operator	All	8.85E+00	2.07	8.12E+00	2.07	7.38E+00	2.07
	general laborer		4.43E+00	2.07	4.06E+00	2.07	3.69E+00	2.07
	Supervisor		2.21E+00	2.07	2.03E+00	2.07	1.84E+00	2.07
	Clerical		2.21E-01	2.07	2.03E-01	2.07	1.84E-01	2.07
Fluorination: Central Loaders	Operator	All	1.71E+01	1.38	1.57E+01	1.38	1.42E+01	1.38
	general laborer		8.54E+00	1.38	7.83E+00	1.38	7.12E+00	1.38
	Supervisor		4.27E+00	1.38	3.92E+00	1.38	3.56E+00	1.38
	Clerical		4.27E-01	1.38	3.92E-01	1.38	3.56E-01	1.38
Scrap Recovery: Furnace Operator (Trays)	Operator	1951 and earlier	2.99E+01	5.00	2.75E+01	5.00	2.50E+01	5.00
	general laborer		1.50E+01	5.00	1.37E+01	5.00	1.25E+01	5.00
	Supervisor		7.49E+00	5.00	6.86E+00	5.00	6.24E+00	5.00
	Clerical		7.49E-01	5.00	6.86E-01	5.00	6.24E-01	5.00

Scrap Recovery: Furnace Operator (Trays)	Operator	1952 and later	2.99E+00	5.00	2.74E+00	5.00	2.49E+00	5.00
	general laborer		1.49E+00	5.00	1.37E+00	5.00	1.24E+00	5.00
	Supervisor		7.47E-01	5.00	6.85E-01	5.00	6.22E-01	5.00
	Clerical		7.47E-02	5.00	6.85E-02	5.00	6.22E-02	5.00
Scrap Recovery: Furnace Operator (Calciner)	Operator	1952 and later	9.98E+00	5.00	9.15E+00	5.00	8.32E+00	5.00
	general laborer		4.99E+00	5.00	4.58E+00	5.00	4.16E+00	5.00
	Supervisor		2.50E+00	5.00	2.29E+00	5.00	2.08E+00	5.00
	Clerical		2.50E-01	5.00	2.29E-01	5.00	2.08E-01	5.00
Scrap Recovery: Digest Operator	Operator	All	2.91E-01	5.00	2.67E-01	5.00	2.43E-01	5.00
	general laborer		1.46E-01	5.00	1.34E-01	5.00	1.21E-01	5.00
	Supervisor		7.29E-02	5.00	6.68E-02	5.00	6.07E-02	5.00
	Clerical		7.29E-03	5.00	6.68E-03	5.00	6.07E-03	5.00
Scrap Recovery: Filtration Operator	Operator	All	1.09E-01	4.94	1.00E-01	4.94	9.11E-02	4.94
	general laborer		5.46E-02	4.94	5.01E-02	4.94	4.55E-02	4.94
	Supervisor		2.73E-02	4.94	2.50E-02	4.94	2.28E-02	4.94
	Clerical		2.73E-03	4.94	2.50E-03	4.94	2.28E-03	4.94
Drum Loading Operations	Operator	All	N/A	N/A	N/A	N/A	N/A	N/A
	general laborer		N/A	N/A	N/A	N/A	N/A	N/A
	Supervisor		N/A	N/A	N/A	N/A	N/A	N/A
	Clerical		N/A	N/A	N/A	N/A	N/A	N/A

9.0 References

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10.0 Glossary

Black Oxide Common name for U_3O_8

Brown Oxide Common name for UO_2

Green Salt Common name for UF_4

Orange Oxide Common name for UO_3

Yellow Cake Common name for U_3O_8

BZ Breathing Zone samples

GA General Area samples

TWA Time Weighted Average. The concentration in ppm or mg/cm^3 of a chemical component multiplied by the time of each individual sampling period, summed for all samples taken during an interval and divided by the total sampling time.

DWA Daily Weighted Average – the sum of the products of the air concentration and the duration of all tasks performed as part of a job divided by the duration of the shift.

UX_1 ^{234}Th

UX_2 ^{234m}Pa