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PRELIMINARY EVALUATION OF HEALTH EFFECTS FOR HYPOTHETICAL EXPOSURES TO CONTAMINANTS FROM THE INTERIM WASTE CONTAINMENT STRUCTURE

TECHNICAL MEMORANDUM

FOR THE NIAGARA FALLS STORAGE SITE LEWISTON, NEW YORK

February 2012

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GENERAL NOTATION

(Acronyms for units of distance, area, volume, mass, and speed are tabulated at the end of this notation. Those defined where used in selected equations are not repeated here.)

ACGIH	American Conference of Governmental Industrial Hygienists
ACM	asbestos-containing material
ACS	American Cancer Society
AEC	U.S. Atomic Energy Commission
AEGL	acute exposure guideline level (EPA/National Research Council)
AERMOD	American Meteorological Society/EPA Regulatory MODel (computer code)
ALARA	as low as reasonably achievable
ARAR	applicable or relevant and appropriate requirement(s)
AT	averaging time
ATSDR	Agency for Toxic Substances and Disease Registry
BMD	benchmark dose
BMDS	benchmark dose software
BMR	benchmark response
BNI	Bechtel National, Inc.
BOP	balance of plant
BRA	baseline risk assessment
BW	body weight
Cal/EPA	California Environmental Protection Agency
CAP88-PC	Clean Air Act Assessment Package-1988-Personal Computer (computer code)
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (as amended)
Ci	curie
CSAF	chemical-specific adjustment factor
CT	computed tomography (scan), also known as computerized axial tomography, or CAT (scan)
d	day(s)
DCF	dose conversion factor
DOE	U.S. Department of Energy
ED	exposure duration
EDE	effective dose equivalent
EF	exposure frequency
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
ET	exposure time
FGR	Federal Guidance Report
FS	feasibility study
FUSRAP	Formerly Utilized Sites Remedial Action Program
HERO	Health and Environmental Research Online (EPA database)
HGL	HydroGeoLogic, Inc.
HI	hazard index

GENERAL NOTATION *(Cont'd.)*

HQ	hazard quotient
hr	hour(s)
ICRP	International Commission on Radiological Protection
IOM	Institute of Medicine
IR	intake rate (ingestion, inhalation)
IRIS	Integrated Risk Information System (EPA database)
ISCORS	Interagency Steering Committee on Radiation Standards
ITRC	Interstate Technology and Regulatory Council
IUR	inhalation unit risk (EPA)
IWCS	Interim Waste Containment Structure
KAPL	Knolls Atomic Power Laboratory
LET	linear-energy-transfer
LOAEL	lowest observed adverse effect level
LOOW	Lake Ontario Ordnance Works
MED	Manhattan Engineer District
MeV	million electron volts
mg/kg-d	milligram(s) per kilogram (body weight) per day
mg/m^3	milligram(s) per cubic meter (air)
$\mu g/m^3$	microgram(s) per cubic meter (air)
µR	microRoentgen
µs	microsecond(s)
min	minute(s)
mrem	millirem(s)
MRL	minimal risk level (ATSDR)
MSL	mean sea level
NAAQS	National Ambient Air Quality Standard(s)
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act
NESHAPs	National Emission Standards for Hazardous Air Pollutants
NFSS	Niagara Falls Storage Site
NIOSH	National Institute for Occupational Health and Safety
NOAEL	no observed adverse effect level
NPL	National Priorities List
NRC	National Research Council
NTP	National Toxicology Program
NYSDEC	New York State Department of Environmental Conservation
NYSDOH	New York State Department of Health
OEHHA	Office of Environmental Health Hazard Assessment (Cal/EPA)
OSHA	U.S. Occupational Safety and Health Administration
OU	operable unit

GENERAL NOTATION *(Cont'd.)*

p-IUR	provisional inhalation unit risk (EPA)
p-RfC	provisional reference concentration (EPA)
p-RfD	provisional reference dose (EPA)
PAH	polycyclic aromatic hydrocarbon(s)
PCB	polychlorinated biphenyl(s)
pCi	picocurie
pCi/L	picocurie/liter
PEL	permissible exposure limit (OSHA)
PM	particulate matter
$PM_{2.5}$	PM with an aerodynamic diameter of a nominal 2.5 microns or less
PM_{10}	PM with an aerodynamic diameter of a nominal 10 microns or less
POD	point of departure
PP	proposed plan
ppm	part(s) per million
PPRTV	provisional peer reviewed toxicity value (EPA)
QA/QC	quality assurance/quality control
rad	radiation absorbed dose
REL	recommended exposure limit (NIOSH)
rem	roentgen equivalent man
RESRAD	RESidual RADioactivity (computer code)
RfC	reference concentration (EPA)
RfD	reference dose (EPA)
RfEL	reference exposure level (Cal/EPA)
RI	remedial investigation
RIR	remedial investigation report
ROD	record of decision
RSL	Regional screening level(s) (EPA Region)
s	second(s)
SARA	Superfund Amendments and Reauthorization Act
SCO	soil cleanup objective(s) (New York)
SF	slope factor
SVOC	semivolatile organic compound(s)
TEDE	total effective dose equivalent
TLV	threshold limit value (ACGIH)
TM	technical memorandum
TNT	trinitrotoluene
TRU	transuranic
UF	uncertainty factor
USACE	U.S. Army Corps of Engineers
USNRC	U.S. Nuclear Regulatory Commission
UTL	upper tolerance limit
VOC	volatile organic compound(s)

GENERAL NOTATION *(Cont'd.)*

WL	working level(s)
WLM	working-level month(s)
WLR	working-level ratio
yr	year(s)

CONTAMINANT-SPECIFIC NOTATION

RADIONUCLIDES

Ac-227	actinium-227
Am-241	americium-241
Cs-137	cesium-137
Np-237	neptunium-237
Pa-231	protactinium-231
Pb-210	lead-210
Pu-238	plutonium-238
Pu-239	plutonium-239
Ra-226	radium-226
Ra-228	radium-228
Rn-222	radon-222
Sr-90	strontium-90
Tc-99	technetium-99
Th-228	thorium-228
Th-229	thorium-229
Th-230	thorium-230
Th-232	thorium-232
Th-234	thorium-234
U-233	uranium-233
U-234	uranium-234
U-235	uranium-235
U-238	uranium-238
Y-90	yttrium-90

CHEMICALS

As	arsenic
B	boron
Ba	barium
Cd	cadmium
Co	cobalt
Li	lithium
Mn	manganese
Mo	molybdenum
Ni	nickel
Pb	lead
U	uranium
V	vanadium

CONVERSION TABLE

Multiply	By	To Obtain
English/Metric Equivalents		
acre (ac)	0.4047	hectare (ha) *(1 ha = 10,000 m^2)*
acre (ac)	4,047	square meter (m^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3) *(= 10^6 cm^3)*
foot (ft)	0.3048	meter (m)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3,785	cubic centimeter (cm^3) *(= 1 milliliter [mL])*
inch (in.)	2.540	centimeter (cm)
inch (in.)	25,400	micron (µm, or micrometer)
knot (kt)	0.5144	meter per second (m/s) *(= 1.852 km/hr)*
mile (mi)	1.609	kilometer (km)
mile per hour (mph)	0.4470	meter per second (m/s)
ounce (oz.)	28.35	gram (g)
pound (lb)	0.4536	kilogram (kg)
short ton (tons)	907.2	kilogram (kg)
short ton (tons)	0.9072	metric ton (t)
square foot (ft^2)	0.09290	square meter (m^2)
square yard (yd^2)	0.8361	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
yard (yd)	0.9144	meter (m)
Metric/English Equivalents		
centimeter (cm)	0.3937	inch (in.)
cubic centimeter (cm^3, or cc)	0.0002642	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	264.2	gallon (gal)
gram (g)	0.03527	ounce (oz.)
hectare (ha)	2.471	acre (ac)
kilogram (kg)	2.205	pound (lb)
kilogram (kg)	0.001102	short ton (tons)
kilometer (km)	0.6214	mile (mi)
liter (L)	0.2642	gallon (gal)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
meter per second	1.944	knot (kt) *(1 kt = 1.151 mph)*
meter per second	2.237	mile per hour (mph)
metric ton (t)	1.102	short ton (tons)
micron (µm, or micrometer)	0.00003937	inches (in.)
milliliter (mL)	0.0002642	gallon (gal)
square kilometer (km^2)	0.3861	square mile (mi^2)
square meter (m^2)	0.0002471	acre (ac) *(1 ac = 43,560 ft^2)*
square meter (m^2)	10.76	square foot (ft^2)
square meter (m^2)	1.196	square yard (yd^2)

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PRELIMINARY EVALUATION OF HEALTH EFFECTS FOR HYPOTHETICAL EXPOSURES TO CONTAMINANTS FROM THE INTERIM WASTE CONTAINMENT STRUCTURE

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) is the lead Federal agency for the Formerly Utilized Sites Remedial Action Program (FUSRAP). The USACE Buffalo District is responsible for addressing the Niagara Falls Storage Site (NFSS) under FUSRAP, in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended. The CERCLA process is being conducted at NFSS via three operable units (OUs), with a feasibility study (FS) prepared to identify and evaluate remedial alternatives for each OU in accordance with standard regulations and guidance established by the U.S. Environmental Protection Agency (EPA).

The Interim Waste Containment Structure (IWCS) at NFSS contains high-activity residues and other, lower-level radioactive materials resulting from past processing and waste management activities conducted decades ago by the U.S. Department of Energy (DOE). The USACE conducts an environmental surveillance program and performs site operations, maintenance, and monitoring to ensure protection of human health and the environment from contaminants contained in the IWCS and elsewhere on the Federally-owned NFSS. Because the IWCS represents the primary source of potential contamination at the site, it is being addressed as the first OU. Topical technical reports are being prepared to support the upcoming FS for the IWCS OU, including this technical memorandum (TM).

ES.2 PURPOSE AND SCOPE

The purpose of this TM is to assess potential health effects from hypothetical exposures to the IWCS contents, to support development of the FS for this OU. The scope focuses on two main concerns: (1) direct exposures at the IWCS and (2) airborne releases that impact air and soil both onsite and offsite. Key radiological concerns are external gamma irradiation and inhalation (including of radon and its decay products). Migration of IWCS contaminants to groundwater is not included in the scope of this TM because that issue has been separately evaluated. This TM focuses on the near term (ten years) in order to complement previous risk analyses for the IWCS, which have considered exposures extending into the longer term. By this approach, the TM aims to strengthen the integrated risk picture for the IWCS to support the upcoming evaluation of remedial alternatives for this OU. The objectives of this TM are:

- Support the FS evaluations of short-term effectiveness, long-term effectiveness, and overall protection of human health and the environment for the different remedial alternatives being considered for the IWCS.
- Describe key release mechanisms and potential onsite and offsite exposures associated with IWCS contaminants, and summarize risk information previously developed for the IWCS to further the state of knowledge for this OU regarding potential health effects.
- Illustrate the approach for estimating doses, cancer risks, and noncarcinogenic health effects for hypothetical exposures not yet assessed for the IWCS, to help frame the development and evaluation of remedial alternatives and associated worker protection measures.
- Provide an early technical evaluation to stakeholders to encourage interactions and foster communication regarding the process for quantifying potential health risks associated with the IWCS while project-specific information is being developed for the FS.

- Facilitate the review and completion process for the FS by providing an opportunity for advance stakeholder comment and technical iteration on illustrative risk estimates for the IWCS, based on early conceptual assumptions for waste excavation and in-place conditions.

ES.3 ROLE OF THE IWCS AND THIS TM IN THE NFSS REMEDIAL ACTION PROCESS

Role of the IWCS OU in the Remedial Action Process for NFSS

The IWCS represents the first of the three OUs for NFSS, as illustrated in Figure ES.1. This OU addresses the wastes DOE placed in the IWCS. The other two OUs will address the remainder of NFSS, i.e., the balance of the physical features and soil (referred to as "balance of plant" or BOP) and groundwater. The specific scopes of these subsequent OUs will be defined after the IWCS remedy is selected, as the scopes will depend on that remedy. This sequenced approach for remedial action assures efficient evaluations for each set of contaminated materials and environmental media at NFSS, with progressive decisions leading to a final sitewide remedy.

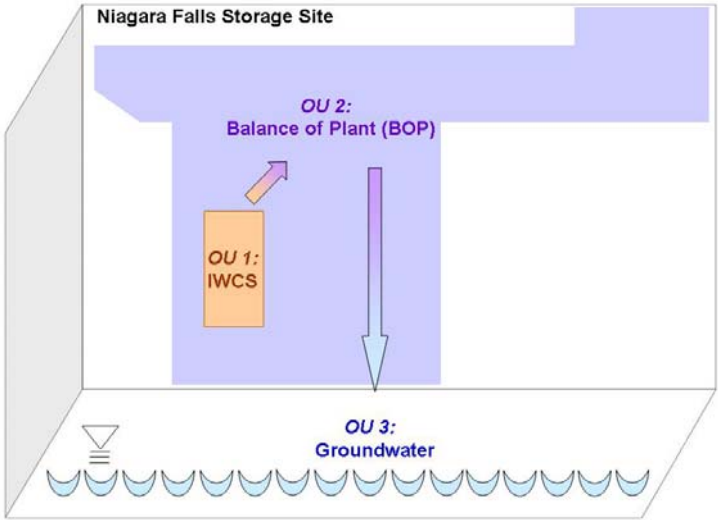

FIGURE ES.1 Schematic of the NFSS Operable Units

Role of this TM in Evaluations for the IWCS OU

The role of this report is to illustrate the process for estimating potential risks from direct exposures and airborne releases at the IWCS, to help frame the development and evaluation of remedial alternatives in the upcoming FS and guide appropriate health protection measures. A number of technical reports have been prepared for NFSS and the IWCS OU, and additional documents are planned as illustrated in Figure ES.2. The first TM in the series for this OU addresses waste disposal options and lessons learned from the recent cleanup of similar wastes at the DOE Fernald site in Ohio.

This health effects TM includes general elements of a health risk assessment as outlined in standard EPA guidance for contaminated sites. The FS for the IWCS OU will use information from this TM and other technical analyses to develop and evaluate remedial alternatives in accordance with the CERCLA process, applying the standard criteria set forth in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP). Health risk information is key to the comparative evaluation of alternatives, as explicitly considered for three criteria: overall protection of human health and the environment, long-term effectiveness and permanence, and short-term effectiveness (which considers risks during the remedial action period). Together with previous analyses for NFSS, this TM highlights information for potential risks from the IWCS wastes to help guide planning for the FS.

Among other technical reports being prepared to support the IWCS FS, the radon assessment TM focuses on emissions of the inert gas radon-222 (Rn-222) from the IWCS and presents preliminary concentration estimates at various locations onsite and nearby. Some information in that TM provides context for the analyses in this TM; for example, the release scenarios and receptor locations evaluated in that TM are

also considered for this report. In extending beyond the contaminant-specific focus of that TM (which was initiated earlier), this health effects TM considers a fuller suite of contaminants (i.e., radionuclides beyond Rn-222, as well as chemicals), other release and transport mechanisms (in some cases qualitatively), and associated exposures to further outline the risk picture for the IWCS.

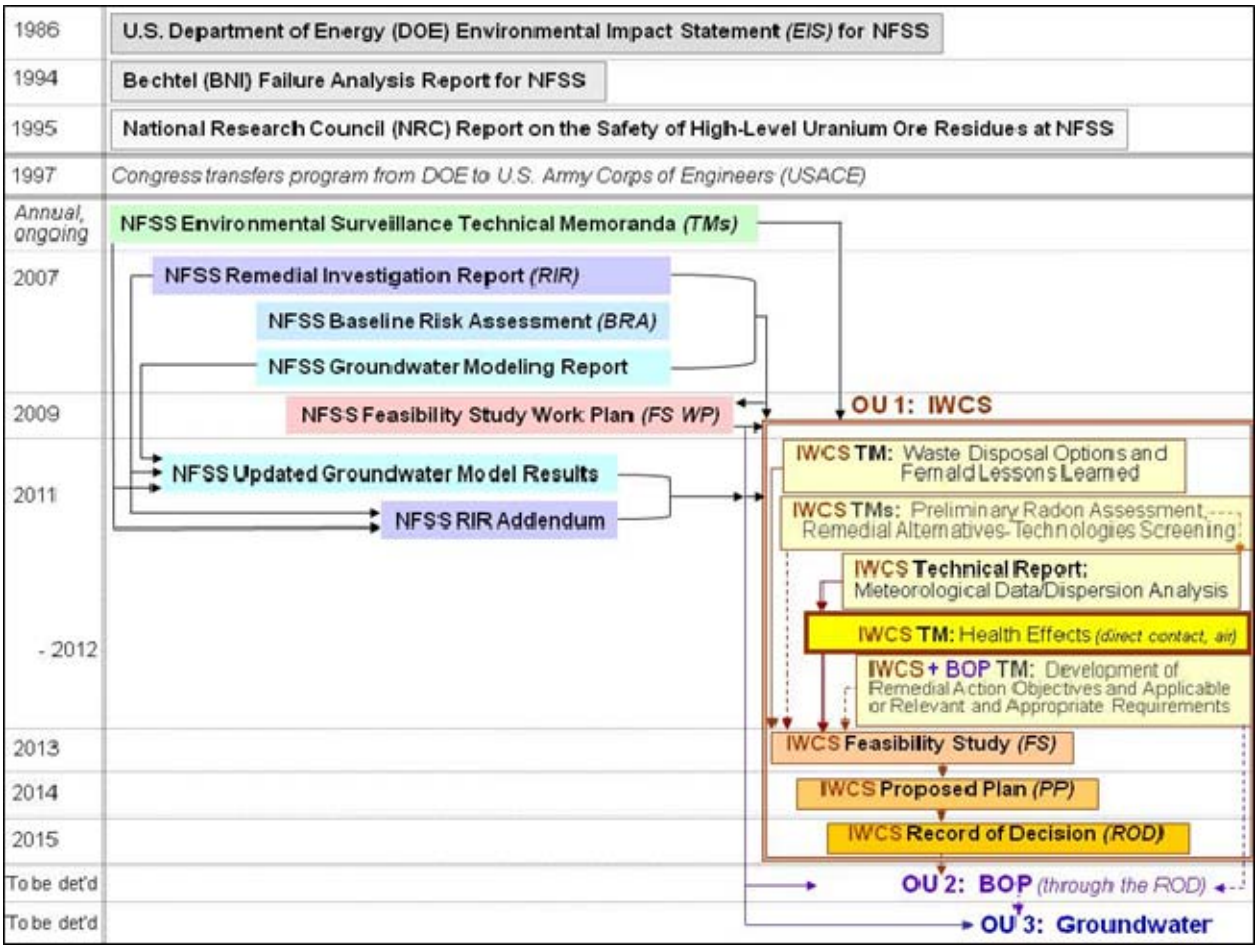

FIGURE ES.2 Key Documents for NFSS and the IWCS OU

(This report is outlined in bold. Dashed arrows indicate other TMs available this year.)

This TM directly uses information in the companion technical report that evaluates meteorological data and air dispersion modeling (see Figure ES.2). Information being developed for other TMs also helps frame the scope of this report. For example, together with the FS Work Plan, preliminary information for the TM being developed for remedial alternatives and screening technologies helps shape the initial groupings of IWCS wastes evaluated in this TM.

Following the practical approach of building on existing information, this TM highlights the findings of earlier risk assessments for the IWCS rather than repeating basic scenarios that have already been assessed. Thus, this TM does not reassess a hypothetical resident at the IWCS because that scenario was addressed by the National Research Council (NRC) in its 1995 study, which in turn built on the evaluation in the environmental impact statement (EIS) for NFSS issued by DOE in 1986 (see Section ES.5.1).

Similarly, the contents of the IWCS were not included in the 2007 baseline risk assessment (BRA) that accompanied the remedial investigation report (RIR) because existing engineering controls and institutional measures were assumed to remain in place, thus limiting exposures to these materials. Instead of quantifying risks for hypothetical IWCS releases, the BRA referenced the findings of the earlier DOE and NRC evaluations to acknowledge that a loss of cover integrity could result in unacceptable risks to human health and the environment. Those findings also frame the development of alternatives for the FS, to assure that any onsite options for the IWCS address potential long–term risks.

Quantitative estimates of health risks in previous analyses for the IWCS are somewhat limited, consistent with the objectives of those studies. Thus, any alternatives considered for the IWCS that would involve leaving all or part of the contents onsite (either in place or in a new facility at NFSS) would warrant more detailed evaluations in the FS, particularly to address the criterion for long-term effectiveness and permanence. That is, for in-situ alternatives, the FS would evaluate the effectiveness and protectiveness of maintaining the materials in the IWCS as part of the evaluation of alternatives, in accordance with the nine evaluation criteria identified in the NCP. If a new onsite disposal facility were considered, the IWCS FS would address potential leaching from the facility as well as other release and transport mechanisms (such as overland flow and discharge to surface water during material staging) as indicated, to support the evaluation of remedial alternatives for the IWCS that assure health and environmental protection into the long term.

ES.4 PRIMARY DATA SOURCES

No new waste characterization was conducted at the IWCS for this TM. The IWCS contents were not sampled during the recent NFSS RI process for three reasons. First, it was determined that sufficient information already exists from historical records and related technical evaluations to support a decision for the IWCS under the CERCLA process. Second, to conduct such intrusive sampling could put those workers at considerable risk, including from exposures over the extended time that would be needed to collect a sufficient number of samples to obtain a statistically significant data set. Third, such characterization activities could compromise the integrity of the IWCS cover, which would increase the likelihood of contaminant releases that might impact the general public.

Thus, historical documentation for the IWCS and NFSS serves as the main source of information for this TM, including the reports shown in Figure ES.2. Beyond the EIS, the documentation includes data DOE collected while implementing the original remedial actions at the site during the 1980s, which involved constructing the IWCS and consolidating radioactive materials within this structure until a permanent disposition could be determined. Considerable historical documentation for the site is also summarized in the 2007 RI and groundwater modeling reports and the spring 2011 updates of each.

Historical documentation for another Federal project with wastes similar to those found in the IWCS also serves as a valuable resource for this TM, specifically reports about the DOE Fernald site in Ohio. Key data regarding those similar wastes are summarized in another TM for the IWCS OU that highlights DOE lessons learned at Fernald (see Figure ES.2). For chemicals, this health effects TM also considers data for the adjacent Lake Ontario Ordnance Works (which was previously Federally owned) as supporting context for site data.

For the air dispersion analyses, this TM relies on information presented in the companion technical report on meteorological data and dispersion analyses (see Figure ES.2). That technical report benefits substantially from measurements that were shared with USACE from meteorological stations on the two commercial landfill properties adjacent to NFSS in late 2010. The USACE Buffalo District installed a new meteorological station onsite in spring 2011. When sufficient measurements are available from this

station, those data will be used in dispersion modeling for the site. Until that time, the data from the adjacent landfill to the north are considered well-suited for use in dispersion analyses for NFSS.

ES.5 SUMMARY OF RESULTS

ES.5.1 Previous Health Risk Analyses

Two studies prepared by DOE a number of years ago serve as primary sources of dose and risk information relevant to the IWCS. These studies are: the EIS for NFSS issued in 1986 and the failure analysis report prepared for the IWCS in 1994. (Although the NRC published a study in 1995 that evaluated the safety of the IWCS and made recommendations, that report generally used information from these two documents rather than reflecting any significant new data.) Information about the hypothetical exposures and corresponding doses and risks assessed in these two reports is given in Table ES.1.

TABLE ES.1 Highlights of Dose and Risk Estimates from Previous Analyses for the IWCS[a]

Hypothetical Receptor	Material/ Location[b]	Estimated Radiation Dose *(mrem)*[c]	Estimated Cancer Risk[d]	Information Source
Onsite				
Resident intruder	IWCS residues	1,100,000 per year[e]	4×10^{-1} per year	EIS
Exploratory driller	On IWCS cap	510	3×10^{-5}	Failure analysis
Remedial action worker	Near IWCS	4.2 per hr	1×10^{-6} per hour	EIS
Offsite				
Camper at KOA campground	0.7 km SSW	11	4×10^{-6}	EIS
Student at nearby school	2.4 km W	1.5	5×10^{-7}	EIS
Resident at trailer park	2.6 km NW	0.80	3×10^{-7}	EIS
Worker at CWM landfill	1.2 km NNE	14	4×10^{-6}	EIS
Nearby potential resident	0.2 km W	94	3×10^{-5}	EIS

[a] The exposure scenarios summarized in this table are described in more detail in the EIS and failure analysis report. The impacts for the onsite remedial action worker and the five offsite receptors are estimated in the EIS for potential onsite remedial activities involving retrieval of residues and wastes from the IWCS. The onsite resident intruder and exploratory driller scenarios might occur in the distant future if contaminated materials were to remain onsite and institutional controls were lost. Current radiation doses in the vicinity of NFSS are much lower than those given in this table, as reported in annual TMs for the environmental surveillance program at NFSS. The radiation doses are given to two significant figures, while estimated cancer risks are given to one significant figure in accordance with standard EPA guidance.

[b] For the onsite scenarios, the receptor is assumed to be either at or near the IWCS. For the offsite receptors, the distances shown here are those given in Table 4.8 of the EIS.

[c] Radiation doses are given as 50-year committed effective dose equivalents (CEDEs). These doses were obtained from the organ-specific doses given in Table 4.10 of the EIS using the organ-weighting factors in effect at the time the EIS was issued. The radiation dose and cancer risk to the exploratory driller is largely from external gamma radiation.

[d] Cancer risks represent the risk of a fatal cancer, consistent with the manner in which this information is given in the EIS. For the hypothetical exploratory driller scenario, the risk of a fatal cancer was obtained by multiplying the radiation dose by a risk factor of 6×10^{-7} per mrem, because much of the dose incurred by this receptor is from external gamma radiation (for which this dose-to-risk estimator is directly relevant). For the other scenarios, the risk of a fatal cancer was obtained using the organ-specific doses and organ-specific cancer mortality factors given in Table 4.30 of the EIS.

[e] This dose is calculated from the annual dose to the bronchial epithelium of 8,000,000 mrem/year given in Table 4.24 of the EIS and cited in the 1995 NRC report, multiplied by 2.27 to account for the higher Ra-226 concentration in the residues (see text). A weighting factor of 0.06 is used to calculate the CEDE from the dose to the bronchial epithelium. The dose and cancer risk for the resident intruder would be higher if other pathways beyond inhalation of Rn-222 decay products were included.

As described in the NFSS EIS, the K-65 residues (and other high-activity residues) represent the main hazard at the IWCS. If these residues were not contained, the high levels of radium-226 (Ra-226) would emit substantial external gamma radiation and release Rn-222 gas to the atmosphere. Without controls, the doses from external gamma irradiation and inhalation of Rn-222 progeny could harm anyone nearby.

In its subsequent study, the NRC determined that if institutional controls were lost and the IWCS cover completely eroded away, then if someone built a house on the residues (and drank underlying water and ate food from an IWCS garden), they would incur an unacceptable risk. The NRC concluded that this hypothetical resident would likely die within a few years due to high radiation doses from inhalation of Rn-222 decay products. Although an onsite residential scenario is quite unrealistic in the near term, some might consider it possible in the distant future if the high-activity residues remained at NFSS, land-use controls were indeed lost, and someone unwittingly (and inexplicably) lived atop these residues.

The estimates presented in the EIS assumed an average Ra-226 concentration of 220,000 pCi/g for the K-65 residues, which reflected information available at that time. The average Ra-226 concentration in all the high-activity residues combined was taken to be 67,000 pCi/g. The hypothetical doses presented in the EIS would have been higher if more recent estimates for Ra-226 had been used. Specifically, the average Ra-226 concentration in the K-65 residues is now estimated to be about 520,000 pCi/g, while the average concentration for all high-activity residues combined is estimated to be about 152,000 pCi/g (due to the higher estimate for the K-65 residues). Thus, to facilitate comparisons with the radiation doses and risks estimated in this TM (see Section ES.5.2), the doses and cancer risks reported in the EIS were adjusted upward by a corresponding factor (2.27) for presentation in Table ES.1, to account for the updated estimates of average Ra-226 concentrations.

Note that the internal radiation doses in the EIS are reported in terms of 50-year committed dose equivalents to the major target organs. The internal doses were converted to 50-year committed effective dose equivalents for presentation in Table ES.1, using the organ-specific weighting factors that were in effect when the EIS was prepared. This conversion was done to allow for a more direct comparison with the doses and risks estimated in this TM (see Section ES.5.2).

The estimated cancer risks in Table ES.1 generally represent the risk of incurring a fatal cancer, because the cancer risks presented in the EIS were limited to cancer mortality and did not include estimates for cancer morbidity. This is consistent with the manner in which radiological cancer risk information was presented in comparable documents at that time (in 1986). Risk estimators for cancer morbidity were not generally available until several years later. Note that the risk estimates calculated in this TM (presented in Chapters 5 and 6 and Appendix A) are for cancer incidence (morbidity), consistent with EPA guidance.

The EPA has noted that about half of all cancers induced by radiation result in death. That is, as a rough approximation, the risk of cancer morbidity can be generically estimated by multiplying the mortality risk by two. However, the difference between cancer morbidity and mortality for the radionuclides in the IWCS is generally less than about 50%, depending on the mode of exposure. For these radionuclides, the cancer morbidity estimates for the scenarios addressed in the EIS can be approximated by multiplying the mortality risk estimates by 1.5. This adjustment will produce conservative estimates of cancer morbidity risks for comparison with the risks calculated in this TM for the six example scenarios.

ES.5.2 Evaluations in this TM

This TM evaluates risks from exposures to contaminants in the IWCS wastes under two conditions: (1) wastes are excavated and contaminants are released to air, with subsequent dispersion and deposition of contaminated particulates on surface soil; and (2) wastes are in place but uncovered.

Potential health effects associated with waste excavation are assessed for six hypothetical receptors:

- Offsite – outdoor worker (assumed at the adjacent landfill), and adult and child residents.
- Onsite – remedial action worker, maintenance worker, and adolescent trespasser.

To guide risk management planning at contaminated sites, the NCP identifies a range of between one in ten thousand (1×10^{-4}, or 0.0001) and one in a million (1×10^{-6}, or 0.000001) for the incremental cancer risk for exposures associated with site contaminants, which is referred to as the target risk range. As a general perspective, based on recent U.S. data, men have a nearly 1 in 2 risk (5×10^{-1}, or 0.5) of developing cancer over a lifetime from all causes combined, and the estimate for women is slightly more than 1 in 3 (3×10^{-1}, or 0.3). Thus, the NCP target range for incremental risk represents a very small fraction (e.g., 0.0002% to 0.03%) of the average U.S. cancer rate. The NCP target levels are noted in this TM simply to provide example context for the preliminary risk estimates presented herein; they are not action levels, rather they serve as illustrative comparison values to help inform planning for the IWCS FS.

The risk estimates in this TM represent the increased probability (above a background rate) that an individual will develop cancer over a lifetime from the exposures assumed for the IWCS contaminants. As perspective for the radionuclides, the National Council on Radiation Protection and Measurements (NCRP) estimates that the U.S. average annual radiation dose is about 620 mrem, with natural and man-made sources (which include medical procedures and consumer products) each contributing about 310 mrem. For natural sources, about two-thirds of the dose (200 mrem/year) is due to indoor Rn-222 gas and its short-lived radioactive decay products. This average background dose corresponds to a lifetime cancer risk of about 3×10^{-2}, or about 3 chances in 100 of getting cancer over a lifetime (based on a risk factor of 8×10^{-7} per mrem for the likelihood of developing a radiogenic cancer and a lifetime of 70 years). In addition, to inform the evaluation of short-term effectiveness for the various remedial alternatives in the FS, radiological dose and chemical air concentrations are compared to limits developed by federal agencies for worker protection.

The evaluation of potential health effects from waste excavation reflects preliminary planning information for waste groupings, exposed excavation areas, and associated emission controls. Results of this assessment are presented in Table ES.2 (radiological doses and risks) and Table ES.3 (chemical hazard indexes [HIs] and risks). For these evaluations, the wastes are organized into three groups based on key radionuclide concentrations (notably Ra-226), which is expected to influence the options for managing these wastes.

- Group 1 consists of the K-65 residues.
- Group 2 consists of the L-30, F-32, and L-50 residues and the tower soils.
- Group 3 consists of the former R-10 pile and other contaminated soils.

Group 3 also includes intermixed rubble and debris, but given the nature of these materials, associated dispersion and deposition are not quantified in this TM. These waste groupings are expected to evolve as project-specific planning for the FS proceeds.

Little offsite impact is projected from waste excavation at the IWCS. With assumed engineering controls, estimated radiation doses for the hypothetical offsite receptors are less than 1 mrem, and both radiological and chemical risks are below 1×10^{-6}. The HI is also well below the NCP comparison level. Even when no controls are assumed, the offsite estimates remain within and below target levels. For the onsite receptors, the doses, risks, and HIs are much higher but only one value exceeds NCP comparison levels.

TABLE ES.2 Estimated Radiological Doses and Risks from Hypothetical Excavation Releases and Direct Waste Exposures at the IWCS[a]

Scenario	Estimated Radiological Doses and Cancer Risks							
	Waste Group 1		***Waste Group 2***		***Waste Group 3***		***Total***	
	K-65 Residues		**L-30, F-32, L-50 Residues and Tower Soils**		**R-10 Pile and Other Contaminated Soils**		**All IWCS Wastes**	
	Dose *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	16	1×10^{-5}	4.4	3×10^{-6}	0.034	2×10^{-8}	21	2×10^{-5}
Maintenance worker	**200**	$\mathbf{2 \times 10^{-4}}$	31	1×10^{-5}	0.23	7×10^{-8}	**230**	$\mathbf{2 \times 10^{-4}}$
Trespasser	2.5	2×10^{-6}	0.35	2×10^{-7}	0.0023	7×10^{-10}	2.9	2×10^{-6}
Offsite: dispersed contaminants								
Outdoor worker	0.46	4×10^{-7}	0.11	5×10^{-8}	0.0016	5×10^{-10}	0.57	4×10^{-7}
Adult resident	0.40	3×10^{-7}	0.065	3×10^{-8}	0.00078	3×10^{-10}	0.47	3×10^{-7}
Child resident	0.39	3×10^{-7}	0.058	3×10^{-8}	0.00066	2×10^{-10}	0.45	3×10^{-7}
Onsite: direct waste exposures[b]								
Incidental ingestion (100 mg)	**430**	$\mathbf{2 \times 10^{-4}}$	11	5×10^{-6}	0.041	2×10^{-8}	**440**	$\mathbf{2 \times 10^{-4}}$
External gamma (8 hr)	**2,000**	$\mathbf{2 \times 10^{-3}}$	38	3×10^{-5}	0.13	1×10^{-7}	**2,000**	$\mathbf{2 \times 10^{-3}}$
Combined direct exposures	***2,400***	$\boldsymbol{2 \times 10^{-3}}$	*49*	4×10^{-5}	*0.17*	1×10^{-7}	***2,500***	$\boldsymbol{2 \times 10^{-3}}$

[a] The dose is the 50-year committed effective dose, and it is given to two significant figures. The cancer risk represents the probability that an exposed individual will develop cancer over a lifetime, and it is rounded to one significant figure. Estimates in bold exceed the comparison levels from the NCP. The waste groups reflect preliminary planning information for the IWCS OU. Excavation areas are assumed to be: 500 m^2 (600 yd^2) for group 1; 1,000 m^2 (1,200 yd^2) for group 2; and 2,000 m^2 (2,400 yd^2) for group 3. Estimated waste volumes (rounded to two significant figures) are: 3,000 m^3 (4,000 yd^3) for group 1; 11,000 m^3 (14,000 yd^3) for group 2; and 110,000 m^3 (84,000 yd^3) for group 3. Assumed daily processing rates are: 20 m^3 (26 yd^3) for group 1; 100 m^3 (130 yd^3) for group 2; and 300 m^3 (400 yd^3) for group 3. For particulates, a control efficiency of 99% is assumed for group 1 (based on an engineered system), and 75% is assumed for groups 2 and 3 (based on water spraying four times daily); a control efficiency of 90% is assumed for Rn-222 emissions from groups 1 and 2 (based on an engineered system); no Rn-222 control is assumed for group 3 because the lower Ra-226 concentrations in those materials are not expected to warrant controls beyond the water spraying four times daily that would be applied to control particulate emissions.

The hypothetical exposure scenarios are described in Chapter 3. For the onsite scenarios, the remedial action worker is assumed to spend the entire time onsite at the IWCS, with personal protective equipment for all but one day during the excavation of each waste group (to account for potential limited failure of the protective equipment, and also to illustrate what the dose and risk would be if exposures were not controlled with respiratory protection). The onsite maintenance worker and trespasser are assumed to spend an average of 10% of their time within 1 m (3 ft) of uncovered IWCS wastes and the rest of the time 50 m (160 ft) and 100 m (330 ft) from the exposed wastes, respectively.

[b] Someone standing 1 m (3 ft) from a 10-m^3 (13-yd^3) pile of unshielded K-65 residues for 8 hours would incur an external gamma dose of 2,000 mrem (2 rem), which corresponds to a risk of 2×10^{-3}. The doses and risks for the other two waste groups are scaled from their Ra-226 concentrations relative to that in the K-65 residues. If someone inadvertently (incidentally) ingested 100 mg (0.0035 ounce) of the K-65 residues directly, the dose would be 430 mrem and the corresponding risk would be 2×10^{-3}. The doses and risks for the other two waste groups are calculated based on the volume-weighted average radionuclide concentrations in the component wastes.

TABLE ES.3 Estimated Chemical Hazard Indexes and Risks for Example Exposures to IWCS Contaminants[a]

Scenario	Estimated Chemical Hazard Indexes and Cancer Risks							
	Waste Group 1		***Waste Group 2***		***Waste Group 3***		***Total***	
	K-65 Residues		**L-30, F-32, L-50 Residues and Tower Soils**		**R-10 Pile and Other Contaminated Soils**		**All IWCS Wastes**	
	Hazard Index	**Risk**	**Hazard Index**	**Risk**	**Hazard Index**	**Risk**	**Hazard Index**	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	0.0002	2×10^{-9}	0.04	3×10^{-8}	0.0006	2×10^{-8}	0.04	4×10^{-8}
Maintenance worker	0.004	1×10^{-8}	0.6	3×10^{-7}	0.01	3×10^{-8}	0.6	3×10^{-7}
Trespasser	0.00005	3×10^{-10}	0.007	5×10^{-9}	0.0002	2×10^{-9}	0.008	8×10^{-9}
Offsite: dispersed contaminants								
Outdoor worker	0.00001	3×10^{-11}	0.003	1×10^{-9}	0.00008	2×10^{-10}	0.003	2×10^{-9}
Adult resident	0.000006	2×10^{-11}	0.002	7×10^{-10}	0.00005	1×10^{-10}	0.002	9×10^{-10}
Child resident	0.000006	2×10^{-11}	0.002	8×10^{-10}	0.00005	2×10^{-10}	0.002	1×10^{-9}
Onsite: direct waste exposure[b]								
Incidental ingestion (100 mg)	**10**	$\mathbf{8 \times 10^{-4}}$	**9**	$\mathbf{3 \times 10^{-4}}$	**4**	$\mathbf{1 \times 10^{-4}}$	**20**	$\mathbf{1 \times 10^{-3}}$

[a] The hazard index (HI) represents the potential for a noncarcinogenic effect (with further consideration warranted when it exceeds 1), and it is rounded to one significant figure (for values less than 1) or to the nearest integer. The cancer risk represents the probability that an individual will develop cancer over a lifetime, and it is rounded to one significant figure. Estimates in bold exceed the comparison levels from the NCP. The waste groups reflect preliminary planning information for this OU, as described in the body of this TM. Assumptions used to estimate airborne releases are summarized in Table ES.2, footnote a.

The standard chemical toxicity values used to estimate potential noncarcinogenic effects (represented by the HI) and the risk of cancer are based on relatively limited human data and thus reflect upper bound, conservative estimates of potential health effects. (This is in contrast to the radiological risk estimators, which reflect a relatively large amount of data from human radiation exposures.) In addition, concentration data for chemicals in the IWCS are limited, so relatively high concentrations are assumed across the combined wastes. For these reasons, the estimates presented in this TM based on limited contaminant data and conservative toxicity values are expected to overestimate the risks associated with nonradiological exposures during waste excavation from the IWCS.

[b] If someone inadvertently (incidentally) ingested 100 mg (0.0035 ounce) of the K-65 residues directly, the HI would be 10 and the corresponding risk would be 8×10^{-4}. The estimated HIs and risks for the other two waste groups are lower, as calculated from the volume-weighted average concentrations of the chemicals in the component wastes.

The estimated onsite doses for exposures associated with waste excavation range from 2.9 to 230 mrem, and corresponding risks range from 2×10^{-6} to 2×10^{-4}. The highest risk is for the hypothetical maintenance worker (just above the NCP target range). Unlike the remedial action worker, the maintenance worker is assumed to wear no respiratory protection.

Inhalation is the dominant pathway for both radionuclides and chemicals, with Rn-222 and progeny being the main contributor. Incidental ingestion and external gamma radiation associated with contaminants deposited on soil are relatively small contributors to the overall risk estimates.

Across all receptors, the radiological risks range from 3×10^{-7} to 2×10^{-4}, with most attributable to the K-65 residues (waste group 1). The radiological risks for the other two waste groups are significantly lower, within or below the NCP comparison range for all six hypothetical receptors. The risks for waste group 2 are roughly 1/10 those for group 1, while those for waste group 3 are lower than group 1 by a factor of more than 100. These differences reflect the very high concentrations of Ra-226 in the K-65 residues and associated contributions of Rn-222 and its short-lived decay products.

The chemical risks associated with particulates released during waste excavation are much lower than the radiological risks and contribute less than 1% to the total cancer estimates. All chemical risks and HIs are below the NCP comparison levels. The highest combined risk is 3×10^{-7} for the hypothetical maintenance worker, which is dominated by exposures associated with the excavation of waste group 2. This risk is primarily from the inhalation of cobalt (70%), with vanadium accounting for most of the remainder. The estimated HI of 0.6 is from inhalation of manganese (50%), with nickel and cobalt contributing most of the rest. The next highest estimates for the combined waste excavations are for the hypothetical remedial action worker, with a risk and HI lower than those for the maintenance worker by roughly a factor of ten, at 4×10^{-8} and 0.04, respectively. The risks and HIs for all other receptors for the three waste groups are even lower (all well below the NCP comparison levels). None of the chemical particulate emissions result in air concentrations that exceed permissible exposure limits for workers or national ambient air quality standards (for lead).

If someone inadvertently ingested 100 mg (0.0035 ounce) of K-65 residues at the IWCS (waste group 1), the dose would be about 430 mrem and the corresponding risk would be 2×10^{-4}. The doses and risks for the other two waste groups would be much lower because their radionuclide concentrations are much lower. The total dose from ingesting this tiny amount of waste from each of the three groups is estimated to be 440 mrem, and the risk would be 2×10^{-4}. The dominant contributor to this ingestion dose and risk is lead-210 (accounting for more than 85% of the risk), with much of this contribution associated with its decay product polonium-210; Ra-226 accounts for most of the remainder.

The chemical risks from ingesting 100 mg (0.0035 ounce) of K-65 residues are somewhat higher (8×10^{-4}), with lead being the main contributor based on its chemical toxicity. The estimated HI of 10 exceeds the NCP comparison level. The total chemical risk from incidentally ingesting this small amount of waste from each IWCS group is estimated to be 1×10^{-3}, and the total HI would be 20. These estimates reinforce the need for stringent controls for anyone near the IWCS wastes, especially the K-65 residues, to minimize the likelihood of any incidental ingestion exposures.

In addition to the potential health effects associated with excavating wastes from the IWCS, it is possible that someone could be exposed for a relatively short time to external gamma radiation emitted from the uncovered wastes in place. Estimates for several hypothetical cap breach conditions indicate that this dose could exceed 1,000 mrem (1 rem) within a number of days or a few weeks, depending on the extent of exposure. A dose of 1,000 mrem corresponds to a risk of 8×10^{-4}, which exceeds the NCP target range. An example risk estimate for exposures incurred while repairing a relatively long fracture in the

cap is 7×10^{-3}. Beyond the risks associated with gamma radiation, uncovered IWCS wastes would also emit Rn-222 gas. The doses and risks associated with the Rn-222 progeny would likely be somewhat lower than those from gamma radiation but in some cases could be comparable.

An overall summary of the risks and HIs estimated for example exposures to all IWCS wastes for the six hypothetical receptors is presented in Table ES.4.

TABLE ES.4 Combined Hazard Indexes and Risks Estimated for Example Exposures to IWCS Contaminants[a]

Scenario	Hazard Index	Chemical Risk	Radiological Risk	Combined Cancer Risk
Onsite: dispersed contaminants				
Remedial action worker	0.04	4×10^{-8}	2×10^{-5}	2×10^{-5}
Maintenance worker	0.6	3×10^{-7}	$\mathbf{2 \times 10^{-4}}$	$\mathbf{2 \times 10^{-4}}$
Trespasser	0.008	8×10^{-9}	2×10^{-6}	2×10^{-6}
Offsite: dispersed contaminants				
Outdoor worker	0.003	2×10^{-9}	4×10^{-7}	4×10^{-7}
Adult resident	0.002	9×10^{-10}	3×10^{-7}	3×10^{-7}
Child resident	0.002	1×10^{-9}	3×10^{-7}	3×10^{-7}
Onsite: direct waste exposures				
Incidental ingestion (100 mg)	**20**	$\mathbf{1 \times 10^{-3}}$	$\mathbf{2 \times 10^{-4}}$	$\mathbf{1 \times 10^{-3}}$
External gamma (8 hr)			$\mathbf{2 \times 10^{-3}}$	$\mathbf{2 \times 10^{-3}}$
Combined direct exposures	***20***	$\boldsymbol{1 \times 10^{-3}}$	$\boldsymbol{2 \times 10^{-3}}$	$\boldsymbol{3 \times 10^{-3}}$

[a] The radiological and chemical risk estimates represent the probability that the hypothetical individual will develop cancer during their lifetime as a result of exposures to IWCS contaminants from excavating all three waste groups from the IWCS. The total risk is the arithmetic sum of the radiological and chemical risks. The estimates in bold exceed the NCP comparison levels. The HI represents the potential for adverse health effects other than cancer and is calculated to assess health effects from chemical exposures; a value of 1 or less indicates no adverse effects are expected. The risks and HIs are rounded to one significant figure. Gray shading indicates the entry is not relevant.

These illustrative doses and risks are based on general conceptual assumptions because project-specific information is not yet available to conduct a representative assessment. These assumptions are conservative (protective), and more realistic (project-specific) inputs are anticipated to produce lower results. Nevertheless, these early example estimates indicate that if the remedy selected for the IWCS OU involves excavating or otherwise uncovering the residues, stringent measures would be warranted to:

- Protect people onsite from external gamma radiation (e.g., by time, distance, and shielding);
- Control Rn-222 and particulate releases; and
- Preclude incidental ingestion.

These controls would be particularly important for the K-65 residues and other high-activity residues because of the high Ra-226 concentrations in those wastes.

ES.6 OVERALL FINDINGS

The example risk information in this report is designed to support the development and evaluation of remedial alternatives in the IWCS and to help frame practical worker protection measures. To support planning for the FS, this report illustrates the process for estimating risks to help guide the determination of appropriate source and exposure control measures that will assure health protection (notably for nearby individuals if wastes are excavated from the IWCS, particularly the high-activity residues). The main findings are:

- Wastes in the IWCS are safely contained, and they will remain safe for as long as active controls are in place at NFSS to prevent inadvertent exposures.

- If the wastes were uncovered and someone were to stay at the IWCS for several days to weeks, substantial doses and serious health effects could result. The main contributors would be external gamma irradiation and inhalation of Rn-222 and its progeny.

- If engineering controls are in place, the wastes can be safely removed from the IWCS with minimal offsite impact.

- During excavation, inhalation is anticipated to be the primary exposure route for onsite receptors. Inadvertent direct ingestion of the IWCS wastes would also be a major health concern, particularly for the high-activity residues.

- Any remedial action alternative that involves excavating the wastes would require stringent source and exposure controls to assure protection of onsite individuals during the cleanup period. Similar stringent controls would be warranted for any in-place alternative to assure sustained health protection.

1 INTRODUCTION

The Niagara Falls Storage Site (NFSS) is being addressed by the U.S. Army Corps of Engineers (USACE) as part of the Formerly Utilized Sites Remedial Action Program (FUSRAP), in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended. The site is located in the town of Lewiston, New York, north of Buffalo (Figure 1.1).

The USACE Buffalo District is responsible for the NFSS. The USACE conducts an environmental surveillance program and performs site operations, maintenance, and monitoring to ensure protection of human health and the environment. These activities are ongoing across the site, including at the Interim Waste Containment Structure (IWCS), which contains contaminated materials from cleanup actions conducted by the U.S. Department of Energy (DOE) more than 20 years ago. The IWCS is the focus of this report.

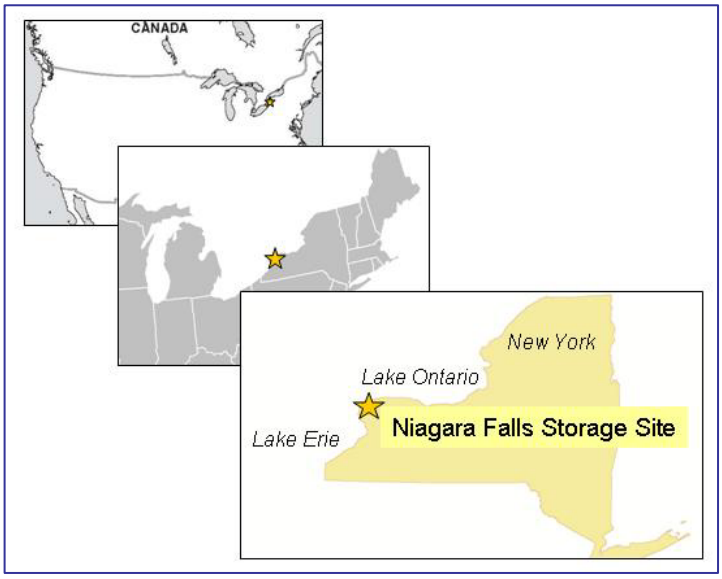

FIGURE 1.1 Location of Niagara Falls Storage Site

Historical context for NFSS is given in Section 1.1, and an overview of the general remedial action process for the site is provided in Section 1.2. The purpose and scope of this technical memorandum (TM) are described in Section 1.3, and primary data sources are identified in Section 1.4. The organization of this report is outlined in Section 1.5.

1.1 HISTORICAL CONTEXT FOR NFSS

The NFSS represents a portion of the former Lake Ontario Ordnance Works (LOOW) that was used by the USACE Manhattan Engineer District (MED) and U.S. Atomic Energy Commission (AEC) to store radioactive residues and other materials beginning in 1944 (DOE 1986, USACE 2007a). Nearly all the radioactive residues in the IWCS at NFSS originated from uranium processing activities conducted for MED and AEC at two locations: the Linde Air Products facility in Tonawanda, New York, and the Mallinckrodt Chemical Works refinery in St. Louis, Missouri. The F-32 residues were generated from past processing activities at the Middlesex Sampling Plant in New Jersey.

The first materials sent to NFSS for storage were low-grade radioactive residues from processing pitchblende ore at the Linde Air Products facility. These residues resulted from processing ores with different uranium (U_3O_8) contents, and they are categorized as follows (USACE 2007a, 2011a):

- R-10 residues: from processing ore with 3.5% U_3O_8,
- L-30 residues: from processing ore with 10% U_3O_8,
- L-50 residues: from processing ore with 7% U_3O_8, and
- F-32 residues: specific U_3O_8 content of the ore was not found in historical documents; however, the amounts of radium-226 (Ra-226) and thorium-230 (Th-230) in these residues were reported as 0.2 curies (Ci) for each radionuclide.

Beginning in 1949, highly radioactive residues from uranium processing at the Mallinckrodt Chemical Works – referred to as the K-65 residues – were shipped to NFSS in 208-L (55-gal) drums for storage. The uranium ore from which these residues were generated contained 35 to 60% U_3O_8. These K-65 residues were subsequently transferred from the 208-L (55-gal) drums to a large concrete tower onsite, referred to as Building 434, from 1950 to 1952. The residues remained in Building 434 until the 1980s when they were transferred by DOE to the IWCS. The K-65 residues represent the main hazard at the IWCS. If left uncontained, the high levels of radium-226 (Ra-226) in these residues would emit substantial external gamma radiation and release radon-222 (Rn-222) gas to air. Without controls, the doses from external gamma irradiation and inhalation of Rn-222 progeny could harm anyone nearby.

In addition to these residues, radioactive wastes from a number of other Federal government programs were sent to NFSS decades ago for storage or disposal. These included radioactive wastes from two locations in the state of New York (Knolls Atomic Power Laboratory [KAPL] in Schenectady and the University of Rochester) and the Middlesex Sampling Plant in New Jersey. Radioactively contaminated materials from decommissioning wartime plants were also sent to the site for storage, including equipment from the Linde facility. Uranium and thorium billets and rods processed at other private facilities were also sent to NFSS for interim storage.

From 1981 to 1992, DOE performed a number of cleanup activities at the site and nearby areas, which are termed vicinity properties. The radioactive materials generated by these activities were placed in an engineered structure on the west side of the NFSS property, the IWCS (see Figure 1.2). Within the IWCS, the more highly contaminated residues (K-65, L-30, L-50, and F-32) were placed in existing concrete structures that had been part of the freshwater treatment plant for the LOOW site during the 1940s. The L-50 residues were placed in Buildings 413 and 414, which are cylindrical structures 18-m (60-ft) in diameter made of reinforced concrete that had been used as clarifier tanks at the treatment plant. The remaining residues were placed in several bays of the reinforced concrete basement of Building 411; because it was part of the original freshwater treatment plant, this building was designed to securely hold liquids. The K-65 residues are in Bays A and C, and the combined L-30 and F-32 residues are in Bays B, C, and D of this building. The locations of the residues in the IWCS are also indicated in Figure 1.2.

Contaminated soil and debris from the DOE cleanup of the site and vicinity properties were placed together with the R-10 residues within the IWCS and then compacted to increase stability. Soils that were contaminated by the K-65 residues during interim storage, referred to as tower soils, were placed in the north end of Bay D. The DOE addressed the R-10 residues in the same manner as contaminated soil due to their similar radionuclide concentrations. Additional contaminated soils and debris were placed in the remaining areas of the IWCS in a manner to ensure the stability of the structure.

The IWCS was constructed by installing a clay dike and cutoff wall around the areas containing all the consolidated wastes. The dike and wall were built while DOE was conducting interim remedial actions at the site, and the wall was tied into the underlying clay formation. A multi-layered cap was placed over the contents after the cleanup actions were completed. These past DOE actions are described in further detail in the Remedial Investigation Report (RIR, USACE 2007a) and the references cited therein.

In September 1986, DOE issued a record of decision (ROD) under the National Environmental Policy Act (NEPA) to store the consolidated residues and other contaminated materials in the IWCS at the NFSS. That ROD identified the IWCS as an acceptable interim solution, with a projected service life of 25 to 50 years. This represented the time frame during which the IWCS was considered safe for containing the radioactive residues and other wastes until a decision on their final disposition could be made. The service life of 25 to 50 years identified in the ROD specifically applies to the IWCS cap; the design service life of the clay dike and cutoff walls surrounding the IWCS and the natural glaciolacustrine clay beneath the IWCS was identified as 200 to 1,000 years by Bechtel National, Inc. (BNI) (BNI 1986).

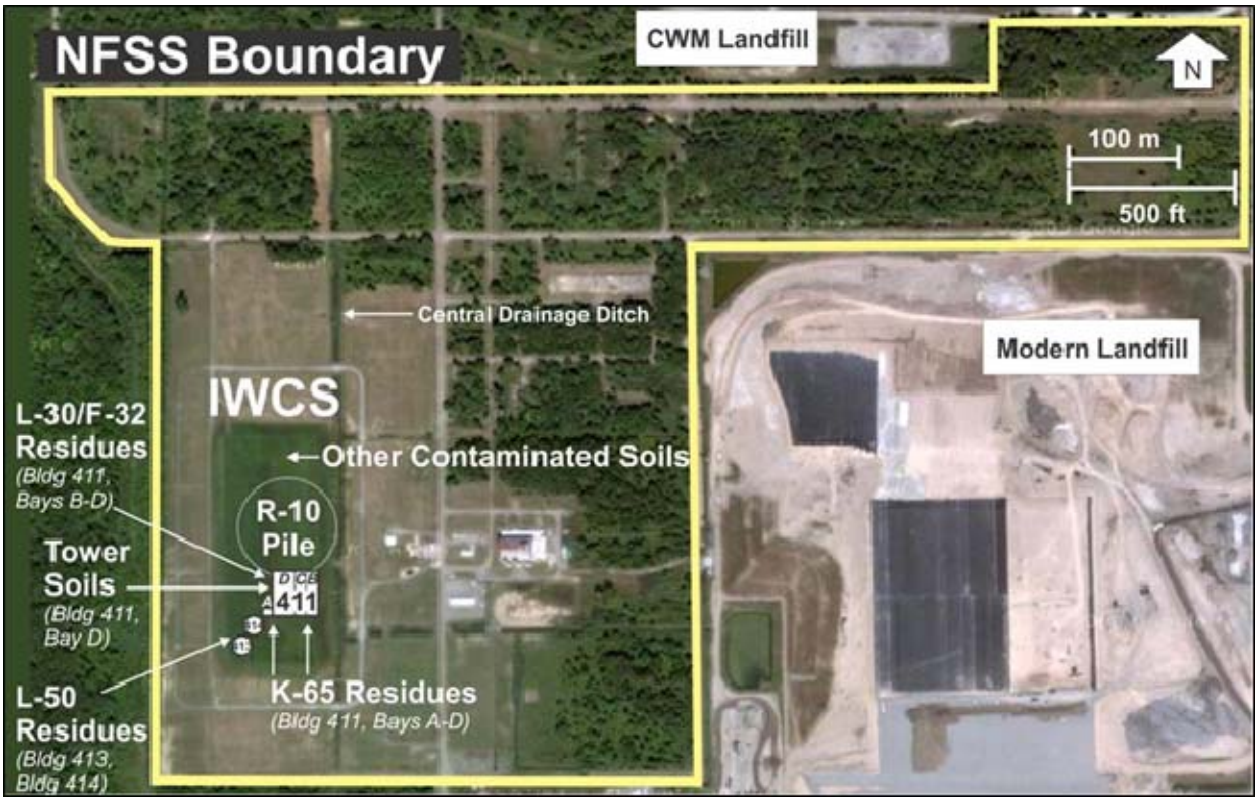

FIGURE 1.2 Location of the IWCS (and Former Buildings) and Stored Residues at NFSS

A sensitivity analysis of the 0.9-m (3-ft) compacted clay cap of the IWCS indicated it was sufficient to control infiltration for the 25- to 50-year design life (BNI 1986). Because the IWCS was constructed in 1986 and further materials were added in 1991, the design life of the cap is assured through 2011 and possibly to 2036; the design life of the clay dike and cutoff walls is anticipated to extend to at least 2186.

In October 1986, Congress passed the Superfund Amendments and Reauthorization Act (SARA), which amended CERCLA and explicitly identified Federal agencies as being subject to CERCLA when conducting remedial actions at sites for which they are responsible. In October 1997, Congress transferred overall responsibility for implementing FUSRAP from DOE to the USACE. With this transfer, the USACE assumed responsibility for the remedial action process at NFSS. Congress directed that FUSRAP remediations be done according to CERCLA, and it is that process which will culminate in a decision on the long-term disposition of this site.

1.2 OVERVIEW OF REMEDIAL ACTION APPROACH FOR NFSS

The USACE Buffalo District has the lead Federal responsibility for planning and implementing remedial actions at NFSS. For this process, NFSS has been organized into three operable units (OUs) that are being addressed in sequence, as described in the Feasibility Study (FS) Work Plan (USACE 2009) and illustrated in Figure 1.3. These three OUs are:

- OU1: The wastes DOE placed in the IWCS.
- OU2: The “balance of plant” (BOP) at NFSS, i.e., all contaminated materials not contained in the IWCS, excluding groundwater.
- OU3: Contaminated groundwater.

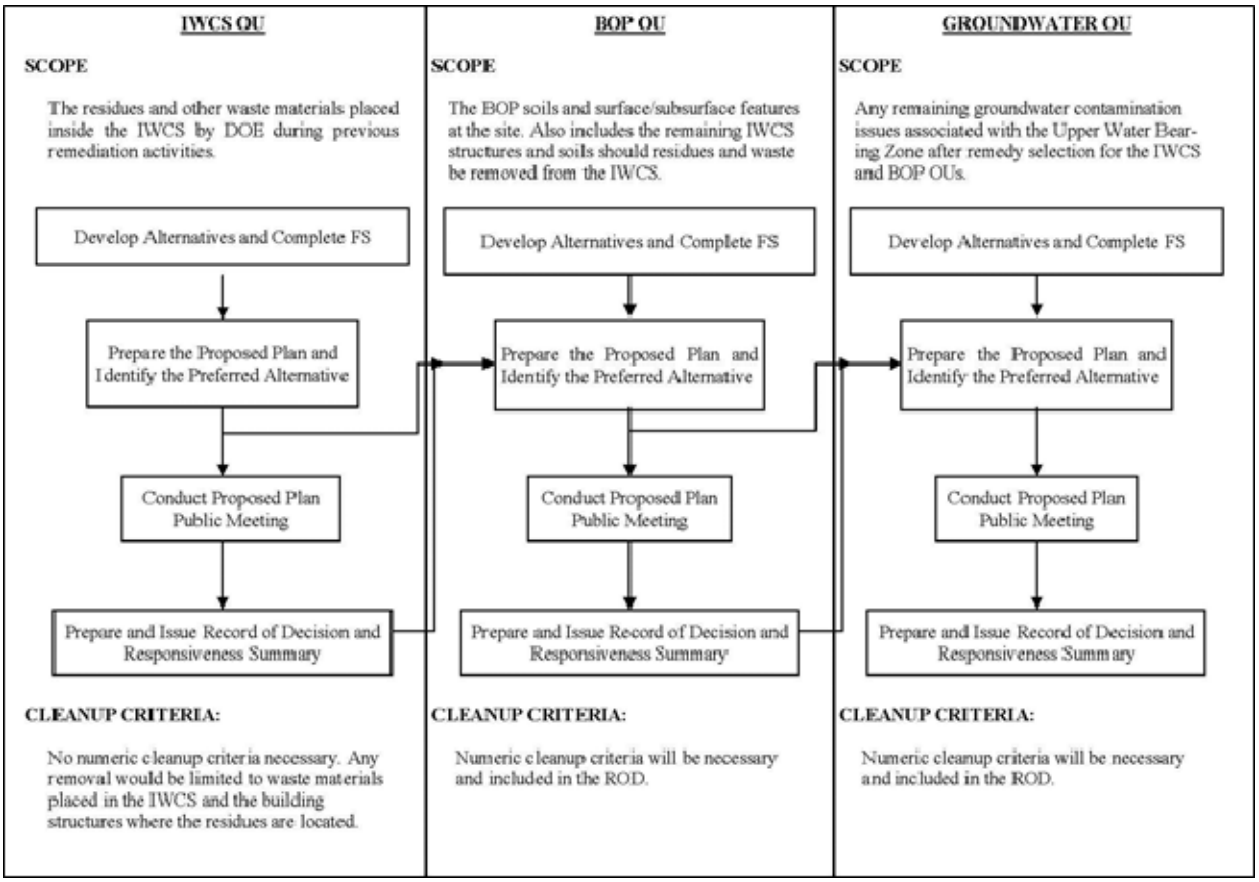

FIGURE 1.3 Sequenced Remedial Action Process for NFSS *(Source: Modified from USACE [2009].)*

The IWCS OU is being addressed first because it contains the highest-hazard materials and poses the greatest potential threat to human health and the environment. In addition to addressing the higher-risk area first, meaningful decisions for the next two OUs (BOP then groundwater) can best be made after the planned disposition of the IWCS contents is known.

The FS for this first OU will identify and evaluate remedial action technologies and alternatives for the IWCS. As part of the process for developing this FS, TMs and other technical reports are being prepared to address specific issues in order to facilitate completion of the overall FS. The analyses in both the FS and supporting reports are being developed in accordance with guidance established by the U.S. Environmental Protection Agency (EPA) (e.g., EPA 1988a, 1989) and the regulations set forth in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (EPA 1990).

Several documents have been prepared for NFSS and the IWCS OU and more are forthcoming, as shown in Figure 1.4. When the USACE was given responsibility for NFSS in the late 1990s, the Buffalo District took over the preparation of annual environmental surveillance reports to provide information to agencies and the public from ongoing site monitoring, which are presented in annual TMs. The District also initiated an updated environmental surveillance program that includes groundwater (not at the IWCS or its underlying footprint), and an RIR was prepared in accordance with standard EPA guidance (EPA 1988a). Note that among other environmental monitoring conducted under this program, radon flux is routinely monitored at the IWCS.

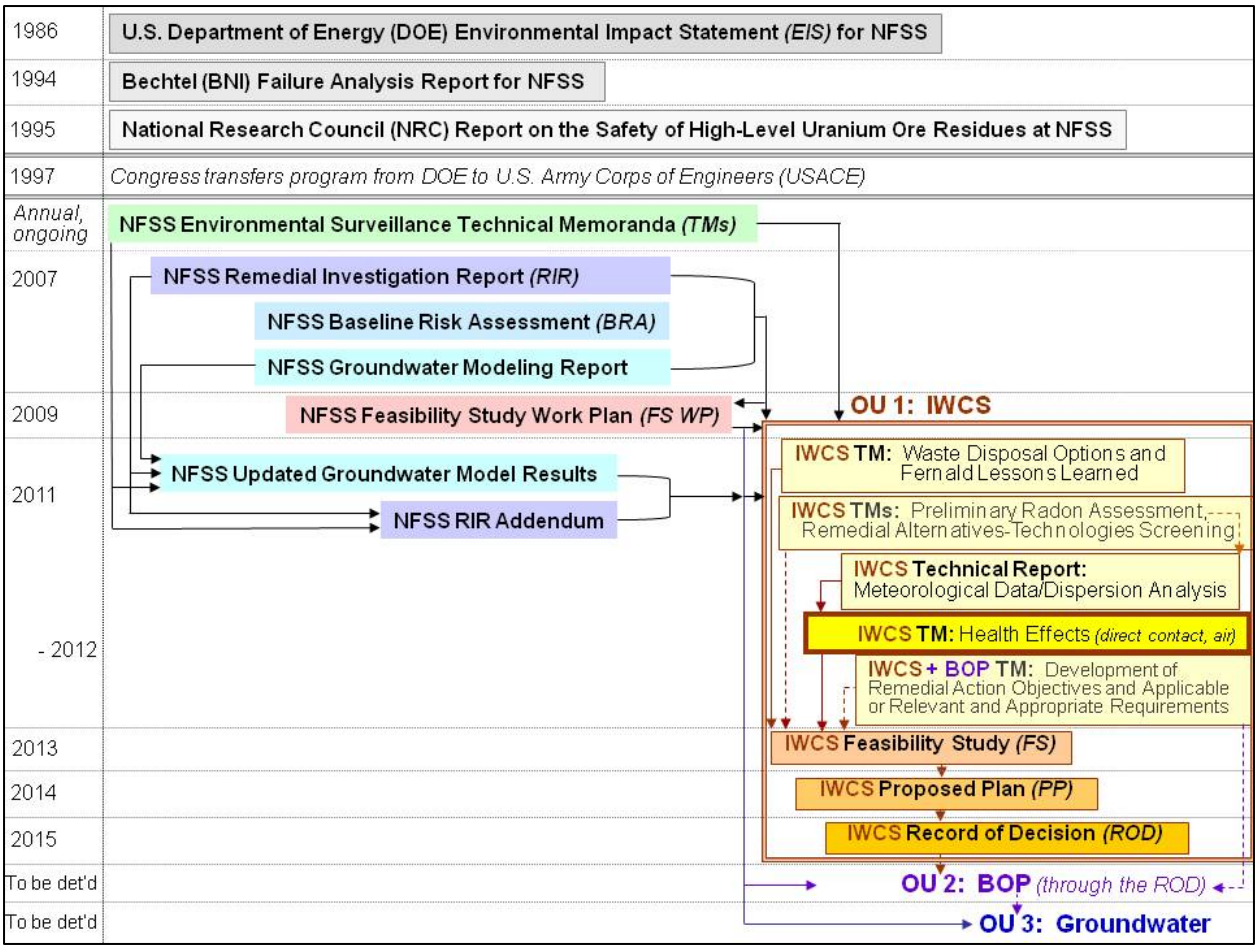

FIGURE 1.4 Key Documents for NFSS and the IWCS OU

(This report is outlined in bold. Dashed arrows indicate other TMs available this year.)

The RIR was completed in 2007 (USACE 2007a) and was recently updated with an addendum to reflect data that have become available since that time (USACE 2011b). Together, the RIR and its addendum characterize the nature and extent of contamination at NFSS beyond the IWCS contents and containment system. Additional data are available from the ongoing USACE environmental surveillance program for NFSS (USACE 2010, 2011c).

The RI process did not include the IWCS contents because it was determined that the considerable amount of historical data available for those materials was sufficient to prepare the FS and select an appropriate remedy for this OU. The baseline risk assessment (BRA) for NFSS (USACE 2007b) excluded the IWCS for the same reason. The underlying IWCS footprint was not included in the RI process because of significant limitations for any data collection effort. As a companion to the RIR, BRA, and RI addendum (USACE 2011b), groundwater modeling was conducted by HydroGeoLogic, Inc. (HGL) to assess potential contaminant transport from the IWCS to groundwater (HGL 2007, 2011). The purpose of these documents, as well as others shown in Figure 1.4, is to provide a technical foundation for the IWCS FS.

Like the other TMs and the technical report for the IWCS shown in this figure (including the preliminary radon assessment [USACE 2012]), the current document addresses a specific technical topic: potential exposures and health risks associated with contaminants in the IWCS if the cover were breached, and

beyond the IWCS from indirect gamma radiation and exposures to contaminants hypothetically released to air during waste excavation and subsequently dispersed and deposited. This TM includes a summary of estimated inventories and concentrations of the key radionuclides and chemicals in the IWCS based on historical information, to guide the preliminary evaluation of potential risks to support the upcoming FS.

The sequenced OU approach being applied for NFSS (shown in Figure 1.3) is designed to address key decisions in a logical sequence for the site. Sufficient information is available for the IWCS contents to complete the FS, so no additional data collection activities were conducted for these materials (see related discussion in Chapter 2). If additional data are determined to be necessary to implement the selected remedy, they would be collected during the detailed engineering design phase for this OU. The potential benefits associated with collecting more data for the IWCS contents at this time were determined to be substantially outweighed by the potential risks associated with breaching the integrity of the IWCS cover required for sampling, which would expose workers and could result in contaminant releases from the IWCS.

1.3 PURPOSE AND SCOPE OF THIS REPORT

The purpose of this TM is to provide early example estimates of exposures and risks for the IWCS wastes, to support the development and evaluation of remedial action alternatives in the FS for this OU. The scope focuses on two main concerns: (1) direct exposures to wastes at the IWCS and (2) airborne releases that could impact air and soil both onsite and offsite. The primary exposures of concern are inhalation (including of radon and its decay products) and external gamma irradiation. Migration to groundwater is not included in the scope of this TM because it was recently evaluated in separate documentation prepared for NFSS (HGL 2007, 2011).

This TM focuses on the near term (ten years) in order to complement risk information already available for the IWCS that extends into the longer term. By this approach, the TM aims to strengthen the integrated risk picture for the IWCS to support the upcoming development and evaluation of remedial alternatives for this OU. The main objectives of this TM are to:

- Describe key release mechanisms and potential onsite and offsite exposures associated with IWCS contaminants, and summarize risk information previously developed for the IWCS to further the state of knowledge for this OU regarding potential health effects.

- Estimate example doses, cancer risks, and noncarcinogenic health effects for hypothetical exposures not yet assessed for the IWCS, to help frame worker protection measures and the development and evaluation of remedial alternatives.

- Provide an early technical evaluation to stakeholders to encourage interactions and foster communication regarding the process for quantifying potential health risks associated with the IWCS while project-specific information is being developed for the FS.

- Facilitate the review and completion process for the FS by providing an opportunity for advance stakeholder comment and technical iteration on illustrative risk estimates for the IWCS, based on early conceptual assumptions for waste excavation and in-place conditions.

This TM assesses potential exposures to radionuclides and chemicals from the IWCS following an assumed cap breach (inadvertent or intentional). Subsequent airborne releases (radon gas and particulates), dispersion, and particulate deposition on surface soil are estimated to assess potential exposures and health effects for a hypothetical set of individuals. The TM focuses on the near term (e.g.,

ten years) to support the development and evaluation of remedial alternatives for the IWCS, with an emphasis on short-term effectiveness (during the remedial action period). Some information in this TM can also be used to frame evaluations for assumed conditions over the longer term. The scope of this TM is outlined in Table 1.1. Elements not quantitatively assessed either have been or will be addressed in other site documents, e.g., in the IWCS FS or reports for the upcoming OUs (BOP and groundwater), as appropriate.

TABLE 1.1 Scope of this TM

Element	Assessed	Not Quantitatively Assessed
Source	IWCS contents (residues and other wastes)	Sources other than wastes in the IWCS, including the rest of the site and offsite (e.g., open vicinity properties)
Contaminants	Representative radionuclides and chemicals	All contaminants in the IWCS, or specific contaminants beyond the IWCS
Release and transport mechanism	Cap breach *(excavation, intrusion, natural disaster)*: External gamma radiation, air dispersion and deposition (radon, particulates)	Leaching to groundwater, surface runoff, biouptake
Environmental media	Air: Onsite and offsite (as affected by assumed release) Soil: Surface soil, onsite and offsite (per particulate deposition from air)	Groundwater (onsite or offsite) Current conditions of soil, sediment, surface water, or air (onsite or offsite, including open vicinity properties)
Hypothetical receptors	Onsite: Maintenance worker, trespasser, remedial action worker Offsite: Outdoor worker, resident adult and child	Onsite resident, recreational visitor, or commercial worker (e.g., other land uses) Ecological receptors
Exposures	External gamma irradiation, inhalation, incidental ingestion (IWCS waste, soil)	Dermal absorption Ingestion of drinking water or food Incidental ingestion of surface water or subsurface soil
Effects	Human health: Cancer, noncarcinogenic effects	Ecological effects

Existing contamination in other areas of the site or offsite are not part of the evaluations in this TM. Surface runoff of IWCS contaminants and biouptake (e.g., from foliar or surface soil deposition following airborne releases) are addressed briefly and qualitatively in this report. Potential exposures to site contaminants from elsewhere (beyond the IWCS) in surface water, sediment, subsurface soil, biota, or air will be addressed as part of the next OU (BOP).

With regard to leaching of IWCS contaminants to groundwater and associated exposures, these elements are not considered in this TM for several reasons. First, this pathway has already been assessed (HGL 2007, 2011) to support the RI/FS process for the IWCS, including to frame the evaluation of long-term effectiveness. Second, potential exposures to site groundwater are not a factor for the period evaluated in this TM; groundwater is neither currently used nor anticipated to be used for drinking water in the near term. Note that groundwater quality will continue to be monitored throughout the RI/FS process for NFSS, so information would be available to limit any such exposures if indicated. Third and most importantly, leaching to groundwater will be addressed as part of the second and third OUs for the site (as described in Section 1.2), so further evaluations (which would reflect future characterization information) will be prepared as part of the RI/FS processes for those OUs.

Similarly, this TM does not evaluate scenarios related to other land uses because current uses are not expected to change during the time frame addressed in this TM. Moreover, regarding the onsite residential scenario, this has already been evaluated in other documents. To assume someone builds a house on the IWCS or directly on its contents at some point in the future, institutional controls (and community knowledge) would have to be lost and the cover eroded away. This scenario was evaluated in the environmental impact statement (EIS) issued for NFSS by DOE (1986), and it was then reevaluated by the National Research Council (NRC). The NRC concluded that a resident living in a house constructed on the IWCS residues would likely die within a few years due to the very large radiation doses (up to 8 million mrem/year [8,000 rem/yr]) to the bronchial epithelium portion of the lung from Rn-222 decay products (NRC 1995). This annual dose to the bronchial epithelium corresponds to a committed effective dose equivalent (CEDE) of about 480,000 mrem/yr if a weighting factor of 0.06 is used for this portion of the lung, as identified by the International Commission on Radiological Protection (ICRP 1981). (See the related discussion of radiation dosimetry concepts in Section 4.1.)

This estimated dose of 8 million mrem/yr (8,000 rem/yr) to the bronchial epithelium is based on a Ra-226 concentration of 67,000 pCi/g across all residues combined (see Table 4.24 of the EIS [DOE 1986]). Using the current estimate of 152,000 pCi/g Ra-226 in the residues, this dose to the bronchial epithelium increases to 18 million mrem/yr (18,000 rem/yr). If this calculation were limited solely to the K-65 residues, which have an average Ra-226 concentration of 520,000 pCi/g (see Table 2.2 in Chapter 2), the dose to the resident would increase by about a factor of eight over that given in the EIS.

The NRC also noted that this hazard would decrease with time due to radioactive decay, but that the Ra-226 concentration would eventually come into secular equilibrium with thorium-230 (Th-230), which has a half-life of 77,000 years. The concentration of Th-230 in the K-65 residues is about 54,000 pCi/g (Table 2.2). At that time (when secular equilibrium is achieved), the Ra-226 concentration would be the same as the Th-230 concentration, and it would then further decrease by radioactive decay with an effective half-life equal to that of the half-life of Th-230. Hence, although this hazard will be reduced with time, it will remain high for an extremely long time.

These considerations led the NRC to recommend that the highly radioactive residues (K-65, L-30, F-32, and L-50) be removed from the IWCS, treated, and disposed of offsite (NRC 1995). Nevertheless, the NRC noted there was no immediate hazard to the offsite public from these residues in their current configuration at the IWCS. As such, it was recommended that appropriate studies be performed incorporating the information developed for managing K-65 residues at the DOE Fernald site, which is being done by the USACE as part of developing the FS for the IWCS OU (see USACE [2011a]).

Two additional recommendations were made by NRC. The first was for remaining contaminated materials to be disposed of onsite under a suitable protective cap. The second was to develop an adequate monitoring and maintenance program that includes consideration of the two contiguous waste disposal areas off the NFSS property, i.e., the hazardous waste landfill operated by CWM Chemical Services, LLC, and the solid waste landfill operated by Modern Landfill, Inc. This recommendation reflected the potential for contaminant influx from those landfills (notably when pumping ceases after the operational period) and the associated potential to impact waste containment and public health.

The first recommendation is within the scope of the IWCS OU and will be addressed in the upcoming IWCS FS. Regarding the second, the USACE has established and continues to implement an extensive monitoring and maintenance program for the site. Further specific monitoring (e.g., considering contaminants from the two nearby waste disposal facilities) would be expected to be addressed as part of the groundwater OU. However, it may be useful to note that the USACE does not have authority to spend Federal funds to monitor groundwater at these commercial disposal areas.

In summary, this TM focuses on potential exposures and risks in the near term to hypothetical members of the public as well as workers performing maintenance and remedial activities at the site. These evaluations will be reflected in the upcoming IWCS FS. The FS will address the protectiveness of alternative remedies being considered for ultimate disposition of the IWCS contents, both over the near term and into the long-term future.

1.4 PRIMARY DATA SOURCES

No new waste characterization was conducted at the IWCS for this TM. The IWCS contents were not sampled during the RI process at NFSS for three reasons. First, it was determined that sufficient information already exists from historical records and related technical evaluations to support a decision for the IWCS under the CERCLA process. Second, to conduct such intrusive sampling could put those workers at considerable risk, including from exposures over the extended time that would be needed to collect a sufficient number of samples to obtain a statistically significant data set. Third, such characterization activities could compromise the integrity of the IWCS cover, which would increase the likelihood of contaminant releases that might impact the general public.

Thus, this TM relies on historical documentation for the IWCS and NFSS. Beyond the EIS, this documentation includes data DOE collected while implementing the original remedial actions at the site during the 1980s, which involved constructing the IWCS and consolidating radioactive materials within this structure until a permanent disposition could be determined. Considerable historical documentation relevant to the IWCS is also summarized in the RIR (USACE 2007a), the groundwater modeling report (HGL 2007), and the spring 2011 updates of each (USACE 2011b, HGL 2011).

Historical documentation for another Federal project with wastes similar to those found in the IWCS also served as a valuable resource for this TM, specifically information about the DOE Fernald site in Ohio. Key data regarding those wastes are summarized in a related TM that highlights lessons learned at Fernald (USACE 2011a). For the chemicals, this health effects TM also considers data for the adjacent LOOW site as supporting context.

The evaluation of airborne contaminant transport in this TM relies on information in the companion technical report (USACE 2011d). That report benefits substantially from measurements that were shared with USACE from meteorological stations on the two commercial landfill properties adjacent to NFSS. A new meteorological station was recently installed at NFSS. When sufficient measurements are available from the onsite meteorological station, those data will be used in dispersion modeling for the site. Until that time, the CWM data are considered well suited for use in dispersion analyses for NFSS.

1.5 DOCUMENT ORGANIZATION

The organization of this TM reflects the general outline for a risk assessment under the CERCLA process for contaminated sites:

Chapter 1 Presents background information about NFSS and ongoing planning and evaluations for the remedial action process, together with a brief description of the scope and objectives of the TM.

Chapter 2 Summarizes information about key radionuclides and chemicals in the wastes stored in the IWCS and identifies the contaminants of potential concern quantitatively assessed in this TM.

Chapter 3 Outlines the conceptual model for exposures to contaminants from the IWCS and describes the scenarios, receptors, approaches for calculating exposure point concentrations, intake equations, and parameters used to calculate example exposures in this TM. (Note for onsite scenarios involving direct contact with contaminants at the IWCS, estimated concentrations are based on historical data and process knowledge. For other scenarios, including offsite exposures, the concentrations of contaminants in the materials within the IWCS serve as the source terms for the dispersion modeling conducted to estimate exposure point concentrations in air and on surface soil following deposition.)

Chapter 4 Presents the toxicity assessment, including toxicity values used for the illustrative calculations in this TM. Information for the radionuclides and chemicals is presented in separate sections of this chapter.

Chapter 5 Characterizes the radiological doses and cancer risks and the chemical cancer risks and hazard indexes (for noncarcinogenic effects) for the example exposures.

Chapter 6 Summarizes the results and findings of this illustrative evaluation, as well as highlighting the results of previous risk analyses for the IWCS.

Chapter 7 Acknowledges the contributions of several colleagues to this report.

Chapter 8 Lists the references cited in this report.

Appendix A Provides supporting details for the estimated radiological doses, dose conversion factors and risk coefficients, and cancer risk estimates.

Appendix B Provides supporting details for the estimated chemical exposure levels and intakes, cancer risks, and hazard indexes.

Appendix C Presents health risk fact sheets for selected contaminants.

Appendix D Provides supplemental estimates of doses and risks for the hypothetical receptors, assuming wastes are excavated without any engineering controls to limit airborne releases, to help guide the determination of appropriate control measures in the FS.

To facilitate the evaluations in this TM, the IWCS wastes are organized into three groups: the K-65 residues represent waste group 1, the other high-activity residues (i.e., L-30, F-32, and L-50 residues) and tower soils comprise waste group 2, and the R-10 pile and the other contaminated soils and debris are waste group 3. This preliminary set of groupings was developed solely to support the early evaluations in this TM because planning information is not yet available for the specific IWCS alternatives; these illustrative waste groups should not be construed as implying any specific approach for managing the IWCS contents, as that context will be incorporated in the upcoming FS.

To support the development of waste excavation options in the FS, this TM also assumes example source areas and control efficiencies for particulate and radon gas control systems because project-specific planning information is not yet available. The actual engineering measures and other approaches that would be used to control airborne releases and human exposures are expected to achieve greater reductions than reflected in this TM. For a bounding comparison, supplemental estimates of doses and risks from imaginary releases if wastes were excavated without any engineering controls are provided separately in Appendix D, to support the conceptual engineering plans being developed for the FS.

Key tables in Chapters 2 through 6 that highlight information used to calculate the example exposures, doses, and risks in this TM are summarized in Table 1.2.

TABLE 1.2 Key Tables Supporting the Example Exposure and Risk Calculations in this TM[a]

Table	Content	Notes
	Contaminant Concentrations	
2.2	Estimated average radionuclide concentrations in the IWCS wastes	Presents waste concentrations used as input to the exposure/dose and risk calculations. The concentrations from these tables for waste groups 2 and 3 are weighted by the respective volumes of the wastes comprising each group to produce the average concentrations used in this TM. For group 1 (K-65 residues), the contaminant concentrations in these two tables are used directly. The product of the contaminant concentration and the particulate matter concentration (in air and deposited on surface soil) gives the exposure point concentration at each receptor location for each contaminant in each waste group.
2.3	Estimated average chemical concentrations in the IWCS wastes	
	Exposure Assumptions	
3.1	Exposure routes assessed for the conceptual waste excavation scenarios, for six illustrative receptors	Summarizes the exposure parameters for each illustrative receptor, developed consistent with EPA guidance as relevant to the focused scope of this assessment, considering site-specific conditions that include Federal ownership and control. A suite of hypothetical receptors with a variety of exposure factors are reflected to address various exposure situations in order to provide preliminary risk estimates that can support development of the FS for the IWCS. (Note that although this TM follows the general format of a CERCLA risk assessment, current data for contaminants and engineering planning are too limited to include all aspects of such an assessment.)
3.2	Exposure assumptions and intake parameters for the six receptors	
3.3	Key assumptions for excavations, emissions, and exposure scenarios, organized by three waste groups	
	Toxicity/Risk Estimators	
4.1	Radiological risk coefficients and dose conversion factors used to estimate cancer risk	These radiological dose and risk factors have been established by national and international organizations to represent the toxicity of radiation exposures from radionuclide-specific intakes and external gamma irradiation. The estimated intakes and exposure levels for each route (inhalation, ingestion, and external gamma) are multiplied by these values to calculate the corresponding doses and risks.
4.5	Chemical toxicity values used to estimate cancer risk	Similar to the radiological risk estimators, these established cancer toxicity values for chemicals are multiplied by the estimated oral intakes and exposure concentrations in air to estimate the cancer risk from those chemical exposures.
4.6	Chemical toxicity values used to estimate the potential for noncarcinogenic effects	The estimated oral intakes and exposure concentrations in air are divided by these established toxicity reference values to indicate the potential for a noncarcinogenic effect from those chemical exposures.
	Example Dose and Risk Estimates *(based on preliminary conceptual assumptions for waste excavation)*	
5.1	Overview of the tables that present preliminary risk estimates	Provides a roadmap of the tables in which preliminary risk estimates are presented in Chapters 5 and 6.
5.2	Radiological doses and risks for the six hypothetical receptors from particulates released during waste excavation (via inhalation of airborne particulates, and incidental ingestion of and external gamma irradiation from deposited particulates), for the three IWCS waste groups	Presents estimated radiation doses and risks from particulates released during excavation for each waste group. (This table does not include the results for Rn-222 and its progeny; those estimates are given separately in Table 5.3.) The external gamma estimates only address exposures to deposited particulates. (Current engineering planning information is insufficient to evaluate direct and skyshine external gamma irradiation during waste excavation; these doses and risks could be very significant for onsite workers and will be addressed in detail in the FS when appropriate planning information is available.)

Table	Content	Notes
	Example Dose and Risk Estimates *(cont'd.)*	
5.3	As described for Table 5.2, but for Rn-222 gas released during waste excavation	Presents estimated doses and risks from inhaling Rn-222 and its progeny based on the total estimated inventory of Rn-222 gas in the interstitial spaces of the IWCS wastes. About 95% of this inventory is attributed to the K-65 residues (waste group 1), and 5% is associated with waste group 2 (other high-activity residues and tower soils). (These results are then combined with those for released particulates in Table 5.2 to estimate the total radiological doses and risks from contaminants released during excavation, given in Table 5.6.)
5.4	Radiological doses and risks from external gamma radiation for several hypothetical cap breach conditions	Presents estimated doses and risks for a range of hypothetical cap breach conditions that could expose workers and/or the public to external gamma radiation; this table includes the breach events evaluated in the radon assessment TM (USACE 2012), to help support anticipated analyses of potential in-place alternatives in the FS.
5.5	Radiological doses and risks from inhalation of Rn-222 decay products for several hypothetical cap breach conditions	Presents estimated doses and risks for the suite of cap breach conditions indicated above, to assess releases of Rn-222 and inhalation of this gas and its short-lived decay products; this table includes the breach events identified in the radon assessment TM (USACE 2012) to help support upcoming analyses as indicated above.
5.6	Combined radiological doses and risks for the six receptors from particulates and Rn-222 released during excavation of the three waste groups	Combines estimates from Tables 5.2 and 5.3 to produce radiological doses and risks for the six receptors from excavating the three waste groups. The Rn-222 results for waste group 1 (given in Table 5.3) are multiplied by 0.95 and added to the corresponding doses and risks from Table 5.2 to produce the total estimates for these K-65 residues. The same basic approach is used for waste group 2, but the Rn-222 results from Table 5.3 are multiplied by 0.05.
5.7	Route-specific chemical risks and hazard indexes for the six receptors from particulates released during excavation for each of the three waste groups.	Presents estimated chemical risks and hazard indexes for the six hypothetical receptors from exposures to particulates released during excavation of each of the waste groups.
5.8	Combined chemical risks and hazard indexes for the six receptors from excavation releases, across all three waste groups	Presents chemical risks and hazard indexes for the six receptors as above, including totals across all the three waste groups.
	Summary of Dose and Risk Estimates	
6.1	Highlights of historical dose and risk estimates from previous analyses of the IWCS	Summarizes dose and risk estimates from previous analyses for the IWCS in a format that facilitates comparisons with the dose and risk estimates developed in this TM.
6.2	Summary of radiological doses and risks for the six receptors for each waste group	Presents radiological dose estimates based on conceptual assumptions for waste excavation to support a comparison to relevant dose standards, to support upcoming planning for the FS.
6.3	Summary of radiological and chemical risks and chemical hazard indexes for the six receptors, for each waste group	Combines estimates from Tables 5.6 and 5.8 to provide overall estimates of radiological and chemical risks and hazard indexes in a single table for each of the waste groups, to facilitate an evaluation of relative radiological and chemical contributions.
6.4	Combined risks and hazard indexes for the six receptors for the three waste groups combined	Similar to Table 6.3, but presents the estimates for all three waste groups combined.

[a] Shading indicates the tables that present only radiological information.

2 CONTAMINANTS OF POTENTIAL CONCERN

Contaminants of potential concern for a given site are identified by reviewing the site's operational history to determine what contaminants would likely be present and by evaluating data from site monitoring or characterization programs and other records (EPA 1989). An additional objective of these reviews is to determine if additional data are needed to assess potential risks and guide the evaluation of remedial alternatives in the FS. For NFSS, these reviews of the site operational history and existing characterization and monitoring data were conducted as part of developing the RIR and BRA (USACE 2007a, 2007b).

From that effort, it was determined that existing information is sufficient to support an informed evaluation of potential alternatives for the IWCS in the FS. Thus, instead of assessing a suite of potential exposures to IWCS wastes as part of the BRA, such evaluations were deferred to the upcoming FS to be addressed as part of the evaluation of short-term and long-term effectiveness of the remedial alternatives considered in detail. This TM provides a foundation for the risk information to be developed for the FS.

A key factor in determining that no additional data are needed for the IWCS contents is that previous analyses have already documented the potential for serious health effects if institutional controls were lost and people were exposed to these wastes. Both the EIS (DOE 1986) and a subsequent evaluation by the NRC (1995) found that hypothetical future residents would incur unacceptable risks.

Furthermore, it would be extremely difficult to adequately sample all the contents of the IWCS. Moreover, that sampling would require breaching the containment structure, which would likely compromise its integrity and might result in releases that impact human health. What is certain is that the workers involved in those characterization activities could incur substantial exposures, including from external gamma irradiation.

Thus, the evaluations in this TM and the FS primarily rely on historical process information and site data from previous characterization activities and ongoing environmental monitoring at NFSS. Additional information is available for analogous wastes at other Federal sites, including the DOE Fernald site in Ohio and the LOOW site adjacent to NFSS to support the identification of radioactive and chemical contaminants, respectively.

Thus, the illustrative calculations in this TM rely on existing contaminant information, recognizing that many of these data would not meet current data quality expectations that were established long after the data were collected. In addition, although considerable information exists for radionuclides in the IWCS, a similar level of detail is not available for the chemicals. While it would be unreasonable to collect those data for this OU, it is understood that this represents a source of uncertainty for the example exposure and risk estimates presented in this document. These uncertainties are discussed in Chapter 5 (Section 5.3).

This chapter is organized as follows. Section 2.1 presents a brief summary of the operational history of the site. An overview of key radionuclides and chemicals at the IWCS is given in Section 2.2, and the contaminants of potential concern and their estimated concentrations are identified in Section 2.3.

2.1 OPERATIONAL HISTORY

The brief history of NFSS provided here highlights information from the RIR (USACE 2007a). More detailed information can be found in that report and the references cited therein.

The USACE built and operated several facilities across the United States to manufacture munitions during World War II. To support the war effort, the USACE acquired about 3,000 ha (7,500 acres) of agricultural land in northwestern New York which became the LOOW site. The Federal government built a plant at this site to produce trinitrotoluene (TNT), and operations began in 1942. This plant only operated for about eight months before the Federal government determined there was excess TNT production capacity in the United States, and TNT production ceased at LOOW at the end of July 1943.

In 1944, the MED was granted use of a portion of LOOW for the storage of radioactive residues generated through the processing of uranium ore at the nearby Linde Air Products facility. In 1948 when the Department of Defense decommissioned the ordnance works at LOOW, the AEC acquired 611 ha (more than 1,500 acres) of the former LOOW site, which included the storage areas. By 1968, the General Services Administration released 525 ha (about 1,300 acres), and in 1975 another 8.9 ha (22 acres) were transferred to the Town of Lewiston. The current NFSS covers an area of about 77 ha (191 acres).

From 1944 through 1953, a variety of radioactive residues and other wastes were shipped to the site for storage or disposal. Most of the radioactive materials were stored in the area later named NFSS, although some were stored on LOOW outside this area. The first residues shipped to the site were the L-30, L-50, and R-10 residues (described in Section 1.1) from the Linde Air Products facility. The L-30 residues were shipped in 1944 and were stored in Building 411. The L-50 residues were transported to the site in bulk starting in 1944 and were stored in Buildings 413 and 414, and the R-10 residues were shipped sometime between 1944 and 1949 and were placed in a pile on open ground north of Building 411. The MED and its successor agencies continued to ship radioactive residues and materials to the NFSS for storage through the early 1950s, including the F-32 residues from the Middlesex Sampling Plant (which were stored in the recarbonation pit west of Building 411).

Beginning in 1949, highly radioactive uranium processing residues (referred to as the K-65 residues) were shipped from the Mallinckrodt Chemical Works to NFSS in 208-L (55-gal) drums for storage. These residues were subsequently transferred from the drums to the large concrete tower (Building 434) at NFSS for storage from 1950 to 1952, where they remained until the 1980s. In addition to these residues, radioactive wastes from a number of Federal government programs were sent to NFSS for storage and disposal, including from KAPL and the University of Rochester. The site was also used as an interim storage site for uranium and thorium billets and rods being processed at private facilities.

Various cleanup activities have been conducted at NFSS, beginning with the consolidation and removal of surface debris during the early years of site operations. In 1972, contaminated soil, sediment, and rubble at offsite areas were excavated and placed on the R-10 storage pile. In 1981, contaminated soil from just east of the site was excavated and moved onto the site. In 1982, cleanup activities at the site were accelerated and an interim remedial action plan was developed by DOE.

From 1982 through 1992, DOE conducted a number of cleanup activities at the site and nearby areas (vicinity properties). The radioactive materials generated by these activities were placed in an engineered structure onsite, the IWCS. The L-30, F-32, L-50, and K-65 residues were placed in existing concrete structures that had been part of the water treatment plant, and the contaminated soils and debris and the R-10 residues were placed directly into the IWCS to the north (not within any existing structure) and compacted to increase stability. The IWCS was constructed by installing a clay dike and cutoff wall around the areas containing the residues and other wastes consolidated therein.

The base of the IWCS consists of naturally occurring clay, and the surrounding clay dike was keyed about 0.5 to 0.6 m (1.5 to 2 ft) into the underlying gray clay. The IWCS was covered by an interim cap

consisting of three layers. The bottom layer consists of 0.9 m (3 ft) of compacted clay keyed into the dike, and this is followed by a 0.3-m (1-ft) layer of fill. The upper layer is a 15-cm (6-in.) topsoil vegetative cover. The more highly radioactive residues (K-65, L-30, and F-32) were placed into the IWCS in the reinforced concrete basement of Building 411, which had been designed to securely hold liquids because it was part of the original freshwater treatment plant. Before placing the materials in the basement of Building 411, drains, pipes, and openings to this building were sealed. The L-50 residues were placed in nearby Buildings 413 and 414.

2.2 OVERVIEW OF CONTAMINANTS IN THE IWCS

The IWCS represents the source of the hazards addressed in this TM, as illustrated in the conceptual model presented in Chapter 3. As described in the FS Work Plan (USACE 2009) and summarized in Chapter 1, the NFSS is being addressed in three OUs. The IWCS contents are being evaluated first because they comprise most of the contaminated materials at the site and pose the greatest potential health risk if engineering and institutional controls were lost. (Appropriate decisions for the other two OUs can best be made following the selection of a remedy for the IWCS.) Thus, the IWCS is the first OU for which an FS is being developed. Consistent with the time frame for this OU, the evaluation in this TM focuses on conditions relevant to the near term, i.e., on the order of ten years. Land use is an important consideration in identifying people who might be exposed to IWCS contaminants. Under current conditions, extensive controls are in place at the site and the containment structure is actively maintained. The six hypothetical receptors described in Chapter 3 are relevant to these conditions.

The IWCS contents can be organized into several groups that reflect the level of radioactivity as well as material location and type:

- K-65 residues
- Other high-activity residues
  - L-30
  - F-32
  - L-50
- Tower soil
- R-10 waste pile
- Other soil (less contaminated than tower soil)
- Rubble and other debris

The last category is not quantitatively evaluated in this TM because the rubble and debris are not amenable to airborne releases, would not be a significant source of risk compared with other materials in the IWCS, and quantitative contaminant data are limited. For the other groups, this TM highlights available contaminant information and outlines the basic approach for assessing risks for several illustrative (hypothetical) receptors, which can be used to evaluate additional potential receptor scenarios in the upcoming FS (by scaling with the information presented in this document). Thus, in addition to directly supporting the evaluation of short-term effectiveness for alternatives to be assessed in the FS, this TM combined with earlier analyses (such as the groundwater reports by HGL [2007, 2011]), will support the evaluation of long-term protectiveness and permanence.

Information about contaminants in the IWCS comes primarily from historical information. The DOE conducted an extensive characterization program for radionuclides in the residues at the site. The residues were generated by processing uranium ores and contain radionuclides in the uranium-238 (U-238), U-235, and Th-232 decay series; see Figures 2.1, 2.2, and 2.3 (taken from the fact sheet for natural decay series in Appendix C). These figures show the manner in which these radionuclides decay, and include the decay mode and half-life. The half-life is the time it takes for a radionuclide to decay to one-half its initial amount. Little chemical-specific information exists for the residues. The lower-contaminated materials in the IWCS include soils removed from onsite and offsite areas impacted by historical releases from the residues during the operational period, including in drainage areas (ditches) at the site. Thus, contaminants found in these materials are expected to be similar to (but with much lower radionuclide concentrations than) those in the residues.

Other materials stored at the site contained additional contaminants, such as fission products including strontium-90 (Sr-90) and cesium-137 (Cs-137), and transuranic (TRU) radionuclides (including isotopes of plutonium). These stored materials were sent offsite during the operational period and characterization activities have found little residual contamination. Relatively low concentrations of some isotopes were identified at discrete locations, except for Cs-137 which was more widespread across the site. Cs-137 (like Sr-90) is widely present in soils across the United States and elsewhere (from fallout of past atmospheric weapons testing) and is easily detected at very low levels (by gamma spectroscopy). Similarly, low levels of plutonium can also be found in U.S. soils from past fallout. Because of their very low concentrations and comparable or lower unit toxicity (risk per picocurie [pCi], see Table 4.1 in Chapter 4) relative to Ra-226 (the most prevalent radionuclide at NFSS), the risks associated with these radionuclides would be much lower than those associated with the residues in the IWCS. Thus, the radionuclides evaluated in this TM are limited to those associated with the three naturally occurring decay series identified above.

In nature, the radionuclides in these three decay series are in a state of secular equilibrium in which the activities of all radionuclides within each series are equal. Two conditions are necessary for secular equilibrium to occur: the parent radionuclide must have a half-life much greater than that of any other radionuclide in the series and a sufficiently long period of time must have elapsed, e.g., more than seven half-lives of the decay product having the longest half-life, to allow for ingrowth of the decay products.

Under secular equilibrium, the activity of the parent radionuclide undergoes no appreciable changes during many half-lives of its decay products. Both conditions for secular equilibrium are met for the U-238, U-235, and Th-232 decay series in naturally occurring ores. However, this natural state is altered during the processing of uranium and thorium ores. The rate at which equilibrium conditions are reestablished depends on the half-lives of the decay products. Radioactive decay products with half-lives of less than six months to one year will reestablish equilibrium conditions with their longer-lived parent radionuclides within ten years. Thus, because the residues and other wastes in the IWCS are associated with uranium processing activities that occurred more than 50 years ago, it can be assumed that all radionuclides with half-lives of less than one year have reestablished equilibrium conditions.

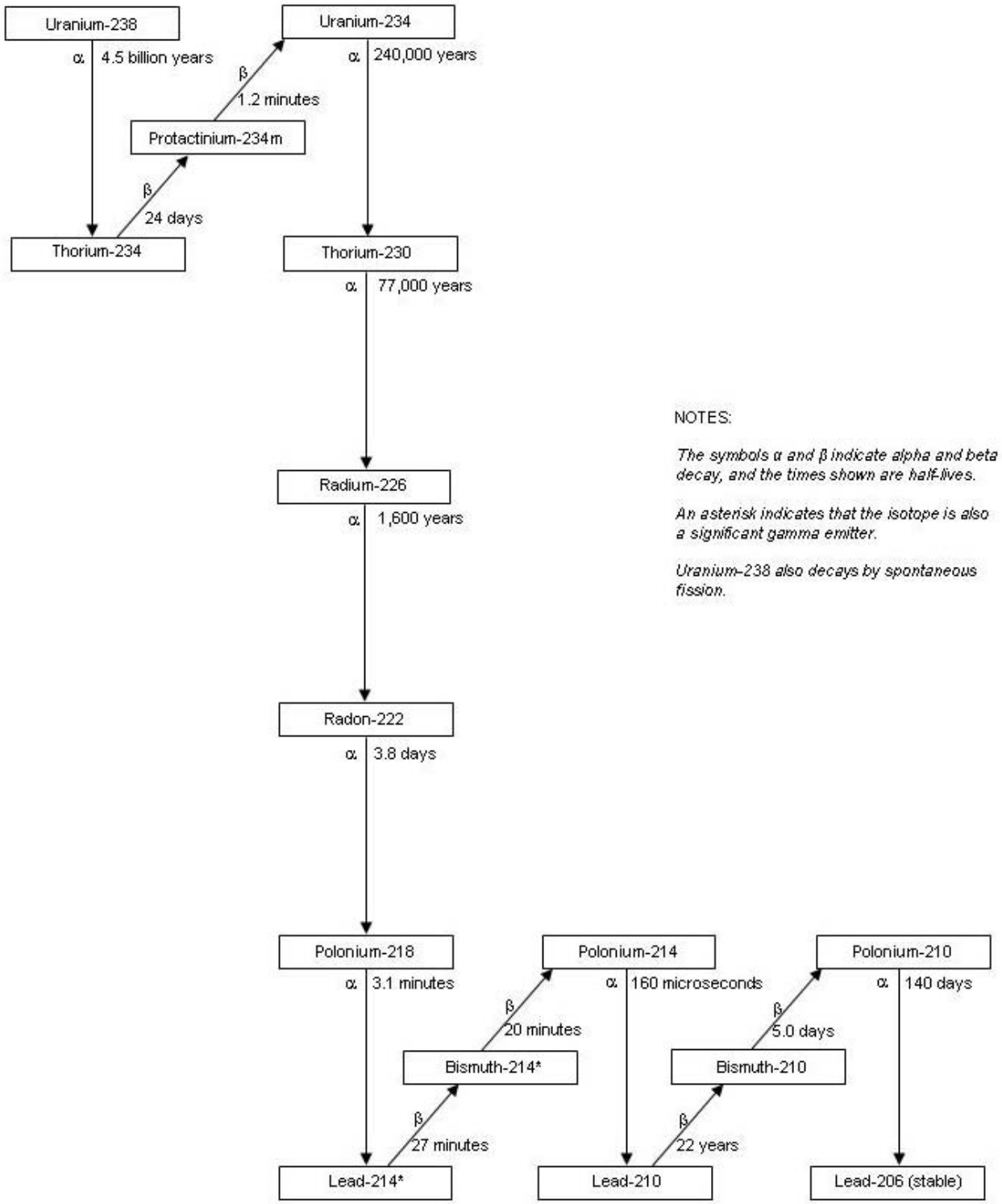

FIGURE 2.1 Uranium-238 Radioactive Decay Series

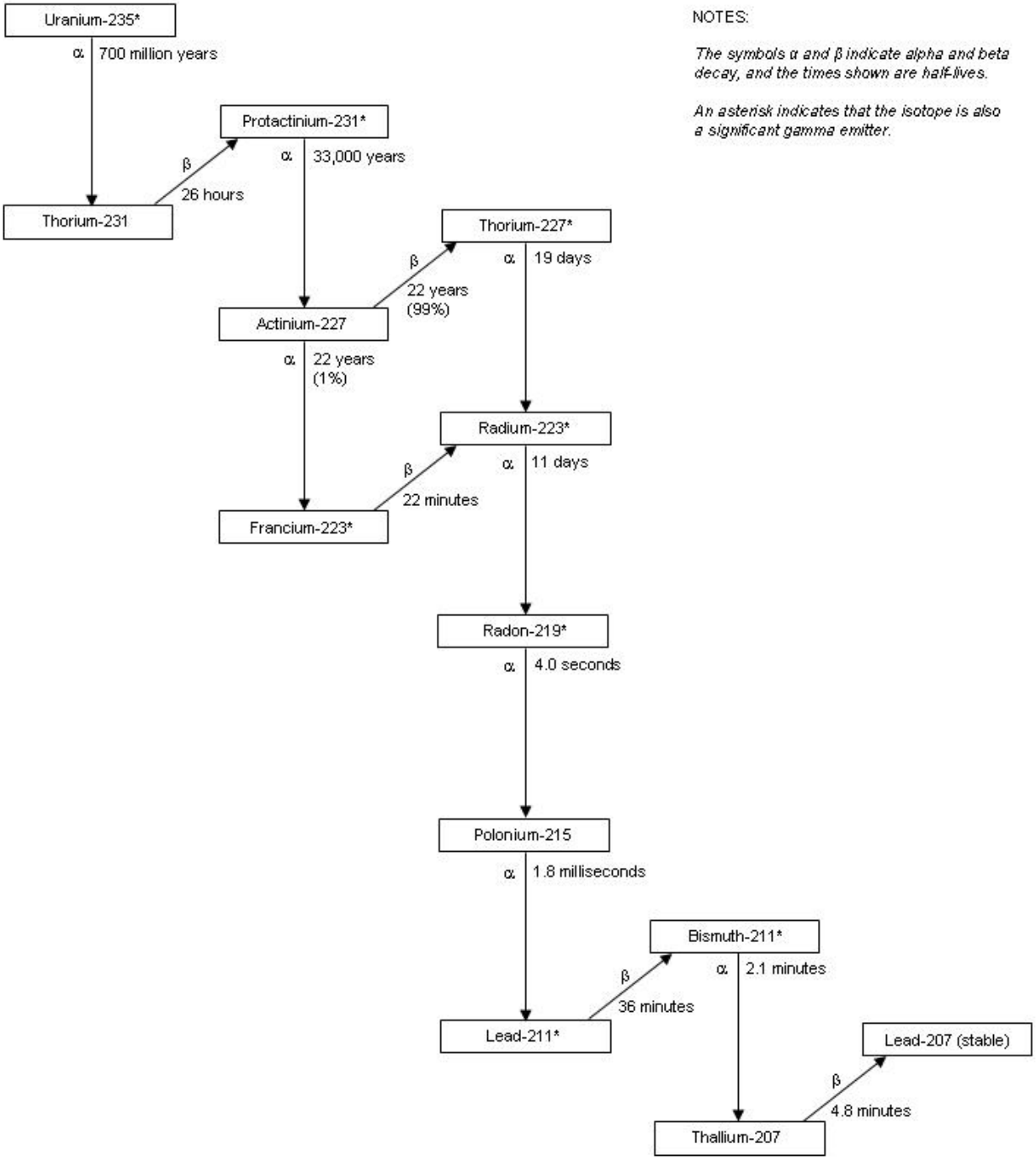

FIGURE 2.2 Uranium-235 Radioactive Decay Series

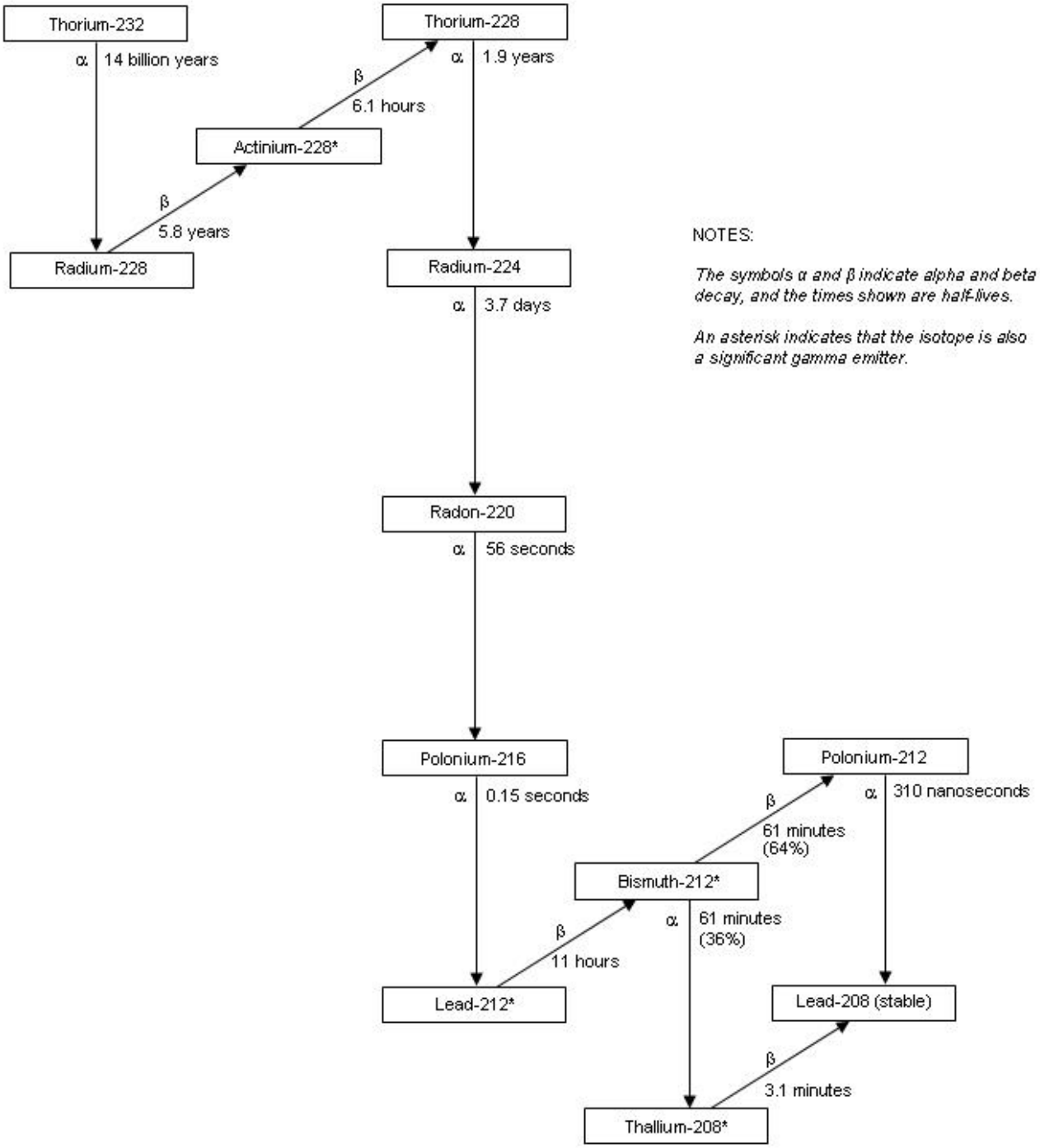

FIGURE 2.3 Thorium-232 Radioactive Decay Series

This assumption is consistent with the presentation in the user's manual for the RESRAD (*RES*idual *RAD*ioactivity) computer code (Yu et al. 2001, 2007), in which the term "principal" radionuclide refers to those radionuclides in decay series with half-lives of more than six months. The decay products of any principal radionuclide in a series down to, but not including, the next principal radionuclide in the decay series are termed "associated" radionuclides and consist of radionuclides with half-lives of less than six months. The principal radionuclide is assumed to be in secular equilibrium with its associated radionuclides at the point of human exposure. This approach is often presented as "+D" in RESRAD evaluations, where the "+D" notation refers to the radioactive decay products in equilibrium with the principal radionuclide. The principal and associated radionuclides for the U-238, U-235, and Th-232 decay series are given in Table 2.1.

The wastes in the IWCS that pose the greatest concern are the radioactive residues, specifically the highly contaminated K-65 residues. The primary focus of this TM is on potential exposures to these residues because risks associated with the other contaminated materials in the IWCS are much lower.

Considerably less information exists for nonradioactive chemicals in the IWCS than for the radionuclides. The residues contain a variety of metals associated with the uranium in the ore originally mined and processed during World War II and shortly thereafter. The soils and debris in the IWCS contain similar metals, albeit at lower concentrations, as well as other chemicals associated with the storage of various materials at the site. Characterization activities conducted by DOE as part of interim actions during the 1980s largely focused on radionuclides because these were determined to be the risk-driving contaminants at the site.

Some information about the chemical contaminants in the IWCS is given in the EIS (DOE 1986). That information serves as a main foundation for identifying the chemicals of interest for this TM. A total of 35 chemicals (mostly metals) are listed in Table 3.7 of DOE (1986) as being present in the K-65, L-30, and L-50 residues.

The RI investigations recently completed by USACE considered both radionuclides and chemicals in soils at the site as contaminants remaining after DOE conducted its remedial actions. As reported in the BRA for NFSS (USACE 2007b), chemicals identified in site soils beyond metals include volatile organic compounds (VOCs); and polychlorinated biphenyls (PCBs), pesticides, polycyclic aromatic hydrocarbons (PAHs), nitroaromatic compounds, and other semivolatile organic compounds (SVOCs). These results are consistent with previous chemical characterization data for NFSS (BNI 1991). Many of these compounds originated from activities previously conducted at the site beyond the storage of the radioactive residues. Because contaminated soils at the site were excavated and placed in the IWCS by DOE as part of past cleanup actions, it can be assumed that these chemicals are associated with the contaminated materials being stored in this containment structure.

In the groundwater modeling report prepared by HGL (2007), this list was screened to seven metals by selecting those most prevalent in the residues and expected to be mobile in the environment if water percolated through the IWCS cover. These seven metals, listed in Table 4.5 of HGL (2007), are: arsenic (As), barium (Ba), boron (B), cadmium (Cd), lead (Pb), molybdenum (Mo), and manganese (Mn). The key objective of that 2007 report was to assess potential impacts to groundwater, so the screening approach used for that analysis emphasized solubility and mobility for downward migration through soil. The scope of this TM differs from that report, i.e., the focus is on potential health effects from airborne releases of IWCS contaminants, as well as selected examples of in-situ exposures (such as from intrusion and direct contact). Thus, a different screening approach is warranted to address the objectives of this report.

TABLE 2.1 Principal and Associated Radionuclides for the U-238, U-235, and Th-232 Decay Series

Principal Radionuclide[a]		Associated Decay Chain[b]		Terminal Radionuclide[c]	
Species	**Half-Life**	**Species**	**Half-Life**	**Species**	**Half-Life**
Uranium-238 Decay Series					
Uranium-238	4.5×10^9 yr	Thorium-234	24 d	Uranium-234	2.4×10^5 yr
		Protactinium-234m	1.2 min		
Uranium-234	2.4×10^5 yr	-	-	Thorium-230	7.7×10^4 yr
Thorium-230	7.7×10^4 yr	-	-	Radium-226	1.6×10^3 yr
Radium-226	1.6×10^3 yr	Radon-222	3.8 d	Lead-210	22 yr
		Polonium-218	3.1 min		
		Lead-214	27 min		
		Bismuth-214	20 min		
		Polonium-214	160 µs		
Lead-210	22 yr	Bismuth-210	5.0 d	Lead-206	(stable)
		Polonium-210	140 d		
Thorium-232 Decay Series					
Thorium-232	1.4×10^{10} yr	-	-	Radium-228	5.8 yr
Radium-228	5.8 yr	Actinium-228	6.1 hr	Thorium-228	1.9 yr
Thorium-228	1.9 yr	Radium-224	3.7 d	Lead-208	(stable)
		Radon-220	56 s		
		Polonium-216	0.15 s		
		Lead-212	11 hr		
		Bismuth-212	61 min		
		[Polonium-212	0.31 µs (64%)		
		Thallium-208	3.1 min (36%)]		
Uranium-235 Decay Series					
Uranium-235	7.0×10^8 yr	Thorium-231	26 hr	Protactinium-231	3.3×10^4 yr
Protactinium-231	3.3×10^4 yr	-	-	Actinium-227	22 yr
Actinium-227	22 yr	[Thorium-227	19 d (98.6%)	Lead-207	(stable)
		Francium-223	22 min (1.4%)]		
		Radium-223	11 d		
		Radon-219	4.0 s		
		Polonium-215	1.8 millisecond		
		Lead-211	36 min		
		Bismuth-211	2.1 min		
		Thallium-207	4.8 min		

[a] Radionuclides with half-lives greater than six months. Half-lives are given to two significant figures.

[b] The chain of decay products of a principal radionuclide extending to (but not including) the next principal radionuclide or a stable nuclide. Branches are indicated by square brackets with branching ratios in parentheses following the half-life; ratios of less than 1% are not included in this table. An "m" means metastable.

[c] The principal radionuclide that terminates the associated decay chain, or stable nuclide, as noted.

To identify the chemicals of potential concern for consideration in the illustrative risk calculations presented in this TM, the average concentrations of chemical contaminants in the K-65, L-30, and L-50 residues given in Table 3.7 of the EIS (DOE 1986) were compared with the EPA regional screening levels (RSLs), which reflect default exposure assumptions (EPA 2011a, 2011b, 2011c). To be protective, the RSLs used in this comparison are those for soil associated with residential uses. The RSLs for soil associated with industrial uses (a more likely future land use at NFSS) are higher. In addition to comparing with these conservative EPA RSLs, these chemical contaminants were also compared with New York remedial program soil cleanup objectives (SCOs) for unrestricted use (NYSDEC 2011). Results of these screening evaluations for the chemical contaminants are included in Section 2.3, together with context for background concentrations of metals in local soil.

Beyond these two screens, a further evaluation was conducted for the chemical contaminants based on noncarcinogenic toxicity, by dividing the weighted-average chemical concentrations provided in the EIS by their corresponding toxicity values (see Chapter 4). Together these evaluations resulted in ten metals being identified as potential concerns for chemical toxicity: As, Ba, cobalt (Co), lithium (Li), Mn, Mo, nickel (Ni), Pb, uranium (U), and vanadium (V). In addition to these metals, PCBs were selected to represent organic compounds in this preliminary risk evaluation because they have been found in site soil and also at LOOW, so some limited concentration data are available. Too few data are available for other organic compounds to support reasonable estimates of source concentrations in the IWCS wastes. Thus, 11 chemicals (including uranium for its chemical toxicity) are identified as being of potential concern for further evaluation in this TM.

Asbestos is among other chemicals considered as part of this contaminant selection process. Historical documentation indicates that asbestos-containing material (ACM) was present in a number of buildings that were demolished as part of interim actions conducted years ago by DOE. The ACM was placed in the IWCS together with other contaminated debris. No information has been found regarding the concentration of ACM in the IWCS. However, debris comprises only a small fraction of the wastes in the IWCS because most of the volume is contaminated soil. The higher-activity residues (which are a main focus of this TM) represent the most hazardous materials in the IWCS, and ACM is not expected to be present in those residues; in addition, it is highly uncertain whether the asbestos would be friable. For these reasons, asbestos is not quantitatively assessed in this TM. Nevertheless, as for other chemicals in the IWCS, its presence is noted and it will be addressed in the IWCS FS as appropriate, including as part of evaluating waste disposal options. Proper precautions would be taken to ensure worker protection during any handling of debris containing asbestos as part of remedial action planning at the site.

In summary, the approach used to select the chemicals for quantitative evaluation in this TM does not encompass all contaminants identified in site soils, debris, and other materials in the IWCS. Rather, it focuses on key chemicals associated with the residues and other wastes, notably metals, based on information in the EIS (DOE 1986). This chemical set also includes an example organic compound (PCBs) found in site soils, notably with underground utilities. Following the same approach applied for the radionuclides (described above), the potential health risks from exposures to other chemicals such as asbestos, VOCs, and PAHs and other SVOCs are expected to be accounted for (outweighed) by the estimates developed for the 11 chemicals identified for this preliminary evaluation.

2.3 IDENTIFICATION OF CONTAMINANTS OF POTENTIAL CONCERN

As described in Section 2.2, the radionuclides of potential concern in the IWCS are the principal radionuclides identified in Table 2.1: U-238, U-234, Th-230, Ra-226, lead-210 (Pb-210), U-235, protactinium-231 (Pa-231), actinium-227 (Ac-227), Th-232, Ra-228, and Th-228. A number of these radionuclides have short-lived (associated) decay products, which are included in the calculations of

radiation dose and cancer risk. While other radionuclides have also been identified at the site, their activity concentrations are very low and associated risks are expected to be much lower than those for the set of radionuclides assessed in this TM for the IWCS. The concentrations of the radionuclides in the materials stored in the IWCS are given in Table 2.2, as summarized from Table 4.5 of HGL (2007). Radiological concentrations generally reflect average values, combined with expert judgment (e.g., levels of contaminants in the tower soils are assumed to be 2% of those in the K-65 residues). Illustrative concentrations of chemicals in the IWCS are presented in Table 2.3. Highlights of estimated Ra-226 inventories for the wastes in the IWCS are shown in Figure 2.4. Note that Ra-226 accounts for 96% of the activity in the IWCS, and Building 411 contains essentially all (99.3%) of the total Ra-226 activity.

The K-65 residues have the highest concentrations of radionuclides of all materials at the site. The average concentration of Ra-226 is reported to be about 520,000 pCi/g. During RI field investigations, a small chip of this residue was found in surface soil with a Ra-226 concentration of 856,000 pCi/g, which is generally consistent with the maximum concentrations reported in historical documents for the K-65 residues. This chip was collected and removed during the field investigations.

The chemical contaminants of potential concern for the IWCS as identified by the screening process are: As, Ba, Co, Li, Mn, Mo, Ni, Pb, U, V, and PCBs. The illustrative concentrations for the ten metals in the various wastes listed in Table 2.3 were obtained from Tables 3.7 and 3.8 of DOE (1986), and they generally reflect reported averages. For PCBs, the concentration assumed for this preliminary evaluation reflects characterization data for soils at NFSS and LOOW because similar materials were likely placed in the IWCS. This value is somewhat higher than (and thus conservative) but generally consistent with the concentration reported for PCBs in the similar K-65 residues that were stored at the Fernald site.

A total of 22 contaminants (11 radionuclides and 11 chemicals) are evaluated in this TM. This evaluation is not intended to address all contaminants in the IWCS. Instead it focuses on a set considered to reflect those of primary concern if the IWCS cap were breached (whether by excavation or other events that could uncover the wastes) and contaminants were released to air and subsequently deposited where onsite workers or the general public could be exposed. By this approach, this TM illustrates the process for quantifying risks associated with such exposures for key IWCS contaminants, to provide the foundation for more specific risk estimates that can be incorporated in the FS when project-specific information for the remedial action alternatives becomes available.

Of this set of 22 key contaminants, only PCBs are not naturally present in soil. Background concentrations of the other radionuclides and chemicals are given in Table 13.1 of the RIR addendum (USACE 2011b), except for Mo for which information from the literature was used. The USACE (2011b) identifies the 95% upper tolerance limit (UTL) for both surface soil (top 15 cm [6 in.]) and soil to a depth of 3 m (10 ft) (or the maximum detected, if the 95% UTL exceeds that value). The values for surface and deeper soils are comparable, so the concentrations reported in Table 2.4 reflect the latter.

Background soil concentrations for the chemicals listed in Table 2.4 are limited to the 10 metals carried through the screening process. Values for additional metals are provided in the RIR addendum (USACE 2011b), and those were used for the comparisons summarized in Table 2.5. The background soil concentrations are well below the concentrations in the IWCS for the radionuclides and also for key chemicals in the higher-activity residues; this condition simplifies the distinction between contributions from the IWCS wastes and from natural sources for the preliminary risk estimates presented in this TM.

Results of the screening process to identify key contaminants for this illustrative risk evaluation, based on comparisons to agency benchmarks (EPA RSLs and New York SCOs) and estimated local background concentrations, are presented in Table 2.5.

TABLE 2.2 Estimated Concentrations of Radionuclides in the IWCS *(pCi/g)*[a]

Contaminated Material in IWCS	Estimated Volume		Uranium-238 Decay Series					Uranium-235 Decay Series			Thorium-232 Decay Series		
	m^3	*yd^3*	*U-238*	*U-234*	*Th-230*	*Ra-226*	*Pb-210*	*U-235*	*Pa-231*	*Ac-227*	*Th-232*	*Ra-228*	*Th-228*
K-65 residues	3,000	4,000	650	650	54,000	520,000	520,000	33	10,000	10,000	1,210	1,210	1,210
L-30 residues	6,000	7,800	970	970	12,000	12,000	18,000	70	82	82	24	24	24
F-32 residues	500	650	1,800	1,800	300	300	450	130	150	150	1.0	1.0	1.0
L-50 residues	1,500	2,000	520	520	3,300	3,300	5,000	37	43	43	7.0	7.0	7.0
Tower soils[b]	3,100	4,100	13	13	1,100	10,000	10,000	0.7	200	200	24	24	24
R-10 waste pile	19,000	25,000	1.7	1.7	50	95	140	0.1	0.1	0.1	0.2	0.2	0.2
Other soils[b]	65,000	85,000	4.8	4.8	16	16	24	0.3	0.4	0.4	0.03	0.03	0.03

[a] Concentrations are from Table 4.5 of HGL (2007) and volumes are from DOE (1986); both are generally rounded to two significant figures except for tower soils (not quantified in DOE [1986]), for which the volume is from USACE (2011a). This TM does not quantitatively assess rubble and other debris (estimated at 36,000 m^3 [47,000 yd^3], USACE [2011a]) because they are not generally amenable to air dispersion, are not anticipated to be a risk driver (relative to the high-activity residues), and contaminant data are lacking.

[b] For the tower soils, radionuclide concentrations are assumed to be 2% of those for the K-65 residues. For the other soils, the volume addresses that placed in the IWCS by DOE; it does not include subsurface soils beyond the IWCS contents, such as those considered part of the containment system.

TABLE 2.3 Estimated Concentrations of Chemicals in the IWCS *(mg/kg)*[a]

Contaminated Material in IWCS	Metals										Organics
	Arsenic	*Barium*	*Cobalt*	*Lead*	*Lithium*	*Manganese*	*Molybdenum*[b]	*Nickel*	*Uranium*	*Vanadium*	*PCBs*
K-65 residues	5	30,000	2,000	56,000	100	100	10,000	3,000	3,800	2,000	50
L-30 residues	27	6,100	5,100	13,000	200	31,000	860	17,000	5,000	2,400	50
F-32 residues[c]	27	6,100	5,100	13,000	200	31,000	860	17,000	5,000	2,400	50
L-50 residues	31	20,000	7,700	4,900	200	71,000	300	24,000	790	2,400	50
Tower soils[d]	1.2	600	40	1,100	2	450	200	60	76	40	50
R-10 waste pile	1.6	230	100	51	240	450	50	240	14	95	50
Other soils[d]	1.2	500	55	4.5	95	450	50	100	14	140	50

[a] Metal concentrations are from Tables 3.7 and 3.8 of DOE (1986), generally rounded to two significant figures. The value for PCBs is considered a conservative estimate for the IWCS based on characterization data for NFSS (USACE 2007a) and LOOW (USACE 2008); for comparison, a slightly lower value was reported for the similar K-65 residues at the Fernald site. Volumes are given in Table 2.2. This evaluation does not quantify risks associated with rubble and other debris for the reasons noted under Table 2.2 above.

[b] Concentrations of molybdenum in both the R-10 waste pile and the other contaminated soils are taken to be 11% of the concentrations for manganese, based on the ratio of the weighted average concentrations for these two chemicals in the residues from Table 3.7 of DOE (1986).

[c] Contaminant concentrations in the F-32 residues are assumed to be the same as for the L-30 residues.

[d] The concentrations of metals in the tower soils are taken to be 2% of those identified for the K-65 residues, except if that puts the value below a common background level, in which case the concentration is assumed to be that reported for sediments in the Central Drainage Ditch, as described in Table 3.8 of DOE (1986). Concentrations for the other soils are also taken to be as reported for these drainage ditch sediments.

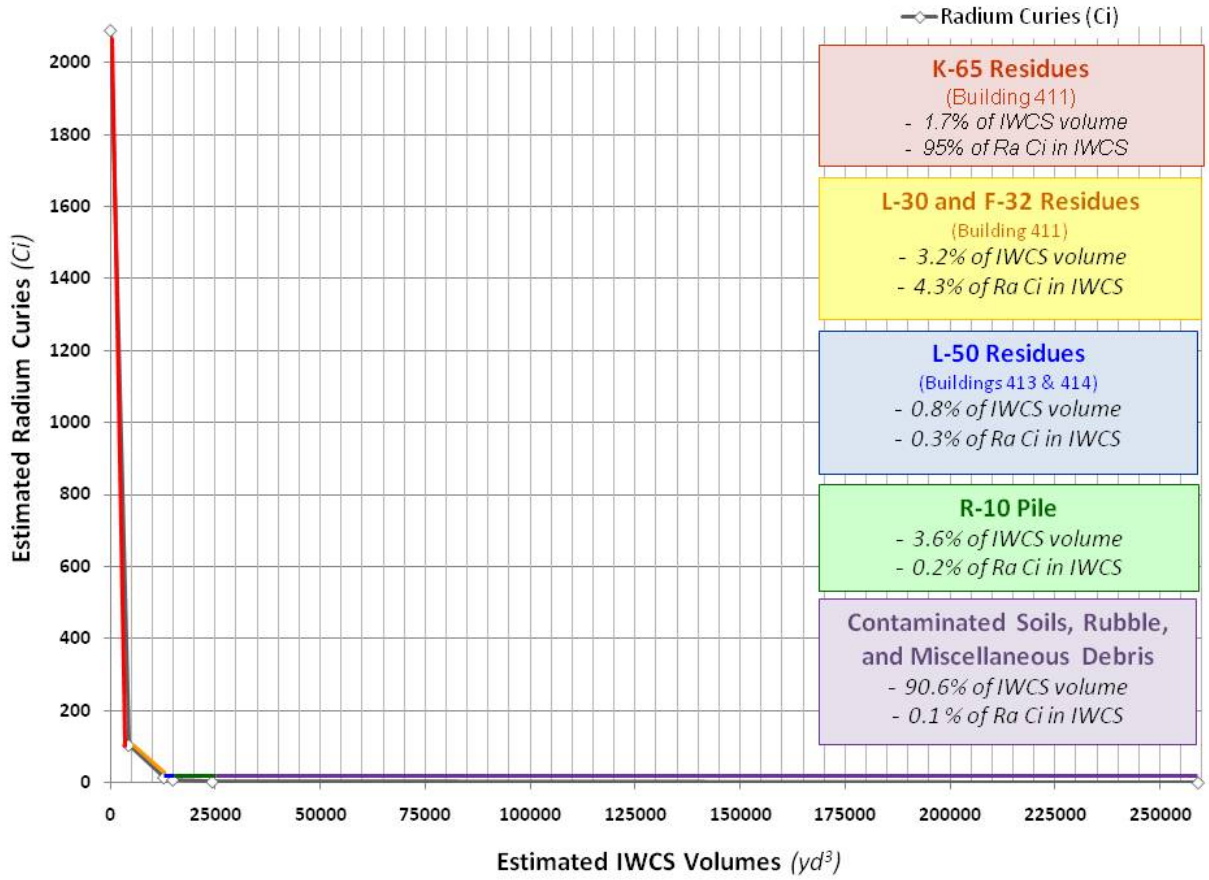

FIGURE 2.4 Estimated Ra-226 Activities in the IWCS Wastes

TABLE 2.4 Background Concentrations of Radionuclides and Chemicals in Soil at NFSS[a]

Constituent	Concentration		Constituent	Concentration
Radionuclides	*(pCi/g)*		**Metals**	*(ppm)*
Uranium-238 Decay Series			Arsenic	8.7
Uranium-238	1.3		Barium	260
Uranium-234	1.7		Cobalt	37
Thorium-230	1.4		Lead	38
Radium-226	1.2		Lithium	37
Lead-210	1.2[b]		Manganese	6,700
Uranium-235 Decay Series			Molybdenum	5[c]
Uranium-235	0.085		Nickel	38
Protactinium-231	0.085[d]		Uranium	3.6
Actinium-227	0.085[d]		Vanadium	35
Thorium-232 Decay Series				
Thorium-232	1.2			
Radium-228	1.3			
Thorium-228	1.6			

[a] PCBs are not included in this table because they are not naturally present in the environment. The soil concentrations in this table represent the 95% UTL for background samples collected to a depth of 3 m (10 ft), as presented in Table 13.1 of USACE (2011b), rounded here to two significant figures.

[b] The concentration of Pb-210 is assumed to equal that of Ra-226.

[c] No background concentration is reported for molybdenum in USACE (2011b). Typical soil concentrations range from 0.2 to 5 ppm, with a suggested average of 1.5 ppm (Schulte 2004, Lavado et al. 1999). Some higher background concentrations (e.g., 9 ppm) have also been reported for certain locations and soil types (Lang and Kaupenjohann 2000). For this analysis, 5 ppm is selected to represent a general upper value for this metal.

[d] The concentrations of Pa-231 and Ac-227 are assumed to equal that of U-235.

TABLE 2.5 Concentration Screen to Identify Contaminants of Potential Concern for this Assessment[a]

Chemical	Residues			Historical Average	EPA RSL	New York SCO	Local Bkground	Highest Res / RSL	Historical Avg / RSL	Highest Res / Bg	Retained?
	K-65	L-30	L-50								
Arsenic	5	27	31	2	0.39	13	8.7	79	5.1	3.6	Y
Barium	30,000	6,100	20,000	15,000	15,000	350	260	2.0	1.0	110	Y
Boron	300	140	100	170	16,000		10	0.019	0.011	30	N
Cadmium	2.5	0.5	0.5	2.1	70	2.5	0.53	0.036	0.030	4.7	N
Cerium	2,000	1,200	240	1,200							N
Cesium	1	1.4	0.71	1.2							N
Chromium III	100	240	140	180	120,000	30	26	0.0020	0.0015	9.5	N
Cobalt	2,000	5,100	7,700	4,700	23		37	330	200	210	Y
Copper	500	2,300	2,400	1,800	3,100	50	49	0.77	0.58	49	N
Fluorine	30	39	50	37	4,700			0.011	0.0079		N
Gold	0.2	0.37	0.1	0.28							N
Iodine	1	0.35	0.55	0.68	780			0.0013	0.00087		N
Iron	5,000	26,000	20,000	19,000	55,000		36,000	0.47	0.35	0.71	N
Lanthanum	2,000	1,000	220	1,100							N
Lead	56,000	13,000	4,900	23,000	400	63	38	140	58	1,500	Y
Lithium	100	200	200	170	160		37	1.3	1.1	5.4	Y
Manganese	100	31,000	71,000	30,000	1,800	1,600	6,700	39	17	11	Y
Molybdenum	10,000	860	300	3,300	390		5	26	8.5	2,000	Y
Mercury	0.5	0.3	0.5	0.5	10	0.18	0.27	0.050	0.050	1.9	N
Neodymium	1,000	160	100	390							N
Nickel	3,000	17,000	24,000	14,000	1,500	30	38	16	9.3	630	Y
Niobium	50	24	14	30							N

Chemical	Residues			Historical Average	EPA RSL	New York SCO	Local Bkground	Highest Res / RSL	Historical Avg / RSL	Highest Res / Bg	Retained?
	K-65	L-30	L-50								
Palladium	20	3.5	2.4	8							N
Platinum	0.5	0.32	0.25	0.41							N
Praseodymium	2,000	55	24	590							N
Selenium	100	50	39	62	390	3.9	0.37	0.26	0.16	270	N
Silver	1.5	1	0.25	1.4	390	2.0	0.27	0.0038	0.0036	5.6	N
Strontium	500	240	240	310	47,000			0.011	0.0066		N
Tellurium	20	24	39	26							N
Thorium	5	2.4	1.4	4.8							N
Uranium	3,800	5,000	790	3,900	230		3.6	22	17	1,400	Y
Vanadium	2,000	2,400	2,400	1,500	390		35	6.2	3.8	68	Y
Yttrium	30	39	30	35							N
Zinc	100	77	200	100	23,000	110	270	0.0087	0.0043	0.75	N
Zirconium	300	100	71	140							N

[a] This table summarizes the screening of contaminant concentrations (in ppm), using the three higher-activity residues for comparisons to agency benchmark values and background concentrations in local soil (abbreviated as Bkground and Bg above). Values are provided to two significant figures where available. Some residue concentrations for cadmium, gold, platinum, and silver were reported as being less than a given value in Table 3.7 of DOE (1986), and in those cases, one-half the indicated concentration was used for this screening. Blank entries indicate a value is not available, and shading is used to distinguish those contaminants screened from further evaluation in this TM.

For each chemical, both the highest of the concentrations in the three residues (abbreviated as Res in the comparison columns above) and the historical average (abbreviated as Avg in the comparison column above), as the volume-weighted average based on summary data in DOE (1986) are compared to the generic EPA RSLs for the default residential scenario; these most restrictive (lowest) benchmark concentrations are conservatively used for this screening step to assure contaminants of potential interest are selected for this preliminary risk evaluation. The New York SCOs for unrestricted use are also shown here for supporting context. For further context, the highest of the concentrations in the three residues is compared to the estimated local background concentrations for the NFSS area; these background concentrations are taken from Table 2.4 of this TM and additional data from USACE (2011b). Those retained for further consideration in this preliminary evaluation are identified with a yes (Y) in the last column; those designated N (no) are not further evaluated in this report.

3 EXPOSURE ASSESSMENT

For an exposure assessment, hypothetical receptors are considered to frame the evaluation of basic exposure questions regarding who, what, where, how much, how often, and for how long an exposure to site contaminants could occur. The specific components of an exposure assessment include the contaminants of interest, the exposure setting, exposure pathways, exposure point concentrations, and estimated contaminant intakes (doses) or exposure levels. The contaminants evaluated in this TM are identified in Section 2.3. The exposure setting at NFSS is characterized in Section 3.1, and potential exposure pathways are described in Section 3.2. This description includes an overview of contaminant sources and potential release mechanisms, contaminant fate and transport, example receptors and locations, and routes of exposure. Estimated exposure point concentrations for the IWCS contaminants at the representative locations are discussed in Section 3.3. The approach for estimating the amount of exposure to these contaminants is presented in Section 3.4.

3.1 ENVIRONMENTAL SETTING

The environmental setting for NFSS frames the evaluation of potential human exposures to the contaminated materials being stored in the IWCS. Information for the site setting is summarized below, taken from the more detailed descriptions in the EIS (DOE 1986), the RIR and its addendum (USACE 2007a, 2011b), the BRA (USACE 2007b), and annual environmental surveillance TMs for the site.

3.1.1 Climate and Meteorology

The NFSS area has a humid, continental climate, experiencing both warm and humid summers and typically snowy winters. The temperature extremes and diurnal and seasonal temperature ranges are moderated by Lakes Erie and Ontario compared with inland areas at a comparable latitude. The temperature is typically cool, with an average daily maximum of about 27°C (80°F) in July and an average daily minimum of about -7°C (19°F) in January and February. Annual precipitation averages about 97 cm (38 in.) and is fairly evenly distributed throughout the year. Thunderstorms occur 33 days a year on average, primarily during June through August. The wettest months are August and November with an average of 9.9 cm (3.9 in.) of precipitation, while February is the driest month with an average of 6.4 cm (2.5 in.). The annual average snowfall in this area is about 230 cm (89 in.), with a maximum of nearly 450 cm (180 in.) reported. Snowfall is generally highest in January, averaging about 61 cm (24 in.) (USACE 2007a). Meteorological data from the adjacent CWM landfill indicate prevailing winds are from the west-southwest, and the average wind speed is about 3.0 m/s (6.7 mph) (USACE 2011d).

3.1.2 Topography and Surface Hydrology

The NFSS is about 5.6 km (3.5 mi) east of the Niagara River and 6.4 km (4.0 mi) south of Lake Ontario on the Ontario Plain that begins at the base of the Niagara Escarpment and slopes gently northwest towards Lake Ontario. The Niagara Escarpment is about 5 km (3 mi) south of NFSS. The plain is relatively flat and featureless except for a few broad shallow valleys and the Niagara River Valley that lead to Lake Ontario. Elevations at NFSS are generally uniform except for the IWCS. Elevations generally range between 96 and 105 m (315 and 344 ft) mean sea level (MSL). The lower elevations correspond to the three man-made drainage ditches on the site and the higher elevations correspond to the top of the IWCS. The natural site elevation is about 98 m (320 ft) (DOE 1986).

The NFSS is nearly level to gently sloping and surface runoff drains primarily via three south-to-north ditches constructed on the site. The main ditch is the Central Drainage Ditch, which lies just east of the IWCS (see Figure 1.2) and is more than 3 m (10 ft) deep across most of the site. The West Drainage Ditch lies along the western boundary of the NFSS and drains the west side of the IWCS as well as some

offsite areas. The third ditch is along the eastern side of the site and is not influenced to any extent by the presence of the IWCS (USACE 2007b). The IWCS is located between the West and Central Drainage Ditches, and surface water in the vicinity of the IWCS flows in a northerly direction in these two ditches. The West Drainage Ditch combines with the Central Drainage Ditch north of NFSS, and the combined flow discharges into Fourmile Creek farther north of NFSS. Surface drainage at NFSS is shown in Figure 2-1 of the RIR (USACE 2007a).

The 100-year flood level within NFSS is estimated to be approximately 97 m (319 ft) MSL, and flooding is generally contained within the Central Drainage Ditch. For most of the year there is very little surface flow, but major runoff occurs in the spring and ponded water is common at NFSS during and following the snowmelt (DOE 1986).

3.1.3 Soil and Geology

Soils in the NFSS area are primarily silty-loam and belong to the Rhinebeck-Ovid-Madalin association. These soils are nearly level to gently sloping, deep, and somewhat poorly to very poorly drained. Subsoils are moderately fine to fine-textured and are of medium to low value for farming. In fact, poor natural drainage is the major limitation to land uses such as farming or urban development. The surface soil properties vary widely over the site. Many areas have been filled with stone, brick, and other materials and then covered with a thin mantle of soil. Much of the original surface soil was either removed as part of previous cleanup activities or was used in constructing the IWCS.

The bedrock of the region is composed of relatively undeformed, flat-lying sedimentary rocks over a basement of metamorphic rock. A 270-m (900-ft) sequence of shales and siltstones of the Queenston Formation lies at the base of the Niagara Escarpment and comprises the uppermost bedrock unit under NFSS. The Queenston Formation underlies NFSS at a depth of about 15 m (50 ft). Unconsolidated glacial deposits overlie the Queenston Formation on the Ontario Plain. At NFSS, these deposits consist of five major stratigraphic units as shown in Figure 2-2 of the RIR (USACE 2007a). The NFSS lies within a generally stable tectonic region. Historically, earthquakes in this region have generally been of moderate seismic intensity (VI and VII or less on the Modified Mercalli scale). A small seismically active area is associated with the relatively large earthquake that occurred near Attica, NY, 40 km (25 mi) southeast of NFSS in 1929. This seismic zone is not well defined, but earthquakes in this zone appear to govern the maximum historical intensity at NFSS (DOE 1986).

3.1.4 Groundwater

Although groundwater is not assessed in this TM, a brief summary of the hydrogeology at NFSS is provided here from USACE (2007a) as part of general information for the environmental setting. Two water-bearing zones lie within 15 m (50 ft) of the ground surface at NFSS. Water quality in both zones is poor, and the groundwater is not used for drinking water. A regional groundwater divide lies about 3 km (2 mi) south of NFSS, and regional groundwater north of the divide flows toward the northwest, while groundwater south of the divide flows toward the southwest.

The upper water-bearing zone at NFSS is in the upper clay till unit, which generally consists of clayey silt and silty clay with occasional lenses of sand and gravel. The thickness of this unit ranges from nearly 2 to 7 m (6 to 23 ft). Coarse-grained deposits are sporadically present near the bottom, at the upper surface of the Gray Clay Unit (which acts as an aquitard separating the two water-bearing zones). The coarse-grained lenses and intermittent pockets and seams in this upper zone vary considerably in thickness and extent, and they range from dry to saturated. Because saturated conditions can occur in both the continuous, low-permeability clays and the discontinuous lenses of sand and gravel, the presence of groundwater in this upper zone varies across the site. The lower water-bearing zone consists of

stratified sands and gravels, with dense silt and sands in some areas, and weathered and fractured upper portions of the Queenston Formation. The thickness of this zone ranges from about 3 to 12 m (10 to 39 ft), and it has a much higher permeability and more lateral continuity than the upper zone. The general direction of groundwater flow in this lower water-bearing zone is to the northwest.

3.1.5 Vegetation and Wildlife

The NFSS is predominantly low-lying, with little topographic relief except for the IWCS. Areas of the site exhibit wetland characteristics such as hydric soils, wetland vegetation, and wetland hydrology. Both terrestrial and wetland ecosystems are present at NFSS. The predominant vegetation on NFSS is elm and ash forest with common reeds and cattails predominating in the low-lying areas. At locations where clearing or construction has taken place (including the IWCS), bluegrass, fescue, and old field vegetation, i.e., vegetation that occurs when an area is cleared and left fallow, dominate. Species such as goldenrod, Queen Anne's Lace, bull thistle, and poison ivy are present at these areas. The IWCS is covered with grasses that are periodically mowed.

Wildlife species at the site include both those considered to be year-round residents and several migratory species. Mammals at the site include white-tailed deer, coyote, red fox, rabbits, raccoons, groundhogs, chipmunks, and mice. Birds identified at NFSS include hawks, herons, pheasants, geese, ducks, and doves. In addition, various amphibians and invertebrates are present at certain locations. No Federally listed threatened or endangered species have been identified at NFSS (USACE 2007b).

3.1.6 Land Use and Demography

The NFSS is located in a generally rural area. The CWM Chemical Services, LLC, hazardous waste disposal facility is located to the north and northeast, the Modern Landfill, Inc., solid waste disposal facility is located to the east and south, and a National Grid (formerly Niagara-Mohawk) Power Corporation transmission corridor is located to the west. The town of Lewiston owns a small parcel northwest of NFSS. These facilities are shown in Figure 1-7 of the RIR (USACE 2007a). Like NFSS, all of these properties were formerly part of LOOW.

Land uses within the townships of Lewiston and Porter are predominantly rural and include row-crop agriculture, orchards, recreational areas, abandoned fields, and second-growth forests. A hydroponic greenhouse has been constructed south of NFSS where a farm field used to be. The Lewiston-Porter public school property is about 2.4 km (1.5 mi) west of NFSS and a public campground is approximately 0.8 km (0.5 mi) southwest of the site. A number of single family residences are also located near the site (USACE 2007a). A trailer park is located 2.6 km (1.6 mi) north-northwest of the IWCS.

Limited population growth is projected for the area, which is expected to remain rural. During summers, visitors use the nearby campground, and hunters occasionally use the area west of the National Grid corridor. A recreational area, Fourmile Creek State Park, is located to the north at the confluence of Fourmile Creek and Lake Ontario (DOE 1986).

3.2 EXPOSURE PATHWAYS

Potential human exposure pathways for the IWCS consider four main factors:

- The locations of the contaminated materials in the IWCS, the types of contaminants associated with those materials, and the potential mechanisms by which they could be released. This TM focuses on releases to air.
- The likely fate and transport of contaminants following an airborne release.

- Estimated concentrations of the contaminants at points of potential human contact (i.e., exposure points) and associated routes of exposure (e.g., inhalation of airborne contaminants and external gamma irradiation).
- The completeness of each exposure pathway, i.e., the presence of each of the following components: a source and a mechanism of contaminant release, an environmental transport medium, a point of human contact with the contaminated source or transport medium, and a route of human exposure at that point. For external gamma irradiation, exposures can occur in the absence of direct human contact with the contaminated medium, as discussed in Section 3.2.2.

These elements are discussed further in the following subsections.

3.2.1 Contaminant Sources

The contaminants addressed in this assessment are within the engineered IWCS on the west side of NFSS. The IWCS was constructed to contain these materials and minimize any releases to the environment. The NFSS and vicinity are monitored for any releases from the IWCS and other areas of NFSS, and results (which are issued annually) demonstrate that no airborne releases are occurring from the contained materials. The environmental surveillance TM for data collected in 2009 was issued in the fall of 2010 (USACE 2010), and the TM that presents data collected in 2010 was recently completed (USACE 2011c).

This TM addresses several contaminant sources:

- K-65 residues.
- Other high-activity residues: the L-30, F-32, and L-50 residues.
- Tower soil.
- R-10 waste pile.
- Other contaminated soil and debris.

These materials can be further grouped based on their levels of contamination (primarily Ra-226) and their location within the IWCS (including co-location with other wastes), as well as material type. The K-65 residues and other high-activity residues and tower soils were placed in former buildings in the southern portion of the IWCS (see Figure 1.2), while the remaining wastes were placed throughout the IWCS to improve its structural stability, with the lower-contaminated R-10 waste pile and other soils placed predominantly in an area north of the buildings. Estimated concentrations of radionuclides and chemicals in these materials are given in Chapter 2 (Tables 2.2 and 2.3).

3.2.2 Fate and Transport

Under current conditions, the IWCS poses no risk. The NFSS is owned by the Federal government and site access is controlled. The IWCS was designed and constructed to safely contain the stored materials until their final disposition could be determined. The site is routinely monitored, and periodic inspections are made for any damage to the IWCS cap that could compromise its integrity; any such damage would be repaired as it was identified. An extensive environmental surveillance program is in place to ensure the safety of the site. These controls will continue to protect people living and working near NFSS throughout the period evaluated in this TM (ten years). Contaminants could potentially be released from the IWCS at some point in the future if the cap were breached either intentionally (e.g., during remedial action work) or inadvertently (e.g., by a burrowing animal) without control or repair. A cap breach could release Rn-222 gas and particulates to the nearby environment. In addition, it is possible that an

individual (e.g., onsite maintenance worker) could be exposed to gamma radiation from the IWCS contents if a hole or crack developed in the cover. Under current conditions, the duration of such an exposure would be limited because any opening would be repaired as it was identified during regular site surveillance and maintenance activities.

The radionuclide of primary concern at the IWCS is Ra-226, due to its high concentrations and potential to emit substantial gamma radiation and release Rn-222 gas. Note that Rn-222 gas is continuously generated within the IWCS (it is in secular equilibrium with Ra-226), but under current conditions this gas decays to solid radioactive particulates before reaching the surface of the IWCS and is not released to the atmosphere in any measurable amount. When Rn-222 is released from any source (such as wastes at the IWCS if uncovered), a number of short-lived radioactive progeny are generated as the gas undergoes radioactive decay. These progeny are charged particulates, and they can attach to nearby dust particles and be dispersed in air, including by wind (as also described in the radon assessment TM, USACE [2012]). The Rn-222 progeny would then be transported in the same manner as other airborne particulates that might be released directly from the residues and other wastes. These particulates can also deposit on the ground, where they might be available for inadvertent ingestion or uptake by biota, thus entering the food chain, and some fraction might also be resuspended to air depending on local mechanical disturbance and wind erosion.

The significant gamma radiation emitted by Ra-226 could result in measurable doses if anyone were near the IWCS when the residues were exposed, especially the K-65 residues. This exposure could occur either at the IWCS or farther away, because the radiation could be scattered by the air and then impact someone at a distance. The scattered (skyshine) radiation is generally a small component of the overall radiation field, but it can be of concern for wastes that emit large amounts of gamma radiation even when there is shielding between the source and receptor. Whereas the dose from inhaled and ingested radionuclides continues after the intake stops (but the radionuclides are still in the body), the dose from external gamma radiation is limited to the time that the individual is in the gamma radiation field.

The exposure pathways considered in this TM include those representing baseline (current) conditions, as well as those that could occur when remedial actions are being implemented. Under baseline conditions, no contaminants are being released to air at the IWCS. Such a release would require the integrity of the cap to be compromised, e.g., by a burrowing animal or a natural event such as an earthquake. Those scenarios will be addressed in further detail in the FS as part of the short-term and long-term effectiveness evaluations for the no action and limited action alternatives.

In contrast to current conditions, contaminants would be released during implementation of any alternative that involves excavating wastes from the IWCS. These releases and associated exposures are a main focus of this TM. For example, if the remedial action involved removing the clay liner of the cap, then Rn-222 gas could escape to the surrounding air; if the action involved removing certain wastes, those wastes would be exposed during the remedial action period such that contaminants could be released to the atmosphere. If the high-activity residues were uncovered without controls, onsite workers and possibly members of the public could potentially incur substantial radiation doses from external gamma radiation; inhalation of Rn-222 progeny could also contribute to unacceptable dose levels. Mitigation measures (such as shielding and radon control systems) would be part of any remedial action that involved opening the cap and disturbing the IWCS wastes, to control releases and exposures.

Surface runoff is not expected to play a significant role in contaminant transport or exposures from the IWCS in the near term. Under current conditions, the residues and other wastes are contained within the IWCS and any runoff from the structure flows to the West or Central Drainage Ditch. If minor cracks or holes were to develop in the cover, water could flow into the IWCS but it is very unlikely to reach the depth of the contained materials. Contaminated groundwater is not included in the scope of the IWCS

OU for reasons described in the FS Work Plan (USACE 2009) and summarized in the Executive Summary of this TM. If some or all of the IWCS contents were removed, it is possible that surface runoff could occur as these materials were staged onsite for subsequent treatment and/or packaging, as appropriate to the selected remedy. However, standard engineering controls would be implemented to minimize the likelihood of such runoff. Also, if some runoff did occur and nearby areas were contaminated, they would be addressed in the subsequent OU for the BOP (see Figure 1.3).

To summarize key fate and transport drivers considered for this TM, if the IWCS cover were breached such that the wastes were exposed, Rn-222 gas (and associated buildup of solid radioactive progeny) and contaminated particulates could be released and dispersed beyond the IWCS with subsequent particulate deposition on soil, thus creating a potential for both inhalation and incidental ingestion by people nearby. In addition, the radioactive contaminants would continue to emit gamma radiation. Particulate deposition on other surfaces such as crop leaves or surface water would be lower than on soil, and associated exposures would be lower. Thus, for purposes of this TM, the quantitative estimates of deposition following airborne releases focus on surface soil. Contaminants deposited on the surface might be resuspended, which could lead to transient localized air impacts; however, those particles would then redeposit. Thus, over the areas for which hypothetical exposures are assessed, the estimates of primary dispersion and deposition are considered to account for any intermediate resuspension and redeposition.

Deposited particulates might also be transported by overland flow after precipitation, but such transport would further disperse (dilute) these contaminants and might reduce their accessibility (e.g., if they were covered by other particles). Thus, to frame the evaluations in this TM, the original deposition is conservatively assumed to account for the portion that might be further transported. (Note the fraction of airborne particulates estimated to be deposited at receptor locations is small [see Section 3.3.3], and relative risk contributions from incidental soil ingestion are low [see results in Section 5.2].) Similarly, downward migration of surface-deposited particulates is assumed to be limited, so the amount deposited is conservatively assumed to be available for exposure via incidental ingestion and external gamma irradiation. Based on these considerations, the primary fate and transport concerns for the IWCS contaminants following a loss of cap integrity are: gamma radiation, airborne transport of Rn-222 gas and associated progeny, airborne transport of waste particulates, and wet/dry deposition on surface soil.

3.2.3 Exposure Points, Receptors, and Exposure Routes

Exposure points represent locations of potential human contact with a contaminated medium. The primary source media are the IWCS wastes: the K-65 residues, other high-activity residues (the L-30, F-32, and L-50 residues) and tower soils, and the R-10 waste pile and other contaminated soils and intermixed rubble and debris. In addition to these IWCS contents, the main secondary media that could be contaminated following an IWCS release are air and surface soil. Over the time frame addressed by this TM, minor cap breaches might release small amounts of contamination (primarily radon), and those breaches would be addressed as part of ongoing routine maintenance activities. If a major breach were to occur, releases could be more extensive but emergency response plans already in place would be activated to limit exposures and control contaminated materials as indicated. Thus, any realistic estimate of potential exposures to workers or members of the public associated with a cap breach would be very small.

Nevertheless, a key objective of this TM is to serve as a technical resource to help guide the development and evaluation of remedial alternatives in the upcoming FS. For this reason, the extensive monitoring and institutional controls in place at the NFSS are assumed to be lost, in order to hypothesize onsite scenarios for the near term that include multiple visits by an imaginary trespasser. The conceptual model outlined to frame the preliminary example analyses in this TM is shown in Figure 3.1.

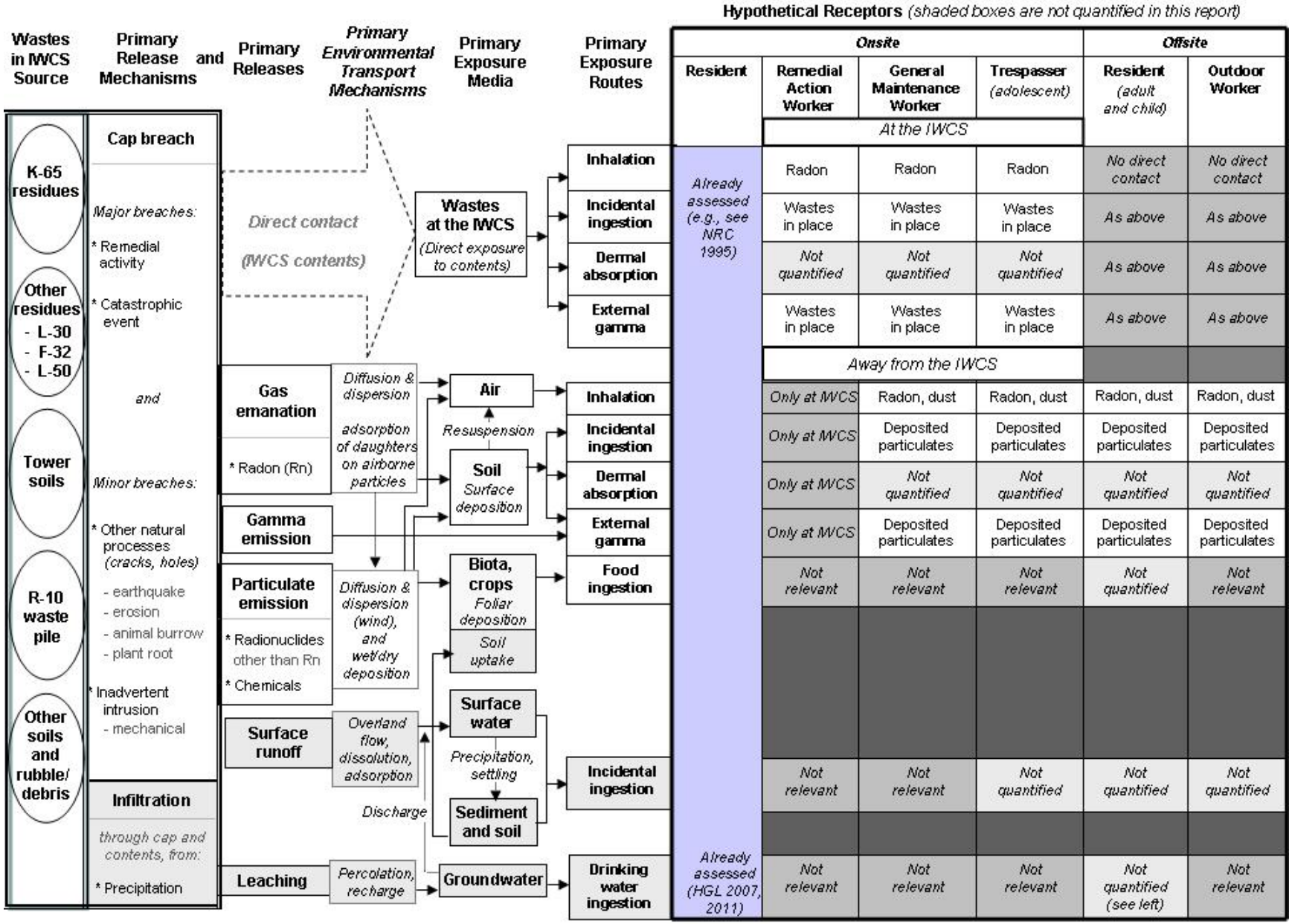

FIGURE 3.1 Conceptual Model for the IWCS OU *(This conceptual model illustrates key pathways considered for the IWCS contents.)*

As illustrated in Figure 3.1, the preliminary conceptual evaluations in this TM focus on two sets of exposures that focus on the main pathways:

- At the IWCS: External gamma irradiation, inhalation, and incidental ingestion of contaminated soil and the waste contents.
- Beyond the IWCS: External gamma irradiation, inhalation, and incidental ingestion of contaminants deposited on soil both onsite and offsite.

Together with the Rn-222 and particulate releases at the IWCS, gamma radiation from exposed residues (the K-65 residues in particular) could be significant. These gamma radiation exposures can be either direct radiation or air-scattered (skyshine) radiation. Both potential pathways for gamma exposures are addressed in this TM. Direct gamma radiation is expected to be largely limited to workers involved in future cleanup activities, but other workers and members of the general public might also be affected under certain situations. Gamma radiation exposures to a member of the general public such as an onsite trespasser would likely be essentially limited to skyshine radiation unless the individual came in direct contact with the IWCS contents.

Hypothetical human activities under current and near-term future conditions were considered in identifying potential receptors at various exposure points. As previously described, an onsite residential scenario is not evaluated in this TM (because earlier assessments have already documented that unacceptable risks would result). Rather, the exposure scenarios considered here are those that might occur within the near term (e.g., ten years), considering onsite personnel conducting routine maintenance activities as well as projected remedial action workers conducting cleanup activities. At this time, a number of areas on the NFSS have relatively low levels of residual contamination from past activities, and any deposition of airborne contaminants from the IWCS would add to those levels. The estimates in this TM focus on the incremental contribution from IWCS releases. Existing contamination in onsite soil will be addressed in the BOP OU, following the remedy determined for the IWCS OU.

Six hypothetical exposure scenarios are evaluated in this TM: three onsite and three offsite. The onsite scenarios address a maintenance worker, a cleanup (or remedial action) worker, and an adolescent trespasser. The three offsite scenarios address exposures for a hypothetical nearby outdoor worker (assumed to work at an adjacent commercial landfill) and an adult and child resident living nearby. These hypothetical receptors are described below.

Maintenance workers currently perform various activities at NFSS, including mowing, inspections, and general maintenance of security barriers such as fences. In addition, individuals are regularly onsite to perform ongoing surveillance activities including measuring the Rn-222 flux on the IWCS cap, obtaining surface and groundwater samples, and installing and collecting gamma radiation monitors. These activities are expected to continue through the near term pending final disposition of the IWCS. If an onsite remedy were selected and implemented, these actions would continue indefinitely. This worker is assumed to be an adult. This scenario also conservatively addresses exposures that could occur to other individuals such as inspectors who infrequently visit the site to ensure the safety of the IWCS.

The remedial action worker represents an individual who implements remedial measures at the IWCS. Although no decision has been made regarding remedial alternatives for the IWCS, for purposes of this TM it is assumed that a range of alternatives will be considered, from no action to full removal of the wastes DOE placed in the IWCS. Thus, the assessment in this TM considers potentially limiting situations in order to help guide planning for worker protection and emission controls, for both contaminated particulates and Rn-222 gas. This remedial action worker scenario is expected to provide information that can be used to help identify the nature and level of emission controls and other protective

measures that would be needed to implement a given remedial action, to support the upcoming evaluations in the FS.

The remedial action worker is assumed to be an adult who would spend the full work day onsite at the IWCS wearing respiratory protection equipment. However, for purposes of this TM (to help guide planning for the development and evaluation of alternatives for the IWCS), to quantify the inhalation and incidental ingestion exposures to IWCS contaminants, it is assumed that this protection (such as a face mask) is lost (fails or is not used) for one 8-hour work shift during remedial action activities for each of the three waste groups: (1) the K-65 residues; (2) the L-30, F-32, and L-50 residues and tower soils; and (3) the R-10 pile and other contaminated soils (see Section 3.3). To evaluate potential exposures and risks associated with not wearing respiratory protection for additional days, this one-day estimate can be scaled upward by that hypothesized number of days (as illustrated in Appendix D, Section D.3). This scaling approach can also be applied to estimate potential risks that could be associated with a no action condition under which institutional controls are hypothetically assumed to be lost such that the cover eventually fails at some point in the future.

The trespasser is assumed to be a teenager who repeatedly enters the site despite access controls and spends a portion of the time onsite very close to the IWCS and the rest of the time nearby. This scenario could also be considered to represent someone who might infrequently access the site for a specific activity such as hunting. Deer and other game animals are found within the fenced boundary of NFSS, and from anecdotal reports, hunters have trespassed onsite while pursuing local game (USACE 2007b). In addition, a campground is nearby, and visitors to that campground might be unaware of the hazardous materials contained in the IWCS and disregard existing access controls.

A number of offsite locations are addressed in the annual National Emission Standards for Hazardous Air Pollutants (NESHAPs) compliance report for NFSS, which is included as Appendix C of the annual environmental surveillance TMs (e.g., see USACE [2010, 2011c]). Eight offsite locations are addressed in these evaluations, and the same eight locations are evaluated in the radon assessment TM (USACE 2012). These locations are also reflected in the dispersion modeling analyses presented in USACE (2011d). The eight locations include two for industrial use activities (adjacent landfill) as well as several nearby residences. Note that the distances to these eight receptor locations differ between the recent environmental surveillance reports and the radon assessment TM, with distances in the former (USACE 2010, 2011c) reported from the center of NFSS, while those in the radon assessment TM (USACE 2012) measured from Building 411 (the high-activity residues in the IWCS are contained within the basement of this former building). In this health effects TM, the IWCS source areas are centered on Building 411.

A worker at the Modern Landfill, Inc., solid waste disposal facility located east and south of NFSS is identified in USACE (2012) as the individual receiving the highest dose from the site. This hypothetical individual is represented here by the offsite outdoor worker, who is assumed to be an adult working exclusively outdoors at the commercial disposal facility next to NFSS. Although other individuals also work near NFSS, this location was predicted to receive the highest offsite impacts from any releases at the IWCS based on initial evaluations in USACE (2010, 2011c, 2012), so this location was selected to represent general outdoor workers in the vicinity of the IWCS. The specific location used for this receptor is about 560 m (1,800 ft) east-southeast of the IWCS (USACE 2011d, 2012).

The evaluation of an offsite residential scenario in this TM considers both a child and an adult. This dual-receptor approach is taken to accommodate flexibility for scaling to other potential exposure durations, to support planning for the FS. Because this TM focuses on a ten-year period, an age-averaged single representative residential receptor would not apply. The example residence is about 660 m (2,200 ft) south-southwest of the IWCS (USACE 2012). This location was identified in USACE (2010, 2011c) as

representing the offsite residence with the highest potential for impacts from site releases. Thus, it conservatively represents others near NFSS who might be affected by airborne releases from the IWCS. The suite of hypothetical receptor locations evaluated to support the analyses in this TM are shown in Figure 3.2. Offsite, the same twelve locations considered in other reports USACE (2011d, 2012) are assessed in this TM. Eight represent current nearby receptor locations, while the other four represent potential future "distant" receptor locations 5 and 10 km (3.1 and 6.2 mi) east and northeast of the site. Additional locations beyond those shown on the figure were also evaluated as illustrative supporting context, including fenceline locations (to compare estimated airborne concentrations with NAAQS limits) and a trailer park/residential area about 2.6 km (1.6 mi) northwest of the IWCS.

Impacts onsite are expected to be much greater than those offsite. For both the hypothetical trespasser and maintenance worker, the exposures would not be controlled as they would routinely be for the cleanup worker (e.g., through such measures as shielding, remote-handling equipment, and personal protective equipment). Because site access is controlled by a security fence and warning signs are posted, only someone who deliberately ignores these controls would be able to come in contact with the IWCS contents in the near term. This direct exposure would be of greatest concern if the IWCS cap integrity were compromised and the wastes therein became accessible. The modes and routes of exposure evaluated in this TM for the primary and secondary sources of contamination are summarized below.

- *K-65 residues, other residues with relatively high levels of radioactivity, and other wastes in the IWCS*. Exposures to these materials are generally limited to the three onsite exposure scenarios, i.e., the two adult workers and the adolescent trespasser. The routes of exposure include (1) direct external gamma irradiation, (2) incidental ingestion of contaminated soil and IWCS contents including the residues and other wastes, and (3) inhalation of Rn-222 and particulates. Secondary gamma irradiation (skyshine) from the K-65, L-30, F-32, and L-50 residues could also impact nearby offsite individuals.

- *Surface soil.* Onsite surface soil can be contaminated by the deposition of particles released to air from the IWCS. This soil is of particular interest for the maintenance worker and trespasser because the remedial action worker is assumed to spend all time onsite at the IWCS, which would result in much higher radiation doses and health risks. Offsite surface soil contaminated by deposition of airborne particulates released from the IWCS is addressed for all three offsite scenarios. The routes of exposure to this soil are: (1) direct external gamma irradiation and (2) incidental ingestion. Secondary gamma irradiation (skyshine) is not an issue for this contaminated soil because it represents a very small component of the direct external gamma irradiation pathway.

- *Air.* Outdoor air is evaluated for all six scenarios, and indoor air is considered for the offsite residential scenarios. Airborne particulates include Rn-222 progeny, which are a key concern because of the high concentrations of Ra-226 in the IWCS residues.

More than 150 potential receptor locations are evaluated in the dispersion modeling analyses conducted for this TM. Most of these locations reflect the practical consideration that the hypothetical onsite receptors would not stay in one place during their time spent onsite, and meteorological conditions (and hence dispersion and deposition) vary throughout the construction (cleanup) season. Hypothetical 36 directional receptors are placed at 1, 10, 50, and 100 m (3, 33, 160, and 330 ft) from the edge of the square source area used to represent the exposed contents of the IWCS in this preliminary analysis. These receptor locations ring the source area in 10-degree increments from its center. The remedial action worker is assumed to stay 1 m (3 ft) from the exposed waste throughout the work day, while the trespasser and maintenance worker are assumed to spend 10% of their time this close, and the rest of their onsite time at distances of 50 m (160 ft) and 100 m (330 ft) from the exposed waste, respectively.

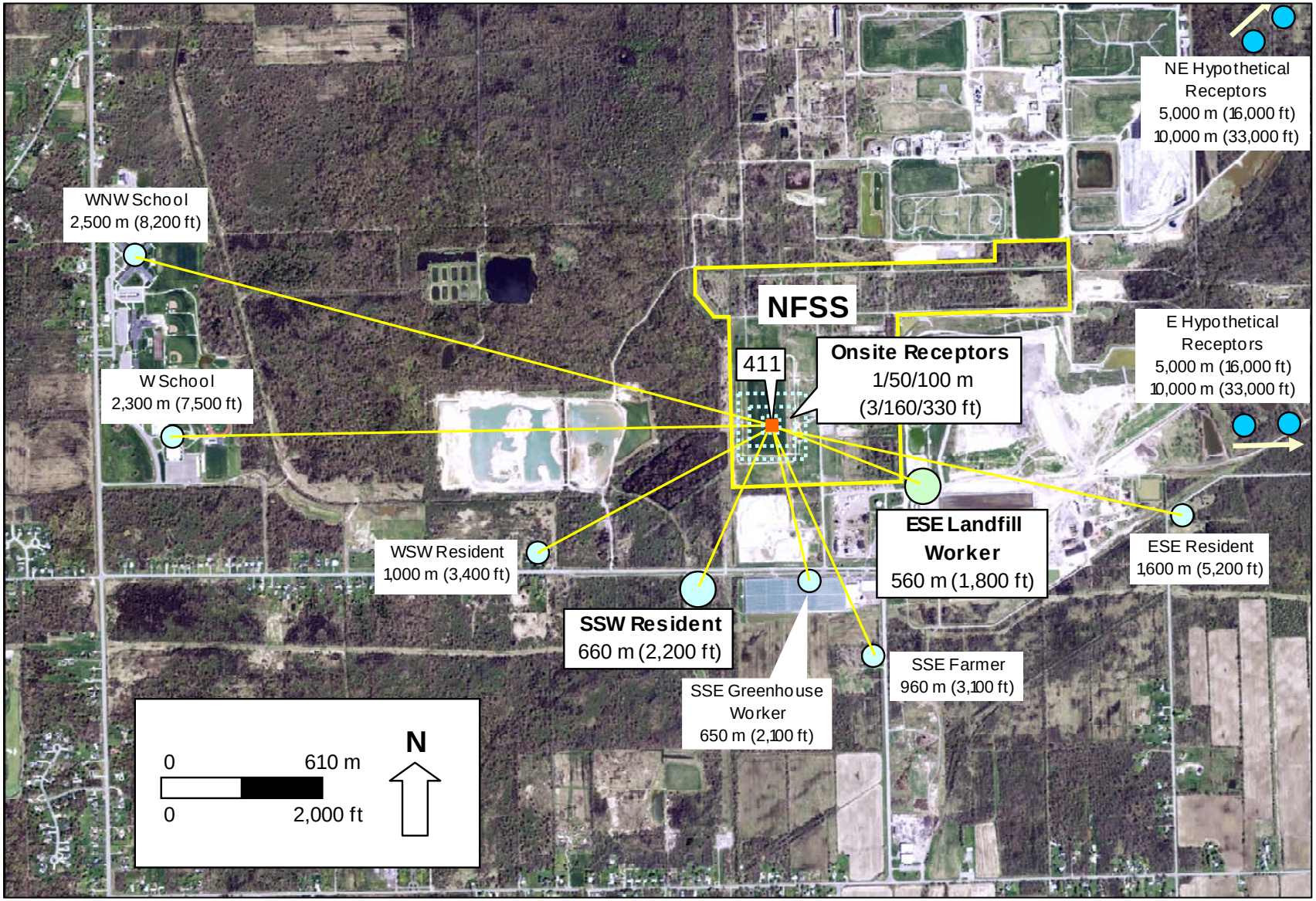

FIGURE 3.2 Hypothetical Receptor Locations *(The six receptors designated with larger bold font represent the core set assessed.)*

3.2.4 Complete Exposure Pathways

For a general health risk assessment, an exposure pathway is considered complete when all elements are present, i.e., a source of contamination, a mechanism of release and transport of contaminants to the environment as indicated, an exposure point at which humans can come into contact with the contaminants, and an exposure route by which this contact can occur.

The exposure pathways considered complete for the IWCS wastes and environmental media that could be contaminated by an airborne release are:

- Wastes in the IWCS: Direct and secondary (skyshine) external gamma irradiation and direct incidental ingestion at the IWCS.
- Air (outdoor and indoor): Inhalation of Rn-222 gas, its progeny, and other particles.
- Surface soil: Direct external gamma irradiation from deposited particulates and incidental ingestion.

The sources of contamination, affected media, exposure points, hypothetical receptors, and primary routes of exposure evaluated in this TM are summarized in Table 3.1. With regard to the potential ingestion of groundwater as a drinking water supply at the IWCS or adjacent areas, that pathway is considered incomplete because no exposure points currently exist nor are they expected to exist during the period addressed by this TM. Groundwater in the vicinity of NFSS is of poor quality and is not used as a source of potable water. That environmental medium will be addressed as part of the subsequent OUs for NFSS.

TABLE 3.1 Primary Exposure Pathways Evaluated[a]

Contaminated Media	Exposure Routes	Hypothetical Receptors					
		Onsite			*Offsite*		
		Remedial Action Worker	Maintenance Worker	Trespasser	Outdoor Worker	Resident: Adult	Resident: Child
IWCS contents	Gamma irradiation	×	×	×	×	×	×
	Incidental ingestion	×	×	×	×	×	×
	Dermal absorption	*×*	*×*	*×*			
Surface soil	Gamma irradiation		×	×	×	×	×
	Incidental ingestion		×	×	×	×	×
	Dermal absorption		*×*	*×*	*×*	*×*	*×*
Outdoor air	Inhalation	×	×	×	×	×	×
Indoor air	Inhalation					×	×

[a] The contaminated media, exposure routes, and hypothetical receptors shown here represent the core set addressed in this TM. An "×" indicates the pathway is considered complete for this OU. Shaded entries indicate the pathway is not quantified in this OU either because it is not relevant (empty entry) or because it is considered complete but exposure and risk estimates are not included in this TM ("*×*"). The evaluation of gamma irradiation for the six hypothetical receptors focuses on exposures to radioactive particulates deposited on surface soil. Dermal exposures are not quantified for arsenic and PCBs (the chemicals assessed in this preliminary evaluation for which absorption factors are available, see Section 4.2) because contributions to overall risk estimates are small. Evaluations for the two OUs following the IWCS will address this pathway while addressing other areas of the site and additional environmental media, including soil, sediment, surface water, and groundwater.

Although this table combines all IWCS contents for simplicity, exposures are considered for three example waste groups based on the type of material and level of radioactivity (see Tables 2.2 and 2.3), also considering their locations within the IWCS.

3.3 ESTIMATION OF EXPOSURE POINT CONCENTRATIONS

Exposures to IWCS contaminants are evaluated for two conditions in this preliminary evaluation: (1) the current configuration with a cap breach and (2) remedial action that involves uncovering and excavating the wastes. The contaminated media and receptors evaluated in this TM are as shown in Figure 3.1 and Table 3.1. Illustrative concentrations of contaminants in three media – wastes at the IWCS, air, and surface soil – at assumed points of human exposure are discussed in the following subsections.

The IWCS OU is defined as the wastes DOE placed in the IWCS, and this TM addresses those wastes plus environmental media estimated to be impacted by airborne releases from the IWCS when the wastes are exposed. Historical data for the IWCS contents and in some cases for analogous wastes (see Section 2.3) are used to estimate the exposure point concentrations for direct contact exposures at the IWCS. The exposure point concentrations for air and surface soil beyond the IWCS are estimated from emission, dispersion, and deposition modeling (see Sections 3.3.2 and 3.3.3, and USACE 2011d).

Contaminant concentrations are expected to either remain unchanged (e.g., nonradioactive metals in the IWCS) or decrease slightly over time as a result of radioactive decay and other natural processes. For this reason, using current concentrations to estimate future exposures (for both radionuclides and chemicals) rather than reducing these levels per natural environmental processes represents a conservative approach.

3.3.1 IWCS Contents

The estimated concentrations of radionuclides and chemicals in the IWCS wastes given in Tables 2.2 and 2.3, respectively, are used as the exposure point concentrations for direct exposures at the IWCS. These concentrations are largely based on historical NFSS data. These estimates are also consistent with information for similar contaminated media from other facilities, such as the Fernald site (radionuclides in K-65 residues) and LOOW (PCBs in soil).

To support the evaluations for both IWCS cases – wastes in place and excavation – a number of square area sources centered on Building 411 have been evaluated. This approach accommodates the assessment of different extents of uncovered waste as indicated by the given breach event, whether natural (e.g., burrowing animal) or intentional (e.g., excavation). The objective is to provide estimates that guide practical planning for the IWCS, including for emission controls and worker protection.

For the in-place case, small source areas are modeled to estimate doses and risks from Rn-222 progeny and external gamma irradiation for several breach events. For the excavation case, larger source areas are modeled that reflect preliminary estimates for the excavation zones. Overall, six source areas have been modeled to support this analysis; these areas range from 1 m^2 (1.2 yd^2) for a crack or hole from natural processes to 2,000 m^2 (2,400 yd^2) for excavation of the lower-contaminated wastes and soils from the northern end of the IWCS (see Figure 1.2). The remaining source areas modeled are: 10, 100, 500, and 1,000 m^2 (12; 120; 600; and 1,200 yd^2). As context, Building 411 is about 3,500 m^2 (4,200 yd^2, or roughly 0.9 acre). The source areas used to model particulate emissions during the waste excavations are:

- K-65 residues: 500 m^2 (600 yd^2).
- L-30, F-32, and L-50 residues and tower soils: 1,000 m^2 (1,200 yd^2).
- R-10 waste pile and other contaminated soils, rubble and debris: 2,000 m^2 (2,400 yd^2).

As part of preliminary planning for the IWCS, various remedial alternatives have been identified that range from little if any waste disturbance to complete removal (USACE 2009), with the specific alternatives still to be defined for the FS. For this reason, the dispersion and deposition modeling illustrated in this early conceptual evaluation considers the individual wastes listed in Tables 2.2 and 2.3, recognizing they could be addressed distinctly or in other combinations than indicated above. By this approach, the dispersion and deposition of contaminated particulates estimated from unit emissions could be scaled to the concentrations in different waste groups to support upcoming evaluations in the FS.

The FS will reflect conceptual information for implementing various alternatives for the IWCS, including the nature and duration of activities per source area, type and number of equipment, and efficiencies of specific emission controls. However, that information is not yet available so general assumptions based on default values and similar activities are used for the illustrative analyses in this TM. These estimates will be refined when that project-specific information becomes available as the FS is developed.

Meanwhile, for this TM, daily processing rates have been estimated to calculate the intervals over which the IWCS contents would be excavated; this information is used in assessing exposures associated with dispersion and deposition for three example waste groups. Estimated concentrations of particulate matter in air and soil at the exposure points evaluated for each receptor can then be scaled from the concentrations in the component wastes (as described in the next subsection). Different wastes would be excavated at different rates to accommodate different levels of emission controls and other handling needs. For example, it is assumed that the highly radioactive residues in the southern portion of the IWCS would be removed more slowly than the soils and other materials with relatively low levels of contamination in the northern portion (see Figure 1.2 for various waste locations).

Although example doses and risks can be estimated for each waste, the results presented in this TM focus on the three waste groups that reflect common location (as a practical matter) and similar contamination levels. Preliminary conceptual estimates of daily processing rates for these three groups, referred to as waste groups 1, 2, and 3, are based on information available for similar wastes at other sites (including the K-65 residues at Fernald, see USACE [2011a]). These assumed daily processing rates are:

- Waste group 1 (K-65 residues): 20 m^3 (26 yd^3).
- Waste group 2 (L-30, F-32, and L-50 residues and the tower soils): 100 m^3 (130 yd^3).
- Waste group 3 (R-10 waste pile and the other contaminated soils and debris): 300 m^3 (400 yd^3).

These processing rates translate to the following durations for complete excavation of each of these wastes, based on a 170-day excavation season (based on work days from April through November):

- Waste group 1 (K-65 residues):
  One excavation season with an assumed down time of 10% *(170 work days).*

- Waste group 2 (L-30, F-32, and L-50 residues and tower soils):
  Nearly two-thirds of an excavation season *(112 work days).*

- Waste group 3 (R-10 waste pile and other contaminated soils and debris):
  1.6 excavation seasons *(275 work days).*

The example calculations in this TM illustrate potential exposures and risks associated with these three groups. Actual groupings that will be reflected in the alternatives developed for the FS are expected to evolve as that preliminary planning proceeds, so these early estimates would be modified accordingly.

3.3.2 Air

Contaminant concentrations in outdoor air are estimated from the source concentrations in Tables 2.2 and 2.3, scaled to the estimated unit emissions and associated dispersion based on the meteorological data and modeling analyses described in USACE (2011d). In addition to estimating air concentrations for input to the calculation of doses and risks for the hypothetical receptors, this analysis is also used to assess compliance with the National Ambient Air Quality Standards (NAAQS) for lead and particulate matter (PM) (inhalable and respirable PM with mean aerodynamic diameters of 10 and 2.5 micron or less, respectively, i.e., PM_{10} and $PM_{2.5}$; see discussion in Chapter 6 of USACE [2011d]); the estimated air concentrations are also used for comparison to occupational exposure levels for worker protection (see Appendix B, Table B.1).

The meteorological data used to estimate the dispersion of airborne releases at the IWCS are from the adjacent CWM landfill, as described in USACE (2011d). That companion report evaluates candidate meteorological data and dispersion models for application at NFSS, and as described therein, these CWM data are supplemented with surface data from the Niagara Falls airport and twice-daily upper air sounding data from the Buffalo airport. (Surface data from the Niagara Falls airport are used to estimate boundary layer parameters for the dispersion calculations, tapping measurements that are consistent across the region such as solar insolation, and in some cases to substitute for missing data. Upper air sounding data are used to determine mixing height, which is the height through which relatively vigorous vertical mixing occurs. The Buffalo airport is the closest meteorological station that collects those data.)

To evaluate the dispersion of contaminant releases during waste excavation at the IWCS, 32 months of CWM meteorological data (April through November, from 2005 through 2008) are used to model dispersion from a unit release at the IWCS, scaled to the emission estimates described below for the different wastes. The thirty-two monthly estimates of airborne and deposited particulate concentrations calculated with the AERMOD (*A*merican Meteorological Society/*E*PA *R*egulatory *MOD*el) computer code (which is described in USACE [2011d]) are then scaled to the estimated concentrations of contaminants in the given wastes hypothetically being excavated to determine the exposure point concentrations. The steps applied to conduct these calculations are further described below.

This TM is being prepared at an early stage of FS planning, and project-specific information is not yet available to support a representative risk evaluation. For example, information is not available at this time regarding the anticipated number and type of heavy equipment that would impact emission estimates, nor for the level of activity or schedule for the alternatives involving excavation. Thus, this TM simply offers early conceptual estimates to serve as a resource document for the FS, by illustrating the process for quantifying risks that may be needed to support the representative evaluations to be reflected in the upcoming FS when such planning information is developed.

When project-specific information is not available, an overall area-wide PM_{10} emission factor can be used (MRI 1996). An emission factor of 0.11 tons/acre/month is commonly used for general construction sites with a low activity level, e.g., those not involving cut-and-fill areas, large-scale earth-moving operations, or heavy traffic volumes. For sites with a high activity level (those involving cut-and-fill areas, large-scale earth-moving, or heavy traffic volumes), a PM_{10} emission factor of 0.42 tons/acre/month is used. Overall, IWCS excavation activities are assumed to fall between heavy and light levels. Thus, an average particulate emission factor of 0.265 tons/acre/month (half the sum of 0.11 and 0.42) is used in this TM to reflect a moderate activity level. This assumption is conservative (protective) because most remedial action activities at the IWCS would likely range from low to moderate activity levels. From this information, assuming a moderate level of activity generates the uncontrolled emissions, the estimated rate of particulate emissions during waste excavation at the IWCS is 0.35 $g/m^2/hr$.

For this early evaluation, conceptual excavation of the K-65 residues is assumed to follow the general approach taken for similar residues at the DOE Fernald site. That is, extensive engineering controls would be applied to minimize releases. For example, a containment system (such as a tent vented through a filtered exhaust system) would be used to capture most airborne particulates, with a radon-specific system used to control Rn-222 emissions (see USACE [2011a] for highlights of the DOE approach). Inside the containment structure (e.g., tent), workers would be expected to be on supplied air to preclude any radiological or chemical intakes. Outside the containment system, workers would be expected to use other equipment such as respirators or air-filtering masks, based on real-time measurements during the remedial activities to assure exposures met occupational limits as further supported by health risk calculations.

This preliminary evaluation assumes an engineered containment system is used when excavating the K-65 residues from the IWCS to reduce particulate emissions 100-fold, based on levels achieved for the Fernald waste (see USACE [2011a]). The other wastes contain somewhat lower Ra-226 concentrations, so this preliminary evaluation assumes water spraying would be used to mitigate particulate releases during their excavation. Note that the $PM_{2.5}$ fraction is assumed to represent 10% of the PM_{10} fugitive dust emissions associated with construction activities, and the control efficiency achieved by twice-daily water spraying on the excavation area is estimated to be 50% (Countess Environmental 2006). (Spraying could be conducted before excavation begins and at midday.) For the wastes other than the K-65 residues, it is assumed that this water spraying rate will be doubled to four times daily to achieve a control efficiency of 75% (Countess Environmental 2006) given the importance of controlling emissions from these materials.

Thus, the controlled emission estimates based on the uncontrolled emission rate of 0.35 $g/m^2/hr$ identified above are assumed to reflect the particulate control efficiencies indicated above – i.e., 99% for the K-65 residues and 75% for the other wastes. The illustrative results in this TM for these assumed particulate controls can be directly scaled to reflect no controls (i.e., no containment structure or water sprays) or lower controls (per less frequent spraying). For example, if it were assumed that no particulate controls would be implemented, the illustrative results in this TM for excavating the K-65 residues could be multiplied by 100 to estimate results for "uncontrolled" particulates, and the conceptual estimates for the other wastes in the IWCS could be multiplied by 4 to estimate results if those particulate emissions were uncontrolled. Appendix D provides supplemental dose and risk estimates for an imaginary case under which the wastes are assumed to be excavated without any engineering controls, for purposes of comparison.

The AERMOD system is used to evaluate the dispersion of airborne releases from the IWCS. As described in USACE (2011d), AERMOD is the current standard EPA dispersion model jointly developed with the American Meteorological Society. For the inhalation calculations, AERMOD is applied to the releases described above assuming practical particulate emissions controls to estimate airborne PM concentrations at the receptor locations in $\mu g/m^3$. These concentrations are then multiplied by the source concentrations of radionuclides and chemicals given in Tables 2.2 and 2.3 (volume-weighted for waste groups 2 and 3 using the volumes of the component wastes given in Table 2.2) to estimate the airborne contaminant concentrations at each receptor location.

For the conceptual inhalation calculations in this TM, it is assumed that all PM is airborne. This is a conservative approach for estimating the inhalation doses and risks associated with particulate emissions at the IWCS. For the deposition calculations, considering total (dry plus wet) deposition rates, it is assumed that the combined PMs are either airborne or deposited, with only a small percent being deposited. The approach used to estimate deposition is described under surface soil in the next section.

In addition, the PM concentrations in this TM are estimated at ground level, consistent with the general practice for modeling air dispersion of ground-level releases from an area source. This approach of estimating PM concentrations in air at the ground level is applied because close to the source, those concentrations are higher than at the breathing height. (This differs from the approach for releases from point sources, such as facility stacks, for which dispersed concentrations are then commonly estimated in the breathing zone.) Pending conceptual plans to be developed for the FS, excavation at the IWCS is represented by ground-level releases from an area source, so modeled ground-level concentrations are used in this TM. This approach results in a conservative estimate of exposure point concentrations close to the IWCS (by roughly a factor of 3 within 1 m [3 ft]), while at distances of 50 m (160 ft) and beyond, the air concentrations estimated at the ground level and breathing height (1.5 m or 5 ft) are essentially the same (see the discussion of estimated concentrations in Section 5.3.2.3).

For the estimates of airborne PM, of the 32 monthly concentration estimates (based on four years of meteorological data for the excavation season of April through November), the maximum monthly PM concentration was identified for each receptor location. For the offsite receptors, this maximum monthly PM concentration was then used to determine the contaminant concentrations in the inhaled air, based on the specific waste(s) being excavated. This exposure point concentration is the product of the particulate concentration in the air being inhaled and the contaminant concentration in the source waste (volume-weighted as indicated), for each radionuclide and chemical.

Unlike the offsite receptors who are assumed to be at fixed locations, the three onsite receptors are assumed to move around within a limited distance of the excavation area. (See Section 3.4.1 for further discussion of the exposure factors assumed for the hypothetical receptors evaluated in this TM.). Thus, for these receptors, the average of the maximum monthly concentration across each of their locations is used to determine the PM concentration from which the exposure point concentration is developed. As an example, the remedial action worker is conservatively assumed to be 1 m (3 ft) from the excavation area at all times onsite, so 36 locations spaced 10 degrees apart are evaluated for this receptor. For each of these 36 locations, the maximum monthly PM concentration is estimated for the 32 months. The average of those maximum monthly PM concentrations across these 36 locations is then used to determine the exposure point concentrations in the wastes being excavated.

For radon, the analysis in this TM considers the two mechanisms for releases from the IWCS that are described in DOE (1986): (1) steady releases, which are assessed in USACE (2012); and (2) "puff" releases as materials are removed. Flux estimates from the K-65 residues are highlighted below for the steady releases. For the analyses in this TM, the estimates of Rn-222 emissions focus on the K-65 residues because those wastes have the highest Ra-226 concentrations. Nevertheless, the contributions of the other high-activity residues are also included in these estimates. It is assumed that a separate system would be used to control Rn-222 releases because particulate control measures would not adequately address those releases from these K-65 residues (per the Fernald experience highlighted in USACE [2011a]).

To estimate indoor air concentrations for the hypothetical offsite residential adult and child scenarios, a filtration factor of 0.5 is assumed (Godish 2004). That is, the structure is assumed to reduce indoor PM concentrations to half the outdoor levels. For Rn-222 progeny, the working-level ratio (WLR) estimated for this offsite receptor location (see Section 5.2.1, Table 5.3) is used to calculate the exposure point concentration.

To evaluate releases associated with the K-65 residues, it is assumed that during excavation a portion of the uncovered residues might be exposed to the environment (e.g., if part of the engineered containment system were compromised). For purposes of this analysis, the exposed area is assumed to be 100 m^2

(120 yd^2). This area is assumed to be within the 500-m^2 (600-yd^2) area used to estimate particulate emissions for the K-65 residues in this preliminary evaluation. (Both of these areas were selected for consistency with the assumptions in the radon assessment TM [USACE 2012].) To be consistent with the duration assumed for the other radiological pathways so that these doses and risks could be summed with those estimated for particulate releases, this partly uncontained condition was assumed to persist throughout the excavation, i.e., 8 hours a day for 170 days (or 1,360 hours). In reality, considerable care would be taken to minimize any time the excavation face was open, and it is anticipated that these activities would only be conducted when the K-65 residues were completely addressed by the radon control system (i.e., the full excavation surface would be encompassed). Thus, the assumptions used for these calculations are extremely conservative.

Part of the reason for conducting this calculation is to provide context for possible future exposures under an assumed loss of institutional controls if no action were taken at the IWCS. Thus, this calculation also represents potential future doses and risks associated with Rn-222 releases from the IWCS wastes if a small area of high-activity residues were uncovered and no corrective measures were taken for a year. Results can be scaled to estimate effects over a shorter or longer time period as desired. Furthermore, this approach helps guide practical planning regarding the level of engineering control and other measures warranted to assure worker protection for any IWCS alternative involving excavation. Using the Rn-222 flux estimates for the K-65 residues from USACE (2012) and the exposed area of 100 m^2 (120 yd^2), the steady Rn-222 release rate is estimated to be about 2.7×10^7 pCi/s. Assuming this release occurs for 1,360 hours, this uncontrolled Rn-222 release would be about 130 Ci.

To estimate the puff releases, it is assumed that all the Rn-222 gas in the interstitial spaces of the residues is available for release when the residues are disturbed. The entire inventory of Ra-226 in the residues and higher-activity wastes in the IWCS is about 1,980 Ci (from Table 1-1 of the RIR, USACE [2007a]), and an equal amount of Rn-222 would also be present. Using a radon emanation coefficient of 0.25 from Appendix A of USACE (2012), the amount of Rn-222 gas expected to be present in the interstitial spaces of the residues is about 500 Ci. A radon abatement system is expected to be used to reduce radon releases to the environment, and for this preliminary analysis it is assumed that this system captures 90% of the available Rn-222. The actual efficiency could be substantially higher (see USACE [2011a]). Hence, the total Rn-222 release from this mechanism over the duration of the remedial action is conservatively estimated to be about 50 Ci; actual releases would likely be lower.

Adding the two sources together gives a total 180 Ci of Rn-222 estimated to be released to the atmosphere during the remedial action period. These results are comparable to the estimate of 200 Ci developed by DOE for excavating the residues from the IWCS, as presented in Table 4.7 of the EIS (DOE 1986). It is important to recognize that this preliminary estimate is conservative, with its main purpose being to guide the determination of the need for significant engineering controls to mitigate releases of Rn-222 gas if the higher-activity materials are to be exposed (e.g., if they will be removed from the IWCS).

This release is assumed to occur over one excavation season (with 8 active field work hours per day, 5 days per week for 34 weeks from April through November). The active work area is assumed to be covered at night and on weekends. If the duration of the releases were longer, the radon emissions from puff releases would be somewhat lower, but this would be offset by higher steady releases. Based on these assumptions, the average release rate of Rn-222 during excavation of the K-65 residues and other high-activity residues (waste groups 1 and 2) is estimated to be about 3.7×10^7 pCi/s; this rate is used to assess the potential doses and risks from Rn-222 releases in this TM.

In summary, steady Rn-222 releases from the wastes in the IWCS are based on the Rn-222 fluxes provided in USACE (2012) and an exposed area of 100 m^2 (120 yd^2). Puff releases of Rn-222 gas are

based on the amount of radon estimated to be present in the interstitial spaces of the wastes in the IWCS using a radon emanation coefficient of 0.25 (USACE 2012). All of this gas is assumed to be released as the wastes are exhumed. The estimated radiation doses and cancer risks from exposures to deposited radioactive particulates resulting from Rn-222 releases (i.e., short-lived radioactive progeny) are not quantitatively assessed in this TM because these estimates would be much lower than those associated with direct inhalation of those radionuclides (as indicated by the working level at the exposure point). Similarly, although deposited radioactive and chemical contaminants could potentially impact nearby surface waters and possibly enter the food chain (e.g., via foliar deposition), those secondary pathways are not quantitatively assessed in this TM because the very low deposition estimates translate to insignificant contributions to potential health effects compared with other pathways.

3.3.3 Surface Soil

Contaminant concentrations in surface soil are estimated by modeling the deposition of airborne particulates using AERMOD, extending from the estimates described in Section 3.2. For the deposition modeling, the AERMOD system uses the fine particle fraction and mass median diameter; to estimate PM_{10} deposition for this analysis, a fine particle fraction of 10% was used (Countess Environmental 2006) and a mass median diameter of 4.6 µm was assumed based on values identified for various hazardous air pollutants (Wesely et al. 2002). To estimate $PM_{2.5}$ deposition as a further supporting evaluation, values of 100% and 0.5 µm were used for these two input parameters, respectively.

This pathway is relevant to both the hypothetical onsite and offsite receptors, with soil concentrations decreasing with distance from the IWCS. From the deposition modeling results, it is estimated that about 20 to 30% of the PM_{10} mass is deposited up to 10 km (6.2 mi) from a source. In contrast, $PM_{2.5}$ acts as a gas due to its small particle size and thus only a small fraction (about 4 to 5%) is predicted to deposit up to this distance. Because the receptors evaluated in this TM are not located beyond 10 km (6 mi) from the IWCS, the estimated deposition of airborne particulates onto surface soil focuses on PM_{10}, because the contribution from $PM_{2.5}$ to overall estimates would be negligible.

The estimated particulate deposition at each receptor location (in $\mu g/m^2$) is assumed to be uniformly distributed in the top 1 cm (0.4 in.) to estimate a surface soil concentration in $\mu g/m^3$. Using an estimated density of 1.8 g/cm^3, this particulate concentration in surface soil is then multiplied by the source concentrations of radionuclides and chemicals given in Tables 2.2 and 2.3 (volume-weighted for waste groups 2 and 3) to estimate the deposited concentrations of contaminants in µg/g at each receptor location (see the tables in Section 3.4.3 for an illustration of these steps). Those contaminant concentrations are then used to calculate exposures via incidental ingestion and external gamma irradiation.

3.4 ESTIMATION OF CONTAMINANT INTAKES AND DOSES

Contaminant intakes or exposure levels and doses are estimated from concentrations at the exposure points evaluated in this assessment (as described in Section 3.3) combined with scenario-specific assumptions and intake parameters. The scenario-specific assumptions include factors such as the age and weight of a potential receptor and the frequency and duration of exposure to contaminated media; intake parameters are specific to the route of exposure, e.g., inhalation or incidental ingestion rates. The assumptions and intake parameters for the exposure scenarios evaluated in this TM are described in Section 3.4.1, and approaches for calculating contaminant intakes at the potential exposure points are described in the subsequent subsections.

Exposure levels, intakes, and doses have been estimated for individual routes of exposure using illustrative exposure point concentrations in accordance with standard risk assessment approaches

(including as presented in EPA 1989, 2009a, 2009b, 2009c, 2009d, 2011a, 2011b). Exposures to radioactive and chemical contaminants can be expressed in terms of intake (dose) and exposure level, respectively. For radionuclides, the intake is represented by the amount of activity (pCi) taken into the body by inhalation or incidental ingestion. For external gamma irradiation (whereby the body is exposed to radiation external to it), intake refers to the length of time that an individual is exposed to a specific concentration of a radionuclide. For contamination on the ground, it is generally assumed to be at a distance of about 1 m (3 ft) to represent the distance above the ground that the major organs are located in a standing adult. The units for intake in this case are the product of concentration (pCi/g) and time (yr).

Consistent with published information on the toxicity of external gamma radiation, this intake is represented in units of pCi-yr/g in this TM. When measured or calculated external gamma exposure rates are available (such as from a temporary storage mound of excavated residues or from skyshine radiation), the intake is simply the product of the exposure rate and the length of time in the radiation field, and it is given as the radiation dose (in mrem). This is the standard approach for calculating the dose (or "intake") of external gamma radiation from radionuclides in soil. For chemical contaminants, the exposure level (concentration in air) is used directly to assess inhalation effects; for incidental ingestion, the intake is the amount of contaminant taken into the body per unit body weight per unit time, expressed as mg/kg-d.

3.4.1 Scenario-Specific Assumptions and Intake Parameters

The assumptions and intake parameters used to estimate radiological and chemical exposures for the hypothetical receptors evaluated in this TM are summarized in Table 3.2 and discussed in Sections 3.4.1.1 through 3.4.1.4. These assumptions are taken from EPA guidance (EPA 1997, 2004a, 2008a, 2009a) and recent information for similar projects. Note that EPA recently released an updated exposure factors handbook, after these exposure assumptions were developed and this TM was prepared. The various input values used for the illustrative evaluations in this TM are the same as or similar to those reflected in the updated handbook (EPA 2011a, 2011b). The exposure factors used in the actual, representative risk assessment to be conducted for the IWCS FS (after project-specific planning information becomes available to define and evaluate the alternatives) will reflect extant values.

3.4.1.1 Exposure Time, Frequency, and Duration

These three parameters – exposure time, exposure frequency, and exposure duration – together define the total extent of exposure at a given exposure point. The exposure time is the number of hours per day (or hours per exposure event) that a hypothetical receptor is assumed to be present at the specific exposure point; the exposure frequency is the number of days per year (or events per year) that exposure is assumed to occur; and the exposure duration is the total number of years over which the exposure occurs. The exposure factors assumed for the illustrative receptors evaluated in this TM are as listed in Table 3.2. Per the focused scope of this TM, the longest exposure duration (assumed for three hypothetical adults) is 10 years. The illustrative estimates in this TM could be scaled as indicated to consider longer durations.

The remedial action worker reflects the second of the two cases evaluated for the IWCS, i.e., waste excavation. This hypothetical worker is assumed to be an average distance of 1 m (3 ft) from the IWCS source area for 8 hours a day, 5 days a week, over the excavation season (April through November, 34 weeks), totaling 170 work days each year. Based on preliminary conceptual assumptions (absent project-specific planning information), the overall duration of remedial action at the IWCS is assumed to be 5 years. The duration of remediation activities for each waste group depends on the processing rate, which reflects the associated level of emission control and worker protection measures, which in turn depend on the contaminant levels in the given waste group. This hypothetical cleanup worker is assumed

to move across various locations within 1 m (3 ft) of the excavation area, so an array of 36 receptor locations (10 degrees apart) is evaluated to support the example exposure and risk calculations in this TM.

TABLE 3.2 Exposure Scenario Assumptions and Intake Parameters[a]

Parameter	Term	Unit	Receptors					
			Onsite			*Offsite*		
			Remedial Action Worker	Maintenance Worker	Trespasser	Outdoor Worker	Resident	
							Adult	Child
Average body weight	BW	kg	70	70	60	70	70	15
Inhalation								
Inhalation rate *(air)*	IR_a	m^3/hr	1.6	1.6	1.5	1.6	1.0	1.0
Exposure time *(to airborne releases, only during work hrs)*	ET	hr/d	8	8	2	8	8	8
Outdoor air			*8*	*8*	*2*	*8*	*2*	*2*
Indoor air							*6*	*6*
Exposure frequency	EF	d/yr	170	170	10	170	170	170
			1 without respirator	*10% at 1 m 90% at 50 m*	*10% at 1 m 90% at 100 m*	*170*		
Exposure duration	ED	yr	5	10	5	10	10	5
Incidental ingestion								
Ingestion rate *(soil/dust)*	IR_s	mg/d	500	100	100	100	50	100
Exposure frequency	EF	d/yr	170	170	10	170	350	350
Exposure duration	ED	yr	5	10	5	10	10	5

[a] The exposure scenario assumptions are described in the text. Shading indicates the entry is not applicable. (To support additional analyses beyond the preliminary examples quantified in this TM, assumptions for dermal absorption are described in Section 3.4.2.4.) The excavation season is assumed be 8 months, from April through November (34 weeks, 170 work days). The same work period (8 hours a day, 5 days a week, 34 weeks a year) is used for the onsite maintenance worker, offsite worker, and offsite resident scenarios to assess inhalation exposure to airborne contaminants released during waste excavation. For these hypothetical receptors, inhalation would only occur when the wastes are being excavated, per exposures to contaminants in the passing plume. For the fraction of airborne contaminants estimated to be deposited on soil, the overall exposure duration is used, as scaled to account for the contribution of each waste group based on the excavation period. A further adjustment is applied for the external gamma calculation to align with the dose conversion factor in units of per year, which is based on 8,760 total hours. Note that for incidental ingestion, the units for ET and ED for the remedial action worker are identified as d/yr and yr respectively, for general consistency with the other receptors; in fact for this hypothetical receptor, the respective units are actually days per overall excavation period and overall excavation period for the given waste group; see Section 3.4.1.3 for a discussion of the relatively high ingestion rate assumed for this hypothetical remedial action worker. The longest exposure duration (assumed for adults) is 10 years, per the focused time frame addressed in this TM.

Local meteorology data covering four years of excavation seasons are used with AERMOD to estimate monthly airborne PM concentrations at each of these 36 locations. The location at which the maximum monthly airborne PM concentration is predicted (of the 32 months) is south or south-southwest of the IWCS. (Note that the prevailing wind direction at NFSS is from the west-southwest, see USACE [2011d]; however, although the prevailing wind direction would indicate expected locations for concentrations averaged over a longer interval [e.g., annually], it does not necessarily determine the location of the maximum monthly concentrations.) For the exposure calculations, the concentration

averaged over the monthly maximum concentrations at each of the 36 locations evaluated for this receptor was conservatively used to represent the exposure point concentration.

The remedial action worker is the only receptor assumed to wear respiratory protection. For purposes of this illustrative analysis it is assumed that this respiratory protection is lost (equipment fails or is not worn) for one day during the excavation of each waste group. For the K-65 residues, this day is assumed to be while outside the containment structure, 1 m (3 ft) from the edge of the waste source. Thus, inhalation and incidental exposures are assumed to occur for one shift (8-hour day) during each of these periods. This frequency could be increased to illustrate potential exposures (and risks) that could be incurred if personal protective equipment were not worn, to help guide planning for worker protection measures (e.g., see Appendix D, Section D.3). In addition, this scenario can be taken to represent other possible adult receptors who might be exposed to uncovered wastes without protection for 8 hours.

The hypothetical maintenance worker is assumed to be responsible for routine activities at NFSS, such as mowing the grass on the IWCS cover (e.g., in areas not actively being remediated) and repairing cracks. (The doses and risks from external gamma radiation and Rn-222 progeny estimated for various cap breach events are presented in Chapter 5.) This individual is assumed to spend 8 hours a day at NFSS, 250 days a year for 10 years. It is assumed for this TM that exposures to contaminants from the IWCS could occur 170 days of each year (the excavation season), because beyond that period, weather conditions are assumed to limit exposures to surface soil. On average, 10% of this time (17 days) is assumed to be spent 1 m (3 ft) from the edge of the IWCS source area. The rest of the time (153 days) is assumed to be spent 50 m (160 ft) from the area of exposed wastes (i.e., uncovered for excavation).

As described for the remedial action worker, the same array of 36 receptor locations (10 degrees apart) 1 m (3 ft) from the edge of the excavation area is considered for 10% of the maintenance worker's exposure, and a parallel array of 36 locations (also 10 degrees apart) at a distance 50 m (160 ft) from the excavation is also evaluated to address the exposures for 90% of the time onsite. At a distance of 50 m (160 ft) from the edge of the square contaminated area, the location of the maximum monthly concentration for this receptor is southeast of the IWCS. This hypothetical onsite maintenance worker is assumed to wear no respiratory protection.

For the hypothetical trespasser, 10% of the onsite time is assumed to be spent at the IWCS an average distance of 1 m (3 ft) from the exposed wastes, and the rest of the time is assumed to be spent an average distance of 100 m (330 ft) from the exposed source area. The same approach described for the maintenance worker, which involves evaluating 72 locations (half ringing the excavation area close to that source, and the other half farther away) is also applied to assess potential exposures for the hypothetical trespasser. (Note that the estimated maximum monthly airborne concentration at a distance of 100 m [330 ft] for this receptor is also southeast of the IWCS.) The overall exposure assumed for the trespasser is 10 visits a year for 2 hours a visit over a period of 5 years.

In fact, site controls such as fences and the presence of onsite workers render this scenario highly unlikely (implausible), particularly if active cleanup were being conducted at the IWCS. Open lands nearby would be an obvious alternative for this illustrative adolescent (instead of NFSS). Nevertheless, these assumptions can be used to help indicate potential future exposures under imaginary conditions if the wastes were assumed to remain in the IWCS, institutional controls were lost, the cover failed, and wastes were exposed – to help guide the development and evaluation of remedial action alternatives in the FS.

The offsite outdoor worker is assumed to be an adult working at an adjacent landfill 600 m (2,000 ft) east-southeast of the IWCS. This individual is assumed to work outdoors 8 hours a day for 10 years. For the exposure frequency, the seasonal adjustment used for the onsite maintenance worker is also assumed for

this similar worker offsite, so the effective frequency of potential exposures to contaminants from the IWCS is 170 days per year. Like the onsite maintenance worker, this offsite landfill worker is assumed to wear no respiratory protection equipment.

The exposure duration of 10 years assumed for the offsite resident adult is consistent with the time period addressed by this TM (see Section 1.2) and generally reflects the central tendency value. For the hypothetical child resident who is assumed to spend some time outdoors, the 5-year duration represents ages 1 to 6. These values are consistent with common residential assumptions (EPA 1997, 2004a, 2008a, 2009a, 2011a, 2011b).

3.4.1.2 Inhalation Rates

An inhalation rate of 1.6 m^3/hr is assumed for worker exposures (from information in EPA [1997, 2009a]), and a value of 1.5 m^3/hr is assumed for the adolescent trespasser (from information in EPA [2008a]). The latter value is supported by data that suggest inhalation rates for an adolescent tend to be similar to those of an adult at the same activity level. For the offsite hypothetical residents, 1.0 m^3/hr is assumed for both the adult and child. This estimate is based on light activity for the adult and moderate activity for the child (EPA 1997, 2008a, 2009a). (Note these inhalation rates are supported by estimates in the recent update of the exposure factors handbook [EPA 2011a, 2011b], with alternate but similar assumptions regarding time spent at different activity levels.)

In evaluating the inhalation of airborne contaminants released during waste excavation, those releases and associated dispersion would only occur during the actual excavation activities. That is, IWCS contaminants would only be inhaled during the 8 hours of the work day, 5 days per work week, over the indicated number of days from April through November conceptually assumed for waste excavation in this illustrative analysis.

3.4.1.3 Incidental Ingestion Rates

Individuals can inadvertently ingest soil by transferring it from hands and fingers to food or cigarettes, or simply by wiping the mouth. The values recommended by EPA as reasonable estimates for soil ingestion are 50 mg/d for adults and 100 mg/d for children (EPA 1997, 2008a, 2009a). These rates are recommended for a resident, assuming ingestion of outdoor soil and indoor dust throughout a day, as well as incidental soil on foodstuffs, so they are not directly applicable to all receptors and exposure situations considered in this assessment.

A common assumption for outdoor workers is to double the rate assumed for a residential adult rate, to 100 mg/d (EPA 1997, 2011c). The primary mechanism of soil ingestion is assumed to be inadvertent ingestion of dust and soil on the hands and mouth. The remedial action worker is assumed to wear respiratory protection equipment that would preclude this activity. However, for purposes of this evaluation, it is assumed that for one shift for each waste group excavation, a lack or loss of this equipment also provides the opportunity for incidental ingestion. As indicated in Table 3.2, the exposure frequency is one day per year for waste groups 1 and 2 (for which the excavation season occurs within one year), while for waste group 3 it represents one day per the overall excavation period for that waste, i.e., per 1.6 years. Considering that the overall exposure duration for the remedial action worker is 5 years, and that incidental ingestion might occur more often than 1 day per waste group excavation (e.g., if the worker did not use respiratory protection equipment more often than 1 day), the incidental soil ingestion rate for this hypothetical remedial action worker is conservatively assumed to be 500 mg per excavation of each waste group.

The other hypothetical receptors are assumed to have no respiratory protection so they would incidentally ingest contaminated soil during each onsite event (day). For this illustrative evaluation, the trespasser and outdoor workers (onsite maintenance worker and offsite landfill worker) are assumed to ingest 100 mg during each of their multiple exposure events. For the hypothetical offsite residents, the values of 50 mg/d for an adult and 100 mg/d for a child are used to estimate combined exposure to soil and dust, based on the values in use when these estimates were developed (EPA 1997), as also supported by the recent update of the exposure factors handbook (EPA 2011a, 2011b). Note that the value for the child represents a central estimate for children 6 months to 16 years old (EPA 2008a).

3.4.1.4 Body Weight and Averaging Time

The value for body weight represents the average over the exposure period for the given hypothetical receptor. The values used in this TM reflect standard defaults in effect when these calculations were developed. That is, a value of 70 kg is assumed as the average adult body weight for the workers and the adult resident. A body weight of 60 kg is assumed for the adolescent trespasser (to represent a gender-weighted average for ages 14 to 18), and a body weight of 15 kg is assumed for the offsite child resident (EPA 1997); these values are generally consistent with information in the child-specific exposure factors handbook (13.8 kg for children 2 to 3 years old, and 18.6 kg for children 3 to 6 years old) (EPA 2008a). Note that the recent update of the exposure factors handbook now indicates a default body weight of 80 kg rather than 70 kg for a generic adult (EPA 2011a, 2011b). Thus, the adult body weight value used in this TM is slightly lower than the new value. The effect of this difference on the illustrative results presented in this TM is insignificant, i.e., it does not alter the overall findings.

Different averaging times are used to evaluate the potential for noncarcinogenic effects and to estimate cancer risk. To assess noncarcinogenic effects, the exposure duration is used as the averaging time (because daily exposures are compared to a “safe” daily level). To assess cancer risk, the total amount of intake is averaged over a lifetime of 70 years (25,550 days).

3.4.2 Equations for Estimating Intakes and Doses

Example exposures are estimated in this TM for radioactive and chemical contaminants from the IWCS, with the main calculations addressing airborne releases during hypothetical waste excavation. The exposure routes assessed in this TM are external gamma irradiation, incidental ingestion, and inhalation. Information is also provided at the end of this section to support the evaluation of dermal absorption if that exposure evaluation is considered useful for the upcoming analyses in the FS.

3.4.2.1 External Gamma Irradiation

Exposures via external gamma irradiation are estimated for radionuclides in the residues and other wastes in the IWCS, as well as those in surface soil impacted by deposition of radioactive particulates from airborne releases. These exposures are calculated by multiplying the length of time an individual is assumed to be exposed to a given radionuclide using the following equation.

$$I_{ei} = R_{si} \times ET \times EF \times ED \times A_f \times D_f \times CF_1 \qquad \text{(Eq. 3.1)}$$

where:

I_{ei} = external gamma irradiation from radionuclide i (pCi-yr/g),
R_{si} = concentration of radionuclide i in soil or residue (pCi/g),
ET = exposure time (hr/d or hr/event),
EF = exposure frequency (d/yr or events/yr),

ED = exposure duration (yr),
A_f = area factor (dimensionless),
D_f = depth factor (dimensionless), and
CF_1= conversion factor (1.14×10^{-4} yr/hr).

The area and depth factors are fractional values used to estimate the external gamma irradiation rate for a specific source area of finite size from that for a source of infinite extent. For the scenarios evaluated in this TM, these values are conservatively assumed to be 1.

When a measured or calculated gamma exposure rate is available for a specific source, the dose can be calculated as follows:

$$I_g = E \times ET \times EF \times ED \times CF_2 \qquad \text{(Eq. 3.2)}$$

where:

I_g = dose from external gamma irradiation (mrem),
E = measured or calculated exposure rate (μR/hr), and
CF_2= conversion factor (0.001 mrem/μR).

The conversion factor reflects a commonly used value to convert exposure (in mR) to dose (in mrem), i.e., unity, multiplied by 0.001 to convert μR to mR.

3.4.2.2 Incidental Ingestion

The intakes from incidental ingestion of radionuclides from the IWCS wastes and soil on which dispersed waste particulates are assumed to be dispersed are calculated with the following equation. (Note that the incidental ingestion rate incorporates the exposure time.)

$$I_{ii} = R_{si} \times IR_s \times EF \times ED \times CF_3 \qquad \text{(Eq. 3.3)}$$

where:

I_{ii} = incidental ingestion intake of radionuclide i (pCi),
R_{si} = concentration of radionuclide i in impacted media (pCi/g),
IR_s = incidental ingestion rate (mg/d or mg/event), and
CF_3= conversion factor (10^{-3} g/mg).

Intakes of chemicals via incidental ingestion are calculated in a similar manner, with the addition of a denominator in the following equation to account for how the chemical toxicity values are derived.

$$I_{si} = \frac{C_{si} \times IR_s \times EF \times ED \times CF_4}{BW \times AT} \qquad \text{(Eq. 3.4)}$$

where:

I_{si} = intake of soil contaminant i (mg/kg-d),
C_{si} = concentration of contaminant i in soil or waste (mg/kg),
CF_4= conversion factor (10^{-6} kg/mg),
BW= body weight (kg), and
AT = averaging time (d).

For the indoor exposures (for the hypothetical offsite resident and child), incidental ingestion is assumed to account for exposures to both soil and dust, in accordance with the standard exposure factors used (e.g., see EPA [2008a]).

3.4.2.3 Inhalation

The intakes from inhalation of radionuclide particulates in air were calculated using the following equation.

$$I_{ari} = R_{ai} \times IR_a \times ET \times EF \times ED \qquad \text{(Eq. 3.5)}$$

where:

I_{ari} = inhalation intake of airborne radionuclide i (pCi),
R_{ai} = air concentration of radionuclide i as respirable particulates (pCi/m^3), and
IR_a = air inhalation rate (m^3/hr).

For chemicals, exposures to airborne contaminants are estimated as follows (see EPA [2009c, 2009d]):

$$EC_{ai} = \frac{C_{ai} \times ET \times EF \times ED}{AT} \qquad \text{(Eq. 3.6)}$$

where:

EC_{ai} = exposure concentration for airborne contaminant i (µg/m^3),
C_{ai} = concentration of contaminant i in air (µg/m^3).

For exposures that total days to weeks (e.g., vs. years), the following is assumed: $EC_{ai} = C_{ai}$.

In this TM, Equation 3.6 is used for all inhalation exposures for general consistency with the approach used to assess inhalation of radionuclides, to facilitate comparisons of results across all receptors. This approach also better supports scaling to longer durations, to accommodate alternate assumptions for selected receptors (e.g., for further days without respiratory protection for the remedial action worker).

3.4.2.4 Dermal Absorption

Dermal exposures are not quantified in this TM because of limitations in characterization data for PCBs, and because this pathway is a small contributor to the risks from inhalation, incidental ingestion, and external gamma irradiation for the other contaminants of potential interest. (Of the IWCS chemicals for which illustrative calculations are developed, only arsenic and PCBs would be relevant to this assessment.)

Nevertheless, the approach applied for this calculation is included here, in the event upcoming analyses (e.g., within the FS) choose to quantify this contribution, e.g., if further characterization were conducted that establishes representative estimates for PCBs. The intakes from dermal contact with contaminated surface soil can be calculated as follows, using information from EPA (2004b):

$$AD_{di} = \frac{C_{si} \times SA \times AF \times ABS_i \times EF \times ED \times CF_4}{BW \times AT} \qquad \text{(Eq. 3.7)}$$

where:

AD_{di} = absorbed dose of contaminant i from dermal exposure (mg/kg-d),
C_{si} = soil concentration of contaminant i (mg/kg),
SA = skin surface area (cm^2/d or cm^2/event),
AF = soil-to-skin adherence factor (mg/cm^2), and
ABS_i = fraction of contaminant i absorbed.

Values specific to the dermal calculation can be derived from available guidance considering site-specific factors such as climate, type of clothing that would be worn, and activities during the exposure event. The values for the other variables are the same as those used to estimate intakes from inhalation and ingestion described above. Based on SAs commonly assumed to date, a value of 5,700 cm^2/d could be considered for the maintenance worker and adult resident, and 2,800 cm^2/d could be considered for the child. Data are also available from which to select activity-specific values for soil loading on the skin (i.e., soil adherence to skin), typically referred to as the soil adherence factor. Using information in EPA (2004b), a factor of 0.02 mg/cm^2 could be considered for the hypothetical workers, a factor of 0.07 mg/cm^2 could be considered for the adult resident, and a value of 0.2 mg/cm^2 could be considered for the onsite adolescent trespasser and offsite child. Per the recent update of the exposure factors handbook (EPA 2011a, 2011b), these example values would be revisited to select appropriate estimates for any future quantitative evaluation of dermal exposures.

The EPA dermal guidance recommends quantitatively evaluating dermal intake only for those chemicals for which dermal absorption fractions are available (EPA 2004b). The absorption fraction recommended for PCBs is 0.14. For metals, EPA notes that speciation is critical to dermal absorption and that too little data are available to develop absorption fractions for metals other than arsenic and cadmium. The absorption fraction [percent] recommended for arsenic in soil is 0.03 (that for cadmium is 0.001).

Dermal exposures are estimated using the same general approach as described for ingestion exposures, except for that pathway the health effect is determined on the basis of an administered dose – which is the mass of a contaminant in contact with the exchange boundary (e.g., the gastrointestinal tract) but does not reflect the amount that penetrates that boundary. For dermal exposures, the health effect is calculated from the absorbed dose – which is the amount of a contaminant that penetrates the exchange boundary (in this case the skin). To address this difference, the toxicity values for dermal exposures are derived from oral reference doses and slope factors (see Chapter 4). For these derivations, the dermal slope factor is calculated by dividing the oral slope factor by the oral absorption fraction, and the dermal reference dose is calculated by multiplying the oral reference dose by the oral absorption fraction. These adjustments are recommended if oral absorption is significantly less than 100%, with "significant" being defined as less than 50% (EPA 2004b).

Dermal exposures are not evaluated in this report because the focus is on illustrating the risk evaluation process for key pathways to help guide planning for the FS, and the health effects estimated for this pathway would be much lower than those for other pathways and contaminants (i.e., these estimates would not impact the overall results). Nevertheless, information is presented in this report to support a quantitative analysis in the future if such an evaluation is desired. For the toxicity value, the oral reference doses for PCBs and arsenic would not be adjusted because oral absorption from the gastrointestinal tract for both is assumed to be higher than 50%. Thus, the reference dose that would be used to assess dermal exposures to PCBs at this time is 2.0×10^{-5} mg/kg-d, and that used to assess dermal exposures to arsenic is 3.0×10^{-4} mg/kg-d, as described in Chapter 4 of this TM.

The following information is provided to support the uncertainty discussion for this pathway. Exposure time is not included as a variable in the dermal equation, and EPA indicates that an assumption underlying the values presented for absorption fraction is that the time per event is 24 hours. The Agency also notes that the absorption fraction per event should not generally be adjusted; rather, the exposure frequency and exposure duration should be adjusted to account for site-specific conditions. Activity-specific adherence factors are developed in conjunction with assumptions about the exposed body parts and the two cannot be separated. Recognizing that the adherence factor will not be the same across the body, EPA has developed adherence factors that are weighted by body part.

Regarding the relationship between absorption fraction and soil loading, EPA notes that an underlying assumption of the standard dermal equation is that absorption fraction is independent of the soil adherence factor. The EPA also indicates that experimental evidence suggests this may not be the case, particularly when the adherence factor is less than the quantity necessary to completely cover the skin in a thin layer (i.e., the monolayer concept). The Agency further states that the currently recommended adherence factors for adults and children are at or less than those required to establish a monolayer and suggests the actual absorption fraction could potentially be higher than the values determined experimentally and indicated in the guidance (EPA 2004b).

3.4.3 Multiple Exposure Pathways

The individual dose and intake estimates developed using the equations in Section 3.4.2 can be combined to assess the collective exposures for the hypothetical receptors by multiple routes. Estimated radiological intakes estimated for the various scenarios are provided in Appendix A; estimated exposure levels and intakes for the chemical contaminants are given in Appendix B. The risks and hazard indexes associated with both radiological and chemical exposures are presented in Chapter 5 and summarized in Chapter 6. Individual components of these calculations are summarized below.

Preliminary conceptual assumptions used for these illustrative evaluations to help guide planning for the FS are highlighted in Table 3.3. It is useful to emphasize that because the estimated doses and risks in this TM are based on these example assumptions rather than project-specific information (because that information is not yet available), the illustrative results are not indicative for other situations for which these assumptions do not apply.

As conceptual engineering information is developed to support the identification and evaluation of alternatives for the FS, it is expected that the example assumptions and illustrative estimates in this TM would be revised accordingly such that the analyses in the FS are representative per project-specific information. The evaluations in this TM are simply intended to offer illustrative indicators of potential exposures and risks to help frame the development and evaluation of alternatives in the FS. A key purpose of this TM is to identify the primary contaminants and potential exposure pathways to help guide the determination of appropriate emission and exposure controls to be reflected in the alternatives outlined in the FS. The estimates of airborne and deposited waste particulates resulting from particulate releases during waste excavation as predicted by AERMOD, based on the preliminary conceptual assumptions for waste excavation in this TM, are presented in Table 3.4.

TABLE 3.3 Preliminary Conceptual Assumptions for Excavating Wastes from the IWCS[a]

Calculation Component	*Waste Group 1*: K-65 Residues	*Waste Group 2*: Other High-Activity Residues (L and F) and Tower Soils	*Waste Group 3*: R-10 Pile and Other Contaminated Soils
Waste volume: m^3 *(yd^3)*	3,000 *(4,000)*	11,000 *(15,000)*	84,000 *(110,000)*
Excavation area: m^2 *(yd^2)*	500 *(600)*	1,000 *(1,200)*	2,000 *(2,400)*
Daily processing rate: m^3 *(yd^3)*	20 *(26)*	100 *(130)*	300 *(400)*
Excavation period: d *(season)*	170 *(1)*	112 *(0.66)*	275 *(1.6)*
Particulate emission rate: $g/m^2/hr$	0.35	0.35	0.35
Emission controls			
Particulates: control efficiency %	99 *(engineered system)*	75 *(water sprays)*	75 *(water sprays)*
scalar for no control	100	4	4
Rn-222 gas: control efficiency %	90 *(engineered system)*	90 *(engineered system)*	1 *(no credit taken for water sprays)*
scalar for no control	10	10	1
Distance from excavation: m *(ft)*			
Remedial action worker	1 *(3)*	1 *(3)*	1 *(3)*
Maintenance worker 10% of time	1 *(3)*	1 *(3)*	1 *(3)*
90% of time	50 *(160)*	50 *(160)*	50 *(160)*
Trespasser: 10% of time	1 *(3)*	1 *(3)*	1 *(3)*
90% of time	100 *(33)*	100 *(33)*	100 *(33)*
Respiratory protection	Remedial action worker, except 8 hr	Remedial action worker, except 8 hr	Remedial action worker, except 8 hr
Time onsite/excavation: hr *(hr/d, d)*			
Remedial action worker	1,360 *(8, 170)*	896 *(8, 112)*	2,200 *(8, 275)*
Maintenance worker	1,360 *(8, 170)*	896 *(8, 112)*	2,200 *(8, 275)*
Trespasser	20 *(2, 10)*	13 *(2, 6.6)*	32 *(2, 16)*

[a] These assumptions simply represent early conceptual estimates, because planning information for waste excavation is not yet available for the FS. Values are generally rounded to two significant figures. For the excavation period, the waste-specific period indicated in parentheses is the fraction of the estimated 170-day excavation season. The distances assumed from the excavation areas are shown for the three hypothetical onsite receptors; for the offsite receptors, the specific distances to those example locations are used. The listed particulate emission rate is uncontrolled, based on a generic average 0.265 tons/acre/month. The indicated control efficiencies are applied to this rate to estimate controlled emissions assumed during waste excavation. No credit is taken for the Rn-222 control by water sprays; no engineered system is assumed for waste group 3 (because of the low Ra-226/Rn-222 content). The "scalar for no control" can be used to convert the results in the body of this TM (which reflect the conceptual assumptions for standard controls during excavation indicated above) to the imaginary case with no engineering controls (see Appendix D). Only the remedial action worker would wear respiratory protection, and that protection is assumed to be lost 1 day during each of the excavations for the three waste groups. This table also highlights selected information for the hypothetical onsite receptors, who would incur the highest exposures during excavation. The maintenance worker is assumed to spend 10% of the time 1 m (3 ft) from the excavation area and 90% of the time 50 m (160 ft) away. The trespasser is assumed to spend 10% of the time just as close, and 90% of the time twice as far, at 100 m (330 ft) from the excavation. See Table 3.2 and the accompanying text for other exposure assumptions. The number of onsite hours for these three receptors per waste group is also shown here, because this number is used in the external gamma dose calculation (for deposited airborne radionuclides and also for direct exposures to the wastes as they are excavated, assuming no shielding is used).

TABLE 3.4 AERMOD Estimates of Airborne and Deposited Particulates Based on Preliminary Conceptual Excavation Assumptions for the IWCS Wastes[a]

Hypothetical Receptor	Distance from Excavation (m)	Estimated Concentration of Particulate Matter (PM) from Each Waste Group for Each Receptor								
Airborne PM		**Maximum Monthly Concentration** *(µg PM / m³ air)*			**Average of Maximum Monthly Concentrations for Locations per Receptor** *(µg PM / m³ air)*					
Onsite: dispersed		*Group 1*	*Group 2*	*Group 3*	*Group 1*	*Group 2*	*Group 3*			
Remedial action worker	1	1.3	35	41	1.0	26	29			
Maintenance worker	1 *(10%)*	1.3	35	41	1.0	26	29			
	50 *(90%)*	0.043	1.8	2.8	0.029	1.2	2.0			
Trespasser	1 *(10%)*	1.3	35	41	1.0	26	29			
	100 *(90%)*	0.017	0.77	1.3	0.0095	0.43	0.76			
Offsite: dispersed										
Outdoor worker	560	0.00032	0.016	0.032						
Adult resident	660	0.00030	0.015	0.030						
Child resident	660	0.00030	0.015	0.030						
Deposited PM		**Cumulative Deposition on Surface Soil** *(µg PM / m² soil)*			**Estimated Mass-Based Concentration** *(µg PM / g soil)*			**Mass-Based Concentration per Waste Excavation Period** *(µg PM / g soil)*		
Onsite: dispersed		*Group 1*	*Group 2*	*Group 3*	*Group 1*	*Group 2*	*Group 3*	*Group 1*	*Group 2*	*Group 3*
Remedial action worker	1	110,000	3,500,000	4,500,000	5.9	130	250	1.5	32	100
Maintenance worker	1 *(10%)*	110,000	3,500,000	4,500,000	5.9	130	250	1.5	32	100
	50 *(90%)*	5,100	220,000	360,000	0.28	12	20	0.070	2.0	100
Trespasser	1 *(10%)*	110,000	3,500,000	4,500,000	5.9	130	250	1.5	32	250
	100 *(90%)*	1,500	67,000	120,000	0.083	3.7	6.6	0.021	0.62	2.7
Offsite: dispersed										
Outdoor worker	560	74	3,700	7,400	0.0041	0.20	0.41	0.0010	0.033	0.17
Adult resident	660	46	2,300	4,600	0.0026	0.13	0.26	0.0064	0.021	0.10
Child resident	660	46	2,300	4,600	0.0026	0.13	0.26	0.00064	0.021	0.10

[a] These PM estimates from AERMOD represent PM_{10} and are based on generic emission estimates that reflect preliminary conceptual assumptions for IWCS waste excavation activities; these particulate estimates are rounded to two significant figures.

For airborne PM, the average of the maximum monthly concentrations for the onsite receptors represents the average of the maximum monthly concentrations across each of the 36 locations assessed at each distance from the excavation area assumed for the remedial action worker (36 total locations) and the maintenance worker and trespasser (72 total locations, 36 at each distance for each receptor). For the offsite receptors, the estimates reflect the maximum monthly values at these locations (one per receptor) evaluated as the representative distance from the excavation.

For deposited PM, the cumulative surface deposition represents the amount deposited in a square meter of soil over the combined 32 months evaluated by AERMOD (four excavation seasons). The mass-based concentration assumes this cumulative deposition is uniformly mixed over a depth of 1 cm (0.4 in.) in soil with an estimated density of 1.8 g/cm³. The mass-based concentration per excavation period is the input used in calculating exposures; it represents the cumulative mass-based concentration divided by the fraction of the overall (32-month) period during which the given waste group is assumed to be excavated (e.g., for waste group 1, the cumulative deposition is divided by 4 because the excavation period for the K-65 residues is assumed to be one excavation season, or 8 months).

The basic AERMOD outputs are as follows:

- Airborne particulates: The maximum monthly concentration of the 32 months assessed (April through November, for 4 years of local meteorological data) across the 36 and 72 locations for the onsite receptors and the single location assessed for each offsite receptor.

- Deposited particulates: The cumulative amount deposited over the 32 months (based on the 8-month excavation season per year with 4 years of local meteorological data) at the same receptor locations indicated above.

As described in Section 3.4.1.1, for the inhalation calculations: Of the 32 monthly estimates of airborne PM_{10} concentrations, the maximum monthly PM_{10} concentration is identified for each receptor location. For the offsite receptors, this maximum monthly PM_{10} concentration is then used to scale to the contaminant concentrations in the wastes being excavated (volume-weighted as indicated, using data from Tables 2.2 and 2.3) to derive the exposure point concentrations.

Unlike the three hypothetical offsite receptors who are assumed to stay at their fixed locations, the three onsite receptors are assumed to move around within a limited distance of the excavation area, so for these receptors the average of the maximum monthly concentration across each of their locations was used to determine the PM_{10} concentration from which the contaminant concentrations were scaled. For example, the remedial action worker is conservatively assumed to be 1 m (3 ft) from the excavation area at all times onsite, so 36 locations spaced 10 degrees apart are evaluated for this receptor. For each of these 36 locations, the maximum monthly PM_{10} concentration of the 32 months is then estimated. This average of those maximum monthly PM_{10} concentrations across these 36 locations is then used to scale to the contaminant concentrations in the wastes being excavated. The suite of locations evaluated for the other two hypothetical onsite receptors also reflects points spaced 10 degrees apart at the two distance(s) from the excavation edge evaluated for each.

For the incidental ingestion calculations, the deposited fraction of PM_{10} for the 32-month period serves as the starting point for estimating the exposure point concentration. That cumulative PM_{10} at each receptor location is then multiplied by the fraction of those 32 months during which the given waste would be excavated. This adjustment produces the deposited PM_{10} associated with excavating that waste group. That deposited PM (as mass/surface area) is then converted to a concentration and scaled to the original waste concentrations (using the data from Tables 2.2 and 2.3) to generate the contaminant exposure point concentrations for incidental ingestion, as described in the last paragraph of Section 3.3.3.

For the remedial action worker, the overall amount of PM_{10} deposited for the given waste over its excavation period (which is the maximum for that waste) thus serves as the conservative PM_{10} estimate for this hypothetical individual's 1-day exposure, from which the contaminant concentrations were scaled (e.g., as if their respirator failed or were not used on the last excavation day for that waste group, to be conservative). Note that because the fraction of PM_{10} deposited over the receptor locations is relatively small compared to the airborne concentrations, this conservative assumption does not affect the risk estimates.

In summary, the exposure point concentration for each contaminant in each of the three waste groups is estimated by multiplying the AERMOD estimates of airborne and deposited particulate concentrations from Table 3.4 by the contaminant concentrations in the emission source (i.e., the component wastes) using the concentrations in Tables 2.2 and 2.3 volume-weighted as indicated.

The estimates of particulate and Rn-222 concentrations used to calculate exposures for each receptor are summarized in Table 3.5.

TABLE 3.5 Estimated Particulate and Rn-222 Concentrations for the Six Hypothetical Receptors[a]

Hypothetical Receptor	Hypothetical Distance from Excavation *(m)*	Airborne Particulates *(µg waste particle per m^3 air)*	Deposited Particulates		Radon-222	
			µg waste per m^2 soil	*µg waste per g soil*	**Rn-222 Gas** *(pCi/L)*	**Particulate Progeny** *(WL)*
***Waste Group 1*: K-65 Residues**						
Onsite: dispersed						
Remedial action worker	1	1.0	26,000	1.5	230	0.25
Maintenance worker	(1, as above) 50	0.029	1,300	0.070	2.5	0.0040
Trespasser	(1, as above) 100	0.0095	370	0.021	0.74	0.0016
Offsite: dispersed						
Outdoor worker	560	0.00032	18	0.0010	0.022	6.4×10^{-5}
Adult resident	660	0.00030	12	0.00064	0.020	6.0×10^{-5}
Child resident	660	0.00030	12	0.00064	0.020	6.0×10^{-5}
***Waste Group 2*: Other High-Activity Residues (L and F) and Tower Soils**						
Onsite: dispersed						
Remedial action worker	1	26	570,000	32	12	0.013
Maintenance worker	(1, as above) 50	1.2	36,000	2.0	0.13	0.00021
Trespasser	(1, as above) 100	0.43	11,000	0.62	0.039	8.5×10^{-5}
Offsite: dispersed						
Outdoor worker	560	0.016	600	0.033	0.0012	3.4×10^{-6}
Adult resident	660	0.015	380	0.021	0.0011	3.1×10^{-6}
Child resident	660	0.015	380	0.021	0.0011	3.1×10^{-6}
***Waste Group 3*: R-10 Pile and Other Contaminated Soils**						
Onsite: dispersed						
Remedial action worker	1	29	1,800,000	100	-	-
Maintenance worker	(1, as above) 50	2.0	140,000	8.0	-	-
Trespasser	(1, as above) 100	0.76	48,000	2.7	-	-
Offsite: dispersed						
Outdoor worker	560	0.032	3,000	0.17	-	-
Adult resident	660	0.030	1,900	0.10	-	-
Child resident	660	0.030	1,900	0.10	-	-

[a] The concentrations of particulates from excavated waste in air and soil are estimated as described in Sections 3.2 and 3.3, based on the airborne and deposited particulate concentrations predicted by the AERMOD model using local meteorological data and conceptual emission assumptions. Values are given to two significant figures. The airborne particulate concentrations represent PM_{10} (respirable fraction), and the estimates of contaminated particulates deposited on soil, as µg/m^2, are then converted to the concentrations of contaminants per g soil by assuming the particulates are deposited on the top 1 cm (0.4 in.) of surface soil with an estimated density of 1.8 g/cm^3. WL represents working level (see Sections 3.3.2 and 4.1).

Hypothetical exposures for the maintenance worker and trespasser are assumed to occur at two distances from the excavation area. Both are assumed to spend 10% of their time 1 m (3 ft) from the excavation, so the particulate estimates for that distance are the same as shown for the remedial action worker. Therefore, the entries for these two receptors above address the concentrations at their second distance from the excavation, 50 m (160 ft) and 100 m (330 ft), respectively. The resident scenarios consider indoor and outdoor air; the values shown here are for outdoor air; those for indoor are half the outdoor values.

The exposure point concentrations of radioactive and chemical contaminants in air and soil for the six hypothetical receptors are calculated by multiplying the particulate concentrations above by the concentrations of the radionuclides and chemicals in the respective waste groups. For Rn-222, both the gas and its decay products are addressed. Most (95%) of the Rn-222 inventory is associated with the K-65 residues (waste group 1), and 5% is associated with waste group 2. The dashes shown for waste group 3 indicates those concentrations are not quantified because they represent a very small fraction of total Rn-222 releases.

4 TOXICITY ASSESSMENT

The toxicity assessment for contaminated sites such as NFSS involves an evaluation of the significance of the contaminants and their concentrations in terms of potential harm to human health. To provide a consistent approach for this evaluation, the EPA and other scientific organizations have evaluated toxicological studies to establish a relationship between route-specific exposures to specific contaminants and the increased likelihood of cancer or the potential for inducing noncarcinogenic effects, such as heart disease, kidney damage, or neurological problems. Data from these evaluations have been used to develop standard toxicity values for estimating health effects from chronic exposures, i.e., exposures that occur over a long period of time. (In some cases, values have also been developed for subchronic exposures, e.g., for periods of two to seven years, and for acute exposures. Note that acute exposures are typically defined as up to 1 day, although some organizations assume this extends for a longer period; e.g., the Agency for Toxic Substances and Disease Registry [ATSDR] assumes acute exposures extend up to two weeks.) This section describes the toxicity values used with the exposures evaluated in this TM to estimate potential health effects.

For both radionuclides and chemical carcinogens, standard EPA toxicity values are used to assess the increased probability (above a background rate) that an individual will develop cancer over a lifetime as a result of chronic exposures. This is referred to as excess lifetime cancer risk, and it is based on population statistics. For general context, the American Cancer Society (ACS) estimates that cancer accounts for nearly 1 in every 4 deaths in the United States, and that men have a slightly less than 1 in 2 risk of developing cancer over a lifetime, while the risk for women is a little more than 1 in 3 (ACS 2011). The cancer risks estimated in this TM for hypothetical exposures to radionuclides and chemical carcinogens from the IWCS would be incremental to these background rates.

The New York State Department of Health (NYSDOH) recently conducted an investigation of newly diagnosed cancer cases in people living near NFSS and LOOW in the towns of Lewiston and Porter in Niagara County from 1991 through 2000 (NYSDOH 2008). Of particular concern was the Lewiston-Porter school campus, which is located on an undeveloped portion of the former LOOW near NFSS. This study found an elevated number of cancers in adults (men and women) and children living near NFSS and LOOW; the elevated number of childhood cancers did not continue after 2000. The study authors were not able to conclude that these elevated cancers were related to exposures associated with these two sites based on the available information and other risk factors for the affected individuals. The study concluded that "the possibility that the occurrence of the cancers was the result of chance can not be ruled out."

In this TM, cancer risks are presented separately for radiological and chemical exposures because of differences in the bases of the respective estimates. Radiological risk coefficients are generally best-estimate, average values that are largely based on human epidemiological data. For chemicals, the standard inhalation toxicity value used to estimate the probability of incurring cancer over a lifetime is the inhalation unit risk (IUR), i.e., incremental lifetime risk of cancer incidence per unit concentration in air. For oral exposures, the toxicity value generally represents the upper bound or upper 95% confidence limit of the slope of the dose-response curve, referred to as the slope factor (SF). Human data for chemicals are relatively limited, so the standard toxicity values are often derived from experiments with laboratory animals. However, compared to oral toxicity values, more inhalation values reflect information for humans (e.g., based on studies of occupational cohorts).

Although ionizing radiation is considered a known human carcinogen, only a relatively small number of chemicals have been identified by the National Toxicology Program (NTP) as known human carcinogens (NTP 2011). These include inorganic arsenic compounds, asbestos, and soluble nickel compounds (see Section 4.2). More commonly, chemical exposures are associated with noncarcinogenic effects. To

estimate the potential for these effects, EPA has established standard reference values expected to be safe for exposures over a lifetime (EPA 2011d); some values have also been identified for less-than-lifetime exposures with supporting context available in online databases. These include: (1) Cal/EPA acute reference exposure levels (RfELs) (Cal/EPA 2009a, 2011a) for exposures up to 8 hours; (2) acute and intermediate minimal risk levels (MRLs), considered safe for exposures from one day to two weeks and for more than two weeks to one year, respectively (ATSDR 2010); and (3) subchronic toxicity values considered safe for exposures of two to seven years, notably provisional values (EPA 2011e); a limited number of standard subchronic values are available in the Integrated Risk Information System (IRIS) database (EPA 2011d) but not for the IWCS chemicals evaluated in this TM.

An additional set of estimators is used in this TM to calculate radiation doses. A dual approach is applied for radionuclides – estimating both doses and cancer risks – because many radiation toxicity studies describe effects in terms of doses or dose rates delivered. Furthermore, most radiation protection standards are given in terms of radiation doses and dose rates, and organizations generally use doses to evaluate the effectiveness of their radiation protection programs. These doses can be calculated using standard dose conversion factors (DCFs).

The Interagency Steering Committee on Radiation Standards (ISCORS) notes that for external sources of low linear-energy-transfer (LET) radiation such as gamma rays and X-rays, the relationship between radiation dose and cancer risk is generally linear. This is because LET radiation tends to irradiate all organs of the body in a generally uniform manner. For such radiation, the ISCORS notes that the risk of cancer incidence (morbidity) and mortality for external exposures can be estimated using risk estimators of 8×10^{-7} cancers per mrem and 6×10^{-7} cancers per mrem, respectively (ISCORS 2003).

However, this relationship does not typically hold for internal exposures. The relationship between dose and risk for internal exposures depends on the type of radiation, the exposure route, and the organs being irradiated by the given radionuclide. Some radionuclides tend to accumulate in specific organs; for example, radium-226 and radium-228 preferentially accumulate in bone, while iodine-131 commonly used in medical diagnostics preferentially accumulates in the thyroid. Hence, for internal exposures of radionuclides, the radiation doses and cancer risk need to be calculated separately. These calculations are conducted for this TM using the appropriate factors, i.e., DCFs and cancer risk coefficients.

Basic concepts associated with the interactions of radiation and matter related to human health effects are provided in Section 4.1.1, and the DCFs and radiological cancer risk coefficients are discussed in Sections 4.1.2 and 4.1.3, respectively. Section 4.1.4 provides information on the approach used in this TM to calculate the doses from gamma radiation for a number of exposure situations that could occur at NFSS near the IWCS. The toxicity values for assessing the carcinogenic and noncarcinogenic effects of the illustrative chemical contaminants in the IWCS are described in Section 4.2.

4.1 TOXICITY VALUES FOR ASSESSING RADIOLOGICAL HEALTH EFFECTS

4.1.1 Radiation Concepts

Radiation is released when an unstable atom of an element (isotope) transforms (decays) into a more stable configuration. The radiation that is released can be in the form of particles (neutrons, alpha particles, and beta particles) or waves of pure energy (gamma rays and X-rays). Radiation can be broadly classified into two categories: ionizing radiation and non-ionizing radiation. Ionizing radiation is generally more energetic than non-ionizing radiation, and can knock electrons out of molecules with which the particles or photons (gamma rays and X-rays) interact, creating ion pairs. Non-ionizing radiation, such as that emitted by a laser or cellular telephone, is different in that it does not create ions

when it interacts with matter but generally dissipates its energy in the form of heat. The type of radiation associated with the radioactive materials in the IWCS is ionizing radiation.

The EPA (1989) and NTP (2011) have identified ionizing radiation as a known human carcinogen. This means that there is sufficient evidence from epidemiological studies that confirm the causal relationship between exposure and carcinogenicity. Additional health effects beyond cancer, including cardiovascular disease and hereditary effects can occur in individuals exposed to radiation. As noted by the NRC (2006), the risk of cardiovascular disease has been shown to increase in persons exposed to high therapeutic doses of radiation and also in atomic bomb survivors exposed to more moderate doses. However, there is no direct evidence of increased risk of cardiovascular diseases at relatively low doses, and data are inadequate to quantify this risk if it exists. The risk of hereditary disease is sufficiently small that it has not been detected in humans, even in thoroughly studied irradiated populations such as those of Hiroshima and Nagasaki (NRC 2006).

The EPA notes that cancer risk is generally the limiting effect for sites contaminated with radionuclides such as NFSS, and suggests that radiation carcinogenesis be used as the sole basis for assessing human health risks (EPA 1989). This is consistent with recent information on the health risks for radiation exposures provided in NRC (2006), and this recommendation is being used in the CERCLA process for NFSS and this TM. That is, the only health effect that is quantified in this TM for exposures to radiation and radionuclides is the risk of developing cancer. In addition to cancer risk, results are also presented in terms of radiation dose as noted above.

Current radiation protection standards and practices are based on the premise that any radiation dose, no matter how small, can result in detrimental health effects such as an increased risk of developing cancer, and that the number of effects produced is in direct proportion to the radiation dose. This concept is referred to as the linear no-threshold hypothesis and is generally considered to result in conservative estimates of the health effects from low doses of radiation. The risk estimators used here are based on this assumption.

The energy deposited by ionizing radiation per unit mass of any material is the absorbed dose and is generally expressed in the unit of rad (for *radiation absorbed dose*). The degree of biological damage caused by different types of radiation varies according to how spatially close together the ionizations occur. For the same amount of absorbed dose, alpha particles will produce significantly more biological harm than will beta particles or gamma rays, since alpha particles produce much higher density regions of ionizations. The unit that describes the health impact associated with the various types of radiation, modes of exposure, and organs irradiated is the rem (for *roentgen equivalent man*) or mrem (for millirem, or one one-thousandth of a rem). The doses given in this TM are generally in the units of mrem.

The most common forms of radiation associated with the radioactive contents of the IWCS are alpha and beta particles, neutrons, and electromagnetic radiation (photons) in the form of gamma rays and X-rays. An alpha particle consists of two protons and two neutrons and is identical to the nucleus of a helium atom. Beta particles can be either positive (positron) or negative (negatron); a negatron is identical to an electron. Gamma rays and X-rays have no electrical charge or mass and can travel long distances in air, body tissues, and other materials. The radionuclides of most concern in the IWCS are those associated with the three naturally occurring decay series shown in Figures 2.1, 2.2, and 2.3. Alpha, beta, and photon radiation are the three types of radiation associated with these radionuclides.

Neutrons are one of the two components of an atom's nucleus (the other being the proton) and are often emitted by unstable TRU radionuclides such as isotopes of plutonium, americium, and curium. The concentrations of TRU radionuclides at NFSS are very low, so neutrons are not expected to be a significant dose contributor. The most likely source of TRU radionuclides at the site is associated with

the previous storage of KAPL wastes. While there are no specific data on the presence of TRU radionuclides in the IWCS residues and other wastes, data collected for various environmental media during the RI field investigations support the very low presence of TRU radionuclides at the site (see related discussion in USACE [2007a, 2011b]).

Ionizing radiation can impart sufficient localized energy in living cells to cause cell damage. This damage may be repaired by the cell, the cell may die, or the cell may reproduce altered cells, sometimes leading to the induction of cancer. Radiation exposures associated with the radioactive residues and other wastes in the IWCS are expected to be limited to chronic effects (effects that occur from low-level exposures over a long period of time). The main health concern associated with chronic exposure to radiation is an increased likelihood of developing cancer.

Very large doses (tens to hundreds of rem) over a short time period are required to cause acute effects, and these are not expected to occur at NFSS to either workers or members of the general public provided access controls remain in place. Direct intrusion into the K-65 residues could result in a gamma dose rate of about 600 mrem/hr, and this may or may not result in some acute affects depending on how long this exposure lasted. As noted in Section 1.3, very high doses could also occur to the bronchial epithelium portion of the lung should an individual construct a house in the residues being stored in the IWCS.

This gamma dose rate of 600 mrem/hr estimated for direct intrusion into the K-65 residues is based on the average Ra-226 concentration in the K-65 residues of 520,000 pCi/g (see Table 2.2) and the Ra-226 DCF for external gamma exposure of 10.6 mrem/yr per pCi/g (see Section 4.1.2, Table 4.1), with the result rounded to one significant figure and given in units of mrem/hr. (For gamma exposures, an absorbed dose of 1 rad will produce an effective dose of about 1 rem.) The K-65 residues are currently buried below 3.8 m (13 ft) of lower activity contaminated soil and clean (uncontaminated) clay and topsoil (USACE 2012).

Evidence linking radiation exposure to observable biological effects has only been found at doses above 25 rad delivered over a short time period. These effects can include nausea and vomiting, malaise and fatigue, increased body temperature, blood changes, epilation (hair loss), and temporary sterility; bone marrow changes have not been identified until the acute doses reach or exceed 200 rad (Cember 1983). Uncontrolled direct contact with the residues for several days or weeks would be necessary to achieve absorbed doses that could produce these effects.

The relationship between radiation dose and health effects is relatively well characterized for high doses of most types of radiation. Some of these exposures can cause cancer which can be fatal, and may take many years to develop and cause this death. Lower levels of exposure might constitute a health risk, but it is difficult to establish a direct cause-and-effect relationship because a particular effect in a specific individual can be produced by different processes. The features of cancers resulting from radiation are not distinct from those of cancers produced by other causes. Hence, the risk of cancer from chronic exposures of ionizing radiation must be extrapolated from data for increased rates of cancer observed at much higher dose rates.

The radiation exposures associated with the radioactive materials in the IWCS are incremental to those from natural and man-made sources of radiation. The National Council on Radiation Protection and Measurements (NCRP) recently estimated that an average individual in the United States receives a radiation dose of about 620 mrem/yr (NCRP 2009). This estimate includes about 310 mrem/yr from natural sources and 310 mrem/yr from man-made sources, which include medical procedures and consumer products. About 200 mrem/yr of the 310 mrem/yr dose from natural sources is due to indoor Rn-222 gas and its short-lived radioactive decay products.

4.1.2 Factors for Calculating Radiation Dose

Radiation doses (in rem or mrem) are estimated in this TM in accordance with EPA guidance, which indicates that it is appropriate to estimate both the incremental cancer risk (for comparison to the NCP target risk range of 1×10^{-6} to 1×10^{-4}) and dose (to assess compliance with relevant radiation protection standards) (EPA 1999a). Ionizing radiation causes biological damage only when the energy released during radioactive decay is absorbed in tissues.

The dose delivered to internal organs as a result of radionuclides being systemically incorporated into the body may continue long after intake of the radionuclide has ceased. After being taken into the body, some radionuclides are eliminated fairly quickly, while others are incorporated into organs and tissues or ultimately deposited in bones and can be retained for many years. This process is in contrast to external doses, which occur only when a radiation field is present.

The committed equivalent dose was developed by the ICRP (1991) to account for doses to internal organs from radionuclides taken into the body. The committed equivalent dose is the integrated equivalent dose to specific organs for a specified number of years. An integrating time of 50 years following intake is commonly used, although other integrating times can be used as well. The doses presented in this TM are the sum of the effective dose from external exposures and the committed effective dose from internal exposures, collectively referred to simply as dose in this TM. The annual dose (which can be used to assess compliance with radiation protection standards, see Section 5.1) is the sum of the annual effective dose from external radiation exposures and the 50-year committed effective dose from radionuclide intakes during the year.

The ICRP has developed DCFs for internal and external exposures based on updated radiation dosimetry models in accordance with the effective dose concept (ICRP 1996). These DCFs were developed using the same models applied to establish the cancer risk coefficients in Federal Guidance Report (FGR) 13 issued by EPA (1999b), and they apply for members of the general public. These DCFs cover a range of ages, from an infant up to an adult. For internal exposures, the DCFs give the committed effective dose (in mrem) per unit intake (pCi) for a number of integrating times.

For external exposures, the DCF represents the effective dose (in mrem) per unit concentration of radionuclide (assumed to be in soil) and unit of time (such as a year). The DCFs used in this TM are given in Table 4.1. To simplify the assessment, adult DCFs are used in this TM and a 50-year time period is used to calculate the committed dose. Other age groups (representing an infant to age 1, and children ages 1, 5, 10, and 15 years old) and other integrating time periods can be used for specific calculations as appropriate.

The age-dependent DCFs for internal exposures (inhalation and ingestion) developed by the ICRP are given in Tables 4.2 and 4.3. Table 4.2 provides the inhalation DCFs and Table 4.3 gives the ingestion DCFs. The DCFs in these two tables give the dose per unit intake at a given age through their lifetime, assumed to be 70 years. This information is used in this TM to qualitatively assess the effect of the radiation exposures occurring at a time that the receptor is not an adult (see discussion in Section 5.3.3).

Exposures to Rn-222 gas and its short-lived decay products are addressed separately in this TM. As noted in the radon assessment TM (USACE 2012), most of the radiation dose and cancer risk associated with Rn-222 is due to the inhalation of its short-lived decay products, which are ions and readily attach to aerosol particles in the air. When attached and unattached Rn-222 decay products are inhaled, these short-lived radionuclides decay quite quickly emitting alpha, beta, and gamma radiation, and can cause large doses to the bronchial epithelium portion of the lung.

TABLE 4.1 Radiological Risk Coefficients and Dose Conversion Factors[a]

Radionuclide	Coefficients for Lifetime Cancer Risk[b]								Dose Conversion Factors[c]		
	Mortality				Morbidity						
	Inhalation	*Food Ingestion*	*Water Ingestion*	*External Gamma*	*Inhalation*	*Food Ingestion*	*Water Ingestion*	*External Gamma*	*Inhalation*	*Ingestion*	*External Gamma*
Ac-227+D	2.02×10^{-7}	4.45×10^{-10}	3.39×10^{-10}	9.98×10^{-7}	2.13×10^{-7}	6.53×10^{-10}	4.86×10^{-10}	1.47×10^{-6}	2.10	4.47×10^{-3}	1.87
Am-241	3.34×10^{-8}	9.47×10^{-11}	7.44×10^{-11}	1.86×10^{-8}	3.77×10^{-8}	1.34×10^{-10}	1.04×10^{-10}	2.76×10^{-8}	3.55×10^{-1}	7.40×10^{-4}	3.72×10^{-2}
Cs-137+D	1.02×10^{-10}	2.55×10^{-11}	2.09×10^{-11}	1.73×10^{-6}	1.12×10^{-10}	3.74×10^{-11}	3.04×10^{-11}	2.55×10^{-6}	1.44×10^{-4}	4.81×10^{-5}	3.20
Np-237+D	2.71×10^{-8}	5.78×10^{-11}	4.38×10^{-11}	5.40×10^{-7}	2.87×10^{-8}	9.10×10^{-11}	6.74×10^{-11}	7.97×10^{-7}	1.85×10^{-1}	4.10×10^{-4}	1.01
Pa-231	5.62×10^{-8}	1.59×10^{-10}	1.22×10^{-10}	9.45×10^{-8}	7.62×10^{-8}	2.26×10^{-10}	1.73×10^{-10}	1.39×10^{-7}	5.18×10^{-1}	2.63×10^{-3}	1.76×10^{-1}
Pb-210+D	2.91×10^{-8}	2.50×10^{-9}	1.96×10^{-9}	2.91×10^{-9}	3.08×10^{-8}	3.44×10^{-9}	2.66×10^{-9}	4.21×10^{-9}	3.70×10^{-2}	7.00×10^{-3}	7.51×10^{-3}
Pu-238	4.40×10^{-8}	1.30×10^{-10}	1.02×10^{-10}	4.53×10^{-11}	5.22×10^{-8}	1.69×10^{-10}	1.31×10^{-10}	7.22×10^{-11}	4.07×10^{-1}	8.51×10^{-4}	1.17×10^{-4}
Pu-239	4.66×10^{-8}	1.34×10^{-10}	1.05×10^{-10}	1.34×10^{-10}	5.51×10^{-8}	1.74×10^{-10}	1.35×10^{-10}	2.00×10^{-10}	4.44×10^{-1}	9.25×10^{-4}	2.63×10^{-4}
Ra-226+D	2.69×10^{-8}	3.55×10^{-10}	2.65×10^{-10}	5.78×10^{-6}	2.83×10^{-8}	5.15×10^{-10}	3.86×10^{-10}	8.49×10^{-6}	3.53×10^{-2}	1.04×10^{-3}	1.06×10^{1}
Ra-228+D	4.14×10^{-8}	1.01×10^{-9}	7.41×10^{-10}	3.08×10^{-6}	4.37×10^{-8}	1.43×10^{-9}	1.04×10^{-9}	4.53×10^{-6}	5.93×10^{-2}	2.55×10^{-3}	5.66
Sr-90+D	4.06×10^{-10}	7.46×10^{-11}	5.96×10^{-11}	1.38×10^{-8}	4.33×10^{-10}	9.53×10^{-11}	7.40×10^{-11}	1.96×10^{-8}	5.98×10^{-4}	1.14×10^{-4}	4.10×10^{-2}
Tc-99	3.58×10^{-11}	2.28×10^{-12}	1.58×10^{-12}	5.48×10^{-11}	3.81×10^{-11}	4.00×10^{-12}	2.75×10^{-12}	8.14×10^{-11}	4.81×10^{-5}	2.37×10^{-6}	1.09×10^{-4}
Th-228+D	1.37×10^{-7}	2.58×10^{-10}	1.84×10^{-10}	5.29×10^{-6}	1.44×10^{-7}	4.22×10^{-10}	2.99×10^{-10}	7.76×10^{-6}	1.61×10^{-1}	5.30×10^{-4}	9.67
Th-229+D	2.17×10^{-7}	4.73×10^{-10}	3.53×10^{-10}	7.94×10^{-7}	2.30×10^{-7}	7.16×10^{-10}	5.28×10^{-10}	1.17×10^{-6}	9.48×10^{-1}	2.27×10^{-3}	1.48
Th-230	2.68×10^{-8}	7.99×10^{-11}	6.18×10^{-11}	5.53×10^{-10}	3.40×10^{-8}	1.19×10^{-10}	9.10×10^{-11}	8.19×10^{-10}	3.70×10^{-1}	7.77×10^{-4}	1.07×10^{-3}
Th-232	4.07×10^{-8}	9.07×10^{-11}	6.92×10^{-11}	2.30×10^{-10}	4.33×10^{-8}	1.33×10^{-10}	1.01×10^{-10}	3.42×10^{-10}	4.07×10^{-1}	8.51×10^{-4}	4.56×10^{-4}
U-233	2.69×10^{-8}	6.25×10^{-11}	4.66×10^{-11}	6.66×10^{-10}	2.83×10^{-8}	9.69×10^{-11}	7.18×10^{-11}	9.82×10^{-10}	3.55×10^{-2}	1.89×10^{-4}	1.27×10^{-3}
U-234	2.64×10^{-8}	6.14×10^{-11}	4.59×10^{-11}	1.68×10^{-10}	2.78×10^{-8}	9.55×10^{-11}	7.07×10^{-11}	2.52×10^{-10}	3.48×10^{-2}	1.81×10^{-4}	3.44×10^{-4}
U-235+D	2.38×10^{-8}	6.17×10^{-11}	4.60×10^{-11}	3.70×10^{-7}	2.50×10^{-8}	9.76×10^{-11}	7.18×10^{-11}	5.43×10^{-7}	3.15×10^{-2}	1.75×10^{-4}	6.92×10^{-1}
U-238+D	2.25×10^{-8}	7.47×10^{-11}	5.46×10^{-11}	7.78×10^{-8}	2.36×10^{-8}	1.21×10^{-10}	8.71×10^{-11}	1.14×10^{-7}	2.96×10^{-2}	1.79×10^{-4}	1.56×10^{-1}

[a] This table provides cancer risk coefficients and dose conversion factors (DCFs) for inhalation, ingestion, and external gamma irradiation for the radionuclides expected to be present in the IWCS, and for others that might also be present. For ingestion and inhalation, the units are cancer risk or dose (in mrem) per picocurie (pCi) taken into the body. The dose is given as the committed effective dose as identified by the ICRP (1991). The units for external gamma exposure are cancer risk or dose (in mrem) per pCi/g of soil for one year of continuous exposure. This external exposure dose is the effective dose. The "+D" notation indicates that short-lived decay products (those with half-lives less than six months) are present along with these radionuclides in equilibrium in the residues and wastes in the IWCS (see Section 2.2). For example, Sr-90 includes the contribution from yttrium-90 (Y-90), and U-238 includes the contribution from Th-234.

[b] The radiological cancer risk coefficients are based on updated dosimetry models developed by the ICRP (1991, 1996), and they represent values averaged over all ages and both genders. The mortality risk represents the lifetime risk of incurring a fatal cancer, and the morbidity risk represents the risk of incurring all cancers, including those that are cured. These coefficients were obtained from the values tabulated in FGR 13 (EPA 1999b). For inhalation of radionuclides, risk coefficients are provided for three types of particulates corresponding to fast (F), medium (M), and slow (S) absorption to blood. The maximum of the three values is given here. For ingestion, separate values are given for food and water intakes. The fractional uptake from the intestines (f_1) varies from 0.0001 to 1.0 for the various radionuclides; only one ingestion risk value (corresponding to a specified value of f_1) is given for each radionuclide in FGR 13. For external radiation, the values given here represent exposure to soil having contamination to an infinite depth, which for practical purposes corresponds to 1 m (3 ft). Contamination to a shallower depth represents a lower risk.

[c] The DCFs represent the values for adults and are based on updated dosimetry models developed by the ICRP (1991, 1996). Inhalation and ingestions DCFs are also available for additional age groups, and those are given in Tables 4.2 and 4.3. The notes provided above for the cancer risk coefficients for the inhalation, ingestion, and external radiation pathways also apply to the DCFs.

TABLE 4.2 Age-Dependent Inhalation Dose Conversion Factors for Radionuclides[a]

Radionuclide	Age-Dependent Dose Conversion Factors for Inhalation *(mrem/pCi)*[b]					
	Infant	**1-Year-Old**	**5-Year-Old**	**10-Year-Old**	**15-Year-Old**	**Adult**
Ac-227+D	6.55	6.12	3.83	2.76	2.16	2.10
Am-241	6.66×10^{-1}	6.66×10^{-1}	4.44×10^{-1}	3.70×10^{-1}	3.40×10^{-1}	3.55×10^{-1}
Cs-137+D	4.07×10^{-4}	3.70×10^{-4}	2.59×10^{-4}	1.78×10^{-4}	1.55×10^{-4}	1.44×10^{-4}
Np-237	3.63×10^{-1}	3.44×10^{-1}	2.22×10^{-1}	1.85×10^{-1}	1.74×10^{-1}	1.85×10^{-1}
Pa-231	8.14×10^{-1}	8.51×10^{-1}	7.03×10^{-1}	5.55×10^{-1}	5.55×10^{-1}	5.18×10^{-1}
Pb-210+D	1.35×10^{-1}	1.20×10^{-1}	7.32×10^{-2}	4.90×10^{-2}	4.11×10^{-2}	3.70×10^{-2}
Pu-238	7.40×10^{-1}	7.03×10^{-1}	5.18×10^{-1}	4.07×10^{-1}	3.70×10^{-1}	4.07×10^{-1}
Pu-239	7.77×10^{-1}	7.40×10^{-1}	5.55×10^{-1}	4.44×10^{-1}	4.07×10^{-1}	4.44×10^{-1}
Ra-226+D	1.26×10^{-1}	1.08×10^{-1}	7.05×10^{-2}	4.46×10^{-2}	3.71×10^{-2}	3.53×10^{-3}
Ra-228+D	1.82×10^{-1}	1.78×10^{-1}	1.19×10^{-1}	7.42×10^{-2}	5.93×10^{-2}	5.93×10^{-3}
Sr-90+D	1.60×10^{-3}	1.51×10^{-3}	1.02×10^{-3}	6.76×10^{-4}	5.99×10^{-4}	5.98×10^{-4}
Tc-99	1.52×10^{-4}	1.37×10^{-4}	8.88×10^{-5}	6.29×10^{-5}	5.55×10^{-5}	4.81×10^{-5}
Th-228+D	7.14×10^{-1}	5.91×10^{-1}	3.30×10^{-1}	2.21×10^{-1}	1.91×10^{-1}	1.61×10^{-1}
Th-229+D	2.22	2.05	1.44	1.15	9.65×10^{-1}	9.48×10^{-1}
Th-230	7.77×10^{-1}	7.40×10^{-1}	5.18×10^{-1}	4.07×10^{-1}	3.66×10^{-1}	3.70×10^{-1}
Th-232	8.51×10^{-1}	8.14×10^{-1}	5.92×10^{-1}	4.81×10^{-1}	4.44×10^{-1}	4.07×10^{-1}
U-233	1.26×10^{-1}	1.11×10^{-1}	7.03×10^{-2}	4.44×10^{-2}	4.07×10^{-2}	3.55×10^{-2}
U-234	1.22×10^{-1}	1.07×10^{-1}	7.03×10^{-2}	4.44×10^{-2}	3.70×10^{-2}	3.48×10^{-2}
U-235+D	1.11×10^{-1}	9.62×10^{-2}	6.29×10^{-2}	4.07×10^{-2}	3.40×10^{-2}	3.15×10^{-2}
U-238+D	1.08×10^{-1}	9.26×10^{-2}	5.93×10^{-2}	3.70×10^{-2}	3.22×10^{-2}	2.96×10^{-2}

[a] This table provides age-dependent dose conversion factors (DCFs) for inhalation for the radionuclides expected to be present in the IWCS, and for others that might be present. The units are dose (in mrem) per picocurie (pCi) taken into the body. The "+D" notation indicates that short-lived decay products (those with half-lives less than six months) are assumed to be present along with these radionuclides in equilibrium in the residues and wastes in the IWCS. For example, the DCF for Sr-90 includes the contribution from Y-90, and the DCF for U-238 includes the contribution from Th-234.

[b] These inhalation DCFs provide the committed effective dose coefficients and are based on updated dosimetry models developed by the ICRP (1991, 1996). For inhalation of radionuclides, the ICRP has developed DCFs for three types of particulates corresponding to fast (F), medium (M), and slow (S) absorption to blood. The maximum of the three values is given here. The DCFs provided here give the age-dependent committed effective dose coefficients from the age of intake through a lifetime of 70 years. That is, the value given for a 1-year old child reflects the dose this individual would incur from the unit (pCi) intake over the next 69 years of life, and that for the 15-year old adolescent reflects the dose this individual would receive over the next 55 years. Inhalation DCFs have also been developed by the ICRP for different integrating periods (ICRP 1996), which can be used for specific calculations that are not relevant to the scenarios assessed in this TM. Thus, those values are not included here.

TABLE 4.3 Age-Dependent Ingestion Dose Conversion Factors for Radionuclides[a]

Radionuclide	Age-Dependent Dose Conversion Factors for Ingestion *(mrem/pCi)*[b]					
	Infant	**1-Year-Old**	**5-Year-Old**	**10-Year-Old**	**15-Year-Old**	**Adult**
Ac-227+D	1.43×10^{-1}	1.58×10^{-2}	1.04×10^{-2}	7.30×10^{-3}	5.87×10^{-3}	4.47×10^{-3}
Am-241	1.37×10^{-2}	1.37×10^{-3}	9.99×10^{-4}	8.14×10^{-4}	7.40×10^{-4}	7.40×10^{-4}
Cs-137+D	7.77×10^{-5}	4.44×10^{-5}	3.55×10^{-5}	3.70×10^{-5}	4.81×10^{-5}	4.81×10^{-5}
Np-237+D	7.44×10^{-3}	8.00×10^{-4}	5.30×10^{-4}	4.14×10^{-4}	4.11×10^{-4}	4.10×10^{-4}
Pa-231	4.81×10^{-2}	4.81×10^{-3}	4.07×10^{-3}	3.40×10^{-3}	2.96×10^{-3}	2.63×10^{-3}
Pb-210+D	1.27×10^{-1}	4.59×10^{-2}	2.44×10^{-2}	1.67×10^{-2}	1.30×10^{-2}	7.00×10^{-3}
Pu-238	1.48×10^{-2}	1.48×10^{-3}	1.15×10^{-3}	8.88×10^{-4}	8.14×10^{-4}	8.51×10^{-4}
Pu-239	1.55×10^{-2}	1.55×10^{-3}	1.22×10^{-3}	9.99×10^{-4}	8.88×10^{-4}	9.25×10^{-4}
Ra-226+D	1.74×10^{-2}	3.56×10^{-3}	2.30×10^{-3}	2.96×10^{-3}	5.55×10^{-3}	1.04×10^{-3}
Ra-228+D	1.11×10^{-1}	2.11×10^{-2}	1.26×10^{-2}	1.44×10^{-2}	1.96×10^{-2}	2.56×10^{-3}
Sr-90+D	9.66×10^{-4}	3.44×10^{-4}	2.11×10^{-4}	2.44×10^{-4}	3.08×10^{-4}	1.14×10^{-4}
Tc-99	3.70×10^{-5}	1.78×10^{-5}	8.51×10^{-6}	4.81×10^{-6}	3.03×10^{-6}	2.37×10^{-6}
Th-228+D	2.43×10^{-2}	4.05×10^{-3}	2.23×10^{-3}	1.56×10^{-3}	1.14×10^{-3}	5.30×10^{-4}
Th-229+D	6.87×10^{-2}	8.81×10^{-3}	5.48×10^{-3}	4.35×10^{-3}	3.70×10^{-3}	2.27×10^{-3}
Th-230	1.52×10^{-2}	1.52×10^{-3}	1.15×10^{-3}	8.88×10^{-4}	8.14×10^{-4}	7.77×10^{-4}
Th-232	1.70×10^{-2}	1.67×10^{-3}	1.30×10^{-3}	1.07×10^{-3}	9.25×10^{-4}	8.51×10^{-4}
U-233	1.41×10^{-3}	5.18×10^{-4}	3.40×10^{-4}	2.89×10^{-4}	2.89×10^{-4}	1.89×10^{-4}
U-234	1.37×10^{-3}	4.81×10^{-4}	3.26×10^{-4}	2.74×10^{-4}	2.74×10^{-4}	1.81×10^{-4}
U-235+D	1.31×10^{-3}	4.90×10^{-4}	3.19×10^{-4}	2.65×10^{-4}	2.61×10^{-4}	1.75×10^{-4}
U-238+D	1.41×10^{-3}	5.37×10^{-4}	3.44×10^{-4}	2.79×10^{-4}	2.63×10^{-4}	1.79×10^{-4}

[a] This table provides age-dependent dose conversion factors (DCFs) for ingestion for the radionuclides expected to be present in the IWCS, and for others that might be present. The units are dose (in mrem) per picocurie (pCi) taken into the body. The "+D" notation indicates that short-lived decay products (those with half-lives less than six months) are assumed to be present along with these radionuclides in equilibrium in the residues and wastes in the IWCS. For example, the DCF for Sr-90 includes the contribution from Y-90, and the DCF for U-238 includes the contribution from Th-234.

[b] These ingestion DCFs provide the committed effective dose coefficients and are based on updated dosimetry models developed by the ICRP (1991, 1996). The fractional uptake of radionuclides from the intestines (f_1) varies from 0.0001 to 1.0; only one ingestion DCF (corresponding to a specific value of f_1) is given for each radionuclide and that value is reflected in this table. The DCFs provided here give the age-dependent committed effective dose coefficients from the age of intake through a lifetime of 70 years. That is, the value given for a 1-year old child reflects the dose this individual would incur from the unit (pCi) intake over the next 69 years of life, and that for the 15-year old adolescent reflects the dose this individual would receive over the next 55 years. Ingestion DCFs have also been developed by the ICRP for different integrating periods (ICRP 1996), which can be used for specific calculations that are not relevant to the scenarios assessed in this TM. Thus, those values are not included here.

Radon is an inert gas, and nearly all of the radiation dose associated with Rn-222 inhalation is from its short-lived decay products; the dose from the Rn-222 gas itself typically represents less than 5% of the dose (ICRP 1981). To calculate the dose from the Rn-222 progeny, it is first necessary to convert the concentration of the Rn-222 decay products from units of pCi/L to units of working level (WL), and exposure to these radionuclides in terms of working-level month(s) (WLM). One WL is any combination of short-lived Rn-222 decay products in one liter of air without regard to the degree of equilibrium that results in the ultimate emission of 1.30×10^5 million electron volts (MeV) of alpha energy. One WL corresponds to a Rn-222 concentration of about 100 pCi/L in 100% equilibrium with its short-lived decay products. It is necessary to know the extent of equilibrium between Rn-222 and its decay products to convert the Rn-222 concentration (in pCi/L) to decay product concentration (in WL). The relationship between Rn-222 concentration in (pCi/L) and WL is given in the following equation.

$$WL = (C_{Rn} \times WLR) / 100 \qquad \text{(Eq. 4.1)}$$

where:

WL = working level,
C_{Rn} = concentration of Rn-222 gas (pCi/L), and
WLR = working-level ratio or equilibrium fraction.

When Rn-222 gas is released from a specific location (such as through a crack or hole in the IWCS cover), there are essentially no decay products accompanying the gas. The decay products are charged particles which attach readily to the solid materials in the overlying cover under current conditions. However, ingrowth of these decay products occurs quite rapidly once the gas is released to the atmosphere. The rate of ingrowth is dictated by the half-lives of the Rn-222 decay products.

The EPA has developed an algorithm for the rate at which Rn-222 decay products are formed; this algorithm is incorporated in the CAP88-PC (Clean Air Act Assessment Package-1988-Personal Computer) code (EPA 2007). The algorithm gives the WLR as a function of the distance from the point of release for a wind speed of 3.5 m/s. The WLR is often called the Rn-222 equilibrium fraction, and this represents the ratio of the potential alpha energy present in the form of short-lived progeny at any location divided by what would be present at secular (or 100%) equilibrium. The CAP88-PC WLR algorithm is shown in Figure 4.1.

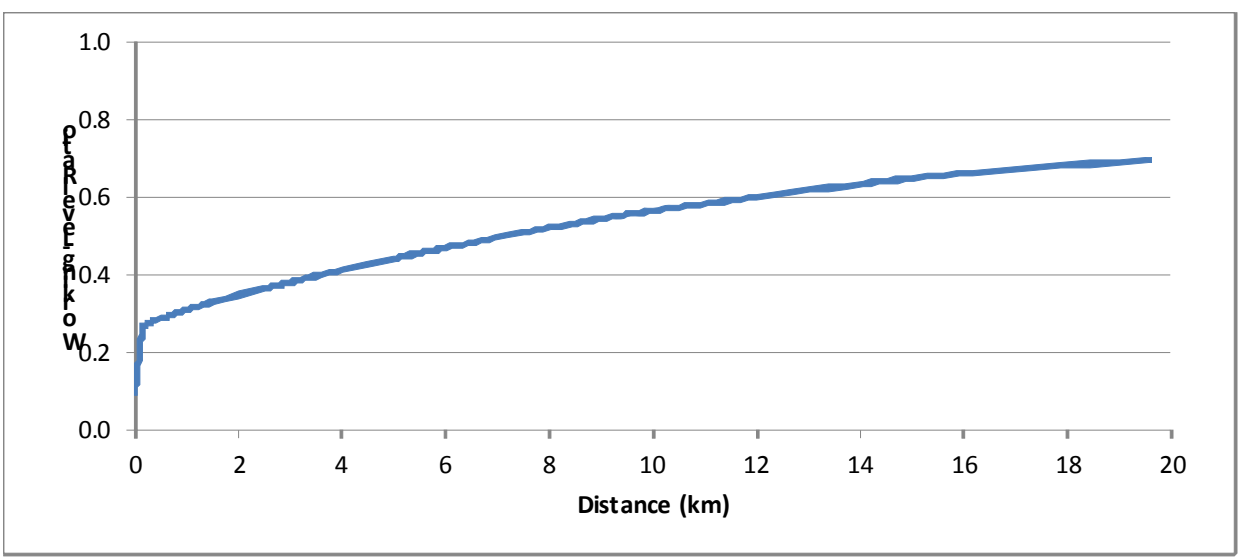

FIGURE 4.1 Algorithm for Working-Level Ratio for Radon-222 Progeny

The WLR algorithm in CAP88-PC is given as a series of values at specific distances from the release point. The WLRs at distances between the specified distances are calculated by linear interpolation. The algorithm begins at a distance of 150 m (490 ft) from the point of release with a WLR of 0.267, and extends to a distance of nearly 20 km (19,551 m) (12 mi) with a WLR of 0.7 (0.698). The WLR remains at this value for all greater distances in CAP88-PC. While the WLR is given as a function of distance, it can be converted to a function of time based on the wind speed of 3.5 m/s used to develop this algorithm, if the WLR at a given location for a specific wind speed is desired.

For this TM, this algorithm was extrapolated to a distance of zero, i.e., at the release point. A WLR of 0.1 is assumed at this location. In actuality, it should be zero right at the point of release (see Figure 4.1). This is done to add conservatism to the results, and to account for the situation in which a driller may be standing over a drill hole while radon gas moves upward in the hole to the atmosphere. As a supporting check, the CAP88-PC algorithm for WLR was compared with that incorporated in the MILDOS-AREA computer code (Yuan et al. 1989). For distances less than about 6 to 8 km (4 to 5 mi), the CAP88-PC algorithm gives a higher value of the WLR than MILDOS-AREA. For greater distances, the MILDOS-AREA model produces higher estimates of the WLR than CAP88-PC. Because the distances of most concern in this TM are within a few miles of the IWCS, use of the CAP88-PC algorithm will produce conservative results for the estimated WLs.

The WLM is the cumulative exposure unit historically applied to uranium miners and is defined as the product of the Rn-222 decay product concentration (in WL) and the duration of exposure normalized to a 170-hour working month. The inhalation rate used for the reference worker in that derivation is 1.2 m^3/hr (ICRP 1981). In this TM, the inhalation rates assumed for the individual receptors are scaled to this rate to calculate the WLM. National and international organizations (ICRP 1981; NCRP 2009) have indicated that it is reasonable to use a value of 1 rem/WLM to convert the exposure to Rn-222 progeny (in WLM) to a committed effective dose. However, it is noted in Appendix C of Yu et al. (2001) that it is appropriate to modify this conversion factor to account for differences in exposures of miners and other individuals and to account for aerosol size distribution, unattached fraction (the fraction of radon decay products not attached to aerosols), and breathing rate and route (nose or mouth). Based on these considerations, factors of 570 mrem/WLM for outdoor exposures and 760 mrem/WLM for indoor exposures are recommended (Yu et al. 2001). These factors are used in this TM to calculate the doses associated with exposures to Rn-222 and its progeny.

4.1.3 Coefficients for Estimating Cancer Risk

The EPA has developed a standard set of radiological risk coefficients and these values have been used in this TM. These coefficients represent the estimated lifetime cancer risk per unit intake averaged over all ages and both genders for a given radionuclide and mode of exposure. An extensive set of these coefficients for estimating cancer risk from various internal and external exposures to more than 800 radionuclides is given in FGR 13 (EPA 1999b). Only a very small subset of these values is used here, because of the limited number of radionuclides present in the IWCS. Coefficients are available for both morbidity and mortality (or illness and fatality). Although mortality values can be much smaller, morbidity may approach mortality for certain types of cancer, e.g., lung cancer. Morbidity risk coefficients are used in this TM to estimate the likelihood of cancer incidence from radiological exposures.

The radiological risk coefficients in FGR 13 were developed using the same updated models as were used to develop the DCFs given in ICRP (1996). These models more accurately address the movement and retention of specific radionuclides in the human body after intake, and are used to develop estimates of the effective dose as a function of time from a chronic intake (inhalation or ingestion) or exposure (external irradiation by gamma rays and X-rays) over a lifetime. Human data were considered in

developing these models, albeit from much higher doses. The estimates of effective dose were combined with cancer risk factors through a life-table analysis, which accounts for competing risk (caused by something other than the radiation exposure, such as a car accident). Competing risks are often much larger than the radiological risks and vary significantly with age, and they are accounted for using mortality statistics for the entire population of the United States. The basis is that people dying from other causes would not die from a radiation-induced cancer, even if they had been exposed to radiation from a contaminated site. Hence, these coefficients provide a conservative but realistic estimate of radiation risk from those exposures.

The radiological risk coefficients used in this assessment are given in Table 4.1 for the radionuclides present in the IWCS. Several additional radionuclides beyond those in the U-238, U-235, and Th-232 decay series are included in that table as some of these are present in low concentrations in other areas of the site. This provides useful information on the relative risks posed by some of the radionuclides not specifically evaluated in this TM. These values can be used in the analyses for subsequent OUs, including for the BOP OU.

For external exposure to gamma radiation that provides nearly uniform irradiation of the body, the cancer risk can be calculated directly from the dose (in mrem) using a dose-to-risk estimator. This approach should not be used for internal (inhalation and ingestion) exposures, as the doses from such exposures can be highly localized (depending on the specific organs in which the radionuclides deposit). Such external doses could occur from direct exposure to the residues and other wastes or as a result of secondary (scattered) radiation including skyshine. Section 4.1.4 presents information that can be used to estimate radiation doses for exposures to Ra-226, which is the most significant gamma-emitting radionuclide at the site. These doses can be converted to cancer risk estimates using factors of 8×10^{-7} per mrem for morbidity and 6×10^{-7} per mrem for mortality (ISCORS 2003). The morbidity value is used for the evaluations in this TM. The ISCORS (2003) and Interstate Technology and Regulatory Council (ITRC) have noted that this approach is an acceptable method for assessing the risks of exposure to low LET radiation such as that associated with gamma rays and X-rays (ITRC 2002).

As noted in the previous section, exposures to Rn-222 gas and its short-lived decay products are handled separately in this TM, as these represent a unique situation relative to the other radionuclides. The cancer risk coefficients for exposure to Rn-222 progeny is taken to be 5.38×10^{-4} per WLM on the basis of information contained in NRC (1999) as summarized in USACE (2012).

4.1.4 External Gamma Exposure Pathway

Another pathway of concern for the IWCS contents is external gamma exposure. In this pathway, workers and possibly members of the general public could be exposed directly to the gamma radiation emitted from the residues and other wastes in the IWCS. This exposure could occur even if the materials are located some distance away. There are two situations that are addressed in this TM, i.e., exposures that could occur when an individual is in the general vicinity of the contaminated materials and there is no intervening material to shield the individual (direct radiation), and exposures that could occur from secondary (or air-scattered radiation), often referred to as skyshine.

If there is a direct line-of-sight between the radiation source and an individual with no intervening shielding, the dose from the direct radiation will be much larger than that from secondary radiation. In these situations, there is no need to calculate the secondary (skyshine) radiation, as this will generally represent less than 1% of the dose from the direct radiation. However, there are situations where the direct radiation may be effectively shielded. In these situations (such as an individual working behind a shielding wall or an individual standing near a hole or crack in the IWCS cover), secondary (air-scattered) radiation may be the main source contributing to the dose from external gamma radiation.

To provide information in a format that will be generally useful for the IWCS FS and other planning activities for NFSS, the results are given in this section on a normalized basis. For the direct gamma radiation component, the computer code MicroShield (Grove 2009) was used to calculate the direct gamma dose for a source term of 1,000 pCi/g of Ra-226 and all of its decay products (including Pb-210), which are assumed to be in secular equilibrium. This isotope (and its radioactive decay products) is the major gamma-emitting radionuclide in the IWCS. This radionuclide together with all of its decay products (to stable Pb-206) is simply referred to as Ra-226 in the following discussion (see also Figure 2.1 and Table 2.1).

The computer code MicroShield used for this analysis includes the external gamma radiation DCFs given in ICRP Publication 74 (ICRP 1997). The doses estimated by this computer code are effective doses, consistent with the DCFs presented in Table 4.1. The source geometry is assumed to be a right circular cylinder on the ground for which the diameter is equal to the height. A number of different volumes are assessed, and gamma radiation doses are calculated for a height of 1 m (3 ft) above the cylinder base for a number of horizontal distances from the source. This height is used to approximate the distance above the ground to the midpoint of a standing adult (such as a worker).

This geometry could represent exposures to an individual from various conditions, e.g., the residues or other wastes placed in a container following retrieval from the IWCS, residues in a waste processing vessel, a mound of materials placed on the ground, or direct exposure to an open area of the IWCS. Several example cases are shown schematically in Figure 4.2. It is recognized that this geometry is only an approximation, but the results are appropriate for use in the comparative analyses to be developed in the upcoming FS for the IWCS OU.

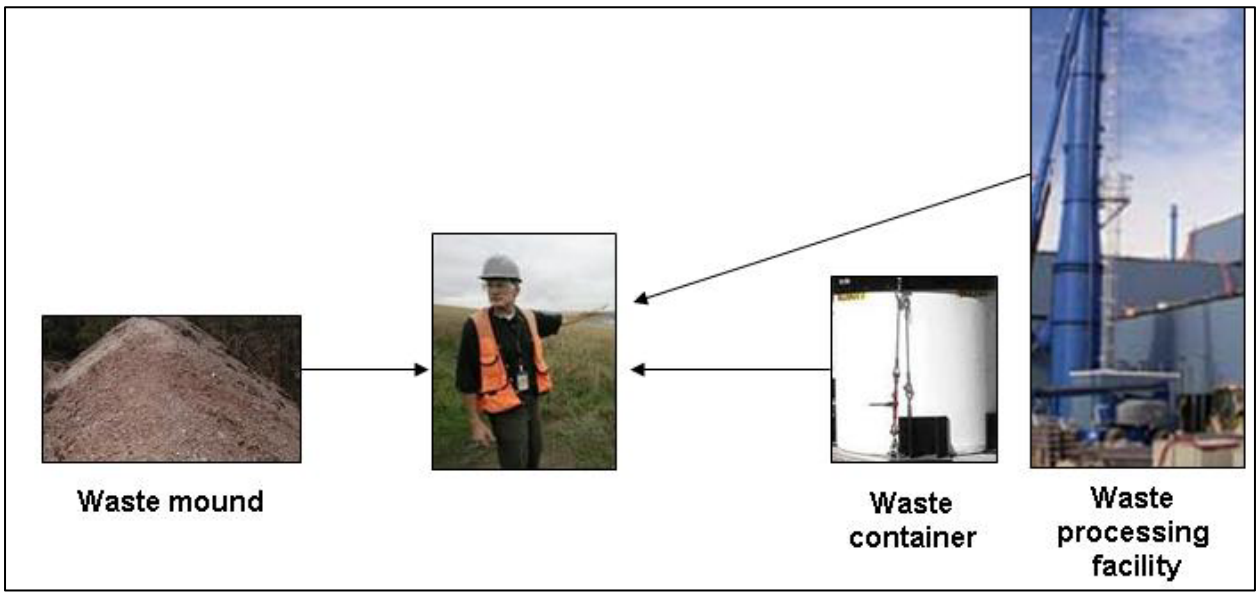

FIGURE 4.2 Schematic of Sources Evaluated for Direct Gamma Exposure

The gamma dose rate to an individual standing on top of a large pile of soil or residues at a Ra-226 concentration of 1,000 pCi/g is about 1.2 mrem/hr. This dose rate corresponds to a height of 1 m (3 ft) above the large source, and it is obtained by multiplying the external gamma DCF of 10.6 mrem/yr per pCi/g for Ra-226 (given in Table 4.1) by 1,000 pCi/g and then dividing the result by 8,760 hours/yr. Note that the contribution from Pb-210 represents less than 1% of the external gamma dose from Ra-226, so that contribution can be ignored in this calculation.

The results of this evaluation are given in Figure 4.3. As shown in this figure, the direct gamma doses are calculated out to a distance of 3 km (1.9 mi) for sources having volumes ranging from 1 m^3 (1.3 yd^3) to 1,000 m^3 (1,300 yd^3). These volumes encompass the expected volumes of material that could reasonably be expected to be exposed at any one time.

As an example of how to use these results, consider the situation where a worker is located 10 m (33 ft) from a mound of K-65 residues having a volume of about 10 m^3 (13 yd^3). The normalized dose rate (to 1,000 pCi/g of Ra-226) to an individual at this distance is estimated from Figure 4.3 to be about 0.015 mrem/hr. Multiplying this value by 520 (to obtain the average concentration in the K-65 residues, 520,000 pCi/g), the dose rate is calculated to be about 7.8 mrem/hr. Interpolation needs to be conducted when the volumes do not match those used to develop Figure 4.3.

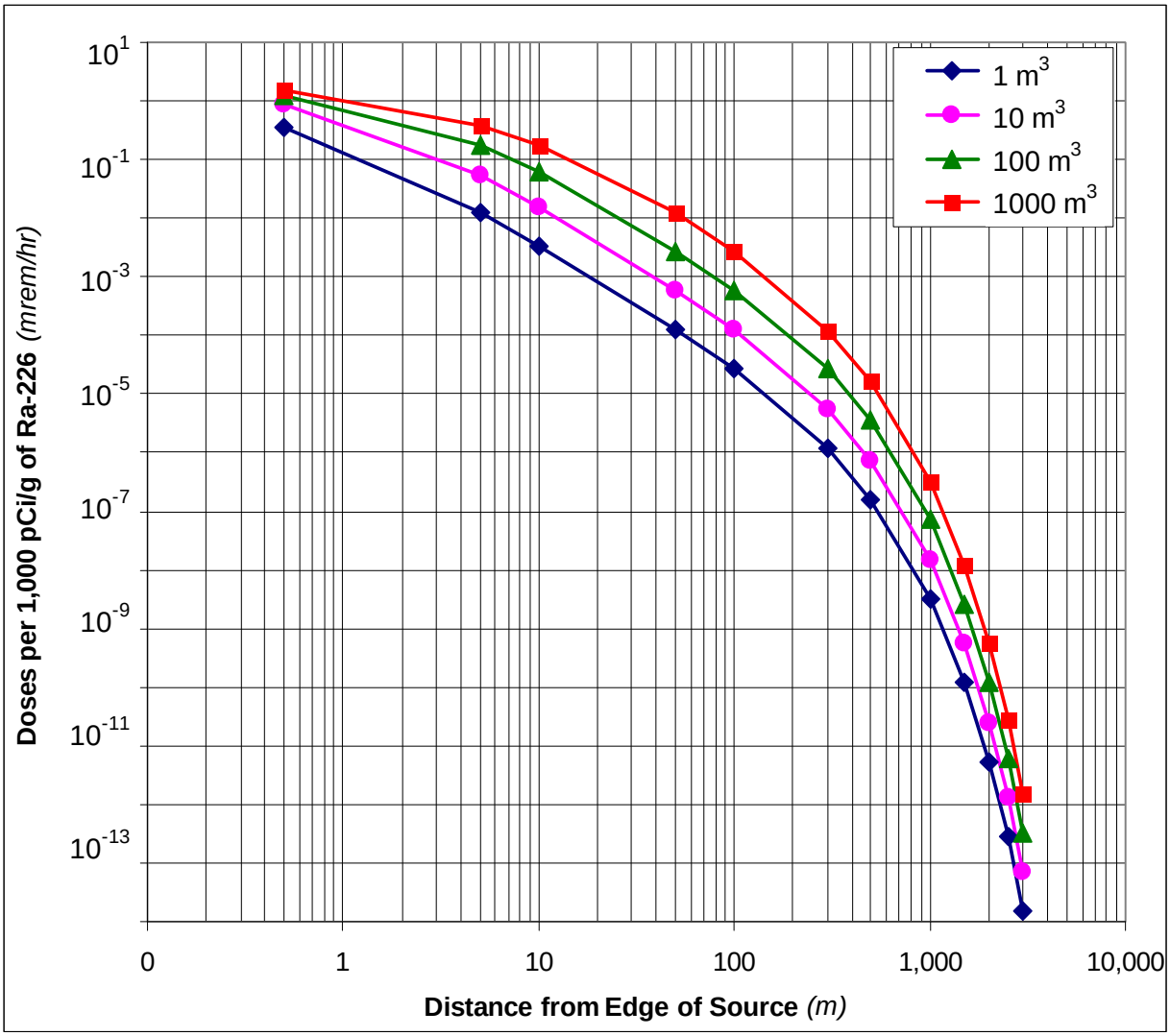

FIGURE 4.3 Normalized Doses from Direct Gamma Exposures

A similar approach was used for the secondary (or skyshine) dose rates from exposure to the IWCS contents. The computer code MicroSkyshine (Grove 2008) was used for this component. This computer code was developed to address radiation exposure from secondary (scattered) radiation when there is shielding between the radiation source and a potentially exposed individual. The shielding would greatly

reduce the dose from direct (unscattered) radiation, but the dose from air-scattered radiation could still be significant. This dose could occur if a mound of K-65 residues were located behind a shielded wall or if there were a hole or a crack in the IWCS cover. In these situations, the gamma radiation from the residues would be emitted to the air above the source, and be scattered by air molecules in the atmosphere. A small fraction of the emitted radiation would be directed towards the nearby individual. MicroSkyshine is a standard computer code used to analyze such situations.

For this assessment, it is assumed that the individual (worker or member of the general public) is shielded from the source term, but that the shielding is only to a given height, i.e., the source term is exposed to the air above it. The height of the shielding is taken to be 3.8 m (13 ft), as this represents the distance from the K-65 residues to the top of the IWCS cap. The source is assumed to be at the bottom of a cylindrical shield, such as would occur if an individual drilled a hole through the cap to the residues. As for the primary radiation assessment, a normalized source concentration of 1,000 pCi/g is used in this analysis for secondary radiation.

The source geometry assumes that a large source having a depth of 4.9 m (16 ft) is at the bottom of the cylindrical shield and that an individual is located at the same height as the top of the shield. The source term depth is the current depth of the K-65 residues in the IWCS. This situation could represent an individual standing on top of the IWCS cover near a hole or a crack. A number of different source areas were addressed, ranging in diameter from 15 cm (6 in.) to 15 m (49 ft). The gamma dose rates were calculated at 1 m (3 ft) above the top of the shield height, to approximate the midpoint of a standing adult. This situation is shown schematically in Figure 4.4. As for the direct gamma radiation calculations, it is recognized that this geometry is only an approximation but the results are appropriate for use in the comparative analyses given in the IWCS FS.

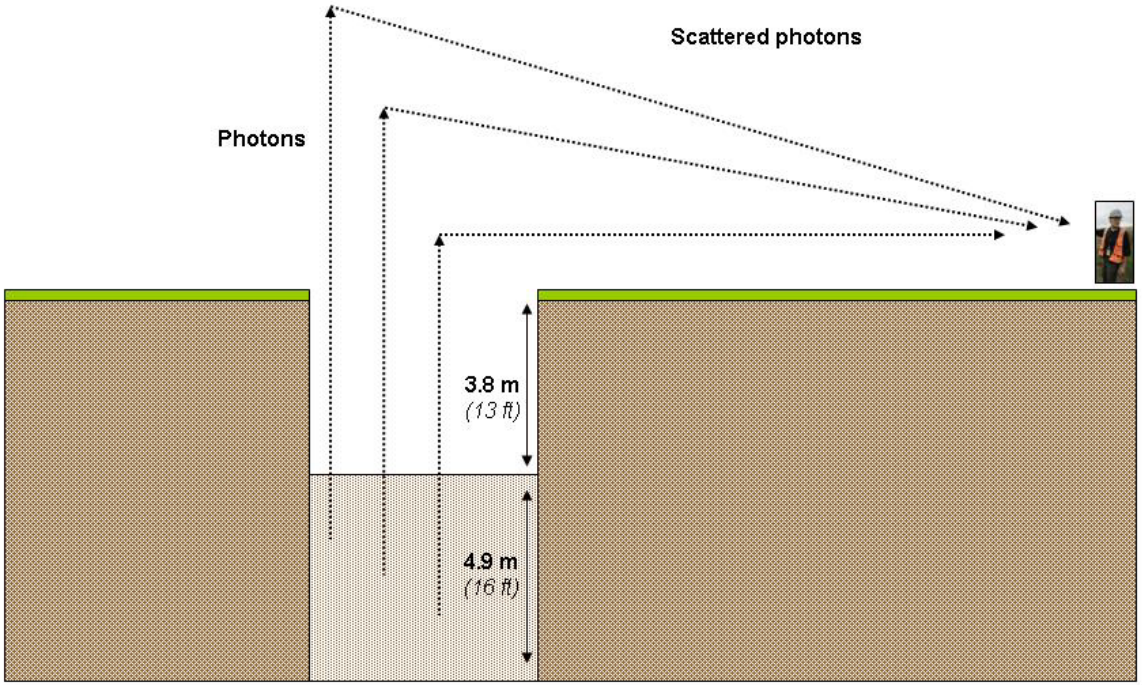

FIGURE 4.4 Schematic of Approach Used to Evaluate Secondary (Skyshine) Gamma Exposure

The results of this evaluation are given in Figure 4.5. As shown in this figure, the secondary (skyshine) gamma radiation doses are calculated out to a distance of 3 km (2 mi) for sources having a range of areas. These areas encompass an illustrative extent of material that could be exposed at any one time following a breach of the IWCS cover.

To illustrate how to use these results, consider the situation where a maintenance worker is located 2 m (7 ft) from the edge of an opening in the cap that is 2 m (7 ft) in diameter and extends to the K-65 residues. The normalized dose rate (to 1,000 pCi/g of Ra-226) at this distance is estimated to be 5×10^{-6} mrem/hr (see Figure 4.5). Multiplying this value by 520 (to produce the estimated concentration in the K-65 residues, which is 520,000 pCi/g), the dose rate to this worker is calculated to be 0.0026 mrem/hr from secondary (skyshine) radiation. Note that Figure 4.5 illustrates the dose estimates for selected openings and distances. Values would need to be interpolated when the exposed areas do not directly align with those reflected in Figure 4.5 (i.e., when they fall between the plotted points).

The results in Figure 4.5 can be used to approximate the significance of the skyshine doses to a number of other situations. For example, it could be used to estimate the secondary gamma radiation to a worker standing behind a shield wall to process the K-65 residues. In this case, the shield wall would be 3.8 m (13 ft) in height, which is reasonable. However, the skyshine results are very sensitive to the source geometry used. Therefore, the results shown in Figure 4.5 may not be appropriate for other situations. For engineering design considerations, the actual geometry involved should be used to perform these types of calculations.

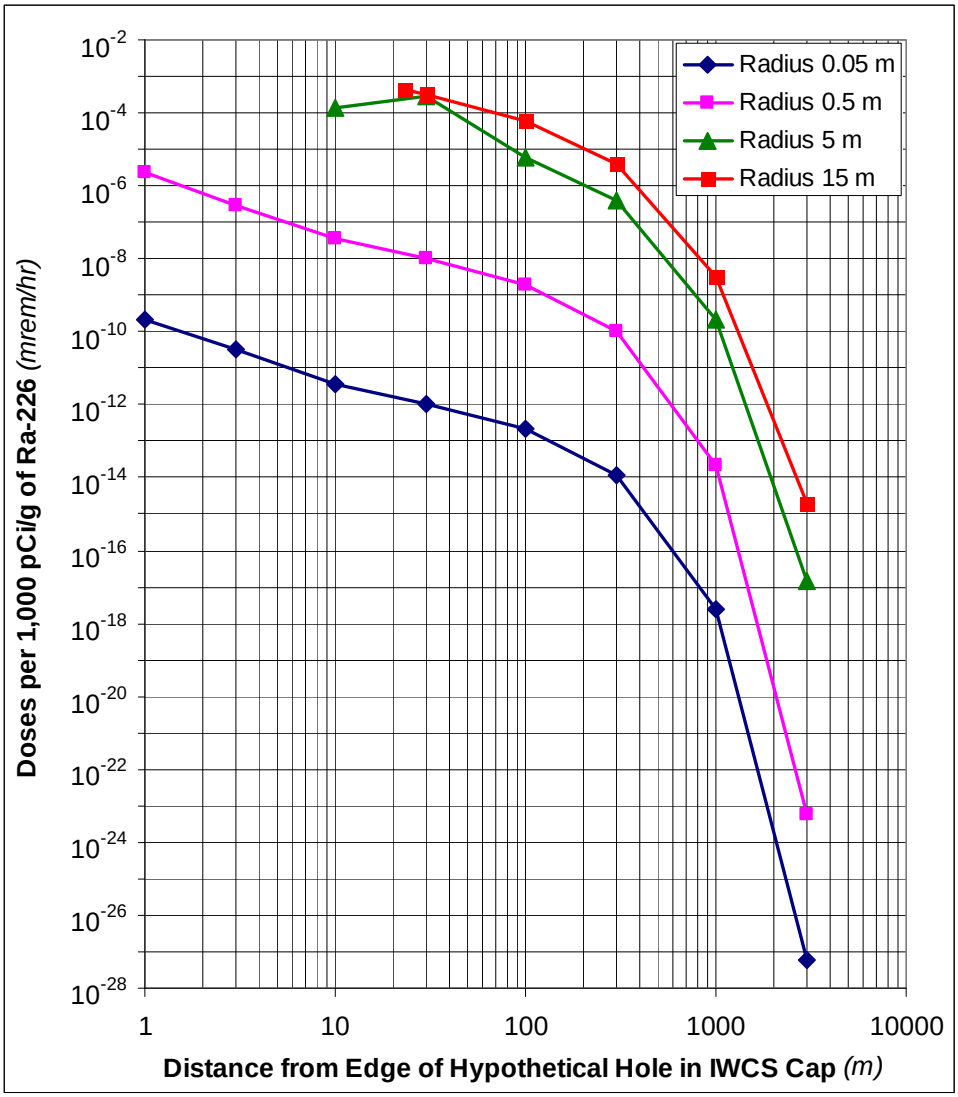

FIGURE 4.5 Normalized Doses from Secondary (Skyshine) Gamma Exposures

4.2 TOXICITY VALUES FOR ASSESSING CHEMICAL HEALTH EFFECTS

The EPA and other agencies have derived toxicity values from scientific studies to estimate cancer risks and the potential for noncarcinogenic effects from environmental exposures. These values are specific to both the chemical and the route of exposure. Standard values have not been developed for all chemicals and exposure routes of interest for the IWCS (in many cases because adverse effects are not indicated as a primary concern for the given chemical/route combination).

The EPA has established a hierarchy for selecting toxicity values to use in risk assessments at contaminated sites (EPA 2003a). This hierarchy is presented in Table 4.4.

TABLE 4.4 Hierarchy for Selecting Toxicity Values

Tier	Key Features	Notes
1 Integrated Risk Information System (IRIS) values	Standard EPA toxicity values, database includes supporting information on toxicity studies and derivation approach. These values undergo extensive internal, intra-agency, external expert, and public reviews.	Widely used nationally and internationally, this database has long been available online (EPA 2011d). (Note a companion database, Health and Environmental Research Online [HERO] also provides useful toxicity information from scientific studies [EPA 2011f].)
2 Provisional Peer Reviewed Toxicity Values (PPRTVs)	Similar derivation process as IRIS values but less extensive external review.	Formerly maintained internally, this database is now available online (EPA 2011e).
3 Others values, from EPA and other agencies, such as the ATSDR and California EPA (Cal/EPA)	Priority is given to peer-reviewed values whose bases are transparent and publicly available (and reflect recent knowledge); sources include ATSDR minimal risk levels (MRLs) and Cal/EPA toxicity values, including reference exposure levels (RfELs).	The online list of MRLs (ATSDR 2010) is updated annually. These values do not consider the cancer endpoint, whereas Cal/EPA provides toxicity values for estimating both cancer risk and noncarcinogenic effects (Cal/EPA 2009a, 2009b, 2009c, 2011a, 2011b).

The toxicity values used to estimate cancer risk for the IWCS chemicals in this TM are given in Table 4.5. Those used to assess the potential for noncarcinogenic effects are given in Table 4.6. Supporting information is provided in Appendix B, with summary general information about how toxicity values are derived outlined in Section B.2. Several chemical fact sheets relevant to selected IWCS contaminants are included in Appendix C.

Many of the toxicity values used in this assessment were established for chronic exposures; therefore, they represent conservative estimates for the hypothetical onsite receptors. Some EPA toxicity values have been developed to assess the potential for noncarcinogenic effects from subchronic exposures (extending two to seven years), and some ATSDR MRLs exist for exposures up to a year (intermediate MRLs); several such values are included in the footnotes of Table 4.6. The organs and systems on which the toxicity values are based are illustrated in Figure 4.6. (Note that to simplify the presentation in this early example assessment, and recognizing that certain values will probably change before the FS is prepared, the citation provided for the IRIS values listed in the following tables is the general link to the IRIS website [EPA 2011d], from which the current chemical-specific information can be readily found.)

TABLE 4.5 Toxicity Values for Assessing Chemical Cancer Risk[a]

Exposure Route and Chemical	Toxicity Value	Type and Agency Source	Date	Carcinogen Classification	Tumor Site
Inhalation Unit Risk *(IUR, as risk per µg/m^3 except for asbestos, for which the risk is per fibers/cm^3)*					
Arsenic	4.3×10^{-3}	IUR *(EPA IRIS)*	1998	Carcinogenic, known (A)	Lung
Cobalt	9.0×10^{-3}	p-IUR *(EPA PPRTV)*	2008	Suggestive, probable (B2)	Lung
Lead*	1.2×10^{-5}	IUR *(Cal/EPA)*	1997	Suggestive, probable (B2)	Kidney
Nickel	2.4×10^{-4}	IUR *(EPA IRIS)*	1991 *(2006)*	Carcinogenic, known (A)	Lung (also nasal)
Vanadium	8.3×10^{-3}	p-IUR *(EPA PPRTV)*	2008	Suggestive, probable (B2)	Lung
PCBs*	5.7×10^{-4}	IUR *(EPA IRIS)*	1997	Suggestive, probable (B2)	Liver
Asbestos	2.3×10^{-1}	IUR *(EPA IRIS)*	1993	Carcinogenic, known (A)	Lung, mesothelium
Oral Slope Factor *(SF, as risk per mg/kg-d)*					
Arsenic	1.5	SF *(EPA IRIS)*	1998	Carcinogenic, known (A)	Skin (prevalence)
Lead	8.5×10^{-3}	SF *(Cal/EPA)*	2000	Suggestive, probable (B2)	Kidney
PCBs	2.0	SF *(EPA IRIS)*	1997	Suggestive, probable (B2)	Liver

[a] Values from the first tier (EPA IRIS) are unshaded, those from the second tier (EPA PPRTVs) are shaded light yellow, and those in the third tier (ATSDR and Cal/EPA) are shaded orange. The date indicates the year the value was established (parentheses indicate when it was last reviewed). An asterisk indicates the inhalation value was derived from an oral study. The traditional classification scheme for carcinogens, still in use by some organizations (including the International Agency for Research on Cancer), includes A = human carcinogen and B2 = probable human carcinogen. The EPA (2005a) guidelines for carcinogens reflect a weight-of-evidence approach that includes a qualitative narrative, as described in Appendix B (Section B.2.1). A recent NTP report identifies the following IWCS contaminants as known human carcinogens: inorganic arsenic compounds, asbestos, and nickel soluble compounds (as well as cadmium and compounds, and hexavalent chromium); chemicals identified as reasonably anticipated to be human carcinogens include the following possible IWCS contaminants: cobalt sulfate, lead and compounds, metallic nickel, and PCBs (NTP 2011). A recent draft report by EPA (2011g) also indicates the likely carcinogenicity of lead. Several updates are in progress for the IRIS program (EPA 2011d), while the list of PPRTV assessments planned or under way through September 2011 did not include any of these chemicals (EPA 2011e). Further context for the chemicals is provided below (in alphabetical order).

For arsenic, the values shown are from IRIS. In 2010, EPA released a draft toxicological report for external review (EPA 2010a) in which a new oral SF is proposed (25.7 per mg/kg-d, based on female combined lung and bladder cancers).

For cobalt, the provisional IUR (p-IUR) is the PPRTV from EPA (2008b); a draft IRIS assessment is under way (EPA 2011d).

For lead, the toxicity values are from Cal/EPA (2009b, 2011a), based on kidney tumors in male rats from oral exposures to lead sulfate; Cal/EPA adjusted the oral toxicity value to derive the inhalation value based on a 5-fold greater absorption for humans by inhalation compared to ingestion.

For nickel, the value shown is for nickel refinery dust; note the extant value established by Cal/EPA (2011a) in 1991 for nickel and compounds is 5.0×10^{-2} per µg/m^3. This value is reported for nickel carbonate, carbonyl, hydroxide, oxide, subsulfide, and nickel refinery dust (as well as other nickel compounds), and it should not be used if the air concentration exceeds 40 µg/m^3 (because underlying assumptions would no longer hold). A subsequent review of the literature led to the conclusion in 2006 that no change was warranted at that time. An updated IRIS evaluation for nickel is under development.

For PCBs, the IUR was derived from the oral SF; the value shown reflects the upper-bound unit risk for the middle tier (1.0×10^{-4}) scaled to the factor for the high risk and persistence category, as recommended in IRIS (EPA 2011d) to apply for inhalation of an aerosol or dust contaminated with PCBs. For the oral SF, the value shown is for the high risk and persistence category to reflect the most conservative (protective) approach. An IRIS assessment is anticipated in the near term.

For vanadium, the p-IUR is based on alveolar/bronchiolar neoplasms in mice for the pentoxide (EPA 2008c). The external review draft IRIS assessment proposes an IUR about 40% lower (3.4 per mg/m^3), with low confidence (EPA 2011h).

For asbestos, although risks are not quantified in this report, toxicity information is included here to support upcoming evaluations for the IWCS FS if needed. The EPA IUR is in units of risk per fibers/milliliter (mL) of air; the value should not be used if the concentration exceeds 0.04 fibers/mL (EPA 2011d) (because assumptions for the underlying mathematical approach would no longer hold). The asbestos IUR from Cal/EPA (2009b, 2011a) is 0.063 per fibers/cc. (A draft assessment for Libby amphibole asbestos may offer insights regarding the general derivation approach; an IUR of 0.17 per fibers/cubic centimeter (cc) was proposed based on the combined risk from lung cancer and mesothelioma [EPA 2011i]; note a reference concentration of 2×10^{-5} fibers/cc was also proposed based on localized pleural thickening, with an uncertainty factor of 100.)

TABLE 4.6 Toxicity Values for Assessing Chemical Noncarcinogenic Effects[a]

Route and Chemical	Toxicity Value	Type of Value *(Agency)*	Date	Uncertainty Factor	Confidence Level	Health Endpoint/System
Inhalation Reference Concentration (RfC) and Other Reference Levels *(µg/m³)*						
Arsenic*	1.5×10^{-2}	RfEL *(Cal/EPA)*	2008	30	*(Not specified)*	Neurobehavioral development, intellectual function
Cobalt	2.0×10^{-2}	p-RfC, subchronic *(EPA PPRTV)*	2008	100	Medium to low	Respiratory tract irritation, reduced pulmonary function
Manganese	5.0×10^{-2}	RfC *(EPA IRIS)*	1993	1,000	Medium	Neurobehavioral effects
Nickel	5.0×10^{-2}	RfEL *(Cal/EPA)*	2000	30	*(Not specified)*	Pulmonary inflammation
Uranium*	3.0×10^{-1}	MRL *(ATSDR)*	1999	30	*(Not specified)*	Kidney (renal effect)
Vanadium	1.0×10^{-1}	p-RfC, subchronic *(EPA PPRTV)*	2008	1,000	Medium	Nonneoplastic lung lesions, inflammation
Oral Reference Dose (RfD) *(mg/kg-d)*						
Arsenic	3.0×10^{-4}	RfD *(EPA IRIS)*	1993	3	Medium	Skin hyperpigmentation, keratosis (possibly vascular)
Barium	2.0×10^{-1}	RfD *(EPA IRIS)*	2005	300	Medium	Nephropathy
Cobalt	3.0×10^{-3}	p-RfD, subchronic *(EPA PPRTV)*	2008	300	Low	Inhibition of iodine uptake by the thyroid
Lithium	2.0×10^{-3}	p-RfD, subchronic *(EPA PPRTV)*	2008	1,000	Low to medium	Impaired renal function (dilute urine, polyuria)
Manganese	1.4×10^{-1}	RfD *(EPA IRIS)*	1996	1	Medium	Central nervous system
Molybdenum	5.0×10^{-3}	RfD *(EPA IRIS)*	1993 *(2003)*	30	Medium	Increased uric acid levels
Nickel	2.0×10^{-2}	RfD *(EPA IRIS)*	1996	300	Medium	Decreased body and organ weights
Uranium	3.0×10^{-3}	RfD *(EPA IRIS)*	1989	1,000	Medium	Weight loss, nephrotoxicity
Vanadium	9.0×10^{-3}	RfD *(EPA IRIS)*	1996	100	Low	Decreased hair cystine
PCBs	2.0×10^{-5}	RfD *(EPA IRIS)*	1996	300	Medium	Eye (ocular exudate, inflamed and prominent Meibomian glands), distorted growth in fingernails and toenails, immune system impairment

[a] Shading is the same as described for Table 4.5. Values are for chronic (lifetime) exposures except as indicated. The date indicates the year the value was established. While several updates are in progress for the EPA IRIS program (EPA 2011d), the list of PPRTV assessments planned or under way through September 2011 does not include any of these chemicals (EPA 2011e). Where inhalation data are unavailable and toxicity is indicated, in some cases oral values have been used to derive a toxicity value (notably where effects are systemic, e.g., if first-pass metabolism and portal-of-entry effects do not influence the toxicity). An asterisk indicates the inhalation value was derived from an oral study. The confidence level in

the toxicity value is based on an assessment of the available studies and overall quality of the human and experimental data used to derive that value; these levels are provided where identified (e.g., for IRIS and PPRTV values in EPA [2011d and 2011e]). The same applies for uncertainty factors, which are described in Appendix B (Section B.2.2). Highlights for each chemical, including other values that are lower in the hierarchy are provided as follows (in alphabetical order).

For arsenic, the values shown are the long-standing IRIS values. An updated IRIS evaluation addressing the noncarcinogenic endpoint is under development (EPA 2011d). The chronic oral MRL subsequently established by ATSDR is the same, which is 60% of the acute MRL of 0.005 mg/kg-day (ATSDR 2007a, 2010) (no intermediate MRL is available for oral exposures, nor are any inhalation MRLs). The Cal/EPA (2011a) RfEL of 0.015 $\mu g/m^3$ is derived from an oral (drinking water) study of children to age 10, with the critical effects being a decrease in intellectual function and adverse effects on neurobehavioral development.

For barium, the EPA IRIS RfD is shown; the same value was subsequently identified as both the intermediate and chronic MRL (ATSDR 2007b, 2010), also based on kidney toxicity with an uncertainty factor of 300.

For cobalt, the inhalation value represents the provisional RfC (p-RfC) for subchronic exposure to metallic cobalt (EPA 2008b, 2011e); for comparison, the ATSDR chronic MRL is more than 30 times higher, at 0.1 $\mu g/m^3$ (ATSDR 2004a, 2010). The oral value shown is the provisional RfD (p-RfD) for subchronic exposure (EPA 2008b, 2011e). The ATSDR intermediate oral MRL is three times higher at 0.01 mg/kg-day (ATSDR 2004a, 2010). A draft IRIS evaluation is under development (EPA 2011d).

For lithium, the provisional subchronic RfD is the same as the chronic value (EPA 2008d, 2011e). As context for the shorter durations associated with exposures to releases during the IWCS remedial action period: the common pediatric therapeutic dose is 15 to 60 mg/kg-d, while the adult dose typically ranges from 300 to 2,700 mg/d (corresponding to about 4 mg/kg-d and higher; the therapeutic dose aims to achieve a desired blood serum level of 0.6 to 1.2 milliequivalents per liter [mEq]/L) (Lee et al. 2010), and levels are generally maintained below 1.5 mEq/L to avoid toxicity. The toxic effects are reversible for shorter-duration exposures, while progressive toxicity has been indicated for exposures that extend a decade and longer.

For manganese, the IRIS RfC shown is similar to the 2010 update of the chronic inhalation MRL to 0.04 $\mu g/m^3$ (ATSDR 2010), as described in the addendum to the toxicological profile (ATSDR 2008/2010). For comparison to the oral RfD of 0.14 mg/kg-d, the recommended dietary intake of this essential nutrient is 0.1 mg/kg-d for a child (4 to 8), about 0.04 mg/kg-d for an adolescent (14 to 18), and about 0.03 mg/kg-d for adults (slightly less for women than for men) (IOM 2001, 2011).

For molybdenum, although the EPA RfD is from 1993, EPA conducted a subsequent literature search in 2003 that did not identify any critical new studies (that would have suggested any changes to the RfD). No MRL has been established for molybdenum (ATSDR 2010). As a note, the recommended dietary allowance for adults translates to 0.64 mg/kg-d (assuming a body weight of 70 kg), which is the same as for an adolescent (assuming 60 kg); the recommended intake is higher for children, at about 1 mg/kg-d or higher (through age three).

For nickel, the oral toxicity value is the IRIS RfD from 1996; a draft IRIS evaluation for nickel soluble salts is under development (EPA 2011d). For inhalation, the chronic RfEL (shown in Cal/EPA 2011a) is for nickel and compounds, which applies to the carbonate, hydroxide, oxide, and subsulfide forms and nickel refinery dust. The chronic RfEL for the oxide is double this value, at 0.1 $\mu g/m^3$. Cal/EPA recently proposed a draft chronic RfEL of 0.02 $\mu g/m^3$ for nickel oxide and a draft value of .014 $\mu g/m^3$ for nickel and other compounds (Cal/EPA 2011c).

For uranium, the values shown are for soluble salts (highly soluble for the MRL). For inhalation, the chronic MRL of 0.3 $\mu g/m^3$ listed here is the extant value from 1999 (ATSDR 2010); a recent draft update of the toxicological profile (ATSDR 2011) identifies a higher value of 0.8 $\mu g/m^3$ (based on monkey data for lung fibrosis); the current intermediate MRL is 0.4 $\mu g/m^3$ and the corresponding draft value is higher at 2 $\mu g/m^3$ (based on kidney effects in dog, uncertainty factor of 100). The IRIS assessment is projected to be finalized in the near term.

For vanadium, the IRIS RfD is for the pentoxide; a p-RfD of 7.0×10^{-4} mg/kg-d applies for other soluble compounds (EPA 2009b, 2011e); for consistency with other values for vanadium, the IRIS RfD is used in this TM. The EPA external review draft IRIS assessment proposes an RfD ten times lower (9×10^{-4}), with an uncertainty factor of 3,000 (EPA 2011h). The chronic MRL for inhalation of the pentoxide is the same as the p-RfC of 0.1 $\mu g/m^3$ (EPA 2008c); this MRL is a draft value (based on respiratory tract lesions, specifically degeneration of respiratory epithelium of the epiglottis from a 2002 NTP study; an uncertainty factor of 30 was applied) (ATSDR 2009, 2010). The recent external review draft IRIS assessment proposes an RfC ten times higher (1×10^{-5} mg/m^3), with an uncertainty factor of 300 (EPA 2011h).

For PCBs, the oral RfD is the IRIS value for Aroclor 1254 (EPA 2011d).

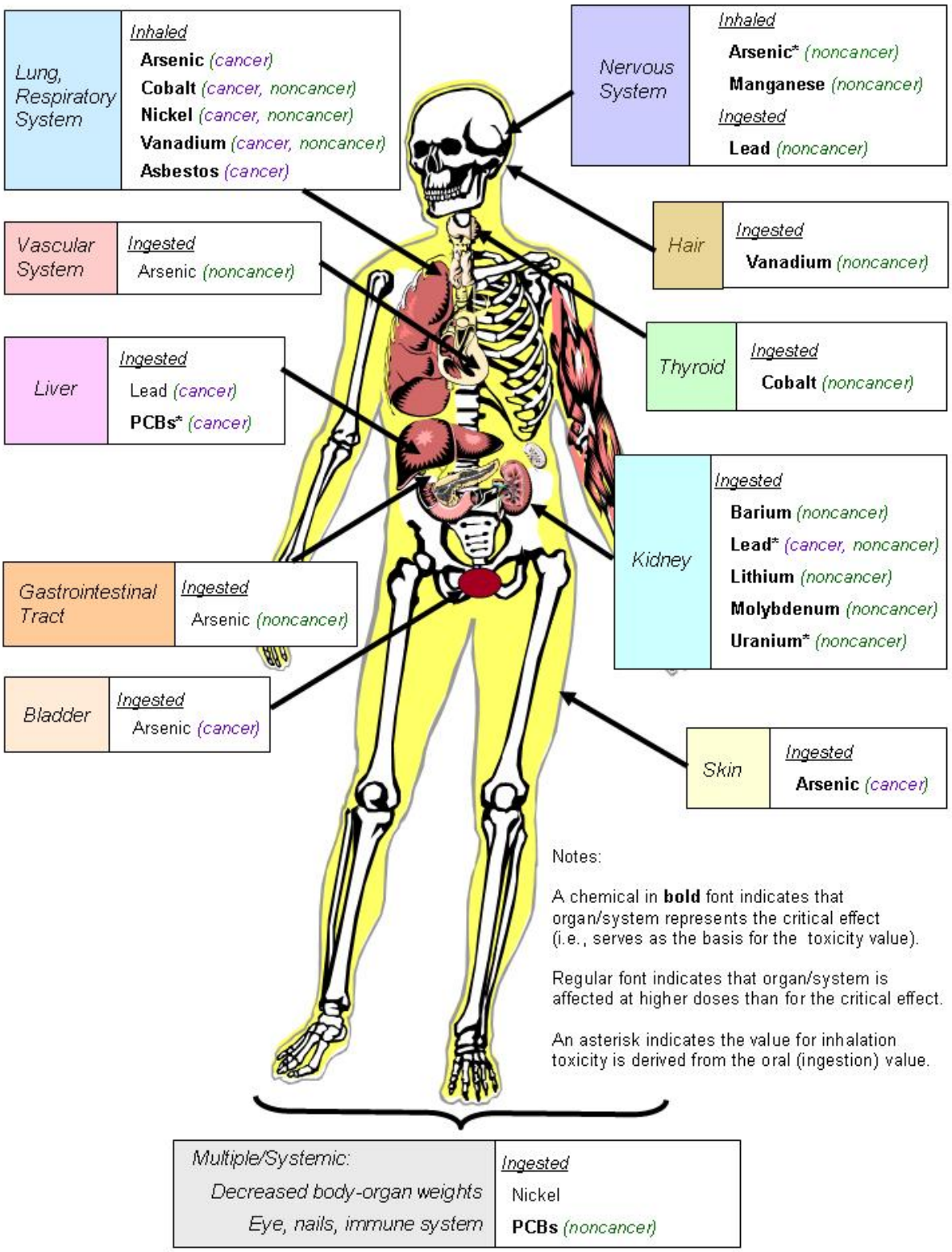

FIGURE 4.6 Critical Organs and Systems for the Chemical Toxicity of IWCS Contaminants

(Some organs affected at higher doses are also included, e.g., for lead and arsenic.)

It is important to note that the EPA has not established a toxicity reference value for lead to estimate potential noncarcinogenic effects from illustrative exposures. Instead, EPA lead models can be used to conduct project-specific assessments (such as the integrated exposure and uptake biokinetic model; an all-ages lead model has also been developed), and EPA has identified a concentration of 400 mg/kg as a screening level for residential soil; see Table 2.5, Section 5.3.3, and supporting information sources including EPA (2003b, 2011c, 2011d, 2011k, 2011l).

Additional information for the IWCS contaminants, including the derivation of selected MRLs, can be found in several ATSDR toxicological profiles (ATSDR 1990a, 1990b, 2000/2011, 2001, 2004a, 2004b, 2005, 2007a, 2007b, 2007c, 2008, 2008/2010, 2009, 2011); other sources also include useful context (e.g., Cal/EPA [2009c]). The MRLs represent an exposure level likely to be without appreciable risk of adverse noncarcinogenic effect. The chronic MRL applies to exposures of 1 year or longer, the acute MRL applies for exposures of 1 through 14 days, and the intermediate MRL applies to the period between (more than two weeks to a year).

In terms of supporting information for the cancer toxicity values, studies conducted by the NTP (within the U.S. Department of Health and Human Services) and evaluations conducted by the International Agency for Research on Cancer provide additional useful context. For example, from the recent NTP (2011) report on carcinogens, the list of chemicals known to be human carcinogens includes the following IWCS contaminants: asbestos, nickel compounds, gamma radiation, radon, and thorium dioxide. The companion list of chemicals reasonably anticipated to be human carcinogens includes the following IWCS contaminants: cobalt sulfate, lead and lead compounds, metallic nickel, and PCBs. As a note, a recent draft assessment conducted to support ongoing evaluations for the lead ambient air quality standard indicates a “likely causal relationship” for cancer (EPA 2011g).

For potential noncarcinogenic effects, it can be useful to consider that some chemicals are essential human nutrients (including micronutrients). Thus, dietary reference intakes developed by the Institute of Medicine (IOM 2001, 2011) offer context for chemicals such as manganese, molybdenum, nickel, and vanadium. Similarly, information about therapeutic doses can provide context in some cases (e.g., arsenic trioxide, which is used to treat acute promyelocytic leukemia [NRC 2010]; and lithium, which is used to treat bipolar disorder [Lee et al. 2010]).

Standard toxicity values are only available for inhalation and oral exposures. To assess dermal exposures, depending on the chemical and the nature of the dermal toxicity (e.g., systemic toxicity rather than skin irritant), oral SFs can be adjusted in accordance with EPA guidance (EPA 2004b) to estimate potential health effects from this route. For many chemicals, toxicity information does not exist to make appropriate adjustments, and the dermal exposure pathway is only quantified for chemicals with EPA-recommended gastrointestinal absorption efficiencies and dermal absorption factors. Dermal exposures and risks have not been quantified in this TM because this pathway is a minor contributor to overall risks. Nevertheless, information is included in this section (and others) to support such calculations in the event they are deemed useful in the future as preparation of the IWCS FS proceeds.

Depending on the toxicokinetic information for a given chemical, a toxicity value to estimate cancer risk from dermal exposure can be calculated by dividing the oral SF by the oral absorption fraction; EPA recommends this adjustment only if the oral absorption is less than 50%. Because oral absorption for both arsenic and PCBs is higher than 50%, no such adjustment would be required (EPA 2004b). Therefore, the oral SF for each would be used directly (as reasonably representative of an absorbed vs. administered dose) to estimate risks from dermal exposures to arsenic and PCBs.

As a final note regarding toxicity values, the EPA supplemental guidance for assessing cancer risk (EPA 2005b) calls for the age-dependent adjustment of the cancer toxicity value to account for increased susceptibility from early-life exposure when the chemical causes cancer via a mutagenic mode of action. These factors are: 10 for ages 0 to 2, and 3 for ages 2 to 16. The determination of carcinogenesis via a mutagenic mode of action has been established for a limited set of chemicals (e.g., certain PAHs, coke oven emissions/coal tar, and several others). The chemicals evaluated in this TM are not among those, so no adjustment is indicated for the hypothetical child scenario or for the fractional duration of the trespasser scenario (60%, covering ages 13 through 15).

5 RISK CHARACTERIZATION

The approach used to characterize the human health risks from the hypothetical exposures evaluated for the IWCS in this TM is discussed in Section 5.1, and results of the calculations are summarized in Section 5.2. Uncertainties associated with this risk assessment process are discussed in Section 5.3.

5.1 APPROACH

The risk characterization for exposures to the IWCS contents depends on a number of factors including the characteristics and concentrations of contaminants in this interim structure (addressed in Chapter 2); the mechanisms that could release these contaminants during the near term and estimated exposure levels and intakes for hypothetical people if those releases occur (addressed in Chapter 3); and the toxicities of the radioactive and chemical contaminants in the IWCS wastes (addressed in Chapter 4). The results of the evaluations presented in Chapters 2, 3, and 4 are integrated in this chapter to provide an overall characterization of potential health effects from exposures to these wastes. These risk results will be used to support the evaluation of remedial action alternatives for the IWCS in the upcoming FS.

This analysis addresses two main sets of exposures. The first considers exposures to the wastes in place if the cap is breached, with Rn-222 release and external gamma radiation being the key concerns. The second addresses exposures associated with waste excavation due to airborne releases and associated deposition. An example evaluation of direct exposures to the uncovered wastes via incidental ingestion is also included to illustrate the importance of exposure controls to prevent this possibility.

The radiological and chemical health risks from exposures to the IWCS contaminants are jointly evaluated in this TM. The potential cancer risks for both radiological and chemical exposures are expressed in terms of the increased probability that an individual would develop cancer over a lifetime. The NCP identifies the incremental target for cancer risk associated with contaminated sites. This range serves as a point of comparison for the estimates in this TM. The NCP risk range represents an excess upper bound lifetime cancer risk to an individual of between one in 10 thousand (1×10^{-4}, or 0.0001) and one in one million (1×10^{-6}, or 0.000001) (EPA 1990). As general context, the ACS estimates the probability that men will develop cancer in their lifetime is nearly 1 in 2, while for women, the risk is slightly more than 1 in 3 (ACS 2011). These estimates translate to risks of about 5×10^{-1} and 3×10^{-1} (0.5 and 0.3), respectively. The NCP target levels are noted in this TM simply to provide context for the example estimates presented herein; these are not action levels, rather they serve as illustrative comparison values to help inform planning for the development of alternatives to be evaluated in the FS.

In addition to cancer risk, the radiation dose (in mrem) is also calculated for exposures to radioactive contaminants. The U.S. Nuclear Regulatory Commission (USNRC) has promulgated a standard of 25 mrem/yr above background for an average member of the critical group of the general public for unrestricted use following site decommissioning activities, with an additional requirement that the residual radioactivity be reduced to levels as low as reasonably achievable (ALARA) (USNRC 2011a). This standard addresses all exposure pathways, including those associated with contaminated groundwater.

For workers, the annual dose limit identified in the USACE (1997) Radiation Protection Manual is 500 mrem, with a further example limit for an ALARA dose of 100 mrem. The latter is considered the point of comparison for the illustrative dose calculations for the remedial action and maintenance workers in this TM. For the general public, this USACE manual identifies the following limits: 100 mrem/yr for facilities licensed by the USNRC, 50 mrem/yr as the maximum allowable dose for effluents from licensed facilities, and 25 mrem/yr as the limit for the release of decontaminated and decommissioned facilities for unrestricted use (USACE 1997). The latter dose limit is considered the point of comparison for the

illustrative dose estimates for the hypothetical public receptors in this TM (i.e., the onsite trespasser and offsite landfill worker and resident adult and child). This value is the same as that identified by the USNRC.

It is important to clarify that mention of dose limits or risk targets is not meant to imply that they are or are not pertinent to decisions for the IWCS. They are indicated here solely to help place the estimated doses in perspective, in a similar manner to inclusion of the target range as a yardstick against which the incremental cancer risk estimates can be measured. Potential applicable or relevant and appropriate requirements (ARARs) for the IWCS are being identified and evaluated separately as part of the FS process. The dose values given here are incremental to the U.S. background radiation dose for an average individual, which the NCRP estimates to be about 620 mrem/yr (NCRP 2009). About 310 mrem/yr of this estimated annual dose is from natural background radiation, and the other half is from man-made sources of radiation, including medical procedures (such as computed tomography [CT] scans) and to a lesser extent consumer products.

The potential for health effects other than cancer from exposure to chemical contaminants has also been assessed. The quantitative measures of noncarcinogenic health effects are the hazard quotient (HQ) and hazard index (HI) (see Section 5.1.2.2). An endpoint-specific (segregated) HI above 1 indicates a potential concern for noncarcinogenic health effects (EPA 1989).

An additional comparison to occupational limits is provided for the hypothetical worker scenarios in this TM. Three sets of occupational limits are commonly considered to guide planning for worker protection: (1) permissible exposure limits (PELs) developed by the U.S. Occupational Safety and Health Administration (OSHA), (2) recommended exposure limits (RELs) developed by the National Institute for Occupational Safety and Health (NIOSH), and (3) threshold limit values (TLVs) developed by the American Conference of Governmental Industrial Hygienists (ACGIH). These occupational limits serve as points of comparison for the airborne concentrations estimated in this TM for the hypothetical workers, to help identify situations where worker protection measures would be warranted, for incorporation in the upcoming FS. The PELs, RELs, and TLVs for the 11 IWCS chemicals are listed in Appendix B (Table B.1).

The radiological and chemical health risks are evaluated separately in this TM because the assumptions underlying these estimates differ somewhat. The most significant difference is the basis for the risk estimators. For radionuclides, the radiological risk coefficients are generally best-estimate, average values, while for chemicals the risk estimators (IURs and oral SFs) generally represent the upper bound of the slope of the dose-response curve. In addition, risk estimators for radionuclides include input from human epidemiological data, whereas those for chemicals are typically derived from experiments with laboratory animals. As a further note, the risk assessment for chemical toxicity considers health effects other than cancer (thus, kidney toxicity is assessed for uranium). Because of the differences in the underlying bases, the uncertainties associated with the radiological and chemical risk estimates differ significantly, which is important to keep in mind when reviewing the overall risk assessment results.

Reporting the radiological and chemical risk estimates separately in this document allows distinctions to be made in terms of the relative contributions from the two types of contaminants and the key risk drivers so this information can be factored into the decision-making process for the IWCS OU as appropriate. The methods used to estimate the radiological and chemical risks are described in Sections 5.1.1 and 5.1.2, respectively.

5.1.1 Radiological Risks

Exposures to ionizing radiation can result in a variety of deleterious impacts including cancer induction, cardiovascular disease, and other detrimental health effects. Low levels of radiation exposure have not been directly linked to adverse health effects, but to be protective, all doses no matter how low are assumed to present a health risk. This is commonly referred to as the linear no-threshold hypothesis in which the health risk is assumed to be linearly proportional to the radiation dose with no threshold. This approach is reflected in the radiological risk estimates presented in this TM. The predominant health concern associated with the radioactive contaminants in the IWCS, which include radionuclides that decay by emitting alpha and beta particles with attendant gamma radiation, is cancer induction.

The radiological health risks presented in this report are limited to cancer in accordance with EPA guidance, which indicates that the risk of cancer is generally the limiting concern and is suggested as the sole basis for assessing radiation-related health effects for sites or facilities contaminated with radionuclides (EPA 1989). Radiation doses associated with hypothetical exposure scenarios have also been calculated to provide additional supporting information for the upcoming FS evaluation of compliance with radiation protection standards (EPA 1999a). As noted previously, radiation protection standards are simply included in this TM for context; ARARs are being evaluated in a separate TM for the IWCS (see Figure 1.4).

The primary radioactive contaminants in the IWCS contents are identified in Section 2.3; alpha, beta, and gamma radiation are released during the radioactive decay of these radionuclides. Each type of radiation differs in its physical properties and ability to induce damage to biological tissue. The relative hazards associated with these types of radiation depend on the manner in which exposures occur.

Alpha particles are primarily a hazard when taken into the body by inhalation or ingestion, because for external exposure, they lose their energy in the outer layer of dead skin cells of the body before reaching living tissue. Within the body, alpha particles result in greater cellular damage than beta or gamma radiation because their energy is completely absorbed by the tissue. Beta particles are primarily an internal hazard, although in some cases of external exposure, very energetic beta particles can penetrate to living skin cells; thus, representing an external hazard as well. However, beta particles deposit less energy to tissue and therefore induce much less damage than alpha particles. Gamma radiation is primarily an external hazard because it can easily penetrate tissue and reach internal organs. However, only a small fraction of the incident energy is deposited in tissue and internal organs because these gamma rays continue on through the organism.

Thus, radiation exposure pathways can be separated into external and internal components and are dependent on the parameters used to define the exposure scenarios. External exposure occurs when the radioactive material is outside the body, and it is primarily a concern only for photons, i.e., gamma rays and X-rays. Internal exposure occurs when radioactive material enters the body by inhalation or ingestion. Inhaled material can be exhaled, expelled from the lungs to be either spit or swallowed and excreted, deposited in the lungs, or absorbed by the blood and relocated to other organs from which it is excreted over time. Some fraction of the ingested material will enter the bloodstream and be either excreted in the urine or feces or relocated to other organs and excreted over time; most insoluble ingested material is not absorbed into the blood but is excreted directly via feces. For internal exposures, alpha and beta particles are the dominant concern because their energy is absorbed in cells before the particles leave the body.

The DCFs and cancer risk coefficients given in Tables 4.1, 4.2, and 4.3 account for these factors as appropriate to the pathway of exposure. For internal exposures, the doses and cancer risks are calculated by multiplying the amount inhaled or ingested (in pCi) by the appropriate DCF or cancer risk coefficient.

For external exposures, the radiation doses and cancer risks are calculated by multiplying the estimated radionuclide concentration and the amount of time that the individual is exposed to this radiation by the appropriate DCF or risk coefficient.

For exposures close to the IWCS, the gamma radiation field was determined using MicroShield and MicroSkyshine, and the radiation dose (in mrem) was calculated as the product of the estimated exposure rate and time of exposure. The estimated doses from external radiation were converted to cancer risks by multiplying the dose by a risk factor of 8×10^{-7} cancers per mrem (see Section 4.1.3). This risk factor is for all cancers (fatal and nonfatal) and is an acceptable method for assessing the risks of exposure to low LET radiation such as that associated with gamma rays and X-rays.

When evaluating the hazards associated with exposures to radionuclides in the IWCS, it is necessary to consider the risks associated with any additional radionuclides that may accompany them. The radionuclides of most concern in the IWCS are those from the three naturally occurring decay chains headed by U-238, U-235, and Th-232. The radionuclides in these three decay series are divided into principal and associated radionuclides as described in Section 2.2. The associated radionuclides are assumed to be in secular equilibrium with the principal radionuclides, as all of the associated radionuclides have half-lives of less than six months. This is also discussed in the Natural Decay Series fact sheet in Appendix C. The radionuclide cancer risk coefficients and DCFs given in Tables 4.1, 4.2, and 4.3 for the principal radionuclides include the contributions of the short-lived associated radionuclides.

5.1.2 Chemical Risks and Hazard Indexes

The standard approach for estimating chemical risks and HIs (EPA 1989, 2002, 2005a) is summarized below.

5.1.2.1 Carcinogenic Risks

The risk to an individual from exposure to a chemical carcinogen is expressed as the increased probability of getting cancer over a lifetime from the given exposure. For incidental ingestion, the risk is calculated by multiplying the estimated daily intake averaged over a lifetime by the chemical-specific SF. The EPA has developed these SFs to represent the incremental lifetime cancer risk per milligram of the chemical taken in per kilogram of body weight per day over an assumed lifetime of 70 years.

For inhalation, the EPA has established chemical-specific IURs to represent the risk per unit mass (in a unit volume of air inhaled, e.g., risk per $\mu g/m^3$ or mg/m^3. (For asbestos, the IUR is expressed as fibers per milliliter or cm^3 of air.) The IUR assumes continuous chronic exposure to the indicated concentration. Thus, it represents a very conservative estimator for the less-than-chronic exposures assessed in this TM. To calculate inhalation risk for a given chemical, its exposure concentration is multiplied by the IUR for that chemical to estimate the risk of getting cancer from continuous exposure to this concentration over a lifetime.

5.1.2.2 Hazard Quotients and Hazard Indexes

The HQ indicates the potential for adverse health effects other than cancer. For a given chemical, the daily oral (or dermal) intake averaged over the exposure period is divided by the RfD for that chemical to determine the HQ. The RfD is the average daily dose that can be incurred without an appreciable risk of deleterious health effects during a lifetime, including to sensitive subpopulations. Thus, dividing an estimated intake by this reference value provides an index that indicates where this intake lies compared to the “reliably safe” dose. A level above 1 simply indicates the estimated intake is higher than this

comparison level, which is conservative (protective) by design. (A common misconception is that simply being above the reference value translates to an adverse effect; the actual adverse effect level could be much higher.) Most available RfDs address chronic daily exposures that are assumed to extend at least seven years to a lifetime; a limited number of RfDs are available for subchronic exposures, which address daily intakes extending from two to seven years. Thus, comparing the incidental ingestion intakes in this TM with the reference values designed for daily exposure over extended durations could overestimate the potential for noncarcinogenic effects.

For inhalation, the EPA has established chronic RfCs that represent the concentration of a given chemical to which someone is continuously exposed for seven years to a lifetime without appreciable risk of deleterious effect. The exposure concentration in air for a given chemical is divided by this RfC to determine the HQ, to estimate the potential for a noncarcinogenic effect.

The individual HQs determined for each contaminant are then summed to determine the HI for each exposure route, and route-specific estimates are then combined as indicated by the given scenario to produce the total HI for the given hypothetical receptor. If an HI exceeds 1, this simply indicates the estimated intake or exposure level is higher than the "reliably safe" comparison level developed for average daily doses or exposure levels over a lifetime.

The total HI for an individual receptor could exceed 1 as a result of the presence of either (1) a single contaminant for which the HQ exceeds 1, or (2) several contaminants whose HQs sum to greater than 1. For the latter case, a more detailed analysis is conducted to determine whether the potential for a noncarcinogenic health effect has been overestimated by the total HI. In such cases, the major target organs and critical effects are considered, with supporting information from other (e.g., secondary) toxicological effects and mechanisms of action. Chemicals that affect the same organ or system are grouped separately from those that affect other organs or systems in a process referred to as segregating the HI. This segregation by endpoint produces estimates relevant to the affected organ, tissue, or system (to replace the initial estimate combined across all organs or systems). If the segregated HI is 1 or below, no adverse effects are indicated.

5.2 RESULTS

Example results for the radiological exposures evaluated in this TM are given in Section 5.2.1 (and Appendix A), and the chemical results are given in Section 5.2.2 (and Appendix B). Estimated concentrations of particulate matter and lead in air associated with waste excavation were also compared with the respective NAAQS limits (EPA 2011j, also see USACE [2011d]). Results indicate that all NAAQS limits would be met. Even for the estimates of emissions associated with uncontrolled excavation of the K-65 residues, the NAAQS for lead of 0.15 $\mu g/m^3$ (3-month average) would not be exceeded at the fenceline. An overview of the tables that present example estimates of doses and risks for the hypothetical exposures evaluated in this TM is provided in Table 5.1, to serve as a general roadmap for key tables in this report.

5.2.1 Estimated Radiological Doses and Risks

Estimated radiological doses and cancer risks for the six hypothetical receptors are given in Tables 5.2 and 5.3 for the three waste groups. The K-65 residues contain the highest concentrations of radionuclides of the materials being stored in the IWCS, and these are expected to represent the main focus of analyses in the FS and supporting documents, including the related evaluation of Rn-222 and its short-lived decay products (USACE 2012).

TABLE 5.1 Overview of Tables with Example Risk Estimates[a]

Table	Release Scenario	Contaminants	Media	Exposure Routes	Notes
Summary Results for the Six Hypothetical Receptors *(three onsite, three offsite)*					
5.2 *(D.1)*	Conceptual excavation: waste groups 1, 2 and 3	Radioactive particulates	Air	Inhalation	Provides the route-specific doses, risks, and HIs from particulate and Rn-222 gas releases for the three waste groups.
			Soil	Incidental ingestion	
				External gamma	
5.7 *(D.6)*		Chemical particulates	Air	Inhalation	
			Soil	Incidental ingestion	
5.3[b] *(D.2)*	Conceptual excavation: waste groups 1 and 2	Rn-222 gas and progeny	Air	Inhalation	
D.3[c]	Conceptual excavation: waste groups 1, 2 and 3 (no engineering controls)	Radionuclides: mainly Ra-226	Air	External Gamma	Results for conceptual excavation without any engineering controls limited to Appendix D.
D.4	Conceptual excavation: waste groups 1, 2 and 3 (no engineering controls)	Radioactive particulates, Rn-222 gas and progeny, and direct gamma radiation	Air	Inhalation	Combines the results from Tables D.1, D.2 and D.3.
			Soil	Incidental ingestion	
				External gamma	
5.6 *(D.5)*	Conceptual excavation: waste groups 1, 2 and 3	Radioactive contaminants and Rn-222 gas and progeny	Air	Inhalation	Combines the results in Tables 5.2 and 5.3 for the six receptors. For Appendix D, provides the information from Table D.4 in the same format as for Table 5.6.
			Soil, waste	Incidental ingestion	
				External gamma	
5.8 *(D.7)*	Conceptual excavation: waste groups 1, 2 and 3	Chemical contaminants	As for Table 5.7 *(D.6)*, plus direct incidental ingestion of waste		Presents results from Table 5.7 *(D.6)* in the same format as Table 5.6 *(D.5)*, including incidental waste ingestion.
6.2	Conceptual excavation: waste groups 1, 2 and 3	Radioactive contaminants	As for Table 5.6 *(D.5)*		Summarizes radiological doses and risks by waste group.
6.3 *(D.8)*	Conceptual excavation: waste groups 1, 2 and 3	Radioactive and chemical contaminants	As for Table 5.6 *(D.5)*		Combines the results of Table 5.6 (*D.5*) and Table 5.8 (*D.7*).
6.4 *(D.9)*	As for Table 6.3				Summarizes results from Table 6.3 (*D.8*) for the combined waste groups.
Additional Risk-Related Results and Information					
5.4	Four hypothetical cap breach events (from USACE [2012]); interim storage of exhumed residues	Radionuclides (other than Rn-222)	Wastes in place or in interim storage	External gamma	Considers worker and member of the public on or near the IWCS with a portion of the wastes uncovered.
5.5		Rn-222 gas and progeny		Inhalation	
6.1	Conceptual excavation: waste groups 1, 2 and 3	As for Table 6.3			Summarizes dose and risk estimates from previous reports.

[a] The tables in Chapters 5 and 6 provide preliminary risk estimates assuming standard engineering controls are used to minimize airborne emissions of particulates and Rn-222 gas. These estimates were largely duplicated in Appendix D, but in this appendix the results do not account for the use of any engineering controls. Where tables in Appendix D provide corresponding information, those table numbers are given in parentheses following the indicated tables for Chapters 5 and 6.

[b] The results provided in Table 5.3 address the entire inventory of Rn-222 gas in the interstitial spaces of the stored residues. Most of the Rn-222 inventory is associated with waste group 1 (K-65 residues), with waste group 2 accounting for most of the remainder.

[c] The external gamma radiation doses and risks associated with waste excavation at the IWCS are limited to the imaginary "uncontrolled" estimates in Appendix D. The conceptual engineering information needed to conduct comparable estimates for a more realistic (and representative) case in Chapter 5 is not yet available. When that information is developed as part of the planning process for the FS, calculations similar to those provided in Appendix D can be conducted at that time.

TABLE 5.2 Estimated Radiological Doses and Risks from Particulates Released during Waste Excavation[a]

Scenario[b]	Exposures Associated with Excavating the Three Waste Groups						Total for Excavating the Three Waste Groups	
	Inhalation of Particulates[c]		Incidental Ingestion[d]		External Gamma Radiation[d]			
	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk
***Waste Group 1:* K-65 Residues**								
Onsite: dispersed contaminants								
Remedial action worker	1.1	5×10^{-7}	0.0032	2×10^{-9}	6.3	5×10^{-6}	7.4	6×10^{-6}
Maintenance worker	23	1×10^{-5}	0.15	7×10^{-8}	1.8	1×10^{-6}	25	1×10^{-5}
Trespasser	0.27	1×10^{-7}	0.0036	2×10^{-9}	0.011	8×10^{-9}	0.29	1×10^{-7}
Offsite: dispersed contaminants								
Outdoor worker	0.059	2×10^{-8}	0.00075	4×10^{-10}	0.0088	7×10^{-9}	0.069	3×10^{-8}
Adult resident	0.021	9×10^{-9}	0.00033	2×10^{-10}	0.023	2×10^{-8}	0.045	3×10^{-8}
Child resident	0.021	9×10^{-9}	0.00033	2×10^{-10}	0.012	9×10^{-9}	0.033	2×10^{-8}
***Waste Group 2:* Other High-Activity Residues (L and F) and Tower Soils**								
Onsite: dispersed contaminants								
Remedial action worker	1.3	3×10^{-7}	0.0018	8×10^{-10}	2.6	2×10^{-6}	3.9	2×10^{-6}
Maintenance worker	21	5×10^{-6}	0.093	4×10^{-8}	0.81	6×10^{-7}	21	6×10^{-6}
Trespasser	0.23	6×10^{-8}	0.0021	1×10^{-9}	0.0045	4×10^{-9}	0.24	6×10^{-8}
Offsite: dispersed contaminants								
Outdoor worker	0.088	2×10^{-8}	0.00063	3×10^{-10}	0.0055	4×10^{-9}	0.095	3×10^{-8}
Adult resident	0.032	8×10^{-9}	0.00028	1×10^{-10}	0.014	1×10^{-8}	0.046	2×10^{-8}
Child resident	0.032	8×10^{-9}	0.00028	1×10^{-10}	0.0072	6×10^{-9}	0.039	1×10^{-8}
***Waste Group 3:* R-10 Pile and Other Contaminated Soils**								
Onsite: dispersed contaminants								
Remedial action worker	0.0048	1×10^{-9}	0.000021	1×10^{-11}	0.029	2×10^{-8}	0.034	2×10^{-8}
Maintenance worker	0.22	6×10^{-8}	0.0012	6×10^{-10}	0.0098	8×10^{-9}	0.23	7×10^{-8}
Trespasser	0.0023	6×10^{-10}	0.000026	1×10^{-11}	0.000052	4×10^{-11}	0.0023	7×10^{-10}
Offsite: dispersed contaminants								
Outdoor worker	0.0015	4×10^{-10}	0.000012	5×10^{-12}	0.000093	7×10^{-11}	0.0016	5×10^{-10}
Adult resident	0.00053	1×10^{-10}	0.0000051	2×10^{-12}	0.00025	2×10^{-10}	0.00078	3×10^{-10}
Child resident	0.00053	1×10^{-10}	0.0000051	2×10^{-12}	0.00012	1×10^{-10}	0.00066	2×10^{-10}

Notes for Table 5.2:

[a] These radiological doses and cancer risks are estimated for hypothetical exposures to airborne particulates released during waste excavation at the IWCS, assuming the use of standard emission controls. The radiation dose is the 50-year committed effective dose as described in Section 4.1.2, rounded to two significant figures. The cancer risk represents the probability of developing cancer over a lifetime from the assumed exposures, rounded to one significant figure. The particulate concentrations at the various receptor locations are estimated by the AERMOD computer code using local meteorological data as described in USACE (2011d) and summarized in Chapter 3 of this TM, based on early conceptual assumptions for waste excavation. Supporting details, including the contributions of individual radionuclides, are given in Appendix A. (Supplemental calculations that do not take credit for any emission controls are given in Appendix D; those calculations were performed to provide additional information to help guide FS planning for appropriate control measures.) The doses and risks estimated for these same six receptors from inhaling Rn-222 gas and its short-lived decay products released during excavation are given in Table 5.3. While this table addresses radioactive particulates released to air during waste excavation and then dispersed, further calculations consider example exposures to the wastes themselves at the IWCS, see footnote d and summary tables at the end of this chapter.

Potential doses and risks were also evaluated for additional locations beyond those summarized in this TM. Results for the representative offsite residential location highlighted in this table (and companion tables) bound the estimates for other nearby residential locations. To illustrate, the estimated doses and risks for the trailer park location are about 10% of the illustrative residential estimates shown here; the estimated airborne and deposited concentrations at the nearby schools are similar to those at the trailer park (so corresponding doses and risks would also be lower than the residential estimates shown here, noting the relatively smaller amount of time a person would spend at the school compared to at home during the construction season as evaluated in this TM).

[b] These hypothetical scenarios are described in Section 3.4.1 and summarized in Table 3.2. The onsite receptors (workers and trespasser) and offsite worker are only exposed outdoors, the latter three without any personal protection. In contrast, the adult and child resident are exposed to contaminants both indoors and outdoors.

[c] For onsite inhalation exposures, the airborne concentrations reflect the average of the maximum monthly concentrations (of the 32 months evaluated) at locations spaced 10 degrees apart for each receptor distance from the excavation area (totaling 36 locations for the remedial action worker and 72 locations for the other two receptors, see Section 3.4). For the offsite receptors, the airborne concentration represents the maximum monthly estimate for each location.

[d] The incidental ingestion and external gamma exposures address particulates released to air and then dispersed and deposited on surface soil, assumed to be uniformly distributed in the top 1 cm (0.4 in). The cumulative four-year deposition estimate from AERMOD is adjusted to the fraction of that overall duration assumed for excavating a given waste group, then scaled to the indicated contaminant concentrations in that group. The external gamma irradiation calculations are further normalized to the total number of hours in a year to align with the dose conversion factors for those exposures (see text for additional details). Beyond the example estimates shown above for dispersed and deposited contaminants following airborne releases during excavation, additional estimates are provided for exposures to the wastes themselves at the IWCS. Gamma radiation doses and risks from directly ingesting 100 mg (0.0035 ounce) of waste from each waste group are included in a subsequent table (see Table 5.6). Estimates for exposures to wastes at the IWCS from external gamma irradiation and from inhaling Rn-222 gas and progeny are given in the next set of tables (Tables 5.4 and 5.5, respectively). The gamma radiation doses associated with excavating the wastes from the IWCS are not quantified in the body of this TM (estimates in Table D.3 of Appendix D assume no shielding is used), because preliminary engineering information is not yet available for the FS alternatives outlining the conceptual approach for retrieving this waste (including the use of shielding). Such evaluations are expected to be incorporated in the FS when that information becomes available.

TABLE 5.3 Estimated Radiological Doses and Risks from Example Exposures to Rn-222 at the IWCS[a]

Scenario[b]	Rn-222 Concentration *(pCi/L)*[c]	Working-Level Ratio *(WLR)*[d]	Exposure *(WLM)*[e,f]	Dose *(mrem)*[g]	Cancer Risk[h]
Onsite					
Remedial action worker	250	0.11	0.017	9.4	9×10^{-6}
Maintenance worker	2.6	0.16	0.32	**180**	$\mathbf{2 \times 10^{-4}}$
Trespasser	0.78	0.22	0.0041	2.3	2×10^{-6}
Offsite					
Outdoor worker	2.3×10^{-2}	0.29	7.2×10^{-4}	0.41	4×10^{-7}
Adult resident	2.1×10^{-2}	0.30	5.0×10^{-4}	0.37	3×10^{-7}
Child resident	2.1×10^{-2}	0.30	5.0×10^{-4}	0.37	3×10^{-7}

[a] The estimated exposure levels and cancer risks in this table are limited to Rn-222 and its short-lived decay products from hypothetical releases associated with disturbance (including from excavation) of the higher-activity residues (groups 1 and 2) from the IWCS. The total Rn-222 release is conservatively estimated to be 180 Ci (see Section 3.3.2). About 95% of this total is associated with the K-65 residues (which are assumed to be excavated in one season) and the remaining 5% is attributable to waste group 2 (which is assumed to be excavated in about two-thirds of a season). Given the small fraction contributed by waste group 2 and the estimate of annual doses and risks for this calculation (because nearly all the Rn-222 is released in one construction season), the effect of extending the exposures over a slightly longer period is inconsequential. The estimate in bold exceeds the comparison level from the NCP.

[b] These scenarios are described in Section 3.4. The maintenance worker and trespasser are assumed to spend 10% of the time 1 m (3 ft) from the exposed wastes, and 90% of the time at distances of 50 m (160 ft) and 100 m (330 ft), respectively. The Rn-222 concentrations and WLRs shown above for the maintenance worker and trespasser are for the farther distances of 50 m (160 ft) and 100 m (330 ft), because the values at 1 m are the same as those given for the remedial action worker. For the offsite residential receptors, the exposure levels, doses, and risks account for the time spent outdoors and indoors. As described in footnote a of Table 5.2, corresponding estimates at the trailer park are about a tenth of those shown for the example residential location in this table.

[c] The Rn-222 concentrations are based on an estimated Rn-222 release rate of 3.7×10^{7} pCi/s (see Section 3.3.2), with subsequent dispersion modeled by AERMOD as described in USACE (2011d) and Chapter 3. For onsite exposures, the concentrations are the average of the maximum monthly concentrations (of the 32 months evaluated), across locations spaced 10 degrees apart around the excavation area at the respective distances for each receptor. For offsite exposures, the concentration represents the maximum monthly concentrations at those example receptor locations.

[d] The WLR is a function of distance from the release point (assumed to be at the center of the exposed area) to the hypothetical receptor (see Figure 4.1). As a point of reference, the WLR for indoor Rn-222 exposures is estimated to be about 0.40 for naturally occurring radon in the environment, with somewhat higher values reported for outdoor exposures (NCRP 2009).

[e] Estimated exposures in WLM are given to two significant figures and are calculated as described in Section 4.1.2. That is, the radon decay product concentration (in WL) is the product of the Rn-222 concentration (in pCi/L) and the WLR divided by 100. The exposure (in WLM) is the product of the WL and length of exposure in working months, which is taken to be 170 hours. The exposure durations for the various scenarios are given in Table 3.2.

[f] The ICRP assumed an inhalation rate of 1.2 m^3/hr when developing risk-related information for exposures to Rn-222 progeny (ICRP 1981). For scenarios in this TM that assume an inhalation rate higher than 1.2 m^3/hr, the estimated exposure (in WLM) was multiplied by the ratio of the assumed inhalation rate to 1.2 m^3/hr to account for the greater intakes by these hypothetical individuals. This adds conservatism to the example estimates presented in this TM.

[g] Estimated doses are given to two significant figures and are calculated as the 50-year committed effective dose using a factor of 570 mrem/WLM for outdoor exposures and 760 mrem/WLM for indoor exposures, as discussed in Section 4.1.2.

[h] Estimated risks are given to one significant figure and are estimated from the exposures in WLM using the risk factor of 5.38×10^{-4} cancers/WLM, as given in Section 4.1.3.

Table 5.2 presents the radiation doses and cancer risks for inhalation of radioactive airborne particulates (PM_{10}), and for incidental ingestion and external gamma irradiation from particulates estimated to then deposit on surface soil. More detailed information is given in Appendix A, including the radionuclide-specific contributions to the doses and risks. These estimates do not reflect radioactive decay because the radionuclides have very long half-lives compared to the time frame assessed in this TM.

Table 5.3 presents the radiation doses and cancer risks associated with Rn-222 releases from wastes at the IWCS. These results reflect Rn-222 releases from all wastes with high Ra-226 concentrations, principally the high-activity residues. Most of the dose and risk (about 95%) is attributable to the K-65 residues, and essentially all of the rest is from the L-30 residues and tower soils (see Table 2.2 for the Ra-226 inventory in the IWCS materials). These doses and risks are largely due to the short-lived radioactive progeny of Rn-222; these results are presented separately (in this table) from those for particulates because the underlying calculation differs significantly (see Chapter 4). The same approach used to evaluate the dispersion and deposition of particulates from airborne emissions was also used to assess the dispersion of Rn-222 and its decay products. This common approach assures consistency in assessing the relative impacts of these two types of airborne emissions, i.e., solid radioactive particulates and Rn-222 gas.

The doses associated with radioactive particulates released during excavation of the K-65 residues (group 1) summarized in Table 5.2 range from 0.033 to 25 mrem. These doses are largely from inhalation of airborne particulates (not including Rn-222 progeny which are given in Table 5.3); incidental ingestion of contaminated soil from surface-deposited radionuclides and external gamma radiation from that soil are relatively minor contributors to this dose and risk. The hypothetical maintenance worker receives the highest dose due to this receptor's proximity to the IWCS and the amount of time assumed to be spent close to the exposed wastes without protection. The radiation doses for the three offsite receptors are all less than 0.1 mrem. Given the conservative assumptions incorporated in these calculations, excavating the K-65 residues is not expected to pose any significant radiation concern to any offsite receptor from these combined pathways.

The radiological risks estimated for the six receptors from excavating the K-65 residues are also shown in Table 5.2. Ranging from 2×10^{-8} to 1×10^{-5}, the risks for all onsite receptors from exposures to these particulates from the K-65 residues are within or below the NCP comparison level of 1×10^{-6} to 1×10^{-4}. As described for the doses, the highest risk estimate is for the hypothetical onsite maintenance worker (for whom no respiratory protection is assumed). The risks for all hypothetical offsite receptors are all well below this range.

The doses and risks for the other waste groups (2 and 3) are comparable to or lower than those for the K-65 residues, largely due to the lower concentrations of radionuclides in these two groups relative to waste group 1. The doses and risks for waste group 2 are comparable to those for the K-65 residues because a substantially lower control efficiency was assumed for these wastes than for waste group 1. This lower control efficiency largely offsets the lower radionuclide concentrations in waste group 2, such that the results are generally the same as those calculated for waste group 1 (the K-65 residues). The doses and risks for waste group 3 are about a factor of 100 lower than those calculated for waste group 2.

As shown in Table 5.3, the radiation doses from Rn-222 releases range from 0.37 to 180 mrem, and the risks range from 3×10^{-7} to 2×10^{-4}. As described for the released particulates, the highest estimates are for the maintenance worker because of the amount of time this individual is assumed to spend near the IWCS without any protection. The cancer risk and radiological dose estimated for the maintenance worker exceed the target range indicated in the NCP and the dose limit for worker protection, respectively, while the risks for the offsite scenarios are all below the comparison range.

The radiation doses and cancer risks associated with inhalation of Rn-222 and its short-lived decay products for these six scenarios are higher than those estimated for particulate releases. This is as expected, given the very high concentrations of Ra-226 in the K-65 residues. The release of Rn-222 gas is assumed to be controlled by an engineered system during excavation of the high-activity residues (including the K-65 residues), and the efficiency of this control system is assumed to be 90%. A higher control efficiency may be necessary to minimize radiation doses to workers (and possibly nearby members of the public) from this radionuclide if these residues are excavated from the IWCS.

In addition to the exposures considered for the six hypothetical receptors, it is possible that someone could be exposed for a relatively short time to external gamma radiation from the wastes in place at the IWCS. Exposures could occur if the IWCS cap were unintentionally breached or its integrity were compromised (such as by a burrowing animal). Estimated radiation doses and risks associated with several such scenarios are summarized in Table 5.4. These estimates were developed using the results obtained from the MicroShield and MicroSkyshine computer codes given in Section 4.1.4, for the specific exposure situations hypothesized in this table. These scenarios are not meant to address all situations that might occur, but rather to provide an illustrative range of potential exposure conditions to help support planning for the FS. Additional exposure situations could be reflected in the FS using the general approach presented in this TM.

For an onsite worker, the external gamma radiation doses could exceed 1,000 mrem (1 rem) within a number of days or a few weeks if the K-65 residues were uncovered (e.g., by an earthquake) or if they were removed and stockpiled without shielding controls (e.g., during excavation) and someone were standing very close to the exposed wastes during this period. A number of breach scenarios could result in doses exceeding occupational limits, and dose limits for the general public could also be exceeded if anyone ventured near the IWCS while the wastes were uncovered. The direct gamma radiation doses and risks are much higher than the indirect doses from skyshine radiation, so shielding will likely be necessary when working with the high-activity residues. The radiation dose from skyshine radiation is generally less than 1% of that from direct radiation when both pathways exist. Some of these exposures could result in incremental cancer risks exceeding 1×10^{-4}, the upper end of the NCP target range that serves as a point of comparison for the illustrative estimates in this TM.

It is important to note that the exposure times used in these illustrative calculations are quite limited, and the radiation dose and cancer risk would increase with greater exposure durations. If such high dose rates were actually measured during the excavation, shielding would be used to reduce worker exposures. The doses and risks associated with the other wastes in the IWCS would be considerably lower because the concentrations of Ra-226 are lower. This is not meant to imply that those wastes do not represent a health hazard, only that the relative hazard is lower than that for the high-activity residues.

The radiation doses and cancer risks from inhalation of Rn-222 progeny would likely be somewhat lower than those from external gamma radiation, but could be comparable. That is, if the cap were breached, Rn-222 gas could be released to the environment resulting in additional short-term exposures. The hypothetical situations under which such exposures could occur are presented in USACE (2012), along with associated release rates. Based on those release rates, the concentrations of Rn-222 at the various receptor locations were estimated using the EPA computer code AERMOD (as described in USACE [2011d]), and the resulting estimates of radiation doses and risks are given in Table 5.5. The method used to calculate the radiation doses and cancer risks from these elevated Rn-222 concentrations is presented in Sections 4.1.2 and 4.1.3. As described above for the external gamma evaluations, these estimates simply indicate potential impacts of illustrative cap breach scenarios; they do not address all possible situations in which Rn-222 gas might be released from the IWCS; rather, they provide examples that can be used to guide upcoming planning for the FS.

TABLE 5.4 Estimated Radiological Doses and Risks from Example Exposures to External Gamma Radiation from Hypothetical Cap Breach Events[a]

Breach Event[b]	Result of Event[b]	Exposure Scenario	Distance from Source *(m)*	Nature of Radiation[c]	Exposure Time *(hr)*	Dose *(mrem)*	Risk
Earthquake fractures cap	390 m^2 K-65 residues exposed	Worker repairs fracture[d]	1	Direct	40	**8,300**	**7×10^{-3}**
		Member of public is onsite during repair	50	Scattered	40	1.9	2×10^{-6}
Cap is damaged by equipment	69 m^2 K-65 residues exposed	Worker repairs cap[e]	10	Direct	40	**320**	**3×10^{-4}**
		Member of public is onsite during repair	50	Scattered	40	1.7	1×10^{-6}
Equipment drills into K-65 residues	15-cm (6-in.) diameter hole in K-65 residues	Worker stands near drill tailings[f]	1	Direct	20	**1,000**	**8×10^{-4}**
		Worker stands 10 m from drill hole	10	Scattered	20	6.1×10^{-7}	5×10^{-13}
		Member of public is onsite during drilling	50	Scattered	20	8.3×10^{-8}	7×10^{-14}
Animal burrows into K-65 residues	0.3-m (1-ft) diameter hole to K-65 residues	Worker repairs hole[f]	10	Direct	8	14	1×10^{-5}
K-65 residues are exhumed and placed near IWCS	100-m^3 mound of exposed K-65 residues	Worker is near excavated mound	10	Direct	80	**2,600**	**2×10^{-3}**
		Offsite person is working outside near NFSS	100	Direct	80	24	2×10^{-5}
		Member of public is onsite during action	50	Direct	80	**110**	9×10^{-5}
L-30 residues are exhumed and placed near IWCS	100-m^3 of exposed L-30 residues	Worker is near excavated mound	10	Direct	80	59	5×10^{-5}
F-32 residues are exhumed and placed near IWCS	100-m^3 of exposed F-32 residues	Worker is near excavated mound	10	Direct	80	1.5	1×10^{-6}
L-50 residues are exhumed and placed near IWCS	100-m^3 of exposed L-50 residues	Worker is near excavated mound	10	Direct	80	16	1×10^{-5}
R-10 pile is exhumed and placed near IWCS	100-m^3 of exposed R-10 pile	Worker is near excavated mound	10	Direct	80	0.47	4×10^{-7}

[a] These radiation doses and cancer risks are limited to external gamma irradiation associated with a range of hypothetical conditions above. The estimated doses are given to two significant figures and represent the 50-year committed effective dose as described in Section 4.1.2. The risks are given to one significant figure and are estimated from the radiation doses using a risk factor of 8×10^{-7} cancers per mrem as described in Section 4.1.3. Numbers may not sum exactly due to rounding. Estimates in bold exceed the comparison levels used in this TM, i.e., annual dose limits for workers and the public (USACE 1997), and the NCP target risk range.

[b] The initiating events and the resulting effects for the first four entries are based on information in USACE (2012).

[c] The type of radiation is either direct or scattered (skyshine) gamma radiation as described in Section 4.1.4.

[d] For this scenario, the results of the MicroShield calculations for a volume of 1 m^3 (1.3 yd^3) was used to calculate the radiation dose and cancer risk. The actual volume of exposed K-65 residues is expected to be less than 1 m^3 and consists of a crack 50-m (160-ft) long that exposes the K-65 residues. A distance of 10 m (33 ft) from the source to the receptor is assumed to better reflect the actual geometry, i.e., an individual standing close to a long linear source located 3.8 m (13 ft) beneath the ground surface.

[e] For this scenario, the results of the MicroShield calculations for a volume of 10 m^3 (13 yd^3) are used to calculate the radiation dose and cancer risk.

[f] For these scenarios, the results of the MicroShield calculations for a volume of 1 m^3 (1.3 yd^3) are used to calculate the radiation dose and cancer risk.

TABLE 5.5 Estimated Radiological Doses and Risks from Example Exposures to Rn-222 Decay Products from Hypothetical Cap Breach Events[a]

Cap Breach Event	Rn-222 Release Rate *(pCi/s)*[b]	Exposure Scenario	Distance from Release *(m)*[c]	Rn-222 Conc. *(pCi/L)*[d]	WLR[e]	Exposure Time *(hr)*	Dose *(mrem)*[f]	Risk[g]
Earthquake fractures cap	1.8×10^6	Worker repairs fracture	1	17	0.10	40	2.3	2×10^{-6}
	1.8×10^6	Member of public is onsite during repair	50	0.15	0.16	40	0.032	3×10^{-8}
Heavy equipment damages cap	1.8×10^7	Worker repairs cap	10	16	0.12	40	2.5	2×10^{-6}
	1.8×10^7	Member of public is onsite during repair	50	1.3	0.16	40	0.28	3×10^{-7}
Exploratory drilling into K-65 residues	6.2×10^5	Worker stands next to drill hole	1	49	0.10	50	8.2	8×10^{-6}
	6.2×10^5	Worker stands near drill hole	10	1.2	0.11	20	0.090	9×10^{-8}
	6.2×10^5	Member of public is onsite during drilling	50	0.054	0.16	20	0.0056	5×10^{-9}
Animal burrowing into K-65 residues	1.4×10^5	Worker repairs hole	10	0.27	0.11	8	0.0082	8×10^{-9}
Releases from Residues and the R-10 Pile *(based on an assumed exposed area of 100 m² [120 yd²] as given in USACE [2012])*								
K-65 residues[h]	2.7×10^7	Worker is near exposed residues at IWCS	10	24	0.12	80	7.5	7×10^{-6}
	2.7×10^7	Offsite person is working outside near NFSS	100	0.57	0.22	80	0.33	3×10^{-7}
	2.7×10^7	Member of public is onsite during activities	50	1.9	0.16	80	0.83	8×10^{-7}
L-30/F-32 residues[h]	9.9×10^5	Worker is near exposed residues at IWCS	10	0.87	0.12	80	0.27	3×10^{-7}
L-50 residues[i]	1.7×10^5	Worker is near exposed residues at IWCS	10	0.15	0.12	80	0.048	4×10^{-8}
R-10 pile[i]	4.9×10^3	Worker is near exposed wastes at IWCS	10	0.0043	0.12	80	0.0014	1×10^{-9}

[a] The estimated radiation doses and cancer risks in this table are limited to exposures to Rn-222 and its short-lived decay products for a range of initiating events and Rn-222 release rates given in USACE (2012); these estimates address scenarios described in that document, which assume no controls.

[b] The Rn-222 release rates for the cap breach events are taken from Section A.2.2 of USACE (2012), and the release rates for the residues and the R-10 pile are based on the flux estimates and Ra-226 concentrations for these materials given in USACE (2012), for an area of 100 m² (120 yd²).

[c] The distance represents the distance from the edge of the exposed area to the hypothetical receptor.

[d] The Rn-222 concentrations were calculated using AERMOD as described in USACE (2011d), consistent with the approach used to model airborne particulates.

[e] The WLR is a function of distance from the release point (assumed to be at the center of the exposed area) to the hypothetical receptor (see Figure 4.1). For the earthquake event, a distance of 10 m (33 ft) from the source to the receptor was used to calculate the WLR for the 1-m (3-ft) distance scenario to better reflect the actual geometry.

[f] Estimated doses are given to two significant figures and represent the 50-year committed effective dose and are calculated from the exposure in WLM using a factor of 570 mrem/WLM for outdoor exposures, as discussed in Section 4.1.2. The doses and cancer risks given in this table were not adjusted to account for different inhalation rates from that assumed by the ICRP in Publication 32 (ICRP 1981) because the specific inhalation rates for these hypothetical receptors are not known.

[g] Estimated risks are given to one significant figure and were estimated from the exposures in WLM using the risk factor of 5.38×10^{-4} cancers/WLM as given in Section 4.1.3.

[h] Based on the radon fluxes for the K-65 residues and the combined L-30 and F-32 residues, as given in Tables A-1 and A-3 of USACE (2012), respectively.

[i] The radon release rates were calculated by multiplying the release rate from the K-65 residues by the ratios of the Ra-226 concentrations in the residues from Table 2.2.

The highest dose for the hypothetical events evaluated in this TM (shown in Table 5.5) is 8.2 mrem, and the corresponding risk is 8×10^{-6}. The example estimates of doses and risks associated with Rn-222 releases further demonstrate that if the K-65 residues (group 1) or other high-activity residues (group 2) were uncovered, the doses and corresponding risks from inhaling Rn-222 and its progeny could be quite high.

These estimates illustrate that if the remedy selected for the IWCS OU involves excavating or otherwise disturbing the residues, stringent controls would be warranted to protect against external gamma radiation (e.g., by time, distance, and shielding) and to control Rn-222 releases. Engineering controls would especially be needed for the K-65 residues because of the high Ra-226 concentrations in these wastes. As described for the external gamma radiation results, the doses and cancer risks for Rn-222 from the K-65 residues are much higher than for the other residues because of the higher concentrations of Ra-226 in these wastes. For each receptor, the estimates for exposures to particulates can be summed with those for Rn-222 to produce the total radiological doses and cancer risks, as described below. Example estimates of the total radiation doses and cancer risks associated with excavating all the wastes from the IWCS are given in Table 5.6. The estimates provided for the three waste groups in this TM reflect early conceptual assumptions, pending the development of project-specific information for the FS.

Waste group 1 consists of the K-65 residues; waste group 2 consists of the L-30, F-32, L-50 residues, and the tower soils; and waste group 3 consists of the former R-10 pile and the remaining contaminated soils currently in the IWCS (see Table 2.2 for the volumes of these various materials). These three groupings used to estimate example doses and risks for six hypothetical receptor scenarios in this TM should not be construed as indicating the manner in which the IWCS contents would ultimately be grouped for purposes of developing and analyzing alternatives in the FS. These groupings simply reflect early conceptual assumptions to support the example calculations in this TM, to serve as a technical resource that illustrates the process by which representative risks can be calculated in the upcoming FS, when project-specific information is available.

The radiation doses and cancer risks illustrated for waste group 1 in Table 5.6 combine the results from Tables 5.2 and 5.3. Because the K-65 residues contain about 95% of the Ra-226 inventory in the IWCS, the doses and risks in Table 5.3 are multiplied by 0.95 and added to the corresponding values for inhalation of particulates in Table 5.2. A similar approach is used for waste group 2, except that the contributions from Rn-222 and its short-lived decay products are multiplied by 0.05 and added to the corresponding values for particulate emissions. Note that the same computer model (AERMOD) was used to model the atmospheric dispersion of both particulate emissions and releases of Rn-222 gas for this TM to assure internal consistency in these example estimates.

As described in Chapter 3 (and highlighted in Table 3.3), an excavation source area of 500 m^2 (600 yd^2) is assumed for waste group 1; an area of 1,000 m^2 (1,200 yd^2) is assumed for waste group 2; and 2,000 m^2 (2,400 yd^2) is assumed for waste group 3. For waste group 1, an emission control efficiency of 99% is assumed for particulates and 90% is assumed for the Rn-222 control efficiency. For waste groups 2 and 3, a control efficiency of 75% is used for particulate emissions; the Rn-222 emissions from waste group 2 are assumed to be reduced by a factor of 10, consistent with the approach assumed for waste group 1. These assumptions for source areas and control efficiencies are considered reasonable but conservative, as a general basis for framing the illustrative estimates in this TM of airborne releases and dispersion associated with waste excavation at the IWCS. That is, larger areas would be considered reasonable for materials with lower levels of contamination, to accommodate more and larger equipment and improve operational efficiencies.

TABLE 5.6 Estimated Radiological Doses and Risks from Excavation Releases and Direct Waste Exposures at the IWCS[a]

Scenario	Estimated Radiological Doses and Cancer Risks							
	***Group 1*: K-65 Residues**		***Group 2*: Other High-Activity Residues (L and F) and Tower Soils**		***Group 3*: R-10 Pile and Other Contaminated Soils**		***Total* Combined Wastes**	
	Dose *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	16	1×10^{-5}	4.4	3×10^{-6}	0.034	2×10^{-8}	21	2×10^{-5}
Maintenance worker	**200**	$\mathbf{2 \times 10^{-4}}$	31	1×10^{-5}	0.23	7×10^{-8}	**230**	$\mathbf{2 \times 10^{-4}}$
Trespasser	2.5	2×10^{-6}	0.35	2×10^{-7}	0.0023	7×10^{-10}	2.9	2×10^{-6}
Offsite: dispersed contaminants								
Outdoor worker	0.46	4×10^{-7}	0.11	5×10^{-8}	0.0016	5×10^{-10}	0.57	4×10^{-7}
Adult resident	0.40	3×10^{-7}	0.065	3×10^{-8}	0.00078	3×10^{-10}	0.47	3×10^{-7}
Child resident	0.39	3×10^{-7}	0.058	3×10^{-8}	0.00066	2×10^{-10}	0.45	3×10^{-7}
Onsite: direct waste exposures[b]								
External gamma (8 hr)	**2,000**	$\mathbf{2 \times 10^{-3}}$	38	3×10^{-5}	0.13	1×10^{-7}	**2,000**	$\mathbf{2 \times 10^{-3}}$
Incidental ingestion (100 mg)	**430**	$\mathbf{2 \times 10^{-4}}$	11	5×10^{-6}	0.041	2×10^{-8}	**440**	$\mathbf{2 \times 10^{-4}}$
Combined direct exposures	***2,400***	$\mathbf{2 \times 10^{-3}}$	*49*	4×10^{-5}	*0.17*	1×10^{-7}	***2,500***	$\mathbf{2 \times 10^{-3}}$

[a] The illustrative estimates of total doses and risks presented here are associated with excavating all wastes placed in the IWCS by DOE. The radiation dose is the 50-year committed effective dose and is given to two significant figures. The risk represents the probability that an exposed individual will develop cancer during their lifetime from the assumed exposures and is rounded to one significant figure. Numbers may not sum exactly due to rounding. Estimates in bold exceed the comparison levels from the NCP. The volumes of the wastes comprising each group are given in Table 2.2. The scenarios are described in Section 3.4.1, and exposure factors are summarized in Table 3.2. Table 3.3 highlights excavation assumptions, including the areas assumed to estimate particulate emissions and the control efficiencies assumed for particulates and Rn-222. (Note that no Rn-222 control is assumed for waste group 3 because of its low Ra-226 inventory.) As indicated in the footnotes of Tables 5.2 and 5.3, results shown for the example offsite residential location in this table bound (account for) corresponding estimates at other nearby residential locations.

The doses and risks for waste group 1 (K-65 residues) represent the sum of the doses and risks given in Table 5.2 (for inhalation, ingestion, and external gamma radiation from released particulates) and Table 5.3 (for inhalation of Rn-222 progeny). Because the K-65 residues contain about 95% of the total Ra-226 inventory in the IWCS (see Table 1-1 of USACE [2007a]), the doses and risks in Table 5.3 are multiplied by 0.95 and added to the corresponding inhalation doses and risks given in Table 5.2. Most of the estimated dose and risk is from inhalation of Rn-222 progeny. Weighted average concentrations of contaminants in waste groups 2 and 3 are used to calculate the concentrations of airborne and deposited particulates at the six receptor locations, and the associated doses and risks are given in Table 5.2. For waste group 2, the doses and risks for Rn-222 given in Table 5.3 are multiplied by 0.05 and added to the corresponding values for particulates because these materials contain about 5% of the total Ra-226 inventory in the IWCS. For waste group 3, the doses and risks are limited to those from radioactive particulates because the contribution from Rn-222 progeny would be very low, given the low inventory of Ra-226 in these wastes.

[b] If someone stood 1 m (3 ft) from a 10-m^3 (13-yd^3) mound of unshielded K-65 residues for 8 hours, they would incur an external gamma dose of about 2,000 mrem (2 rem), which corresponds to a risk of 2×10^{-3}. The doses and risks for the other two waste groups are scaled from their Ra-226 concentrations relative to that in the K-65 residues. If someone inadvertently (incidentally) ingested 100 mg (0.0035 ounce) of the K-65 residues directly, the dose would be 430 mrem and the corresponding risk would be 2×10^{-4}. The doses and risks for the other two waste groups are calculated based on the volume-weighted average radionuclide concentrations in the component wastes.

As summarized in Table 5.6, for the three onsite receptors, the radiation doses estimated for excavating all wastes from the IWCS range from 2.9 to 230 mrem, and the corresponding risks range from 2×10^{-6} to 2×10^{-4}. The highest dose and risk are for the maintenance worker (for whom no respiratory protection equipment is assumed), with the risk just above the target comparison level from the NCP. In contrast, the radiation doses at all three of the offsite receptor locations are all less than 1 mrem, and the cancer risks are below the NCP target range. These estimates indicate that stringent engineering controls will be needed to minimize exposures to workers and other onsite individuals at NFSS if the remedy selected for the IWCS involves excavating the K-65 residues or other high-activity residues from the IWCS. That is, releases and exposures can be controlled to safe levels using established engineering and other worker protection measures. (Supplemental estimates for the imaginary case that assumes wastes are excavated without any engineering controls are presented in Appendix D; those estimates also indicate that offsite doses and risks would be below the NCP target comparison levels.)

The inhalation pathway is the dominant contributor to the doses and risks for all six receptors, primarily from Rn-222 and its radioactive progeny. In addition, although the doses and risks associated with external gamma irradiation for these six receptors are generally low (see Table 5.2), it should be noted that these estimates are limited to those from exposures to particulates from airborne releases that are then deposited on surface soil. The direct and indirect (skyshine) component of the gamma radiation emitted by these residues and wastes as they are retrieved will likely produce an elevated radiation field in the vicinity of the IWCS. To reduce the extent of this radiation field, the open excavation area should be kept as small as practical, and fixed and portable shielding should be used as necessary. While the major concern is the direct radiation, exposures from indirect (skyshine) radiation should not be ignored.

Similarly, direct ingestion of wastes from the IWCS would result in substantial radiation doses and cancer risks. The dose to someone who inadvertently ingests 100 mg (0.0035 ounce) of K-65 residues (e.g., from wiping their mouth with a contaminated glove during waste excavation) would be about 430 mrem, and the corresponding risk would be 2×10^{-4}. The dominant contributor is lead-210 (accounting for more than 85% of the dose and risk), with much of this contribution associated with its decay product polonium-210; Ra-226 contributes most of the remainder. The doses and risks from incidentally ingesting other IWCS wastes would be lower. For example, the radiation doses from ingesting 100 mg (0.0035 ounce) of wastes from groups 2 and 3 are estimated to be 11 mrem and 0.041 mrem, respectively. The corresponding risks are 5×10^{-6} and 2×10^{-8} (which are within and below the NCP risk range).

These estimates reinforce the importance of stringent health physics controls (including face masks and other protective measures) when working with the residues – in particular the K-65 residues – to minimize the likelihood of any such exposure. Table 5.6 includes the doses and risks associated with this direct exposure to wastes at the IWCS, in addition to results for combined exposures away from the IWCS due to inhalation of airborne contaminants and incidental ingestion of contaminated surface soil. In fact, to understand the importance of engineering controls when the IWCS wastes are uncovered, the estimated exposures and risks in this TM can be scaled upward by factors that offset the emission controls assumed for both radon and particulates for the respective waste groups (e.g., multiplying by 100 to estimate exposures and risks to particulates from the K-65 wastes). Absent engineering controls, estimated risks would be substantially higher. These results are presented in Appendix D.

5.2.2 Estimated Chemical Risks and Potential for Noncarcinogenic Effects

The example estimates of pathway-specific chemical risks and HIs from airborne particulates released during waste excavation are provided in Table 5.7. Estimates for combined exposures to these particulates and from incidentally ingesting waste at the IWCS are given in Table 5.8.

TABLE 5.7 Estimated Chemical Hazard Indexes and Risks from Particulates Released during Waste Excavation[a]

Hypothetical Receptor	Exposure Route				Total Hazard Index and Risk	
	Inhalation of Particulates		Incidental Ingestion			
	Hazard Index	Risk	Hazard Index	Risk	Hazard Index	Risk
***Waste Group 1:* K-65 Residues**						
Onsite: dispersed contaminants						
Remedial action worker	0.00018	5×10^{-10}	0.000015	1×10^{-9}	0.0002	2×10^{-9}
Maintenance worker	0.0038	1×10^{-8}	0.0000021	2×10^{-10}	0.004	1×10^{-8}
Trespasser	0.000048	1×10^{-10}	0.0000019	2×10^{-10}	0.00005	3×10^{-10}
Offsite: dispersed contaminants						
Outdoor worker	0.0000097	3×10^{-11}	0.000000010	9×10^{-13}	0.00001	3×10^{-11}
Adult resident	0.0000056	1×10^{-11}	0.0000000032	3×10^{-13}	0.000006	2×10^{-11}
Child resident	0.0000056	1×10^{-11}	0.000000030	2×10^{-12}	0.000006	2×10^{-11}
***Waste Group 2:* Other High-Activity Residues (L and F) and Tower Soils**						
Onsite: dispersed contaminants						
Remedial action worker	0.038	2×10^{-8}	0.00028	9×10^{-9}	0.04	3×10^{-8}
Maintenance worker	0.61	3×10^{-7}	0.000044	1×10^{-9}	0.6	3×10^{-7}
Trespasser	0.0072	3×10^{-9}	0.00011	1×10^{-9}	0.007	5×10^{-9}
Offsite: dispersed contaminants						
Outdoor worker	0.0026	1×10^{-9}	0.00000030	1×10^{-11}	0.003	1×10^{-9}
Adult resident	0.0015	7×10^{-10}	0.000000093	3×10^{-12}	0.002	7×10^{-10}
Child resident	0.0015	7×10^{-10}	0.00000087	3×10^{-11}	0.002	8×10^{-10}
***Waste Group 3:* R-10 Pile and Other Contaminated Soils**						
Onsite: dispersed contaminants						
Remedial action worker	0.00027	7×10^{-10}	0.00038	1×10^{-8}	0.0006	2×10^{-8}
Maintenance worker	0.012	3×10^{-8}	0.000065	3×10^{-9}	0.01	3×10^{-8}
Trespasser	0.00013	3×10^{-10}	0.000059	2×10^{-9}	0.0002	2×10^{-9}
Offsite: dispersed contaminants						
Outdoor worker	0.000081	2×10^{-10}	0.00000062	2×10^{-11}	0.00008	2×10^{-10}
Adult resident	0.000047	1×10^{-10}	0.00000020	8×10^{-12}	0.00005	1×10^{-10}
Child resident	0.000047	1×10^{-10}	0.0000018	7×10^{-11}	0.00005	2×10^{-10}

[a] These illustrative HIs and cancer risks are estimated for particulates released during excavation of the three waste groups from the IWCS. The HI is a measure of the potential for noncarcinogenic health effects, with a value above 1 indicating a potential concern. The risk represents the probability of developing cancer over a lifetime as a result of the assumed exposure. Numbers may not sum exactly due to rounding. Risks are rounded to one significant figure, the route-specific HIs are rounded to two significant figures (to limit internal rounding errors), and the total HIs are rounded to one significant figure. The scenarios and approaches for estimating particulate concentrations in air and soil are as described for the radionuclides in the text and summarized in Table 5.2.

As indicated in the footnotes of Tables 5.2, 5.3, and 5.6, results shown for the example offsite residential location in this table bound (account for) corresponding estimates at other nearby residential locations.

TABLE 5.8 Estimated Chemical Hazard Indexes and Risks from Excavation Releases and Direct Waste Exposures at the IWCS[a]

Scenario	Estimated Chemical Hazard Indexes and Cancer Risks							
	Waste Group 1		***Waste Group 2***		***Waste Group 3***		***Total***	
	K-65 Residues		**L-30, F-32, L-50 Residues and Tower Soils**		**R-10 Pile and Other Contaminated Soils**		**Combined Wastes**	
	Hazard Index	**Risk**	**Hazard Index**	**Risk**	**Hazard Index**	**Risk**	**Hazard Index**	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	0.00019	2×10^{-9}	0.038	3×10^{-8}	0.00065	2×10^{-8}	0.04	4×10^{-8}
Maintenance worker	0.0038	1×10^{-8}	0.61	3×10^{-7}	0.012	3×10^{-8}	0.6	3×10^{-7}
Trespasser	0.000050	3×10^{-10}	0.0073	5×10^{-9}	0.00019	2×10^{-9}	0.008	8×10^{-9}
Offsite: dispersed contaminants								
Outdoor worker	0.0000098	3×10^{-11}	0.0026	1×10^{-9}	0.000082	2×10^{-10}	0.003	2×10^{-9}
Adult resident	0.0000056	2×10^{-11}	0.0015	7×10^{-10}	0.000047	1×10^{-10}	0.002	9×10^{-10}
Child resident	0.0000056	2×10^{-11}	0.0015	8×10^{-10}	0.000049	2×10^{-10}	0.002	1×10^{-9}
Onsite: direct waste exposure[b]								
Incidental ingestion (100 mg)	**10**	$\mathbf{8 \times 10^{-4}}$	**9**	$\mathbf{3 \times 10^{-4}}$	**4**	$\mathbf{1 \times 10^{-4}}$	**20**	$\mathbf{1 \times 10^{-3}}$

[a] These illustrative estimates based on chemical toxicity indicate potential HIs and risks associated with particulate releases during excavation of the three waste groups from the IWCS. The HI is a measure of the potential for noncarcinogenic health effects; a value above 1 indicates a potential concern. The chemical cancer risk represents the probability that an individual will develop cancer during their lifetime as a result of exposure to chemicals at the IWCS. Numbers may not sum exactly due to rounding. The total HIs summed across waste groups are rounded to one significant figure (group-specific values are rounded to two significant figures to limit internal rounding errors); cancer risks are rounded to one significant figure. Estimates in bold exceed comparison levels from the NCP.

The scenarios are described in Section 3.4, basic exposure assumptions are highlighted in Tables 3.2 and 3.3, volumes of the component wastes are given in Table 2.2, and their estimated chemical concentrations are given in Table 2.3. For the example calculations in this TM, the hypothetical maintenance worker is assumed to routinely be very near the open waste excavation area without respiratory protection equipment; these estimates can also be used to help indicate potential exposure issues if institutional controls were lost at NFSS in the distant future and the IWCS cover failed such that wastes were exposed and contaminants were released to air. As indicated in the footnotes of Tables 5.2, 5.3, 5.6, and 5.7, results shown for the example offsite residential location in this table bound (account for) corresponding estimates at other nearby residential locations.

[b] If someone inadvertently (incidentally) ingested 100 mg (0.0035 ounce) of the K-65 residues directly, the HI would be 10 and the corresponding risk would be 8×10^{-4}. The HIs and risks estimated for the other two waste groups are lower, as calculated based on the volume-weighted average concentrations of the chemicals in the component wastes.

For all three waste groups, the estimated risks and HIs for the hypothetical offsite receptors are well below the NCP comparison levels. Although the estimated risks and HIs are higher for the onsite receptors, all values are below the NCP comparison levels. In addition, chemical-specific air concentrations provided in Appendix B (Tables B.5 and B.6) indicate that permissible exposure limits for worker protection would not be exceeded onsite (see Table B.1).

As shown in Tables 5.7 and 5.8, the preliminary cancer risk estimates range from 9×10^{-10} (for the offsite adult resident) to 3×10^{-7} (for the onsite maintenance worker). The potential for noncarcinogenic effects from chemical toxicity is represented by the HI, with a value above 1 indicating a possible concern. The HIs calculated for the six hypothetical receptors in this TM are all below this target level, ranging from 0.002 for the offsite adult and child residents to 0.6 for the maintenance worker. Note that the hypothetical maintenance worker is assumed to be onsite with no respiratory protection equipment.

Among the three waste groups, the highest risk and HI estimates are from excavating group 2, the L-30, F-32, and L-50 residues and tower soils. This is because the average concentrations of relatively toxic chemicals are higher in these wastes than in the K-65 residues, and a lower particulate control efficiency is assumed (based on the preliminary conceptual assumption that water sprays would be used rather than an engineered system for waste group 2). The risk of 3×10^{-7} for the maintenance worker is primarily from inhalation of cobalt (70%), with vanadium accounting for most of the remainder. The estimated HI for this receptor is 0.6, primarily from inhalation of manganese (50%); nickel and cobalt contribute most of the rest.

Nonetheless, the total chemical risks and hazards are below the benchmark values used for comparison in this TM, and the air concentrations are below occupational limits. Thus, with the possible exception of lead (discussed below), chemicals should not pose adverse health effects. This indicates that engineering controls that are designed to protect against radiological exposures (radon gas and particulate emissions and external gamma) should be protective for chemical exposures. However, this is based on limited IWCS characterization data and may need to be confirmed in the remedial design phase for any remedial action alternative chosen.

The next highest estimates are for the hypothetical remedial action worker. The risk and HI estimated for this receptor are lower than those for the maintenance worker by roughly a factor of ten, at 4×10^{-8} and 0.04, respectively; waste group 2 is the main contributor. The estimated risks and HIs for all other receptors for the three waste groups are even lower.

Note that lead is considered a contaminant of potential concern for the IWCS due to its high concentrations in the wastes compared to the generic EPA screening level (see Section 2.3). The cancer risks associated with lead are included in this TM based on an available toxicity value (see Table 4.5). Beyond these preliminary example estimates, it is expected that lead will be evaluated in the FS when project-specific information becomes available to support a representative analysis using an EPA model (e.g., the integrated exposure and uptake biokinetic model).

Estimated chemical concentrations in the wastes that comprise each of the three groups (1, 2, and 3) are given in Table 2.3. As described in Section 3.3.2, a lower particulate control efficiency is assumed for excavating waste group 2 (75%) than for waste group 1 (99%). An engineered system is assumed for the latter, to significantly reduce any airborne emissions from the K-65 residues because of the high radionuclide concentrations in that waste. If the same particulate control efficiency were assumed for waste group 2, the HIs and risks for those wastes would decrease by a factor of 25. That assumption would result in all estimates being far below the NCP comparison levels. The example estimates of incidental ingestion of deposited particulates indicate that such intakes would not be significant for the six

hypothetical receptors. However, if someone were to incidentally ingest the wastes directly at the IWCS, both the chemical risk and HI would exceed the NCP comparison levels. If the onsite remedial action worker inadvertently ingested 100 mg (0.0035 ounce) of K-65 residues, the HI would be 10 and the risk would be 8×10^{-4}. Lead is the dominant risk contributor based on its chemical toxicity (80%), with PCBs accounting for most of the rest. The chemical risks and HIs for the other wastes would be somewhat lower but would still exceed the target comparison levels. If the remedial action worker were to inadvertently ingest this small amount from each waste group during their respective excavation periods, the estimated combined risk would be 1×10^{-3}.

The health effects estimated for chemical exposures in this TM are intentionally conservative to provide information that can be used to help guide planning for the FS, including to scale for smaller or greater extents of exposure. The example results shown in Table 5.8 indicate the potential chemical hazards associated with the IWCS contaminants and the importance of source and exposure controls to limit any possibility of incidentally ingesting the wastes directly.

5.3 UNCERTAINTY IN THE RISK ASSESSMENT PROCESS

The example risk calculations in this TM are based on available historical data and characterization data and exposure scenarios designed to indicate how people might be exposed to the IWCS contaminants, to help guide the development and evaluation of remedial action alternatives in the FS for this OU. A number of assumptions were made because project-specific information is not yet available at this early stage of the FS process. Beyond these limitations, a number of uncertainties are inherent to the risk assessment process itself. To address the potential impact of key uncertainties on the results presented in this TM, the rationale for the major assumptions used in this assessment and the associated uncertainties introduced by these assumptions are discussed in Sections 5.3.1 through 5.3.4.

5.3.1 Contaminants of Potential Concern

The identification of contaminants of potential concern for this evaluation of health risks relies on both an assessment of characterization data for the IWCS contents and the application of a selection process for chemicals. No additional characterization has been conducted for this OU because available data are considered sufficient for completing the FS and supporting an informed decision for the IWCS. Furthermore, it would be extremely difficult to collect representative data and such an effort would require breaching the containment structure, thus compromising its integrity and increasing the potential for contaminant releases that could impact workers and possibly the public. The uncertainties associated with using existing data for the IWCS contents and with the selection process applied to determine contaminants of potential concern are discussed in Sections 5.3.1.1 and 5.3.1.2, respectively.

5.3.1.1 Characterization Data

Historical data are used in this report to evaluate potential exposures and risks for the IWCS wastes. It is recognized that many of these data were collected decades ago and would therefore not meet data quality requirements for site characterization established since that time. However, a considerable amount of information is available on the processes used to generate the wastes in the IWCS, and the concentrations of key contaminants are consistent with those found in comparable materials at other locations, such as at the Fernald site in Ohio. For this reason, using historical data for the risk evaluations in this TM is not expected to introduce substantial uncertainty in the results because those data are considered reasonably indicative of the major contaminants in the IWCS, especially for the radionuclides.

A considerable amount of historical data is available for the radionuclides in the IWCS residues and other wastes. These data reflect both the data collected by DOE while performing the interim remedial actions

at the site in the 1980s and corroborating information collected in site soils during the RI data collection process. The radionuclides in the IWCS are primarily those in the U-238, U-235, and Th-232 decay series, and the radiological risks evaluated in this TM are limited to radionuclides in these three decay series; average concentrations of the principal radionuclides are used in the calculations, consistent with the manner in which these data are reported. Although low concentrations of other radioactive contaminants including fission products and TRU radionuclides are also present in site soils (and presumably within the IWCS), the low concentrations of these radionuclides would not have a significant impact on the estimated radiation doses and cancer risks.

Although substantial information is available for the radioactive contaminants, a similar level of detail is not available for the chemicals. Chemical contaminants in the residues would be expected to largely consist of the metals present in the uranium ore initially processed during World War II and shortly thereafter. Recent field characterization investigations for site soils performed for the RIR (USACE 2007a) identified a number of additional chemicals at the site including VOCs; PCBs, PAHs and other SVOCs; and explosives. Many of these chemical contaminants (other than the metals) originated from various activities previously conducted at the site beyond the storage of the radioactive residues, and these chemicals are also likely present (albeit in generally low concentrations) in the contaminated soil and debris currently stored in the IWCS. Except for PCBs (for which a concentration from analogous waste at the Fernald site is used for all waste, as supported by soil contamination data for NFSS and LOOW), quantitative data for the organic compounds are insufficient to support reasonable estimates of source concentrations in the IWCS.

Information about a number of chemicals (mostly metals) in the residues is included in the EIS (DOE 1986), and that information was used to identify chemicals of potential concern for evaluation in this TM. The EIS is the main source of data for chemicals in the IWCS, with some supporting information from subsequent documents (including characterization data for LOOW). A screening process (described in the next section) was used to select those IWCS chemicals expected to pose the greatest health concern. A total of 35 chemicals are identified in the EIS, and while this set does not include all chemicals present in the IWCS, it is considered adequate for purposes of this TM. Although the EIS does not report VOCs, PAHs or other SVOCs, or asbestos, the risks associated with those contaminants are expected to be represented by the estimates for the 22 key radionuclides and chemicals addressed in this TM. Thus, the overall uncertainty in the risk results associated with using historical information for this risk evaluation is considered low, largely because good data exist for the contaminants of primary concern for human health.

5.3.1.2 Selection Process

Uncertainty associated with selecting contaminants of potential concern for a risk assessment results from a number of factors, including limitations in data relative to locations and specific constituents. For most assessments, limitations in the current data collection and analytical considerations (such as laboratory procedures) can affect the determination of chemical contaminants of potential concern. However, these issues do not apply to this preliminary evaluation because no data were collected or laboratory analyses conducted for this effort. The information used was of necessity limited to historical data.

The uncertainty associated with the radioactive contaminants in the IWCS contents is considered low. Data exist for all 11 principal radionuclides in the U-238, U-235, and Th-232 decay series, and these were used in this assessment. No screening was conducted to reduce the list of radionuclides of potential concern for this TM.

The data for chemical contaminants are very limited, and only one source of information was identified for this information. The 35 chemicals identified in DOE (1986) were screened to reduce the number of

contaminants carried forward for quantitative analysis. This process involved comparing the concentrations available for the IWCS contaminants (or if not available, an estimated value from analogous material) to the generic screening levels established by EPA regional offices for soil under unrestricted residential use (EPA 2011c). Because these values are conservative (lower than RSLs for industrial/commercial use), little uncertainty is associated with the benchmark component of the screening process.

Nevertheless, an additional screen was conducted whereby these IWCS contaminant concentrations were compared to the remedial program soil cleanup objectives established by the state of New York (NYSDEC 2011). A further check screen was conducted in which the contaminant concentrations were combined with EPA toxicity values to identify those indicated to exceed target risk and HQ levels (targeting 0.1 for the latter). Results led to the selection of 10 metals to be evaluated in this TM. PCBs were also selected, to represent the organic compounds because these chemicals have been identified in areas across the site and also at the adjacent LOOW site. Because similar results are obtained using multiple approaches, uncertainty in the selected process itself is considered moderate.

Historical information indicates that asbestos was present in a number of buildings that were demolished as part of the DOE interim actions. No information was identified regarding the amount or concentrations of asbestos that might be found in the demolition debris within the IWCS, so this contaminant was not quantitatively assessed in this TM. Nevertheless, to support upcoming analyses if information becomes available to estimate asbestos concentrations in the various IWCS wastes, summary toxicity information is included in this report so corresponding risks could be readily estimated following the same process for calculating exposure point concentrations for airborne and deposited fractions associated with the given scenario assessed. For other chemicals in the IWCS, data are simply insufficient to support a reasonable risk assessment.

Although characterization data do not exist for all chemicals contained in the IWCS, information does exist for key chemicals, and this limitation is offset by the good historical data for the radionuclides. Furthermore, the information available for the chemicals that are quantitatively evaluated in this TM is more than adequate to support the development and evaluation of alternatives for the IWCS and the selection of a remedy for this OU. Therefore, the overall uncertainty associated with the selection of contaminants of potential concern for the IWCS is considered low.

5.3.2 Exposure Assessment

Key uncertainties for the exposure assessment are associated with three main components: (1) the hypothetical receptors assessed, including the activity patterns and exposure factors; (2) the primary exposure pathways assessed; and (3) the estimates of exposure point concentrations. Uncertainties associated with each of these components are described in the following subsections.

5.3.2.1 Hypothetical Receptors

The hypothetical scenarios evaluated in this TM are intended to support the development and evaluation of remedial alternatives for the IWCS, not to assess realistic exposures for the near term. In addition, these scenarios are designed to help guide the determination of appropriate emission controls and worker protection measures as part of planning for this OU. They also address exposures to the wastes in place, with supporting estimates for various cap breach events that consider direct exposures to uncovered wastes at the IWCS.

The IWCS encompasses only about 5% of NFSS in the southwestern portion of the site (see Figure 1.2). The NFSS is fenced and adjoined by two commercial waste disposal facilities. The physical setting of

this area is a key consideration in developing the scenarios for this assessment. Onsite residential use at the IWCS is highly unlikely because it would be unrealistic to assume anyone would build a home on or near this relatively small IWCS within the fenced NFSS. Continued Federal ownership of NFSS would preclude such land use, signs are posted indicating the nature of materials being stored in the IWCS, and the community is well aware of the wastes being contained on NFSS. Moreover, the onsite residential scenario has already been assessed (DOE 1986, NRC 1995). Thus, it was not evaluated in this TM. Similarly, recreational and commercial uses of the site are not consistent with the setting for the time period assessed.

The most likely scenarios for current conditions and reasonable projections of future conditions are those involving workers onsite – both those responsible for ongoing maintenance activities and those who could be involved in remedial actions in the future. Considering the nearby homes, schools, and local campground, an onsite trespasser is also plausible. Offsite, the receptors evaluated are considered illustrative of potential individuals and locations that could potentially be impacted by airborne releases from the IWCS. Corresponding estimates for other residential locations (including the trailer park northwest of NFSS) are lower than those presented for the example offsite residential location in this TM.

From this information, the uncertainty associated with the six hypothetical receptors selected for this TM is considered low – onsite remedial action worker, maintenance worker, and adolescent trespasser; and offsite outdoor (landfill) worker, and adult and child residents. That is, the types of receptors are considered appropriate for the current land use at NFSS (controlled) and reasonable projections of future land use during the near term, considering the adjoining landfills as well as the nearby offsite residents.

The Lewiston-Porter school campus is about 2.3 km (1.4 mi) west of the IWCS, which is upwind of prevailing winds. Note that monitoring at the school has not identified any elevated contamination from past activities. The Stevenson Elementary School is located about 6.4 km (4 mi) east-northeast of the IWCS in Ransomville, which is downwind of the predominant wind direction (see USACE [2011d]). The risks estimated for the offsite residents in this TM bound those for exposures at these school campuses, given not only the lower extent of exposures at those locations but the farther distances from the IWCS.

For the three offsite receptors, the activity patterns and intake parameters are considered reasonably indicative and consistent with EPA guidance. Thus, the uncertainty associated with those assumptions is considered moderate to low. In contrast, the activity patterns assumed for the three onsite receptors are considered unrealistically conservative, particularly for the onsite maintenance worker and trespasser at the IWCS. However, this “uncertainty” in terms of the plausibility of certain activities and locations is intentional. For example, all three receptors are assumed to spend time in the same area very near the active excavation zone. Of course neither the maintenance worker nor trespasser would stay in that area with a remedial action worker. These conservative activity patterns are simply assumed so the illustrative evaluations in this report can also account for other possible scenarios that might be postulated for the longer term, e.g., if institutional controls were assumed to be lost such that future individuals might be exposed to uncovered wastes. These conservative assumptions are consistent with the objectives of this report, i.e., to help guide the determination of appropriate control measures for inclusion in the alternatives evaluation of the FS, and to help frame health and safety plans for the site that assure workers and the public are protected from any adverse health effects.

That is, these assumptions with high uncertainty (very low plausibility) are by design, so exposures and risks can be assessed for a variety of conditions that may be relevant to various remedial alternatives. Because the information is presented in this TM in a way that accommodates scaling up or down to assess different combinations of wastes and different extents of exposure as indicated for the alternatives to be developed and assessed in the FS, the effective uncertainty is considered moderate. The intake

parameters used for these receptors are consistent with EPA guidance and reflect information from the scientific literature and context for the local setting (including periods of snow cover).

Note that the estimate of 5-year exposure duration for the remedial action worker (5 excavation seasons) accounts for the fifth season during which rubble and debris would be excavated and other supporting remediation activities would be conducted. (Unlike particulates from the other wastes in the IWCS, limited releases are expected from the rubble and debris, so exposures associated with such releases are not quantified in this TM; see Table 2.2 footnote a). The conservatism incorporated in the exposure and risk estimates for the other IWCS wastes are expected to adequately cover the risks associated with these materials. Thus, the overall uncertainty in the exposure factors is considered low.

5.3.2.2 Exposure Pathways

The exposure pathways quantified in this TM are consistent with available characterization data and the site conceptual model, as well as with the scope of the IWCS OU. A key factor in this evaluation is the site setting, i.e., the IWCS is a relatively small area within a fenced facility owned by the Federal government, with two commercial waste landfills (one for hazardous waste and one for municipal waste) on adjoining properties. Access to the IWCS is controlled and the contaminated materials are physically isolated from the environment in an engineered structure that is regularly inspected and maintained. The uncertainty associated with other pathways (in terms of being complete and measurable contributors to risk estimates) is low for the scope of this TM. Because this analysis focuses on the near term and contaminant migration from the IWCS to groundwater has been assessed separately (HGL 2007, 2011), that pathway is not included in this assessment.

Under current conditions, no member of the general public is being exposed to any IWCS contents. An extensive environmental surveillance program is in place at NFSS, and results of this program are published annually. The only way exposures could occur in the near term is if the integrity of the IWCS containment system were breached. In this TM, potential events that might release contaminants from the IWCS are considered, and hypothetical exposure scenarios are postulated so the significance of such releases can be evaluated. The exposure pathways considered in this TM are illustrative of those that would be relevant if such releases occurred. The uncertainty associated with the likelihood of these exposure pathways occurring is considered moderate to high, because the events that could result in these releases combined with the sustained exposures assumed in this TM are very unlikely (particularly given the long-standing surveillance, monitoring, and maintenance programs). Note this moderate to high uncertainty is in the conservative direction, resulting in overestimates of the risks associated with the IWCS in the near term. This approach is consistent with providing conservative estimates that can be scaled up or down to accommodate the components of the preliminary alternatives and conceptual planning information as those alternatives are developed.

5.3.2.3 Exposure Point Concentrations

A number of factors contribute to uncertainties in the exposure point concentrations, including data availability, contaminant heterogeneity, and the selection of the concentrations used to represent dispersed and deposited contaminants. This TM addresses exposures for two cases, with a focus on the near term: (1) wastes in place at the IWCS, assuming they are uncovered by a cap breach; and (2) wastes uncovered during excavation, with particulates and Rn-222 gas released to air.

For direct exposures to the wastes in place, the exposure point concentrations for direct incidental ingestion are based on the estimated values for the radionuclides and chemicals given in Tables 2.2 and 2.3. External gamma irradiation was modeled using two standard computer models and the results are consistent with expectations, i.e., results were verified by independent calculations. The uncertainty

associated with direct gamma irradiation exposure is considered moderate in the conservative direction. The approach used to estimate Rn-222 releases also reflects established methods and assumptions. The uncertainty is similar to that for external gamma irradiation.

The excavation case is the primary focus of this assessment. Exposure point concentrations are developed for both air and surface soil, with the latter addressing particulates deposited due to wet or dry deposition (only a small fraction of airborne particulates is estimated to deposit on soil at the receptor locations). These air and soil concentrations are estimated using the current standard EPA dispersion modeling system (AERMOD) with an assumed source area based on preliminary planning information and an emission rate considered to conservatively represent fugitive dust releases from the excavation activities.

From a practical field perspective, the source area assumed for the K-65 residues (group 1) is considered small, which could result in underestimating particulate concentrations in air. However, these wastes are assumed to be within an engineered containment system so the net effect of this assumption on emission estimates is expected to be minor. A common default value was used to estimate the uncontrolled emission rate, the particulate control efficiencies for groups 2 and 3 reflect the default assumption based on field insights, and for group 1 (the K-65 residues), the radon and particulate control efficiencies are based on experience with similar wastes at Fernald. Because these assumptions are based on field experience, the associated uncertainties are considered moderate to low. Additional discussion of uncertainties underlying the calculation of the exposure point concentrations, including some quantitative estimates, is offered below.

Note that the deposition estimates are used to estimate external gamma irradiation (as well as incidental ingestion exposures), including at offsite receptor locations. As described for the onsite gamma irradiation calculations, the uncertainty associated with direct gamma irradiation exposure is considered moderate in the conservative direction.

Gamma irradiation from direct exposures to the IWCS wastes as they are uncovered is not quantified in this chapter for the six hypothetical receptors because such exposures are highly dependent on a number of factors that have not yet been defined as part of planning for the IWCS FS. These factors include the use of permanent shielding (such as surrounding an excavation area), temporary shielding (to protect specific workers or other individuals), the conceptual approach used to remove the wastes and any inherent shielding this may provide (such as various types of large equipment), the specific locations and length of time workers could be exposed to these wastes, any shielding inherent in the waste containers or processing vessels, and more. Thus, to provide such estimates would be premature (and possibly misleading) without conceptual engineering information regarding the approach that may be used to retrieve the wastes. Such an evaluation would be possible once sufficient engineering planning information is available, and such an evaluation is expected to be included in the FS. This limitation results in an underestimate of the potential radiation dose and risk from gamma irradiation, notably to the imaginary onsite receptors. The extent of this uncertainty cannot be quantified at this time; however, an example bounding estimate is offered in Appendix D. Assuming no engineering controls are used during excavation (which is implausible), the radiation doses and risks to onsite individuals would be very high. Those example estimates for this imaginary case indicate the importance of sound conceptual engineering planning to be reflected in the FS, so that this pathway can be appropriately evaluated.

Meteorological Data Used to Model Dispersion and Deposition. The meteorological data used to estimate air dispersion and deposition contribute to uncertainties in the exposure (and risk) calculations. To reduce this uncertainty, a detailed evaluation of candidate data was conducted to assess representativeness for modeling dispersion at NFSS, and specific modeling approaches were also evaluated (USACE 2011d). Those analyses serve as a key foundation for the evaluation of air dispersion in this TM. Most previous dispersion modeling analyses for NFSS have used meteorological data from

the nearby Niagara Falls International Airport, in part because suitable data were not available from closer locations to the site. However, data recently became available from the adjacent CWM landfill, and USACE (2011d) found that these data (from 2005 through 2008) are appropriate for use in modeling air dispersion for NFSS.

The uncertainty associated with using these meteorological data is considered low because the CWM site abuts NFSS so the surrounding land cover is similar, the data were collected from a standard tower height, and they reflect a sufficient level of quality assurance/quality control (QA/QC) for use in air dispersion modeling. Use of the CWM meteorological data produces estimated airborne concentrations at nearby receptor locations that can be more than twice as high as those predicted using the default data set for NFSS in the CAP88-PC model (i.e., 1950s data from the Niagara Falls airport). The difference varies by location, with factors ranging from essentially the same to 2.2-fold (averaging 1.5) across the 12 offsite receptor locations considered in that evaluation (USACE 2011d). Much of this increase is likely due to a lower average wind speed at the CWM site (3.0 m/s) compared to the Niagara Falls airport (4.4 m/s), which reflects differences in land cover (the airport is in a more open while the site is in a more vegetated area).

For the illustrative dispersion analyses in this TM, four years of CWM meteorological data spanning the daily work hours and eight months assumed for the excavation seasons (April through November) were used with the AERMOD model. This overall duration aligns with the estimated conceptual period for excavating all three waste groups from the IWCS (which is based on USACE field experience and insights from other projects, including as described in USACE [2011a].)

In summary, the CWM meteorological data are considered well suited for modeling dispersion of airborne releases at NFSS at this time. Use of these data reduces the uncertainty associated with meteorological data from stations located farther away. The USACE Buffalo District installed a meteorological tower onsite in spring 2011, and when a sufficient period of collection is achieved and these data have undergone standard QA/QC reviews, they will be used in future dispersion modeling, further reducing any uncertainty associated with meteorological data.

Computer Model Used to Calculate Air Dispersion and Deposition. The EPA AERMOD model was used to calculate airborne and deposited particulate concentrations at the hypothetical receptor locations. This model system is the current standard for evaluating air dispersion and assessing air quality impacts. Jointly developed by the American Meteorological Society and EPA beginning in the 1990s, it was incorporated into the Federal air quality regulations in 2005 (see the discussion in USACE [2011d]). Although a number of other computer codes exist based on the Gaussian plume atmospheric dispersion model, many are dated and thus, do not include advances since that time (e.g., to consider complex terrain), and they do not accommodate the calculation of short-term concentrations.

A review of validation studies for the straight-line Gaussian plume atmospheric dispersion model for various release conditions conducted about 20 years ago concluded that annual average air concentrations over flat terrain could be predicted within a factor of two to four. However, the accuracy of the results was found to decrease as the averaging time decreased and/or the complexity of the meteorological and terrain conditions increased (Miller and Hively 1987). It was in part to address these issues that the AERMOD code was developed. Thus, use of this current standard model helps reduce uncertainties associated with estimating contaminant concentrations resulting from airborne releases at the IWCS for a suite of receptor locations for short-term exposures (compared with estimates based on computer codes that have historically been used at radioactively contaminated sites).

As with any model, uncertainty is inherent. Nevertheless, AERMOD is a well-established model system that has undergone extensive validation and continues to be enhanced. With sound meteorological and

source data, AERMOD calculations generally reflect an accuracy in the range of ±10 to 40 percent. This general accuracy primarily reflects uncertainty in the specific time and location, not in the concentration estimate itself; i.e., the model is fairly reliable in predicting the maximum concentration estimated to occur sometime within the given area (Turner and Schulze [2007]). The emissions estimates represent a basic uncertainty for these analyses, which simply reflects the fact that this TM is being prepared at an early stage of the FS process before excavation plans are available to guide the calculation of more project-specific estimates. The uncertainty associated with using AERMOD is considered to be low to moderate in the conservative direction.

Estimated Airborne and Deposited Concentrations. For the airborne contaminants, AERMOD is used with hourly meteorological data from CWM to predict monthly airborne PM_{10} concentrations at each offsite receptor location, based on preliminary, illustrative emission estimates for excavating wastes from the IWCS. While these offsite receptor locations are fixed, the onsite receptors are assumed to move within a given distance of the excavation area rather than standing in one place throughout their entire time onsite. To address these variable locations, AERMOD was used to predict PM_{10} concentrations at an array of locations at the distances from the excavation source assumed for these three receptors.

To partly offset the conservatism introduced by considering the "maximum month" to represent airborne PM_{10} concentrations across 32 months, the average concentration of the maximum monthly concentrations across the array of locations is selected as the PM_{10} concentration in air for each receptor. For the onsite receptors, this concentration is determined for 36 directional locations for the remedial action worker, and 72 locations for the other two (to account for the large portion of their time onsite spent farther from the excavation source).

That is, for the remedial action worker, airborne PM_{10} concentrations are predicted for 36 locations (spaced 10 degrees apart) 1 m (3.3 ft) from the edge of the excavation area. For the maintenance worker, these same concentrations are used for 10% of the exposure, and for the rest, airborne PM_{10} concentrations are predicted for a parallel set of 36 locations around the excavation area, but 50 m (160 ft) away. For the trespasser, the same predictions are used for the 10% near-field component, and for the rest, airborne PM_{10} concentrations are predicted for 36 additional locations spaced 10 degrees apart 100 m (330 ft) from the excavation. The average PM concentration of the maximum months across all the locations considered for the given onsite receptor is then used to calculate the exposure point concentration in air, by multiplying these PM estimates by the contaminant concentrations in the wastes being excavated (volume-weighted for waste groups 2 and 3).

An evaluation of the median month across all 32 months was conducted to assess the conservatism introduced by the approach used in this TM. Based on that evaluation, this approach likely overestimates the air concentrations by a factor of roughly 2 to 3 compared to what would be expected over a longer period. (The maximum monthly value is higher than the median monthly value by roughly this factor across the various distances from the excavation areas assessed.)

As additional context, for the suite of offsite receptors considered for this TM, the average airborne PM_{10} concentration over the full 32-month period ranges from about 7% to 26% of the maximum monthly concentration at each location. This suggests that the protective assumption used to estimate offsite exposures in this TM (based on the maximum monthly concentrations) might overpredict potential impacts at those receptor locations by factors ranging from about 4 to 15.

Further conservatism is reflected in the air concentrations estimated very close to the excavation area. As described in Section 3.3.2, releases from the excavation areas would be at ground level, so the ground-level estimates of air concentrations from AERMOD were used to determine the exposure point

concentrations. At 1 m (3 ft), ground-level concentrations are about 3 times higher than the concentrations at the breathing height (1.5 m [5 ft]), but they converge to the same concentration within less than 50 m (160 ft). Thus, inhalation estimates for the hypothetical remedial action worker are high by about a factor of 3, bringing the conservatism in the air concentration to nearly an order of magnitude for this receptor. The factor is not quite as high for the maintenance worker or trespasser because only 10% of their exposure time is assumed to be at 1 m (3 ft) from the open excavation. The estimated conservatism for each of the waste groups is indicated below.

For the K-65 residues (waste group 1), the ground-level concentration at 1 m (3 ft) from the edge of the 500-m^2 (600-yd^2) source area is about 3.2 times higher than in the breathing zone. Thus, the estimated inhalation exposures and risks for the remedial action worker are conservative by more than 3-fold. For the maintenance worker, this conservative factor drops to 1.2 because only 10% of the total exposure is the same distance from the excavation as the remedial action worker, and by 50 m (160 ft) (where this receptor is assumed to spend the rest of the time), the ground-level and breathing-height concentrations are the same. For the trespasser, the same factor of 1.2 applies because this individual is also assumed to be 1 m (3 ft) from the source for 10% of the time, with the rest of the time spent twice the distance away as the maintenance worker (where ground-level and breathing-zone concentrations are the same).

For the other high-activity residues and tower soils (waste group 2), the ground-level concentration at 1 m (3 ft) from the edge of the 1,000-m^2 (1,200-yd^3) source area is nearly 2.6 times higher than in the breathing zone. This means the estimated inhalation exposures and risks for the remedial action worker are conservative by this amount. For the maintenance worker and trespasser this factor would be 1.2.

For the R-10 pile and other contaminated soils (waste group 3), the ground-level concentration at 1 m (3 ft) from the edge of the 2,000-m^2 (2,400-yd^3) source area is about 2.1 times higher than in the breathing zone. This means that the estimated inhalation exposures and risks for the remedial action worker are conservative by this amount. For the maintenance worker and trespasser, the factor drops to 1.1. This conservative factor does not apply to the offsite receptors because the estimated ground-level concentrations in air are the same as those at the breathing height. For the offsite residential scenario, the uncertainty associated with the assumption that indoor air concentrations are half of the outdoor concentrations is considered moderate to low.

For both airborne and deposited estimates of PM, the preliminary evaluation in this report focuses on PM_{10} because this inhalable fraction (which includes the respirable fraction, $PM_{2.5}$) is a key concern for releases during potential remediation at the IWCS. Larger particles would also be released during material handling, but essentially all of those would be deposited closer to the excavation source rather than being transported farther distances to where members of the public could be exposed, e.g., at homes nearby (see Watson and Chow [2000], EPA [2004c], and EPA [2010b]). Note that the hypothetical onsite scenarios developed for this TM are highly implausible because their primary objective is to inform conceptual planning for the FS, notably for emission and exposure controls to assure protection of remedial action workers (who would incur the highest exposures associated with the IWCS). The impact of the PM assumptions on estimated exposures to deposited contaminants for these imaginary onsite receptors would be substantially outweighed by other conservative assumptions applied, such that the risks estimated for these scenarios bound potential effects in order to help guide appropriate planning for the FS.

The amount of particulates deposited in surface soil was estimated by AERMOD covering four excavation seasons, so these values are expected to be reasonably representative over the time frame of the remedial action per the general emissions assumptions used. The specific concentration selected for the remedial action worker is conservative because the cumulative value over the excavation period for a given waste group was used. The uncertainty associated with this approach for estimating the surface soil

concentrations is considered high in the conservative direction, because the estimated deposition concentrations are quite low. Even with the conservative assumptions applied, estimated risks and HIs from exposures to deposited contaminants over each of the excavation periods never dominate the estimates for all pathways combined. Thus, this conservative approach provides reasonable assurance that the control measures developed for any alternatives involving waste excavation would be guided by those for inhalation and direct exposures at the IWCS, including external gamma radiation (thus reducing that uncertainty).

In addition to the exposures considered for the six hypothetical scenarios addressed in this TM that focus on excavating the IWCS contents, it is possible that an individual could be exposed for a relatively short period of time to external gamma radiation from the residues and wastes in the IWCS. Beyond gamma radiation, Rn-222 gas could be released to the environment if the IWCS contents were exposed by an event that breached the cap (e.g., an earthquake or burrowing animal). These evaluations were performed using standard computer codes and models, and the uncertainties associated with these calculations are moderate to low.

The overall uncertainty associated with the approach used to develop exposure point concentrations is considered moderate. Conservative assumptions are used to ensure that the resultant concentrations do not underestimate potential doses and risks, so the information in this TM can be factored into the development and evaluation of remedial action alternatives in the FS.

5.3.3 Toxicity Assessment

Established toxicity values are used to estimate health effects from exposures to the radionuclides and chemicals assessed for the IWCS. These toxicity values and inherent uncertainties are highlighted in Chapter 4. The overall impact of these uncertainties on the risk results is considered low for radionuclides, but relatively high for the chemical risk and HI results.

The health risks associated with radiation exposure have been studied for many years and are well known. The radiological risk estimators used in this assessment are generally accepted by the scientific community as representing realistic projections of the hazards associated with radiation exposure. The DCFs are intended for use in evaluating exposures to members of the general public, and they cover ages ranging from an infant to an adult. For internal exposures by inhalation and ingestion, the DCFs give the committed effective dose per unit intake for a number of integrating periods (50 years was used in this TM). For external exposures, the DCF represents the effective dose per unit concentration of the radionuclide per unit time. The doses from internal and external exposures can be added together (as done for this TM) to estimate the total dose.

The radiation doses calculated in this TM reflect the most recent adult DCFs developed by the ICRP. Use of these updated adult DCFs given in ICRP (1996) should result in lower uncertainties than if the previous values given in FGR 11 (EPA 1988b) and FGR 12 (EPA 1993) were used. The DCFs in FGRs 11 and 12 were obtained using a standardized adult as defined in ICRP (1975), generally referred to as reference man.

Also, the internal dosimetry models used to evaluate the absorption, distribution, and retention of radionuclides in the human body have been significantly improved since those older values were released. The updated dosimetry models developed by the ICRP were used to derive the DCFs in a manner similar to that used to derive the radiological cancer risk coefficients. Use of the newer adult DCFs lends greater consistency to the results presented in this TM in terms of radiation dose and resultant cancer risk. The newer adult DCFs are generally somewhat lower than those previously given in FGRs 11 and 12 with some exceptions, including for inhalation of Ra-226 which is higher by a factor of about four.

The radiation doses were calculated using adult DCFs to provide consistency with current Federal and New York state radiation protection standards and guidelines. These standards and guidelines generally reflect doses to adults, i.e., the reference man, and do not specifically provide age-dependent radiation dose limits. Even though some regulations identify specific requirements for doses for minors and women who declare themselves to be pregnant (see, for example, monitoring requirements from USNRC [2011b]), the calculation of expected doses to such individuals is based on the DCFs developed for the reference man. The approach used in this TM is considered the best compromise between using the most recent information for DCFs (developed for a number of age groups) while maintaining consistency with current radiation protection standards and guidelines (to assess the significance of these dose estimates).

The age-specific DCFs for younger children and adolescent youths could have been used for two scenarios in this TM, i.e., the offsite child resident and the adolescent trespasser. The internal exposure DCFs for the key radionuclides at the IWCS are highest for infants and decrease with age. This reflects both the greater sensitivity of young children to radiation and also a longer time over which the dose could occur. However, young children have much smaller intakes than adults, and this tends to offset this difference to some extent. The degree to which the inhalation and ingestion DCFs vary by age group depends on the radionuclide (see Tables 4.2 and 4.3).

For Ra-226 (the radionuclide of most concern in the IWCS), the inhalation and ingestion DCFs are higher for an infant than for an adult by factors of 36 and 17 for the same intake (in pCi), respectively. However this ratio decreases to 11 (for inhalation) and 5 (for ingestion) for a teenager relative to an adult (as represented by a 15-year-old in these two tables). Higher doses would be estimated for the exposures considered in this TM if these DCFs for younger ages were considered. However, most of the scenarios evaluated in this TM are for adults, and the DCFs for adults were used in this TM because the results are intended to address a number of possible exposures in the future, including to workers.

In addition, most Federal and New York state regulations are based on adult exposures (reference man). If estimates of exposures at other ages are desired, the results given here can be adjusted to reflect both the higher DCFs for younger ages and the corresponding lower intakes. On a comparative basis (both between exposures scenarios and also with regulatory criteria), the results based on adults are appropriate to use in the FS. The uncertainties associated with the DCFs used in this TM are low, provided they are used as intended.

Exposures to short-lived decay products of Rn-222 were calculated in WLM by converting the Rn-222 gas concentrations (in pCi/L) to decay product concentrations (in WL) using the algorithm given in the CAP88-PC computer code, and multiplying this value by the exposure duration in working months (one working month is 170 hr). The uncertainty introduced by this approach is considered to be moderate, as the algorithm in CAP88-PC is based on a wind speed of 3.5 m/s (which is comparable to the average wind speed at the CWM site of 3.0 m/s), and there are a number of additional assumptions built into this algorithm. This result does not depend on the age of the individual; it is simply the amount of Rn-222 progeny to which an individual is exposed.

Estimates of the WLR were compared to those predicted by another computer code, MILDOS-AREA, which indicated that the CAP88-PC algorithm was conservative for distances within a few miles of the site. Also, CAP88-PC is an EPA-approved approach and has been used in numerous analyses at other locations. The exposures in WLM were converted to the risk of cancer incidence using a factor of 5.38×10^{-4} per WLM. The uncertainty associated with this cancer risk factor for Rn-222 progeny is considered to be low.

The radiological cancer risk coefficients for internal exposures used in this TM were also obtained from FGR 13 (EPA 1999b). These coefficients represent the estimated lifetime cancer risk per unit intake averaged over all ages and both genders for a given radionuclide and mode of exposure. These cancer risk coefficients were developed using the same updated models as were used to develop the DCFs. Human data were considered in developing these models and the estimated effective dose was combined with cancer risk factors through a life-table analysis which accounts for competing risks. These cancer risk coefficients have been used in a wide variety of radiological risk assessments for EPA and many other agencies, and they provide a realistic estimate of the risks associated with radiation exposure. The uncertainty associated with using these cancer risk coefficients is considered to be low.

Separate calculations were performed to estimate the radiation doses from external gamma radiation to better address various exposure events that could occur at the IWCS. These calculations were performed using MicroShield and MicroSkyshine. These two computer codes were developed specifically to calculate the radiation dose under different configurations of gamma-emitting waste, shielding, and geometry relative to the exposed individual. These results are most relevant for potential onsite exposures that may occur to workers performing activities on and near the IWCS in the future. A risk factor of 8×10^{-7} per mrem was used to convert the dose to cancer incidence. This factor is only applicable to low LET radiation (such as gamma rays and X-rays), and has been recommended for use in these situations by the ISCORS and ITRC. The uncertainty associated with using this factor is considered low.

Considerably less uncertainty is associated with toxicity information for the radionuclides than for the chemicals. The DCFs and radionuclide cancer risk coefficients are based on data for humans exposed to radiation. The human exposure levels from which those DCFs were derived are higher than those expected for the NFSS scenarios addressed in this TM, because high doses are needed for biological effects to be observed (see Section 4.1.1). Because they reflect human data, those factors provide a very strong basis for estimating radiological risk (which is not matched for the chemicals).

Available scientific information is insufficient to provide a complete understanding of the human health effects from exposures to environmental chemicals. Therefore, it is generally necessary to infer toxicity by extrapolating from data obtained from laboratory animals. Although reliance on animal data has been widespread in general risk assessment practice, chemical absorption, distribution, metabolism, and elimination (toxicokinetics), and toxic responses (toxicodynamics) can differ between humans and the species for which experimental toxicity data are available. Additional uncertainties in using animal data to predict potential effects in humans are introduced when routes of exposure in animal studies differ from human exposure routes, when the exposures in animal studies are short-term or subchronic, and when effects that are seen at relatively high exposure levels in animal studies are used to predict effects at much lower environmental exposure levels for humans.

To compensate for uncertainties that result from using animal data to assess human exposures and health effects, the RfD and RfC for noncarcinogenic effects are often based on effects seen in the most sensitive animal species. Doses or exposure levels are then adjusted using “uncertainty” factors (which can be referred to as adjustment factors because they also account for variability). These adjustments compensate for the lack of knowledge regarding interspecies and other extrapolations, including to guard against the possibility of humans being more sensitive than the most sensitive animal species tested. The use of uncertainty factors is considered to be protective of human health. For carcinogens, the use of animal data also translates to uncertainty. Although many substances are carcinogenic in one or more animal species, only a relatively small number of substances are known to be carcinogenic to humans. It is reasonable to infer that not all animal carcinogens are human carcinogens, and not all human carcinogens are animal carcinogens. To prevent the underestimation of cancer risks, the general assumption underlying these toxicity values is that humans are at least as sensitive to the carcinogen as the most sensitive animal species.

Historically, the development of SFs for carcinogens has been predicated on the assumption that no threshold exists for carcinogens, i.e., there is some risk of cancer at all exposure levels above zero, and the dose-response relationship is linear in the low-dose portion of the curve. Under these assumptions, the SF is a constant and cancer risk is directly proportional to intake. In fact, recent toxicity studies have indicated that a threshold does exist for certain carcinogens, i.e., exposures below a certain level do not appear to result in cancer induction. Nevertheless, the use of SFs based on the protective assumption of a linear no-threshold dose-response relationship has until recently been the default approach for estimating chemical cancer risks. Now, if otherwise indicated by the weight of scientific evidence, a threshold approach could be applied. However, the burden of proof as described in the EPA cancer guidelines and guidance (EPA 2005a, 2005b) makes it difficult to apply this threshold approach to estimate cancer risk.

For noncarcinogens, scientific evidence indicates that a threshold does exist, with adverse effects being observed only after exposures exceed a certain level. (Note that for essential nutrients, adverse effects are also observed if exposures do not reach a minimum level.) Comparing the intake estimated for a noncarcinogen to the exposure level identified as "safe" can indicate whether an adverse effect is likely to result from that exposure. The reference values used for these comparisons (RfDs and RfCs) reflect protective adjustments that account for such issues as extrapolating human effects from animal studies and variability among human responses. (These adjustments are typically factors of ten, or the square root of ten when the mode of action is expected to be the same across animals and humans, e.g., for contact irritants. See Appendix B [Section B.2] for additional discussion, including of the benchmark dose approach currently applied to derive toxicity values, and the recent harmonization of approaches for deriving the oral RfD [to align with that used for the SF] regarding allometric scaling.)

Most of the toxicity values used to calculate the cancer risks and potential for noncarcinogenic effects in this assessment apply to chronic exposures. (This is even the case for one of the subchronic PPRTVs, as the value is the same as the chronic PPRTV.) It is important to emphasize that the PPRTV values undergo much less rigorous independent scientific review than IRIS values, and many are derived from limited databases. Therefore, the uncertainty in these PPRTV values is considered inherently higher than for the standard IRIS values. The RfC and IUR assume continuous daily exposure. This distinction is important because the handful of risks and HIs from exposures to nonradioactive chemicals that (modestly) exceed the NCP target levels are due to the inhalation estimates. The subchronic (noncarcinogenic toxicity) values are assumed to apply up to seven years, which translates to more than 61,000 hours.

The time conceptually assumed in this TM to excavate waste groups 1, 2, and 3 from the IWCS is nearly 4,500 hours (not continuous). Based on overnight and weekend recovery times, other benchmarks could also offer insights for the adult receptors, such as health-based occupational exposure limits (notably the threshold limit values established by the American Conference of Governmental Industrial Hygienists, ACGIH [2011]). Similarly, for the one-day inhalation exposures evaluated for the remedial action worker (based on loss of respiratory protection), related health-based comparison levels would include the 8-hour acute exposure guideline levels (AEGLs) (EPA 2011m) and acute RfELs (Cal/EPA 2011a, 2009a), with acute MRLs from ATSDR (2010) also offering context for the noncarcinogenic endpoint.

To promote internal consistency between the radiological and chemical estimates in this TM and to accommodate scaling options for longer durations, the inhalation calculations in this TM account for the averaging time (as assessed for longer-term exposures).

As a note, only provisional values (Tier 2) are available for certain chemicals that contribute to the chemical estimates, and IRIS reassessments are under way for some of these (EPA 2011d). Cobalt, nickel, and vanadium contribute to estimated risks and HIs for various receptors, and the toxicity values

used for these three metals are provisional (Tier 2) values. The EPA recently released an external review draft IRIS assessment for vanadium pentoxide (EPA 2011h), and the IUR is slightly lower than (40% of) the provisional value used in this assessment. Assessments are also under way for cobalt and nickel (EPA 2011d). Thus, uncertainty is associated with the values used in these example calculations given their tier status and pending updates for Tier 1.

In fact, of the 25 toxicity values used to estimate chemical risks and HIs in this TM, five are Tier 3 values (from Cal/EPA and ATSDR). Two are the oral and inhalation cancer toxicity values for lead from Cal/EPA (2009b, 2011a). These toxicity values are used in this assessment because no Tier 1 (IRIS) or Tier 2 (PPRTV) values are available. The EPA uses a modeling approach to estimate blood lead levels corresponding to various exposures (EPA 1998, 2003b, 2011k, 2011l), and the models require a certain amount of exposure to establish quasi-steady state for this internal dose metric. Guidance is available to assess intermittent exposures, but that application also depends on a minimum exposure frequency and duration (1 day a week for 3 to 4 months). That condition would not be satisfied for the trespasser or remedial action worker as illustrated in this TM. Therefore, to maintain consistency across the receptor evaluations in this preliminary evaluation, the Tier 3 toxicity values available to assess potential health effects (from Cal/EPA) are used. More detailed analyses are anticipated to be reflected in the FS. (Note that chemical-specific cleanup criteria are not being developed for this OU; rather, the evaluations in the FS will be used to support the decision for managing the IWCS wastes, while cleanup criteria would be developed for the follow-on OUs; see Section 1.2.)

Two of the other three Tier 3 values are also from Cal/EPA (2011a, 2011b); these are the chronic inhalation RfELs for nickel and arsenic (the latter is based on an oral exposure study). A draft reassessment is under development for the noncarcinogenic toxicity of arsenic (EPA 2011d). (Note the external review draft for the IRIS reassessment for cancer toxicity [EPA 2010a] only proposes a value for the oral SF, i.e., no change is identified for the IUR. If the SF were finalized as proposed, the risk estimates for arsenic ingestion would increase about 17-fold; that change would not alter the overall risk results presented in this TM.)

Overall, the toxicity values used in this assessment are considered more conservative (protective) than warranted for the exposure scenarios evaluated in this TM. They are also more conservative than the corresponding values used for radionuclides because the latter are generally best estimates that reflect information from human exposures. In addition, EPA assessments for updated and new IRIS values are under way that might result in changes to the toxicity values used in this initial framing evaluation. As a result, more uncertainty is associated with the estimates of risk and HI based on the chemical toxicity values than with the radiological doses and risks based on the DCFs and the cancer risk coefficients for radionuclides. This uncertainty is considered generally moderate in the conservative (protective) direction because chemicals do not contribute significantly to the main results in this illustrative assessment.

Scientists at EPA and other agencies continue to refine the derivation methods and incorporate evolving data into updated and new toxicity values. For example, recent recommendations further harmonize the approaches used to derive the cancer and noncarcinogenic toxicity values for oral exposures based on allometric scaling, replacing the toxicokinetic component of the uncertainty factor used for the RfD (EPA 2011n). Thus, over time, the uncertainty in the chemical toxicity values is expected to continue to be reduced – similar to the evolution and ongoing improvement of the derivation methods and estimators used for the radionuclides.

5.3.4 Risk Characterization

The radiological and chemical risks are calculated separately because of differences in the quality of characterization data for the IWCS wastes and in the approaches applied to identify the contaminants of potential concern and fill data gaps. In addition, considerable differences exist in the methods used to estimate cancer risks from exposures to radionuclides and chemicals. The most significant difference in the risk assessment approach is the basis for the risk estimators. For radionuclides, the risk coefficients are best estimate, average values; for chemicals, the risk estimators (e.g., SFs) generally represent the upper bound or upper 95% confidence limit of the slope of the dose-response curve. In addition, the risk coefficients for radionuclides are derived from human epidemiological data where available, while the estimators for chemicals are commonly derived from experiments with laboratory animals because of limitations regarding human data. Hence, the uncertainties associated with the risk estimates for radionuclides and chemicals differ significantly.

Some of the approaches and assumptions used to estimate health risks, combined with inherent uncertainties in the risk assessment process, might underestimate certain components of the calculations. In this TM, the radiological health effects are given in terms of both radiological cancer risk and radiation dose. The radiation doses were estimated using DCFs designed to address adult exposures. These same factors were used for all hypothetically exposed individuals in this TM, i.e., for the child resident and adolescent receptors as well as the adults. This approach will underestimate the dose for internal exposure pathways for younger receptors even when adjustments are made for the different intakes. However, current radiation protection standards and guidelines are generally based on an adult receptor, so this approach allows for better comparisons with existing requirements. Information is provided in Tables 4.2 and 4.3 to adjust the doses to better reflect younger receptors if desired.

Overall, the assumptions used in this TM tend to overestimate rather than underestimate potential risks – including conservative assumptions for the exposure scenarios. Consider for example the number of times a trespasser is assumed to be very close to the IWCS. These unrealistic assumptions were simply made to help understand what the risks might be if the wastes were left in place and at some point in the future controls were lost, the wastes were uncovered, and someone were exposed.

Uncertainties in the estimated health effects that result from limitations in the toxicological data are addressed separately for radiological and chemical effects. The radiological cancer risks are estimated using coefficients developed by EPA as given in FGR 13 (EPA 1999b). These coefficients represent the estimated lifetime cancer risk per unit intake averaged over all ages and both genders, and they include the impact of competing risks. These risk coefficients were in part based on the extensive data file associated with human radiation toxicity including data on individuals who survived the atomic bombs at Hiroshima and Nagasaki; epidemiological studies of medical exposures to humans including the use of colloidal Th-232 (thorotrast) injected into patients as a radiographic contrast medium between 1928 and 1955; and studies of radium dial painters, radium chemists, and technicians exposed through medical procedures in the early 1900s. These studies are identified and discussed in FGR 13 and the references cited therein. The uncertainty associated with the radiological risk coefficients used to assess radiation toxicity is considered to be low.

For the chemical risk characterization, the standard EPA approach was applied to estimate the risk from exposures to multiple carcinogens, with chemical- and route-specific estimates summed to estimate the total cancer risk. The underlying assumption is that the risks from carcinogens with different target organs are additive. This assumption contributes to the uncertainty in the risk assessment and may result in underestimated or overestimated risks, depending on whether there are synergistic or antagonistic interactions among these chemicals. Furthermore, most cancer SFs currently in use are an upper 95th percentile estimate of potency. Because the upper 95th percentiles of probability distributions are not

strictly additive, the total estimated cancer risk may become artificially more conservative as risks for a number of different carcinogens are summed. In addition, the IURs (and RfCs) are based on continuous exposures.

The HIs represent the sum of HQs for exposures to chemicals not expected to induce the same type of effects or that do not act by the same mechanism. Summing the HQs without considering type of effect tends to overestimate the total HI. For this reason, the HI is segregated when the initial screening estimate exceeds the target value of 1 because of the contributions from multiple chemicals. In this assessment, the risks and HIs that exceed the NCP target levels are for direct waste ingestion and for the imaginary case of uncontrolled excavation (see Appendix D). The segregated HI exceeds 1 for these example estimates. Note that a toxicity value is not available to easily quantify the noncarcinogenic effects of lead; given its high concentration in some of the IWCS wastes, this metal is considered a contaminant of concern for the IWCS OU, and a further evaluation of this metal that accounts for noncarcinogenic effects is anticipated to be reflected in the FS (after project-specific planning information becomes available to support a representative risk assessment).

With regard to the additivity assumption for noncarcinogenic effects, deviations from this default approach are unlikely at typical environmental concentrations. However, if an acute exposure were to occur to highly contaminated residues (e.g., waste group 2), then toxic interactions might be considered. The ATSDR has developed an interaction profile that considers the joint toxicity of four metals, including lead and arsenic (ATSDR 2004b, see highlights in the last fact sheet of Appendix C). This metal pair can cause higher-than-additive effects on the nervous system, while the joint toxicity could be less-than-additive on the kidney and hematological system. This potential for cumulative effects that deviate from the default additivity assumption is not considered a factor for the exposure levels evaluated in this TM.

Considering the combined uncertainties underlying the risk results presented in this TM, those associated with the radionuclides are considered low, and those for the chemicals are considered moderate in the context of the overall results. The scope of this evaluation is limited to the near term and is based on historical data. Good information is available for the radioactive contaminants in the IWCS materials. Generally conservative assumptions are used to define the exposure scenarios, which is expected to more than offset any underestimates of the radiation doses associated with using adult DCFs in this TM for all receptors. Cancer risk coefficients are available for all the radionuclides (because all are considered carcinogenic to humans) and cancer toxicity values are also available for several metals as well as for PCBs. (Note uranium is a radiological carcinogen, i.e., it causes cancer due to its radioactive properties, not chemical toxicity; the estimated chemical toxicity translates to HQs well below the NCP target level.) The general uncertainty in the toxicity values used to estimate the potential for health effects is considered moderate, given that IRIS assessments are under way such that some values will change, but the effective uncertainty is low because chemicals are not dominant contributors to the risks indicated in this TM.

Overall, uncertainty is considered low in terms of the radiological characterization data and toxicity values, and moderate for the chemical characterization data and toxicity values. Uncertainty in the amounts of exposure assumed for the onsite maintenance worker and trespasser are considered high in the conservative direction, in terms of the probability that such exposures would actually occur. Both of these receptors are hypothetically assumed to spend 10% of their time very close to (1 m [3 ft]) from exposed wastes at the IWCS without any protection.

Given the extensive set of engineered and institutional controls in place at NFSS, these assumptions are obviously unrealistic for the near term, which makes the conservatism (and uncertainty) high for current conditions. However, this approach is used so these receptors can be considered to represent possible future exposures associated with a no-action or leave-in-place alternative, e.g., if wastes were onsite and institutional controls were lost at some point in the distant future such that the wastes were exposed.

Thus, for that purpose, the uncertainty in terms of potential exposures and health effects that might occur in the unforeseeable future is reduced toward moderate. Beyond the substantial (intentional) conservatism reflected in the exposure estimates, the general uncertainty is considered moderate to low for the radiological risk estimates and moderate for the chemical risk estimates.

The EPA has developed toxicity values for a number of chemicals, and considerable uncertainty is associated with many of these (as indicated in Table 4.6 and Section 5.3.3). In addition, toxicity values are not available for both routes and both health endpoints (cancer and noncarcinogenic effects) for all chemicals. This limitation might contribute to an underestimation of hazards posed by these chemicals. However, the impact on the overall risk estimates is considered low, because estimated radiological effects dominate. (As a note, the contaminants for which data are not available are naturally occurring metals so they are always present in soil, or in this case, in waste derived from ore processing; if adverse effects had been indicated for exposures to these chemicals, a toxicity value would likely have been developed to guide exposure limits, with the exception of lead for which EPA models are available (e.g., the exposure uptake and biokinetic model) to estimate blood lead levels, which can then be used to indicate potential health effects. Finally, a number of IRIS reassessments are under way, so it will be important to check for updates of the chemical toxicity values from Tier 1 and beyond, to assure that the best current values are used in upcoming risk calculations to be developed for the FS.

6 SUMMARY AND CONCLUSIONS

This risk evaluation was prepared to support the FS being developed for the IWCS OU, and it follows the general approach outlined in EPA guidance for risk assessments at contaminated sites. This TM focuses on near-term exposures and does not address contaminated groundwater for several reasons. Contaminant migration from the IWCS to groundwater has been separately assessed (HGL 2007, 2011), groundwater is not used as a source of drinking water at the site, and it will be addressed in a future OU (see Section 1.2). Results of the human health assessment for the IWCS are summarized in this chapter, organized according to the four traditional steps of a risk assessment: data evaluation and identification of contaminants of potential concern, exposure assessment (including development of exposure scenarios and input parameters), toxicity assessment (the dose-response evaluation for the contaminants of potential concern), and characterization of the risks (presentation of results).

6.1 CONTAMINANTS OF POTENTIAL CONCERN

Conceptual planning information for the IWCS FS is not yet available to conduct a representative risk assessment, from which contaminants of concern would then be determined. Thus, as an early illustrative evaluation to help guide planning for the FS, this TM only considers contaminants of potential concern. Both radionuclides and chemical contaminants are present in the IWCS. The primary radionuclides are those in the U-238, U-235, and Th-232 decay series associated with the residues and other wastes that were transferred to NFSS for storage more than 50 years ago (now contained in the IWCS). The radionuclide of most concern is Ra-226, due to both its high concentrations in the residues and its radiation toxicity. Ra-226 decays to Rn-222, a radioactive gas which is also being assessed in a separate TM (USACE 2012). There are 11 principal radionuclides in these three decay series, and characterization data are available for each of them.

Additional radionuclides including fission products such as Sr-90 and Cs-137, and TRU radionuclides including isotopes of plutonium have been identified in soils at NFSS (USACE 2007a). They are present in relatively few locations and the concentrations are generally low. The exception is Cs-137, which will be addressed as a radionuclide of potential concern in the BOP OU given its apparent widespread distribution on the site (note these radionuclides are present in surface soils throughout the world as a result of past atmospheric testing of nuclear weapons). These radionuclides are also likely present in low concentrations in the IWCS from soil excavated by DOE and placed therein during the 1980s. However, these radionuclides do not pose a significant hazard to human health relative to the 11 principal radionuclides of the three natural decay series. For this reason, potential exposures and risks are not quantified for these radionuclides in this TM.

The chemical contaminants of potential concern for the IWCS consist of ten metals (As, Ba, Co, Li, Pb, Mn, Mo, Ni, V, and U) and PCBs. These metals were reported in materials stored at the site (DOE 1986), and they were selected by a screening process in which the concentration of each was compared to the respective EPA RSLs for residential soil (to be conservative) and state of New York soil cleanup objectives. PCBs were added as a further contaminant of concern to represent organic compounds because they have been found in soils and other materials at NFSS and also at LOOW. Based on the preliminary evaluations in this TM, the primary chemicals of interest are Co, Pb, Mn, Ni, V, and PCBs.

Data for other chemicals in the IWCS wastes are too limited to support a meaningful estimate of potential health effects. Asbestos is among those other chemicals. This material was present in a number of buildings that were demolished and placed in the IWCS by DOE, but no data were found on the amount or concentrations of ACM that might be present in the debris stored in the IWCS. Moreover, demolition debris comprises a relatively small volume of wastes in the IWCS (most is contaminated soil), so asbestos is not expected to affect the overall risk estimates for the IWCS. Its presence is acknowledged in this TM

so proper precautions can be incorporated into the upcoming FS evaluations and further planning to assure appropriate protective measures are in place if debris containing asbestos is encountered at the IWCS.

6.2 EXPOSURE ASSESSMENT

A general conceptual site model was developed as part of the exposure assessment to outline the sources of radioactive and chemical contaminants, release mechanisms, transport media, exposure routes, and potential hypothetical receptors for the IWCS. This conceptual site model (presented in Figure 3.1) was developed in the context of the local setting described in Chapter 3. These considerations include the relatively small area of the IWCS within the larger fenced NFSS that is owned by the Federal government. This ownership is expected to continue well beyond the time frame addressed for this TM, effectively precluding construction of a residence on the IWCS. In addition, two commercial landfills (one for hazardous waste and one for municipal waste) adjoin the NFSS property.

The IWCS is an engineered structure that contains radioactively and chemically contaminated wastes that were generated by past DOE remedial actions conducted in the 1980s. While the estimated service life of the engineered cap was identified as 25 to 50 years in the NEPA ROD issued by DOE in 1986, the cap is routinely monitored and maintained by the USACE Buffalo District. This active management is expected to extend the life of the cap well past 50 years. In addition, the design service life of the clay dike and cutoff walls surrounding the IWCS and the natural glaciolacustrine clay beneath the structure is 200 to 1,000 years. Thus, the safety of the IWCS can be ensured as long as the Federal government owns NFSS, continues current surveillance and monitoring, and repairs any crack or gap in the cover as it is identified.

However, the current situation does not represent a long-term solution for the IWCS. It is possible for certain events (such as an earthquake or a burrowing animal) to compromise the integrity of the engineered cap, which could release contaminants (particulates and Rn-222 gas) to the atmosphere for a limited time until the cap was repaired (under current site conditions). In addition, direct exposure to the gamma radiation emitted from the high-activity residues (in particular the K-65 residues) could result in elevated doses to individuals near the IWCS.

Contaminants in the IWCS wastes could impact receptors via two main release mechanisms: external gamma radiation (principally from the residues) and airborne releases with associated dispersion and deposition of contaminated particulates on surface soil (which could then be incidentally ingested or emit gamma radiation). Deposited contaminants might also enter the food chain but this pathway is considered minor relative to the primary exposure pathways: inhalation of airborne particulates (including Rn-222 decay products) and external gamma irradiation.

To evaluate potential health risks, a number of hypothetical scenarios were developed to represent various human activities and locations for possible exposures to IWCS contaminants. These exposures consider current and expected future land uses at NFSS and the nearby area. Three onsite scenarios were assessed: maintenance and remedial action workers and an adolescent trespasser. Three offsite scenarios were assessed as well: an outdoor worker and an adult and a child living near the site. Exposures to students and staff at nearby schools including the Lewiston-Porter school campus were not quantitatively assessed because potential exposures for those individuals are expected to be accounted for by the hypothetical receptors evaluated in this TM.

6.3 TOXICITY ASSESSMENT

The toxicities of the IWCS contaminants evaluated in this TM consider both radiological and chemical effects. The health effects associated with low-level ionizing radiation include an increase in the

probability of cancer induction, cardiovascular disease, and other detrimental health effects. The main health concern for the IWCS contaminants is cancer induction, and the evaluation of radionuclides is limited to this issue. This approach is consistent with EPA guidance, which notes that cancer risk is generally the limiting effect for radionuclides and can be used as the sole basis for assessing the human health risks at radioactively contaminated sites.

Ionizing radiation is a known human carcinogen, and the relationship between radiation dose and the probability of developing cancer is generally well characterized for high doses. Although chronic doses of low-level radiation have not been shown to cause cancer, this effect is nonetheless assumed to assure protectiveness and support development of appropriate standards. Because most radiation protection standards are given in terms of radiation dose (in mrem), the doses associated with exposures to the IWCS wastes are included in this assessment. Standard coefficients developed by the ICRP and EPA are used to estimate the radiological doses and risks in this report. These factors have been widely used in risk assessments for radioactively contaminated sites and facilities.

The health effects for chemical contaminants include an increase in the likelihood of developing cancer as well as noncarcinogenic effects. Arsenic, nickel, and asbestos are classified as known human carcinogens, while lead and PCBs are classified as probable human carcinogens, with evidence suggesting carcinogenicity to humans based on experimental data from animal studies. Organs and systems that can be affected by inhaling or ingesting chemicals found in the IWCS (above a certain dose) include the respiratory system, central nervous system, and kidney.

6.4 RISK CHARACTERIZATION

Risk information from two key analyses of the IWCS conducted by DOE a number of years ago are presented in Section 6.4.1. Results of the risks estimated in this TM are presented in Section 6.4.2.

6.4.1 Highlights of Dose and Risk Information from Previous Analyses for the IWCS

Two studies prepared by DOE and its technical teams a number of years ago serve as primary sources of dose and risk information relevant to the IWCS. These studies are: the EIS for NFSS issued in 1986 and the failure analysis report for the IWCS issued in 1994 (BNI 1994). Although the NRC published a study in 1995 that evaluated the safety of the IWCS and made recommendations (NRC 1995), that report generally used information from these two documents rather than reflecting any significant new risk information.

In its study, the NRC determined that if institutional controls were lost and the IWCS cover completely eroded away, then if someone built a house on the residues (and drank underlying groundwater and ate food from an IWCS garden) they would incur an unacceptable risk. The NRC concluded that this hypothetical resident would likely die within a few years due to the very large radiation doses from Rn-222 decay products. Although an onsite residential scenario is quite unrealistic in the near term, some might consider it possible in the distant future if the high-activity residues remained at NFSS, land-use controls were indeed lost, and someone unwittingly (and inexplicably) lived atop these residues.

Key information for the various exposure scenarios evaluated in these two primary reports is summarized in Table 6.1. The estimates presented in the EIS assume an average Ra-226 concentration of 220,000 pCi/g for the K-65 residues (which was the concentration estimated at that time). The average Ra-226 concentration in all the residues combined was taken to be 67,000 pCi/g. The hypothetical doses presented in the EIS would have been higher if current estimates of the Ra-226 concentrations in the residues had been used.

TABLE 6.1 Highlights of Dose and Risk Estimates from Previous Analyses for the IWCS[a]

Hypothetical Receptor	Material/ Location[b]	Estimated Radiation Dose *(mrem)*[c]	Estimated Cancer Risk[d]	Information Source
Onsite				
Resident intruder	IWCS residues	1,100,000 per year[e]	0.4 per year	EIS
Exploratory driller	On IWCS cap	510	3×10^{-5}	Failure analysis
Remedial action worker	Near IWCS	4.2 per hour	1×10^{-6} per hour	EIS
Offsite				
Camper at KOA campground	0.7 km SSW	11	4×10^{-6}	EIS
Student at nearby school	2.4 km W	1.5	5×10^{-7}	EIS
Resident at trailer park	2.6 km NW	0.80	3×10^{-7}	EIS
Worker at CWM landfill	1.2 km NNE	14	4×10^{-6}	EIS
Nearby potential resident	0.2 km W	94	3×10^{-5}	EIS

[a] The exposure scenarios summarized in this table are described in more detail in the EIS (DOE 1986) and failure analysis report (BNI 1994). The impacts for the onsite remedial action worker and the five offsite receptors are estimated in the EIS for potential onsite remedial activities involving retrieval of residues and wastes from the IWCS. The onsite resident intruder and exploratory driller scenarios might occur in the distant future if contaminated materials were to remain onsite and institutional controls were lost. Current radiation doses in the vicinity of NFSS are much lower than those given in this table, as reported in annual TMs for the environmental surveillance program at NFSS. The radiation doses are given to two significant figures, while estimated cancer risks are given to one significant figure in accordance with standard EPA guidance. Numbers may not sum exactly due to rounding.

[b] For the onsite scenarios, the receptor is assumed to be either at or near the IWCS. For the offsite receptors, the distances shown here are those given in Table 4.8 of the EIS. (Note the potential resident does not represent an existing residential location.)

[c] Radiation doses are given as 50-year committed effective dose equivalents (CEDEs). These doses were obtained from the organ-specific doses given in Table 4.10 of the EIS using the organ-weighting factors in effect at the time the EIS was issued. The radiation dose and cancer risk to the exploratory driller is largely from external gamma radiation.

[d] Cancer risks represent the risk of a fatal cancer, consistent with the manner in which this information is given in the EIS. For the hypothetical exploratory driller scenario, the risk of a fatal cancer was obtained by multiplying the radiation dose by a risk factor of 6×10^{-7} per mrem, because much of the dose incurred by this receptor is from external gamma radiation (for which this dose-to-risk estimator is directly relevant). For the other scenarios, the risk of a fatal cancer was obtained using the organ-specific doses and organ-specific cancer mortality factors given in Table 4.30 of the EIS.

[e] This dose is calculated from the annual dose to the bronchial epithelium of 8,000,000 mrem/yr given in Table 4.24 of the EIS and cited in the 1995 NRC report, multiplied by 2.27 to account for the higher Ra-226 concentration in the residues (see text). A weighting factor of 0.06 was used to calculate the CEDE from the dose to the bronchial epithelium. The dose and cancer risk for the resident intruder would be higher if other pathways beyond inhalation of Rn-222 decay products were included.

The average Ra-226 concentration in the K-65 residues is now estimated to be about 520,000 pCi/g, while the average Ra-226 concentration for all residues combined is estimated at about 152,000 pCi/g (due to the higher estimate for the K-65 residues). To facilitate comparisons with the doses and risks estimated in this TM, the doses and risks reported in the EIS were increased by a factor of 2.27 for presentation in Table 6.1 to account for the updated estimates of average Ra-226 concentrations.

Note that the internal radiation doses in the EIS are reported in terms of 50-year committed dose equivalents to the major target organs. The internal doses were converted to 50-year CEDEs for presentation in Table 6.1, using the organ-specific weighting factors that were in effect when the EIS was prepared. This conversion was done to allow for a more direct comparison with the doses and risks estimated in this TM.

The preliminary risk estimates in Table 6.1 generally represent the risk of incurring a fatal cancer, because the risks presented in the EIS were limited to cancer mortality and did not include estimates for cancer morbidity. This is consistent with the manner in which radiological cancer risk information was presented in comparable documents at that time (in 1986). Risk estimators for cancer morbidity were not generally available until several years later, e.g., in documents such as FRG 13 (EPA 1999b). Note that the risk estimates calculated in this TM are for cancer incidence (morbidity), consistent with current EPA guidance for radiological risk assessment.

The EPA has noted that about half of all cancers induced by radiation result in death. That is, as a rough approximation, the risk of cancer morbidity can be estimated by multiplying the mortality risk by two. The fraction of fatal cancers ranges from about 10% in the case of thyroid cancer to 100% for liver cancer (EPA 1989). However, the difference between cancer morbidity and mortality for the radionuclides in the IWCS is generally less than 50%, depending on the mode of exposure. As shown in Table 4.1, the morbidity risk factors for the radionuclides contributing most of the risk for the scenarios addressed in this TM (i.e., Ac-227, Th-230, Ra-226, and Pb-210) are higher than the mortality values by about 5 to 30% for inhalation exposures, and by about 40 to 50% for ingestion and external gamma irradiation exposures. Also, because most lung cancers are fatal, the morbidity and mortality risk estimators for exposures to Rn-222 progeny are comparable. Based on these considerations, cancer morbidity can be approximated for the scenarios addressed in the EIS by multiplying the mortality risk estimates by 1.5. This adjustment will produce conservative estimates of the cancer morbidity risks for comparison with the risk calculated in this TM for the six example scenarios.

6.4.2 Summary of Doses and Risks Estimated in this TM

Potential radiological and chemical health effects have been evaluated for hypothetical exposures to contaminants at the IWCS to support the FS being developed for this OU. The estimated cancer risks represent the increased probability (above a background rate) that an individual will develop cancer over a lifetime from the assumed exposures to IWCS contaminants. To guide risk management planning, the NCP identifies a range of between one in ten thousand (1×10^{-4}, or 0.0001) and one in a million (1×10^{-6}, or 0.000001) for the incremental cancer risk for exposures associated with contaminated sites, which is referred to as the target risk range. For comparison, based on recent U.S. data, men have a nearly 1 in 2 risk (5×10^{-1}, or 0.5) of developing cancer over a lifetime from all causes combined, and the estimate for women is slightly more than 1 in 3 (3×10^{-1}, or 0.3). Thus, the NCP target range for incremental risk represents a very small fraction (e.g., 0.0002% to 0.03%) of the average U.S. cancer rate. The NCP target levels are noted in this TM simply to provide example context for the preliminary risk estimates presented herein; they are not action levels, rather they serve as illustrative comparison values to help inform planning for the IWCS FS.

The radiological doses and risks estimated for hypothetical exposures in this TM are incremental to those from natural and man-made sources of radiation. (Also note that the estimates of potential exposures and effects for all contaminants are intentionally conservative, based on protective assumptions; more realistic estimates are expected to be lower.) The example estimates of radiological doses and risks developed for this TM based on early conceptual assumptions for waste excavation are presented in Table 6.2. For perspective, the NCRP estimates that an average individual in the United States receives an annual radiation dose of about 620 mrem, with natural background radiation and that from man-made sources including medical procedures each contributing about 310 mrem (NCRP 2009). For natural sources, about two-thirds of the dose (200 mrem/yr) is due to indoor Rn-222 gas and its short-lived radioactive decay products. The U.S. average annual radiation dose corresponds to a lifetime cancer risk of about 3×10^{-2}, or about 3 chances in 100 of getting cancer over a lifetime, assuming an individual lifetime of 70 years and using a risk factor of 8×10^{-7} per mrem for the likelihood of developing a radiogenic cancer.

TABLE 6.2 Estimated Radiological Doses and Risks from Excavation Releases and Direct Waste Exposures at the IWCS[a]

Scenario	Estimated Radiological Doses and Cancer Risks							
	Waste Group 1		***Waste Group 2***		***Waste Group 3***		***Total***	
	K-65 Residues		**L-30, F-32, L-50 Residues and Tower Soils**		**R-10 Pile and Other Contaminated Soils**		**All IWCS Wastes**	
	Dose *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	16	1×10^{-5}	4.4	3×10^{-6}	0.034	2×10^{-8}	21	2×10^{-5}
Maintenance worker	**200**	$\mathbf{2 \times 10^{-4}}$	31	1×10^{-5}	0.23	7×10^{-8}	**230**	$\mathbf{2 \times 10^{-4}}$
Trespasser	2.5	2×10^{-6}	0.35	2×10^{-7}	0.0023	7×10^{-10}	2.9	2×10^{-6}
Offsite: dispersed contaminants								
Outdoor worker	0.46	4×10^{-7}	0.11	5×10^{-8}	0.0016	5×10^{-10}	0.57	4×10^{-7}
Adult resident	0.40	3×10^{-7}	0.065	3×10^{-8}	0.00078	3×10^{-10}	0.47	3×10^{-7}
Child resident	0.39	3×10^{-7}	0.058	3×10^{-8}	0.00066	2×10^{-10}	0.45	3×10^{-7}
Onsite: direct waste exposures[b]								
Incidental ingestion (100 mg)	**430**	$\mathbf{2 \times 10^{-4}}$	11	5×10^{-6}	0.041	2×10^{-8}	**440**	$\mathbf{2 \times 10^{-4}}$
External gamma (8 hr)	**2,000**	$\mathbf{2 \times 10^{-3}}$	38	3×10^{-5}	0.13	1×10^{-7}	**2,000**	$\mathbf{2 \times 10^{-3}}$
Combined direct exposures	***2,400***	$\boldsymbol{2 \times 10^{-3}}$	*49*	4×10^{-5}	*0.17*	1×10^{-7}	***2,500***	$\boldsymbol{2 \times 10^{-3}}$

[a] The dose is the 50-year committed effective dose, and it is given to two significant figures. The cancer risk represents the probability that an exposed individual will develop cancer over a lifetime, and it is rounded to one significant figure. Estimates in bold exceed the comparison levels from the NCP. The waste groups reflect preliminary planning information for the IWCS OU.

The hypothetical exposure scenarios are described in Chapter 3. For the onsite scenarios, the remedial action worker is assumed to spend the entire time onsite at the IWCS, with personal protective equipment for all but one day during the excavation of each waste group (to account for potential limited failure of the protective equipment, and also to illustrate what the dose and risk would be if exposures were not controlled with respiratory protection). The onsite maintenance worker and trespasser are assumed to spend an average of 10% of their time within 1 m (3 ft) of uncovered IWCS wastes and the rest of the time 50 m (160 ft) and 100 m (330 ft) from the exposed wastes, respectively.

[b] If someone stood 1 m (3 ft) from a 10-m^3 (13-yd^3) pile of unshielded K-65 residues for 8 hours, they would incur an external gamma dose of 2,000 mrem (2 rem), which corresponds to a risk of 2×10^{-3}. The doses and risks for the other two waste groups are scaled from their Ra-226 concentrations relative to that in the K-65 residues. If someone inadvertently (incidentally) ingested 100 mg (0.0035 ounce) of the K-65 residues directly, the dose would be 430 mrem and the corresponding risk would be 2×10^{-3}. The doses and risks for the other two waste groups are calculated based on the volume-weighted average radionuclide concentrations in the component wastes.

The radiological and chemical risks are calculated separately in this report because of differences in the quality of the characterization data and approaches applied to identify the contaminants of potential concern and fill data gaps, as well as differences in the methods used to estimate cancer risks. The most significant difference in the assessment approaches is the basis for the risk estimators. For radionuclides, the risk coefficients are best estimate, average values; for chemicals, the risk estimators generally represent the upper bound or upper 95% confidence limit of the slope of the dose-response curve. Furthermore, the radiological risk coefficients are derived from human epidemiological data, while the estimators for chemicals are commonly derived from experiments with laboratory animals. Hence, the uncertainties associated with the risk estimates for radionuclides and chemicals differ significantly.

The illustrative risks estimated in this TM based on early conceptual assumptions for waste excavation, pending the upcoming development of project-specific estimates for the FS, are summarized in Tables 6.3 and 6.4. These tables provide the example estimates of radiological and chemical cancer risks for each of the three waste groups for the six hypothetical receptors, in addition to the combined (total) risk estimate associated with excavating all wastes from the IWCS. These estimates are based on early conceptual assumptions for waste excavation, pending the upcoming development of project-specific estimates for the FS. This table also includes the estimated chemical HIs for potential noncarcinogenic effects.

With standard engineering controls, little offsite impact is projected from waste excavation at the IWCS. The radiation doses are less than 1 mrem, and both the radiological and chemical risks are below the NCP comparison range (i.e., less than 1×10^{-6}). The HI is also well below the NCP target level of 1. (Even without engineering controls, the offsite estimates remain within or below the target levels.) The doses, risks, and HIs for the onsite receptors are significantly higher than those for the offsite receptors, but in only one instance does the estimate exceed an NCP target level. The risk estimated for the hypothetical maintenance worker is 2×10^{-4}, which is slightly above the NCP target range.

Most of the radiological risk is attributable to the K-65 residues (waste group 1). The radiological risks estimated for the other two waste groups are significantly lower and are within or below the NCP risk range for all hypothetical receptors. The risks estimated for waste group 2 are lower than those for group 1 by about a factor of ten, while those for waste group 3 are lower by a factor of more than 100. These results reflect the very high concentrations of Ra-226 in the K-65 residues and the inhalation risks associated with Rn-222 and its short-lived decay products.

Inhalation is generally the main exposure pathway for both radionuclides and chemicals, with Rn-222 being the main contributor to the radiological (and total) doses and risks. Incidental ingestion and external gamma radiation associated with contaminants deposited on soil are lesser contributors to the overall risk estimates. The highest risk estimate is for the maintenance worker, who unlike the remedial action worker is assumed to wear no respiratory protection equipment. Noting that highly unrealistic assumptions underlie these hypothetical estimates (including proximity to active waste excavation areas) in order to bound possible impacts, if actual onsite conditions ever indicated any such potential exposures for an onsite worker, the worker would be appropriately protected.

The chemical risks are much lower than the radiological risks, contributing less than 1% to the total risk estimates. All chemical risks and HIs are below the NCP comparison levels. The highest combined risk is 3×10^{-7} for the hypothetical maintenance worker, which is dominated by exposures associated with the excavation of waste group 2. This risk is primarily from the inhalation of cobalt (70%), with vanadium accounting for most of the remainder. The estimated HI of 0.6 is from inhalation of manganese (50%), with nickel and cobalt contributing most of the rest. The next highest estimates for the combined waste excavations are for the hypothetical remedial action worker, with a risk and HI lower than those for the maintenance worker by roughly a factor of ten, at 4×10^{-8} and 0.04, respectively. The risks and HIs for all other receptors for the three waste groups are even lower (all well below the NCP comparison levels).

TABLE 6.3 Summary of Example Risks and Hazard Indexes from Excavation Releases and Direct Waste Exposures at the IWCS[a]

Scenario	Estimated Cancer Risks and Chemical Hazard Indexes										
	Waste Group 1			***Waste Group 2***			***Waste Group 3***			***Total***	
	K-65 Residues			**L-30, F-32, L-50 Residues and Tower Soils**			**R-10 Pile and Other Contaminated Soils**			**Combined Wastes**	
	Radiological Risk	**Chemical Risk**	**Hazard Index**	**Radiological Risk**	**Chemical Risk**	**Hazard Index**	**Radiological Risk**	**Chemical Risk**	**Hazard Index**	**Total Risk**	**Total HI**
Onsite: dispersed contaminants											
Remedial action worker	1×10^{-5}	2×10^{-9}	0.0002	3×10^{-6}	3×10^{-8}	0.04	2×10^{-8}	2×10^{-8}	0.0006	2×10^{-5}	0.04
Maintenance worker	$\mathbf{2 \times 10^{-4}}$	1×10^{-8}	0.004	1×10^{-5}	3×10^{-7}	0.6	7×10^{-8}	3×10^{-8}	0.01	$\mathbf{2 \times 10^{-4}}$	0.6
Trespasser	2×10^{-6}	3×10^{-10}	0.00005	2×10^{-7}	5×10^{-9}	0.007	7×10^{-10}	2×10^{-9}	0.0002	2×10^{-6}	0.008
Offsite: dispersed contaminants											
Outdoor worker	4×10^{-7}	3×10^{-11}	0.00001	5×10^{-8}	1×10^{-9}	0.003	5×10^{-10}	2×10^{-10}	0.00008	4×10^{-7}	0.003
Adult resident	3×10^{-7}	2×10^{-11}	0.000006	3×10^{-8}	7×10^{-10}	0.002	3×10^{-10}	1×10^{-10}	0.00005	3×10^{-7}	0.002
Child resident	3×10^{-7}	2×10^{-11}	0.000006	3×10^{-8}	8×10^{-10}	0.002	2×10^{-10}	2×10^{-10}	0.00005	3×10^{-7}	0.002
Onsite: direct waste exposures[b]											
Incidental ingestion (100 mg)	$\mathbf{2 \times 10^{-4}}$	$\mathbf{8 \times 10^{-4}}$	**10**	5×10^{-6}	$\mathbf{3 \times 10^{-4}}$	**9**	2×10^{-8}	$\mathbf{1 \times 10^{-4}}$	**4**	$\mathbf{1 \times 10^{-3}}$	**20**
External gamma (8 hr)	$\mathbf{2 \times 10^{-3}}$			3×10^{-5}			1×10^{-7}			$\mathbf{2 \times 10^{-3}}$	
Combined direct exposures	$\boldsymbol{2 \times 10^{-3}}$	$\boldsymbol{8 \times 10^{-4}}$	***10***	4×10^{-5}	$\boldsymbol{3 \times 10^{-4}}$	***9***	1×10^{-7}	$\boldsymbol{1 \times 10^{-4}}$	***4***	$\boldsymbol{3 \times 10^{-3}}$	***20***

[a] These estimated radiological and chemical cancer risks and HIs are for excavating all the wastes from the IWCS consistent with the definition of the IWCS OU. The estimates in bold exceed the NCP target levels. The volumes of the component wastes are given in Table 2.2; the three waste groups are based on preliminary planning information for this OU. The cancer risks represent the probability that an exposed individual will develop cancer during their lifetime and are given to one significant figure. The HI is a measure of the potential for noncarcinogenic health effects as a result of exposures to chemicals in the IWCS; a value above 1 indicates a potential concern; HIs are rounded to one significant figure. Gray shading indicates the entry is not relevant.

[b] Someone standing 1 m (3 ft) from a 10-m^3 (13-yd^3) pile of unshielded K-65 residues for 8 hours would incur an external gamma dose of about 2,000 mrem (2 rem), which corresponds to a risk of 2×10^{-3}. The radiological doses and risks for the other two groups are calculated from their Ra-226 concentrations relative to that in the K-65 residues. If someone inadvertently (incidentally) ingested 100 mg (0.0035 ounce) of the K-65 residues directly, the dose would be 430 mrem and the corresponding risk would be 2×10^{-4}. The estimated chemical risk is four times higher (8×10^{-4}), and the estimated HI is 10. The risks and HIs estimated for the other two waste groups are lower, as calculated from the volume-weighted average contaminant concentrations in those component wastes.

TABLE 6.4 Combined Hazard Indexes and Risks Estimated for Example Exposures to IWCS Contaminants[a]

Scenario	Hazard Index	Chemical Risk	Radiological Risk	Combined Cancer Risk
Onsite: dispersed contaminants				
Remedial action worker	0.04	4×10^{-8}	2×10^{-5}	2×10^{-5}
Maintenance worker	0.6	3×10^{-7}	**2×10^{-4}**	**2×10^{-4}**
Trespasser	0.008	8×10^{-9}	2×10^{-6}	2×10^{-6}
Offsite: dispersed contaminants				
Outdoor worker	0.003	2×10^{-9}	4×10^{-7}	4×10^{-7}
Adult resident	0.002	9×10^{-10}	3×10^{-7}	3×10^{-7}
Child resident	0.002	1×10^{-9}	3×10^{-7}	3×10^{-7}
Onsite: direct waste exposures				
Incidental ingestion (100 mg)	**20**	**1×10^{-3}**	**2×10^{-4}**	**1×10^{-3}**
External gamma (8 hr)			**2×10^{-3}**	**2×10^{-3}**
Combined direct exposures	***20***	***1×10^{-3}***	***2×10^{-3}***	***3×10^{-3}***

[a] The radiological and chemical risk estimates represent the probability that the hypothetical individual will develop cancer during their lifetime as a result of exposures to IWCS contaminants from excavating all three waste groups from the IWCS. The total risk is the arithmetic sum of the radiological and chemical risks. The estimates in bold exceed the NCP comparison levels. The HI represents the potential for adverse health effects other than cancer and is calculated to assess health effects from chemical exposures. An HI of 1 or less indicates no adverse effects are expected. The risks and HIs are rounded to one significant figure. Gray shading indicates the entry is not relevant.

None of the chemical particulate emissions result in air concentrations that exceed permissible exposure limits for workers or national ambient air quality standards (for lead). In addition to evaluating potential health effects for the six hypothetical receptors associated with waste excavation, further evaluations were conducted to assess potential exposures if the wastes were uncovered in place at the IWCS. If someone were at the IWCS without exposure protection when the wastes were uncovered, the dose from external gamma radiation could exceed 1,000 mrem (1 rem) within a number of days or a few weeks depending on whether the exposure was continuous or not. The risk corresponding to this dose is 8×10^{-4}, which exceeds the upper end of the NCP target range. As a further illustration of potential risks associated with the wastes left in place, if a fairly long fracture developed in the cap, the risk estimated for someone repairing that fracture is 7×10^{-3} (see Table 5.4). The doses and risks associated with the release of Rn-222 gas from uncovered wastes and inhalation of Rn-222 progeny would likely be somewhat lower than that from external gamma radiation but could be comparable.

Similarly, if someone were to inadvertently ingest 100 mg (0.0035 ounce) of K-65 residues at the IWCS, the dose would be about 430 mrem and the corresponding risk would be 2×10^{-4}. The doses and risks for the other two waste groups would be much lower because their radionuclide concentrations are much lower. The total dose from ingesting this tiny amount from each of the three waste groups is estimated to be 440 mrem, and the resultant risk would be 2×10^{-4}. The dominant contributor to this ingestion dose and risk is Pb-210 (accounting for more than 85% of the total), with much of this contribution associated with its decay product polonium-210; Ra-226 accounts for most of the remainder.

The chemical risks associated with ingesting 100 mg (0.0035 ounce) of K-65 residues would be somewhat higher (8×10^{-4}) with lead again the main contributor, based in this case on its chemical toxicity; PCBs would also contribute to this incidental ingestion risk. The chemical HI of 10 estimated for that exposure exceeds the NCP target level. The total chemical risk from ingesting this tiny amount of waste from each waste group is estimated to be 1×10^{-3}, and the total HI would be 20. These estimates reinforce the need for stringent controls to minimize the likelihood of such exposures for anyone who might be near the IWCS wastes, especially the K-65 residues.

If institutional controls were lost at NFSS in the future and the high-activity residues were uncovered, a member of the general public could be exposed to high levels of external gamma radiation and Rn-222 and its progeny at the IWCS. Dose limits for the general public for uncontrolled areas could be exceeded within a few days (or weeks if exposures were not continuous), and the incremental risks would exceed NCP target levels.

These estimates indicate that whether the remedial action alternative involves excavating wastes or leaving them in place, stringent control measures would be warranted at the IWCS to assure protection from external gamma radiation (e.g., by time, distance, and shielding) and to control Rn-222 releases, as well as to prevent any access that could result in incidental ingestion. The most rigorous controls would be needed for the K-65 residues and other high-activity residues because of their high Ra-226 concentrations.

The example risk information in this report is designed to support the development and evaluation of remedial alternatives in the IWCS and to help frame practical worker protection measures. To support planning for the FS, this report illustrates the process for estimating risks to help guide the determination of appropriate source and exposure control measures that will assure health protection (notably for nearby individuals if wastes are excavated from the IWCS, particularly the high-activity residues). The main findings are:

- Wastes in the IWCS are safely contained, and they will remain safe for as long as active controls are in place at NFSS to prevent inadvertent exposures.

- If the wastes were uncovered and someone were to stay at the IWCS for several days to weeks, substantial doses and serious health effects could result. The main contributors would be external gamma irradiation and inhalation of Rn-222 and its progeny.

- If engineering controls are in place, the wastes can be safely removed from the IWCS with minimal offsite impact.

- During excavation, inhalation is anticipated to be the primary exposure route for onsite receptors. Inadvertent direct ingestion of the IWCS wastes would also be a major health concern, particularly for the high-activity residues.

- Any remedial action alternative that involves excavating the wastes would require stringent source and exposure controls to assure protection of onsite individuals during the cleanup period. Similar stringent controls would be warranted for any in-place alternative to assure sustained health protection.

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APPENDIX A:

ESTIMATED INTAKES, DOSES, AND RISKS FOR EXPOSURES TO RADIONUCLIDES

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APPENDIX A:

ESTIMATED INTAKES, DOSES, AND RISKS FOR EXPOSURES TO RADIONUCLIDES

This appendix presents preliminary estimates of radionuclide intakes, radiation doses, and radiological cancer risks for exposures to particulates assumed to be released during waste excavation from the Interim Waste Containment Structure (IWCS). Radionuclide intakes are discussed in Section A.1, and the associated radiation doses and radiological cancer risks are discussed in Section A.2. Supporting information for the dose conversion factors (DCFs) used in these calculations is presented in Section A.3.

The information is organized according to three main waste groups representing the IWCS contents:

- Group 1: K-65 residues,
- Group 2: Other high-activity residues (L and F) and tower soils, and
- Group 3: R-10 pile and other contaminated soils.

The average radionuclide concentrations presented in Table 2.2 are used in the calculations presented in this technical memorandum (TM). The concentrations for the K-65 residues (group 1) from this table are used directly, while for groups 2 and 3, the volume-weighted concentrations of the component wastes are used. The exposure factors and other scenario assumptions are as described in Chapters 2 and 3, including in Table 3.2 (which highlights the exposure factors) and Table 3.3 (which highlights the preliminary conceptual assumptions for the excavation scenarios, which simply represent early estimates because information is not yet available from FS planning to reflect in this TM).

An engineered containment system is assumed to be in place to control particulate emissions when excavating the K-65 residues, because of its high content of radium-226 (Ra-226) and other radionuclides. This system is assumed to reduce particulate emissions 100-fold, from a generic assumption of 0.35 $g/m^2/hr$ (see Table 3.3) to 0.0035 $g/m^2/hr$ (see Section 3.3.2). The radionuclide inventory in the other IWCS wastes (groups 2 and 3) is lower so the controls assumed for those wastes are based on water spraying rather than an engineered containment system. This spraying is assumed to reduce emissions to 25% of the uncontrolled rate, i.e., 0.088 $g/m^2/hr$.

Combined with the excavation areas assumed for the three waste groups (see Table 3.3), the controlled emission rate for the K-65 residues is estimated to be 1.8 g/hr. The emissions for the other two waste groups are higher because of their larger excavation areas and higher processing rates (the excavation rate is five times higher for group 2 and another three times higher for group 3). This increase offsets the fraction of the excavation season for group 2 (0.66); for group 3, the excavation would take longer than for the K-65 residues, extending 1.6 seasons. These particulate emissions assumed for this preliminary analysis are conservative; actual releases would likely be lower.

Using the early conceptual assumptions for particulate emissions during excavation, the dispersion of airborne particulates and associated deposition on surface soil was modeled using the AERMOD system (see USACE 2011). These preliminary estimates of airborne and deposited particulate matter (PM) are summarized in Tables A.1 and A.2, respectively.

For the airborne particulates, inhalation exposures are limited to the actual time during which these releases would occur, i.e., 8 work hours a day, 5 days a week for the period estimated for excavating each waste group. For the remedial action worker, it is assumed that respiratory protection fails (or is not used) for one day during excavation of each of the waste groups, so inhalation would only occur that day. (This assumption is simply made to support this example calculation, to indicate what the exposures and risks

could be if standard worker protection controls were not in place.) Similarly, the remedial action worker would only incidentally ingest contaminated surface soil on that one day without respiratory protection (e.g., when hand-to-mouth transfer could occur). For the other receptors, incidental ingestion of the contaminated surface soil is assumed to occur throughout their overall exposure periods. The same applies for external gamma radiation exposures from the deposited particulates, because they would continue to emit gamma radiation throughout that time.

The dose conversion factor used for the external gamma calculation is in units of "per year" and is based on 8,760 hours in a year. Thus, for each receptor, the amount of actual exposure in years is needed to calculate the doses from external gamma radiation. The overall durations assumed for the hypothetical receptors (from Table 3.2) are:

- 5 years for the remedial action worker, trespasser, and offsite child resident; and
- 10 years for the other three receptors (onsite maintenance worker, and offsite outdoor worker and adult resident).

The corresponding effective durations used for the external gamma calculations to assess exposures to deposited particulates are:

- 0.78 years for the remedial action worker,
- 1.6 years for the onsite maintenance worker,
- 0.11 years for the trespasser,
- 1.6 years for the offsite outdoor worker,
- 3.3 years for the offsite child resident, and
- 6.5 years for the offsite adult resident.

The total detriment to human health is the sum of the radiation doses and cancer risks from all radionuclides for all relevant exposure pathways. Radioactive decay is not a significant factor for the radionuclides addressed in this evaluation because of their long half-lives and the relatively short time period addressed by this TM. (See the health risk fact sheets in Appendix C.)

It is important to clarify that this appendix only presents the preliminary estimates for particulates released from the IWCS wastes during excavation. Radon-222 (Rn-222) calculations are not included in this appendix. This radionuclide represents a particular concern for the high-activity residues (especially the K-65 residues) in the IWCS, and the doses and cancer risks associated with exposures to this inert gas and its short-lived (particulate) decay products are addressed separately in the body of this report (Section 5.2.1). This approach allows updated dosimetry information for Rn-222 and its decay products to be applied to estimate those unique doses and risks (e.g., see NRC [1999] and Marsh [2010]).

Beyond the hypothetical exposures to radioactive particulates released from the IWCS wastes during excavation, additional preliminary calculations have been performed to assess various hypothetical cap breach events for the wastes at the IWCS (see USACE 2012.) These evaluations consider exposures to wastes uncovered in place – resulting in elevated levels of gamma radiation and the release of Rn-222 gas – as well as example scenarios that involve limited (e.g., exploratory) drilling and staging of the tailings removed. The calculations for these example exposures to both external gamma radiation and Rn-222 progeny from these hypothetical cap breach events are summarized in Tables 5.4 and 5.5 of this TM and are not repeated here.

A.1 RADIONUCLIDE INTAKES

Preliminary intake estimates for three radiological exposure pathways are presented in this appendix:

- Inhalation of airborne particulates released from the IWCS wastes during excavation,
- Incidental ingestion of the airborne particulates that were deposited on surface soil, and
- External gamma irradiation from these deposited particulates.

For each of these exposures, the combined radionuclide intakes represent the amount of radioactivity taken into the body by inhalation and incidental ingestion for 11 radionuclides for internal exposures, plus the amount of gamma radiation from the deposited radionuclides for external exposures. The internal intakes are given in terms of the activity of each radionuclide (in pCi) inhaled or ingested, while the external component is given in terms of the exposure to radioactively contaminated soil (in pCi-yr/g) from deposited airborne particulates (which are assumed to be deposited on surface soil, with an estimated density of 1.8 g/cm^3, over a depth of 1 cm [0.4 in.]).

The intakes estimated for the six hypothetical receptors from exposures to radioactive particulates released during excavation of the K-65 residues are presented in Tables A.3 through A.8. (All tables are provided at the end of this appendix.) These intakes are based on the exposure point concentrations developed as described in Section 3.3 and summarized in Tables A.1 and A.2, using the exposure parameters and equations given in Table 3.2 and Section 3.4. These estimated intakes are then used to calculate the radiation doses and radiological cancer risks as described in Section A.2. Similar intake tables are provided for waste group 2 (Tables A.15 through A.20) and waste group 3 (Tables A.27 through A.32).

A.2 RADIATION DOSES, DOSE CONVERSION FACTORS AND RADIOLOGICAL RISKS

The radiation doses and cancer risks associated with particulates released during excavation of the K-65 residues for the six hypothetical receptors evaluated in this TM are presented in Tables A.9 through A.14. These estimates were obtained using the intakes given in Tables A.3 through A.8 and the radiological cancer risk coefficients and DCFs given in Table 4.1. These cancer risk factors are age-averaged values, while adult DCFs are used in this TM as discussed in Sections 4.1.2 and 5.3.3. Parallel tables for the other two waste groups follow those for the K-65 residues (i.e., Tables A.21 through A.26 present results for the other high-activity residues and tower soils, and Tables A.33 through A.38 present results for the R-10 waste pile and lower-contaminated soils).

The radiological cancer risk represents the increased probability that an individual would develop cancer over the course of a lifetime from exposures associated with excavating the residues and contaminated soils from the IWCS. Standard radiological risk coefficients developed by the U.S. Environmental Protection Agency (EPA) given in Federal Guidance Report (FGR) 13 are used in this assessment (EPA 1999). These coefficients consider all cancers, including those that are not fatal. That is, the morbidity values identified in Table 4.1 are used in this analysis. These coefficients account for the mode of exposure, i.e., inhalation, incidental ingestion, and external gamma irradiation, and they include the contributions of short-lived decay products. For ingestion, the risk coefficients for food are used rather than those for drinking water, because they are more relevant to a soil matrix and also more protective (conservative). (See Section 4.1.3 for further discussion of the radiological risk coefficients.)

The radiation doses presented in Tables A.9 through A.14, Tables A.21 through A.26, and Tables A.33 through A.38 are estimated using the DCFs given in Publication 72 of the International Commission on

Radiological Protection (ICRP 1996). These DCFs are based on the same updated dosimetry models used to develop the cancer risk values given in FGR 13 (EPA 1999), and these factors are also given in Table 4.1. The DCFs are used to estimate the total effective dose and are based on a metabolic and anatomical model for an adult. While DCFs are also available for younger ages, the adult DCFs were used in this TM for consistency with Federal and state radiation protection standards, which are based on adult exposures. As for the radiological risk factors, the DCFs account for the mode of exposure and include the contributions of short-lived decay products. The DCFs are further discussed in Section 4.1.2 and Section A.3.

In addition to the DCFs and radiological risk factors identified above, a separate factor can be used to convert the measured radiation doses associated with external gamma irradiation to the risk of cancer induction. The radiological cancer risk can be estimated by multiplying the radiation dose (in mrem) by a factor of 8×10^{-7}. This factor is recommended by the Interagency Steering Committee on Radiation Standards (ISCORS), and it applies for cancer morbidity (ISCORS 2003). This factor is appropriate for use with the radiation dose resulting from low linear-energy-transfer (LET) radiation such as gamma rays and X-rays, consistent with its use here. Additional discussion regarding the use of this factor in this assessment is presented in Section 4.1.3.

A.3 SUPPORTING INFORMATION FOR THE DOSE CONVERSION FACTORS

A general description of the DCFs used in this TM is provided in Section 4.1.1. These DCFs are the most recent values available and are based on the *effective dose* concept first introduced by the ICRP in Publication 60 (ICRP 1991). These DCFs are tabulated in ICRP Publication 72 (ICRP 1996), which serves as the source of the values presented in this TM. Prior to that time, radiation doses were calculated based on the *effective dose equivalent* (EDE) concept as given in ICRP Publication 26 (ICRP 1977). The ICRP first introduced the EDE concept in 1977 to normalize the unequal biological effects produced by different types of radiation in different organs of the body.

Although this approach was updated by ICRP in Publication 60 (ICRP 1991), the radiation protection requirements of most Federal and state agencies (including the U.S. Army Corps of Engineers [USACE], U.S. Department of Energy, U.S. Nuclear Regulatory Commission, and various New York state agencies) still use the older terminology and approach given in ICRP (1977). Federal agencies are generally in the process of converting to the new methodology, but this process will take some time to complete. The current approach in ICRP (1991) is largely the same as that given in ICRP (1977), although the dosimetry models and organ weighting factors have been updated to reflect more recent knowledge. In the new approach, organ doses are expressed as *equivalent doses* (these doses were previously referred to as *dose equivalents*), and the weighted sum of these organ-specific equivalent doses is expressed as the *effective dose* (previously referred to as EDE).

This section provides information on these two dosimetry concepts to help explain the terminologies and approaches. While the two concepts are very similar, subtle differences exist that warrant explanation to avoid misinterpretation of results. For example, regulatory agencies have tended to use radiation protection standards that are based on the concepts given in ICRP 26, so it is important to clarify that the values presented in this TM are based on the methods given in the updated ICRP 60. The practical effect of using these current values is insignificant, but this distinction is useful to understand (e.g., for reflection in future agency decisions).

The dose delivered to internal organs as a result of radionuclides being systemically incorporated into the body can continue long after intake of the radionuclide has ceased. After being taken into the body, some radionuclides are eliminated fairly quickly, while others are incorporated into organs and tissues or ultimately deposited in bones and can be retained for many years. This process is in contrast to external

doses, which occur only when a radiation field is present. The *committed effective dose equivalent* (CEDE) was developed by the ICRP using Publication 26 methods to account for doses to internal organs from radionuclides taken into the body. The CEDE is the integrated dose equivalent to specific organs for a specified number of years. An integrating time of 50 years following intake is commonly used, although other integrating times can be used as well.

The concepts of EDE and CEDE were developed by the ICRP to account for the differing rates of harmful health effects (generally cancer and genetic defects) from chronic exposures to radiation in different organs and tissues in the body. The dose equivalent in a tissue or organ was given as the product of the absorbed dose (in *rad*, an acronym for *radiation absorbed dose*) and a quality factor, which is designed to account for the relative biological effectiveness for the various types of radiation. The EDE and CEDE are weighted sums of the organ-specific dose equivalents and committed dose equivalents.

The weighting factors used to calculate the EDE and CEDE were based on selected stochastic risk factors and represent the proportion of the stochastic risk resulting from exposures to a specific organ or tissue relative to the risk when the whole body is irradiated uniformly (ICRP 1977). By this approach, the EDE and CEDE can be used for comparison to specific standards for radiation protection purposes. The *total effective dose equivalent* (TEDE) is the sum of the EDE for external radiation and the CEDE for internal radiation.

The ICRP revised this approach in 1991 with the development of the effective dose concept. The *effective dose* is comparable to the EDE, and the *committed effective dose* is comparable to the CEDE. However, whereas the EDE and CEDE are calculated from the absorbed dose using a quality factor related to the collision-stopping power in water at the point of interest (as a surrogate for biological damage), the effective dose and committed effective dose are calculated as the product of the absorbed dose and a radiation weighting factor.

The same approach used to calculate the EDE and CEDE from the individual organ doses is used to calculate the effective dose and committed effective dose. That is, the equivalent dose to each organ is multiplied by a weighting factor that accounts for the likelihood that the equivalent dose to this organ will result in measurable harm to the human body (such as causing cancer). The weighted doses to the various organs are then summed over all relevant organs to give the effective dose. The weighting factors for the various organs used in this calculation sum to one, so they represent the relative sensitivities of the various organs to radiation doses. As for EDE and CEDE, the effective dose and committed effective dose is typically expressed in the unit of *rem* (an acronym for *roentgen equivalent man*) or *mrem* (for millirem, or one one-thousandths of a rem).

The EDE and effective dose are the same for those radiations for which the quality factor (per ICRP 26) is the same as the radiation weighting factor (per ICRP 60), such as for low-LET radiations including gamma rays and X-rays. The updated weighting factors used to calculate the effective dose and committed effective dose are based on the total detriment associated with radiation exposure and consist of four components: the probability of a fatal cancer, the probability of a nonfatal cancer, the probability of severe hereditary effects, and the relative length of life lost (ICRP 1991). The last factor represents the most significant change in the new approach, i.e., the detriment includes the amount of life lost from a fatal cancer.

The sum of the effective dose from external exposures and the committed effective dose from internal doses is the *total effective dose* and is comparable to the TEDE. Note that all four of the doses identified here are doubly weighted absorbed doses (to account for both the type of radiation and the sensitivity of the specific organ or tissue to radiation damage), and they are meant to accommodate comparisons of

various types of radiation exposures to assess radiation protection. To simplify the presentation in this TM, the total effective dose from internal and external exposures is referred to simply as the *dose*.

As noted above, the ICRP has developed DCFs for internal and external exposures based on updated radiation dosimetry models in accordance with the effective dose concept. These DCFs are given in ICRP Publication 72 (ICRP 1996) and are for members of the general public. The DCFs cover ages ranging from an infant to an adult. The previous DCFs based on ICRP 26 methods were limited to adults (*reference man* as described in ICRP [1975]) and are given in FGRs 11 and 12 (EPA 1988 and 1993).

For internal exposures, the DCFs give the committed effective dose (in mrem) per unit intake (in pCi) for a number of integrating times. For external exposures, the DCF represents the effective dose (in mrem) per unit concentration of radionuclide (assumed to be in soil) and unit of time (such as a year). The DCFs used in this TM are given in Table 4.1. In addition to these values, the external gamma doses associated with direct exposure to radioactive materials and from indirect (skyshine) radiation are provided in graphical format in Figures 4.3 and 4.5, respectively, to provide information to support specific evaluations including those associated with hypothetical cap-breach situations. To simplify the assessment, adult DCFs are used in this TM, and a 50-year time period is used to calculate the committed dose. Other age groups (representing an infant and children ages 1, 5, 10, and 15 years) and other integrating time periods can be used for specific calculations as appropriate.

The updated adult DCFs given in ICRP Publication 72 are developed in accordance with the same dosimetry models used to calculate cancer risk coefficients in FGR 13, and they are generally comparable to those in FGRs 11 and 12 (see, for example, the DCFs given in Table 3.6 of USACE [2007]). Most Federal and New York state agencies either still use the older dosimetry models and terminology or are in the process of converting their radiation protection standards and guidelines to reflect these updated dosimetry models. Because the updated values have been incorporated into a number of commonly used computer codes, including RESRAD (for *RES*idual *RAD*ioactivity) (Yu et al. 2001), and they do not differ markedly from the previous values for adults, these updated values are used in this analysis to reflect the best available information for calculating radiation doses.

The dosimetry models used to obtain these updated DCFs were also used to derive the cancer risk coefficients given in FGR 13 (see additional discussion in Section 4.1.3), which are very similar to the coefficients used in previous evaluations for NFSS (see Table 3.5 of USACE [2007]). In summary, the approach used in this TM to calculate radiation doses and cancer risks promotes general consistency and reflects the most recent radiation dosimetry information for these estimates.

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TABLE A.1 Preliminary Estimates of Airborne Particulates at the Hypothetical Receptor Locations from Releases during Waste Excavation at the IWCS[a]

Illustrative Receptor	Hypothetical Distance from Excavation *(m)*	Airborne Concentration of Particulates *(µg waste particle per m^3 air)*
***Waste Group 1*: K-65 Residues**		
Onsite: dispersed contaminants		
Remedial action worker	1	1.0
Maintenance worker	(1, as above) 50	0.029
Trespasser	(1, as above) 100	0.0095
Offsite: dispersed contaminants		
Outdoor worker	560	0.00032
Adult resident	660	0.00030
Child resident	660	0.00030
***Waste Group 2*: Other High-Activity Residues (L and F) and Tower Soils**		
Onsite: dispersed contaminants		
Remedial action worker	1	26
Maintenance worker	(1, as above) 50	1.2
Trespasser	(1, as above) 100	0.43
Offsite: dispersed contaminants		
Outdoor worker	560	0.016
Adult resident	660	0.015
Child resident	660	0.015
***Waste Group 3*: R-10 Pile and Other Contaminated Soils**		
Onsite: dispersed contaminants		
Remedial action worker	1	29
Maintenance worker	(1, as above) 50	2.0
Trespasser	(1, as above) 100	0.76
Offsite: dispersed contaminants		
Outdoor worker	560	0.032
Adult resident	660	0.030
Child resident	660	0.030

[a] The concentrations of particulates in air from releases during waste excavation are estimated as described in Sections 3.2 and 3.3, based on the airborne concentrations predicted by the AERMOD model with early conceptual assumptions for waste excavation. Values are given to two significant figures. The airborne particulate concentrations represent PM_{10} (respirable fraction). Hypothetical exposures for the maintenance worker and trespasser are assumed to occur at two distances from the excavation area. Both are assumed to spend 10% of their time 1 m (3 ft) from the excavation, so the particulate concentrations at that distance are the same as shown for the remedial action worker. Therefore, the entries for these two receptors address the concentrations at their second distance from the excavation, 50 m (160 ft) and 100 m (330 ft), respectively. The resident scenarios consider indoor and outdoor air; the values shown here are for outdoor air; those for indoor air are half the outdoor values. The exposure point concentrations of radioactive and chemical contaminants in air for the six illustrative receptors are calculated by multiplying the particulate concentrations above by the concentrations of the radionuclides and chemicals in the respective waste groups at the IWCS (volume-weighted for waste groups 2 and 3).

TABLE A.2 Preliminary Estimates of Deposited Particulates at the Hypothetical Receptor Locations from Releases during Waste Excavation at the IWCS[a]

Hypothetical Receptor	Hypothetical Distance from Excavation *(m)*	Deposited Particulates	
		µg waste per m² soil	*µg waste per g soil*
***Waste Group 1*: K-65 Residues**			
Onsite: dispersed contaminants			
Remedial action worker	1	26,000	1.5
Maintenance worker	(1, as above) 50	1,300	0.070
Trespasser	(1, as above) 100	370	0.021
Offsite: dispersed contaminants			
Outdoor worker	560	18	0.001
Adult resident	660	12	0.00064
Child resident	660	12	0.00064
***Waste Group 2*: Other High-Activity Residues (L and F) and Tower Soils**			
Onsite: dispersed contaminants			
Remedial action worker	1	570,000	32
Maintenance worker	(1, as above) 50	36,000	2.0
Trespasser	(1, as above) 100	11,000	0.62
Offsite: dispersed contaminants			
Outdoor worker	560	600	0.033
Adult resident	660	380	0.021
Child resident	660	380	0.021
***Waste Group 3*: R-10 Pile and Other Contaminated Soils**			
Onsite: dispersed contaminants			
Remedial action worker	1	1,800,000	100
Maintenance worker	(1, as above) 50	140,000	8.0
Trespasser	(1, as above) 100	48,000	2.7
Offsite: dispersed contaminants			
Outdoor worker	560	3,000	0.17
Adult resident	660	1,900	0.10
Child resident	660	1,900	0.10

[a] The concentrations of particulates released from excavated waste and deposited on soil are estimated as described in Sections 3.2 and 3.3, based on the particulates at deposited at each location predicted by the AERMOD model using early conceptual assumptions for waste excavation. Values are given to two significant figures. The estimates of contaminated particulates deposited on soil, as µg /m^2, are then converted to an estimate of the concentration of contaminant per g soil by assuming the particulates are deposited on the top 1 cm (0.4 in.) of surface soil with an estimated density of 1.8 g/cm^3. Hypothetical exposures for the maintenance worker and trespasser are assumed to occur at two distances from the excavation area. Both are assumed to spend 10% of their time 1 m (3 ft) from the excavation, so the particulate estimates for that distance are the same as shown for the remedial action worker. Therefore, the entries for these two receptors above address the concentrations at their second distance from the excavation, 50 m (160 ft) and 100 m (330 ft), respectively. The resident scenarios consider indoor and outdoor air; the values shown here are for outdoor air; those for indoor air are half the outdoor values. The exposure point concentrations of radioactive and chemical contaminants in soil for the six illustrative receptors are calculated by multiplying the particulate concentrations above by the concentrations of the radionuclides and chemicals in the respective waste groups.

TABLE A.3 Radiological Intakes for a Remedial Action Worker from Particulates Released from the K-65 Residues[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
K-65 Residues				
Uranium-238	650	8.3×10^{-3}	4.8×10^{-4}	7.4×10^{-4}
Uranium-234	650	8.3×10^{-3}	4.8×10^{-4}	7.4×10^{-4}
Thorium-230	54,000	6.9×10^{-1}	4.0×10^{-2}	6.1×10^{-2}
Radium-226	520,000	6.7	3.8×10^{-1}	5.9×10^{-1}
Lead-210	520,000	6.7	3.8×10^{-1}	5.9×10^{-1}
Uranium-235	33	4.2×10^{-4}	2.4×10^{-5}	3.8×10^{-5}
Protactinium-231	10,000	1.3×10^{-1}	7.3×10^{-3}	1.1×10^{-2}
Actinium-227	10,000	1.3×10^{-1}	7.3×10^{-3}	1.1×10^{-2}
Thorium-232	1,210	1.6×10^{-2}	8.9×10^{-4}	1.4×10^{-3}
Radium-228	1,210	1.6×10^{-2}	8.9×10^{-4}	1.4×10^{-3}
Thorium-228	1,210	1.6×10^{-2}	8.9×10^{-4}	1.4×10^{-3}

[a] These preliminary intake estimates are for a hypothetical remedial action worker exposed to particulates released from the K-65 residues during excavation, rounded to two significant figures. (Estimates for direct exposures to wastes at the IWCS, including from Rn-222, are presented separately; see Chapter 5). Basic exposure assumptions are presented in Chapter 3 (including Tables 3.2 and 3.3). The remedial action worker is assumed to be 1 m (3 ft) from the uncovered K-65 residues during the excavation, with respiratory protection assumed for all but 1 day, so inhalation and incidental ingestion exposures only occur during that day. Estimated airborne and deposited particulate concentrations in $\mu g/m^3$ are scaled to the estimated contaminant concentrations in the K-65 residues. The external gamma exposure is estimated from the deposited soil concentration, adjusted to the effective duration in elapsed years during which the worker is assumed to be onsite excavating these wastes (because the DCF is in units of per year), resulting in an effective duration of 0.78 years.

TABLE A.4 Radiological Intakes for an Onsite Maintenance Worker from Particulates Released from the K-65 Residues[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
K-65 Residues				
Uranium-238	650	1.8×10^{-1}	2.3×10^{-2}	2.1×10^{-4}
Uranium-234	650	1.8×10^{-1}	2.3×10^{-2}	2.1×10^{-4}
Thorium-230	54,000	15	1.9	1.8×10^{-2}
Radium-226	520,000	140	19	1.7×10^{-1}
Lead-210	520,000	140	19	1.7×10^{-1}
Uranium-235	33	9.1×10^{-3}	1.2×10^{-3}	1.1×10^{-5}
Protactinium-231	10,000	2.7	3.6×10^{-1}	3.3×10^{-3}
Actinium-227	10,000	2.7	3.6×10^{-1}	3.3×10^{-3}
Thorium-232	1,210	3.3×10^{-1}	4.3×10^{-2}	4.0×10^{-4}
Radium-228	1,210	3.3×10^{-1}	4.3×10^{-2}	4.0×10^{-4}
Thorium-228	1,210	3.3×10^{-1}	4.3×10^{-2}	4.0×10^{-4}

[a] These preliminary intake estimates are for a hypothetical maintenance worker exposed to particulates released from the K-65 residues during excavation; values are rounded to two significant figures. Basic exposure assumptions are presented in Chapter 3 (including Tables 3.2 and 3.3). This worker is assumed to spend 10% of the time 1 m (3 ft) from the uncovered wastes and the rest of the time 50 m (160 ft) from the wastes. No respiratory protection is assumed, so inhalation exposures correspond to the excavation activities, i.e., 8 hours a day and 5 days a week over the excavation season. Exposures to particulates deposited from these residues via incidental ingestion and external gamma irradiation would occur throughout the overall 10-year exposure duration. For external gamma irradiation from the deposited particulates, the deposition estimate is further adjusted by dividing by the exposure duration (hours onsite divided by total number of hours per year) to align with the DCF (in units of per year), producing an effective duration of 1.6 years.

TABLE A.5 Radiological Intakes for an Onsite Trespasser from Particulates Released from the K-65 Residues[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
K-65 Residues				
Uranium-238	650	2.1×10^{-3}	5.4×10^{-4}	1.2×10^{-6}
Uranium-234	650	2.1×10^{-3}	5.4×10^{-4}	1.2×10^{-6}
Thorium-230	54,000	1.8×10^{-1}	4.5×10^{-2}	1.0×10^{-4}
Radium-226	520,000	1.7	4.3×10^{-1}	9.8×10^{-4}
Lead-210	520,000	1.7	4.3×10^{-1}	9.8×10^{-4}
Uranium-235	33	1.1×10^{-4}	2.7×10^{-5}	6.3×10^{-8}
Protactinium-231	10,000	3.3×10^{-2}	8.3×10^{-3}	1.9×10^{-5}
Actinium-227	10,000	3.3×10^{-2}	8.3×10^{-3}	1.9×10^{-5}
Thorium-232	1,210	4.0×10^{-3}	1.0×10^{-3}	2.3×10^{-6}
Radium-228	1,210	4.0×10^{-3}	1.0×10^{-3}	2.3×10^{-6}
Thorium-228	1,210	4.0×10^{-3}	1.0×10^{-3}	2.3×10^{-6}

[a] These preliminary intake estimates are for a hypothetical trespasser assumed to be near the IWCS 2 hours a day for 10 days during excavation of the K-65 residues. Values are rounded to two significant figures. The basic exposure assumptions are presented in Chapter 3 (including Tables 3.2 and 3.3). The trespasser is assumed to spend 10% of the time 1 m (3 ft) from the uncovered K-65 residues and the rest of the time 100 m (330 ft) from these wastes. Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the onsite maintenance worker (Table A.4), except the overall exposure extends over 5 yr (instead of 10) and the exposure time and frequency are lower, resulting in an effective duration of 0.011 years.

TABLE A.6 Radiological Intakes for an Offsite Outdoor Worker from Particulates Released from the K-65 Residues[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
K-65 Residues				
Uranium-238	650	4.6×10^{-4}	1.1×10^{-4}	1.0×10^{-6}
Uranium-234	650	4.6×10^{-4}	1.1×10^{-4}	1.0×10^{-6}
Thorium-230	54,000	3.8×10^{-2}	9.4×10^{-3}	8.6×10^{-5}
Radium-226	520,000	3.6×10^{-1}	9.0×10^{-2}	8.3×10^{-4}
Lead-210	520,000	3.6×10^{-1}	9.0×10^{-2}	8.3×10^{-4}
Uranium-235	33	2.3×10^{-5}	5.7×10^{-6}	5.2×10^{-8}
Protactinium-231	10,000	7.0×10^{-3}	1.7×10^{-3}	1.6×10^{-5}
Actinium-227	10,000	7.0×10^{-3}	1.7×10^{-3}	1.6×10^{-5}
Thorium-232	1,210	8.5×10^{-4}	2.1×10^{-4}	1.9×10^{-6}
Radium-228	1,210	8.5×10^{-4}	2.1×10^{-4}	1.9×10^{-6}
Thorium-228	1,210	8.5×10^{-4}	2.1×10^{-4}	1.9×10^{-6}

[a] These preliminary intake estimates are for a hypothetical offsite outdoor worker 560 m (1,800 ft) east-southeast of the IWCS; values are rounded to two significant figures. Basic exposure assumptions are presented in Chapter 3 (including Tables 3.2 and 3.3). No respiratory protection is assumed for this outdoor worker, so inhalation exposures correspond to the excavation time, i.e., 8-hour work days and 5-day work weeks over the excavation season (170 days is assumed for excavating the K-65 residues). Exposures to the deposited contaminants via incidental ingestion and external gamma irradiation are estimated for the 10-year exposure duration as described for the onsite maintenance worker (Table A.4), with all exposures at the single offsite location) for an effective period of 1.6 years.

TABLE A.7 Radiological Intakes for an Offsite Adult Resident from Particulates Released from the K-65 Residues[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
K-65 Residues				
Uranium-238	650	1.6×10^{-4}	5.0×10^{-5}	2.7×10^{-6}
Uranium-234	650	1.6×10^{-4}	5.0×10^{-5}	2.7×10^{-6}
Thorium-230	54,000	1.4×10^{-2}	4.1×10^{-3}	2.3×10^{-4}
Radium-226	520,000	1.3×10^{-1}	4.0×10^{-2}	2.2×10^{-3}
Lead-210	520,000	1.3×10^{-1}	4.0×10^{-2}	2.2×10^{-3}
Uranium-235	33	8.3×10^{-6}	2.5×10^{-6}	1.4×10^{-7}
Protactinium-231	10,000	2.5×10^{-3}	7.6×10^{-4}	4.2×10^{-5}
Actinium-227	10,000	2.5×10^{-3}	7.6×10^{-4}	4.2×10^{-5}
Thorium-232	1,210	3.0×10^{-4}	9.2×10^{-5}	5.1×10^{-6}
Radium-228	1,210	3.0×10^{-4}	9.2×10^{-5}	5.1×10^{-6}
Thorium-228	1,210	3.0×10^{-4}	9.2×10^{-5}	5.1×10^{-6}

[a] These preliminary intake estimates are for a hypothetical offsite adult resident about 660 m (2,200 ft) south-southwest of the IWCS. Values are rounded to two significant figures. See Chapter 3 for the basic assumptions underlying these calculations. This receptor is assumed to spend 2 hours a day outdoors and 22 hours a day indoors. During excavation, the indoor concentration is assumed to be 50% of the outdoor concentration. Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the onsite maintenance worker (Table A.4), except all exposures are at this single location and both the exposure time and frequency are longer (24 hours a day instead of 8, and 238 days instead of 170, from April through November including weekend days); resulting in an effective exposure period of 6.5 years. For external gamma exposures, no credit is taken for shielding by the structure.

TABLE A.8 Radiological Intakes for an Offsite Child Resident from Particulates Released from the K-65 Residues[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
K-65 Residues				
Uranium-238	650	1.6×10^{-4}	5.0×10^{-5}	1.4×10^{-6}
Uranium-234	650	1.6×10^{-4}	5.0×10^{-5}	1.4×10^{-6}
Thorium-230	54,000	1.4×10^{-2}	4.1×10^{-3}	1.1×10^{-4}
Radium-226	520,000	1.3×10^{-1}	4.0×10^{-2}	1.1×10^{-3}
Lead-210	520,000	1.3×10^{-1}	4.0×10^{-2}	1.1×10^{-3}
Uranium-235	33	8.3×10^{-6}	2.5×10^{-6}	6.9×10^{-8}
Protactinium-231	10,000	2.5×10^{-3}	7.6×10^{-4}	2.1×10^{-5}
Actinium-227	10,000	2.5×10^{-3}	7.6×10^{-4}	2.1×10^{-5}
Thorium-232	1,210	3.0×10^{-4}	9.2×10^{-5}	2.5×10^{-6}
Radium-228	1,210	3.0×10^{-4}	9.2×10^{-5}	2.5×10^{-6}
Thorium-228	1,210	3.0×10^{-4}	9.2×10^{-5}	2.5×10^{-6}

[a] These preliminary intake estimates are for a hypothetical offsite child resident about 660 m (2,200 ft) south-southwest of the IWCS. Values are rounded to two significant figures. Basic exposure assumptions are as described in Chapter 3 (including Tables 3.2 and 3.3. Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the adult resident in Table A.7 above, except the duration is 5 years instead of 10, resulting in an effective exposure period of 3.3 years.

TABLE A.9 Radiological Doses and Risks for a Remedial Action Worker from Particulates Released from the K-65 Residues[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
K-65 Residues				*Radionuclide-Specific*
Uranium-238	$2.5 \times 10^{-4} / 2.0 \times 10^{-10}$	$8.5 \times 10^{-8} / 5.8 \times 10^{-14}$	$1.2 \times 10^{-4} / 8.4 \times 10^{-11}$	$3.6 \times 10^{-4} / 2.8 \times 10^{-10}$
Uranium-234	$2.9 \times 10^{-4} / 2.3 \times 10^{-10}$	$8.6 \times 10^{-8} / 4.6 \times 10^{-14}$	$2.5 \times 10^{-7} / 1.9 \times 10^{-13}$	$2.9 \times 10^{-4} / 2.3 \times 10^{-10}$
Thorium-230	$2.6 \times 10^{-1} / 2.4 \times 10^{-8}$	$3.1 \times 10^{-5} / 4.7 \times 10^{-12}$	$6.6 \times 10^{-5} / 5.0 \times 10^{-11}$	$2.6 \times 10^{-1} / 2.4 \times 10^{-8}$
Radium-226	$2.4 \times 10^{-1} / 1.9 \times 10^{-7}$	$4.0 \times 10^{-4} / 2.0 \times 10^{-10}$	$6.3 \times 10^{0} / 5.0 \times 10^{-6}$	$6.5 \times 10^{0} / 5.2 \times 10^{-6}$
Lead-210	$2.5 \times 10^{-1} / 2.1 \times 10^{-7}$	$2.7 \times 10^{-3} / 1.3 \times 10^{-9}$	$4.4 \times 10^{-3} / 2.5 \times 10^{-9}$	$2.5 \times 10^{-1} / 2.1 \times 10^{-7}$
Uranium-235	$1.3 \times 10^{-5} / 1.1 \times 10^{-11}$	$4.2 \times 10^{-9} / 2.4 \times 10^{-15}$	$2.6 \times 10^{-5} / 2.0 \times 10^{-11}$	$3.9 \times 10^{-5} / 3.1 \times 10^{-11}$
Protactinium-231	$6.6 \times 10^{-2} / 9.8 \times 10^{-9}$	$1.9 \times 10^{-5} / 1.7 \times 10^{-12}$	$2.0 \times 10^{-3} / 1.6 \times 10^{-9}$	$6.9 \times 10^{-2} / 1.1 \times 10^{-8}$
Actinium-227	$2.7 \times 10^{-1} / 2.7 \times 10^{-8}$	$3.3 \times 10^{-5} / 4.8 \times 10^{-12}$	$2.1 \times 10^{-2} / 1.7 \times 10^{-8}$	$2.9 \times 10^{-1} / 4.4 \times 10^{-8}$
Thorium-232	$6.3 \times 10^{-3} / 6.7 \times 10^{-10}$	$7.5 \times 10^{-7} / 1.2 \times 10^{-13}$	$6.3 \times 10^{-7} / 4.7 \times 10^{-13}$	$6.3 \times 10^{-3} / 6.7 \times 10^{-10}$
Radium-228	$9.2 \times 10^{-4} / 6.8 \times 10^{-10}$	$2.3 \times 10^{-6} / 1.3 \times 10^{-12}$	$7.8 \times 10^{-3} / 6.2 \times 10^{-9}$	$8.7 \times 10^{-3} / 6.9 \times 10^{-9}$
Thorium-228	$2.5 \times 10^{-3} / 2.2 \times 10^{-9}$	$4.7 \times 10^{-7} / 3.7 \times 10^{-13}$	$1.3 \times 10^{-2} / 1.1 \times 10^{-8}$	$1.6 \times 10^{-2} / 1.3 \times 10^{-8}$
Route-Specific Total	$1.1 \times 10^{0} / 4.6 \times 10^{-7}$	$3.2 \times 10^{-3} / 1.5 \times 10^{-9}$	$6.3 \times 10^{0} / 5.1 \times 10^{-6}$	$7.4 \times 10^{0} / 6 \times 10^{-6}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical remedial action worker are based on the intake estimates in Table A.3; values are rounded to two significant figures except total risk, which is rounded to one significant figure. The basic exposure assumptions are given in Chapter 3 (including Tables 3.2 and 3.3). The inhalation doses and risks assume no respiratory protection equipment for 1 day (8 hours) during this excavation. The ingestion and external gamma irradiation estimates are for workday exposures over 5 years. The ingestion doses and risks reflect particles deposited on surface soil during excavation of the K-65 residues, with this deposited activity assumed to be uniformly mixed in the top 1 cm (0.4 in.) of soil. The external gamma doses and cancer risks are based on uniform contamination to an infinite depth (rather than being limited to the top cm), which overestimates the hypothetical doses and risks from external gamma irradiation by about a factor of five.

TABLE A.10 Radiological Doses and Risks for an Onsite Maintenance Worker from Particulates Released from the K-65 Residues[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
K-65 Residues				*Radionuclide-Specific*
Uranium-238	$5.3 \times 10^{-3} / 4.2 \times 10^{-9}$	$4.2 \times 10^{-6} / 2.8 \times 10^{-12}$	$3.3 \times 10^{-5} / 2.4 \times 10^{-11}$	$5.3 \times 10^{-3} / 4.2 \times 10^{-9}$
Uranium-234	$6.2 \times 10^{-3} / 5.0 \times 10^{-9}$	$4.2 \times 10^{-6} / 2.2 \times 10^{-12}$	$7.3 \times 10^{-8} / 5.4 \times 10^{-14}$	$6.2 \times 10^{-3} / 5.0 \times 10^{-9}$
Thorium-230	$5.5 \times 10^{0} / 5.0 \times 10^{-7}$	$1.5 \times 10^{-3} / 2.3 \times 10^{-10}$	$1.9 \times 10^{-5} / 1.4 \times 10^{-11}$	$5.5 \times 10^{0} / 5.0 \times 10^{-7}$
Radium-226	$5.0 \times 10^{0} / 4.0 \times 10^{-6}$	$1.9 \times 10^{-2} / 9.6 \times 10^{-9}$	$1.8 \times 10^{0} / 1.4\times 10^{-6}$	$6.9 \times 10^{0} / 5.0 \times 10^{-6}$
Lead-210	$5.3 \times 10^{0} / 4.4 \times 10^{-6}$	$1.3 \times 10^{-1} / 6.4 \times 10^{-8}$	$1.3 \times 10^{-3} / 7.2 \times 10^{-10}$	$5.4 \times 10^{0} / 4.5 \times 10^{-6}$
Uranium-235	$2.9 \times 10^{-4} / 2.3 \times 10^{-10}$	$2.1 \times 10^{-7} / 1.2 \times 10^{-13}$	$7.5 \times 10^{-6} / 5.9 \times 10^{-12}$	$2.9 \times 10^{-4} / 2.3 \times 10^{-10}$
Protactinium-231	$1.4 \times 10^{0} / 2.1 \times 10^{-7}$	$9.4 \times 10^{-4} / 8.1 \times 10^{-11}$	$5.8 \times 10^{-4} / 4.5 \times 10^{-10}$	$1.4 \times 10^{0} / 2.1 \times 10^{-7}$
Actinium-227	$5.8 \times 10^{0} / 5.9 \times 10^{-7}$	$1.6 \times 10^{-3} / 2.3 \times 10^{-10}$	$6.1 \times 10^{-3} / 4.8 \times 10^{-9}$	$5.8 \times 10^{0} / 5.9 \times 10^{-7}$
Thorium-232	$1.4 \times 10^{-1} / 1.4 \times 10^{-8}$	$3.7 \times 10^{-5} / 5.8 \times 10^{-12}$	$1.8 \times 10^{-7} / 1.4 \times 10^{-13}$	$1.4 \times 10^{-1} / 1.4 \times 10^{-8}$
Radium-228	$2.0 \times 10^{-2} / 1.5 \times 10^{-8}$	$1.1 \times 10^{-4} / 6.2 \times 10^{-11}$	$2.2 \times 10^{-3} / 1.8 \times 10^{-9}$	$2.2 \times 10^{-2} / 1.6 \times 10^{-8}$
Thorium-228	$5.3 \times 10^{-2} / 4.8 \times 10^{-8}$	$2.3 \times 10^{-5} / 1.8 \times 10^{-11}$	$3.8 \times 10^{-3} / 3.1 \times 10^{-9}$	$5.7 \times 10^{-2} / 5.1 \times 10^{-8}$
Route-Specific Total	$2.3 \times 10^{1} / 9.8 \times 10^{-6}$	$1.5 \times 10^{-1} / 7.4 \times 10^{-8}$	$1.8 \times 10^{0} / 1.5 \times 10^{-6}$	$2.5 \times 10^{1} / 1 \times 10^{-5}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical maintenance worker are based on the intake estimates in Table A.4, which reflect the basic exposure assumptions presented in Chapter 3 (including Tables 3.2 and 3.3); values are rounded to two significant figures except total risk, which is rounded to one significant figure.

TABLE A.11 Radiological Doses and Risks for an Onsite Trespasser from Particulates Released from the K-65 Residues[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
K-65 Residues				*Radionuclide-Specific*
Uranium-238	$6.3 \times 10^{-5} / 5.0 \times 10^{-11}$	$9.6 \times 10^{-8} / 6.5 \times 10^{-14}$	$1.9 \times 10^{-7} / 1.4 \times 10^{-13}$	$6.3 \times 10^{-5} / 5.0 \times 10^{-11}$
Uranium-234	$7.4 \times 10^{-5} / 5.9 \times 10^{-11}$	$9.8 \times 10^{-8} / 5.1 \times 10^{-14}$	$4.2 \times 10^{-10} / 3.1 \times 10^{-16}$	$7.4 \times 10^{-5} / 5.9 \times 10^{-11}$
Thorium-230	$6.5 \times 10^{-2} / 6.0 \times 10^{-9}$	$3.5 \times 10^{-5} / 5.3 \times 10^{-12}$	$1.1 \times 10^{-7} / 8.4 \times 10^{-14}$	$6.5 \times 10^{-2} / 6.0 \times 10^{-9}$
Radium-226	$6.0 \times 10^{-2} / 4.8 \times 10^{-8}$	$4.5 \times 10^{-4} / 2.2 \times 10^{-10}$	$1.0 \times 10^{-2} / 8.4 \times 10^{-9}$	$7.1 \times 10^{-2} / 5.7 \times 10^{-8}$
Lead-210	$6.3 \times 10^{-2} / 5.2 \times 10^{-8}$	$3.0 \times 10^{-3} / 1.5 \times 10^{-9}$	$7.4 \times 10^{-6} / 4.1 \times 10^{-12}$	$6.6 \times 10^{-2} / 5.4 \times 10^{-8}$
Uranium-235	$3.4 \times 10^{-6} / 2.7 \times 10^{-12}$	$4.8 \times 10^{-9} / 2.7 \times 10^{-15}$	$4.3 \times 10^{-8} / 3.4 \times 10^{-14}$	$3.4 \times 10^{-6} / 2.7 \times 10^{-12}$
Protactinium-231	$1.7 \times 10^{-2} / 2.5 \times 10^{-9}$	$2.2 \times 10^{-5} / 1.9 \times 10^{-12}$	$3.3 \times 10^{-6} / 2.6 \times 10^{-12}$	$1.7 \times 10^{-2} / 2.5 \times 10^{-9}$
Actinium-227	$6.9 \times 10^{-2} / 7.0 \times 10^{-9}$	$3.7 \times 10^{-5} / 5.4 \times 10^{-12}$	$3.5 \times 10^{-5} / 2.8 \times 10^{-11}$	$6.9 \times 10^{-2} / 7.0 \times 10^{-9}$
Thorium-232	$1.6 \times 10^{-3} / 1.7 \times 10^{-10}$	$8.5 \times 10^{-7} / 1.3 \times 10^{-13}$	$1.0 \times 10^{-9} / 7.8 \times 10^{-16}$	$1.6 \times 10^{-3} / 1.7 \times 10^{-10}$
Radium-228	$2.3 \times 10^{-4} / 1.7 \times 10^{-10}$	$2.6 \times 10^{-6} / 1.4 \times 10^{-12}$	$1.3 \times 10^{-5} / 1.0 \times 10^{-11}$	$2.5 \times 10^{-4} / 1.8 \times 10^{-10}$
Thorium-228	$6.4 \times 10^{-4} / 5.7 \times 10^{-10}$	$5.3 \times 10^{-7} / 4.2 \times 10^{-13}$	$2.2 \times 10^{-5} / 1.8 \times 10^{-11}$	$6.6 \times 10^{-4} / 5.9` \times 10^{-10}$
Route-Specific Total	$2.8 \times 10^{-1} / 1.2 \times 10^{-7}$	$3.6 \times 10^{-3} / 1.7 \times 10^{-9}$	$1.1 \times 10^{-2} / 8.4 \times 10^{-9}$	$2.9 \times 10^{-1} / 1 \times 10^{-7}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical trespasser are based on the intake estimates in Table A.5; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.12 Radiological Doses and Risks for an Offsite Outdoor Worker from Particulates Released from the K-65 Residues[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
K-65 Residues				*Radionuclide-Specific*
Uranium-238	$1.3 \times 10^{-5} / 1.1 \times 10^{-11}$	$2.0 \times 10^{-8} / 1.4 \times 10^{-14}$	$1.6 \times 10^{-7} / 1.2 \times 10^{-13}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$
Uranium-234	$1.6 \times 10^{-5} / 1.3 \times 10^{-11}$	$2.0 \times 10^{-8} / 1.1 \times 10^{-14}$	$3.6 \times 10^{-10} / 2.6 \times 10^{-16}$	$1.6 \times 10^{-5} / 1.3 \times 10^{-11}$
Thorium-230	$1.4 \times 10^{-2} / 1.3 \times 10^{-9}$	$7.3 \times 10^{-6} / 1.1 \times 10^{-12}$	$9.2 \times 10^{-8} / 7.0 \times 10^{-14}$	$1.4 \times 10^{-2} / 1.3 \times 10^{-9}$
Radium-226	$1.3 \times 10^{-2} / 1.0 \times 10^{-8}$	$9.4 \times 10^{-5} / 4.7 \times 10^{-11}$	$8.8 \times 10^{-3} / 7.0 \times 10^{-9}$	$2.2 \times 10^{-2} / 1.7 \times 10^{-8}$
Lead-210	$1.3 \times 10^{-2} / 1.1 \times 10^{-8}$	$6.3 \times 10^{-4} / 3.1 \times 10^{-10}$	$6.2 \times 10^{-6} / 3.5 \times 10^{-12}$	$1.4 \times 10^{-2} / 1.2 \times 10^{-8}$
Uranium-235	$7.3 \times 10^{-7} / 5.8 \times 10^{-13}$	$1.0 \times 10^{-9} / 5.6 \times 10^{-16}$	$3.6 \times 10^{-8} / 2.8 \times 10^{-14}$	$7.7 \times 10^{-7} / 6.1 \times 10^{-13}$
Protactinium-231	$3.6 \times 10^{-3} / 5.3 \times 10^{-10}$	$4.6 \times 10^{-6} / 3.9 \times 10^{-13}$	$2.8 \times 10^{-6} / 2.2 \times 10^{-12}$	$3.6 \times 10^{-3} / 5.4 \times 10^{-10}$
Actinium-227	$1.5 \times 10^{-2} / 1.5 \times 10^{-9}$	$7.8 \times 10^{-6} / 1.1 \times 10^{-12}$	$3.0 \times 10^{-5} / 2.3 \times 10^{-11}$	$1.5 \times 10^{-2} / 1.5 \times 10^{-9}$
Thorium-232	$3.5 \times 10^{-4} / 3.7 \times 10^{-11}$	$1.8 \times 10^{-7} / 2.8 \times 10^{-14}$	$8.8 \times 10^{-10} / 6.6 \times 10^{-16}$	$3.5 \times 10^{-4} / 3.7 \times 10^{-11}$
Radium-228	$5.0 \times 10^{-5} / 3.7 \times 10^{-11}$	$5.4 \times 10^{-7} / 3.0 \times 10^{-13}$	$1.1 \times 10^{-5} / 8.7 \times 10^{-12}$	$6.2 \times 10^{-5} / 4.6 \times 10^{-11}$
Thorium-228	$1.4 \times 10^{-4} / 1.2 \times 10^{-10}$	$1.1 \times 10^{-7} / 8.9 \times 10^{-14}$	$1.9 \times 10^{-5} / 1.5 \times 10^{-11}$	$1.6 \times 10^{-4} / 1.4 \times 10^{-10}$
Route-Specific Total	$5.9 \times 10^{-2} / 2.5 \times 10^{-8}$	$7.5 \times 10^{-4} / 3.6 \times 10^{-10}$	$8.8 \times 10^{-3} / 7.1 \times 10^{-9}$	$6.9 \times 10^{-2} / 3 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite worker assumed to work at the adjacent landfill are based on the intake estimates in Table A.6; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.13 Radiological Doses and Risks for an Offsite Adult Resident from Particulates Released from the K-65 Residues[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
K-65 Residues				*Radionuclide-Specific*
Uranium-238	$4.8 \times 10^{-6} / 3.9 \times 10^{-12}$	$8.9 \times 10^{-9} / 6.0 \times 10^{-15}$	$4.2 \times 10^{-7} / 3.1 \times 10^{-13}$	$5.3 \times 10^{-6} / 4.2 \times 10^{-12}$
Uranium-234	$5.7 \times 10^{-6} / 4.6 \times 10^{-12}$	$9.0 \times 10^{-9} / 4.8 \times 10^{-15}$	$9.4 \times 10^{-10} / 6.9 \times 10^{-16}$	$5.7 \times 10^{-6} / 4.6 \times 10^{-12}$
Thorium-230	$5.0 \times 10^{-3} / 4.6 \times 10^{-10}$	$3.2 \times 10^{-6} / 4.9 \times 10^{-13}$	$2.4 \times 10^{-7} / 1.9 \times 10^{-13}$	$5.0 \times 10^{-3} / 4.6 \times 10^{-10}$
Radium-226	$4.6 \times 10^{-3} / 3.7 \times 10^{-9}$	$4.1 \times 10^{-5} / 2.0 \times 10^{-11}$	$2.3 \times 10^{-2} / 1.9 \times 10^{-8}$	$2.8 \times 10^{-2} / 2.2 \times 10^{-8}$
Lead-210	$4.8 \times 10^{-3} / 4.0 \times 10^{-9}$	$2.8 \times 10^{-4} / 1.4 \times 10^{-10}$	$1.6 \times 10^{-5} / 9.2 \times 10^{-12}$	$5.1 \times 10^{-3} / 4.2 \times 10^{-9}$
Uranium-235	$2.6 \times 10^{-7} / 2.1 \times 10^{-13}$	$4.4 \times 10^{-10} / 2.5 \times 10^{-16}$	$9.6 \times 10^{-8} / 7.5 \times 10^{-14}$	$3.6 \times 10^{-7} / 2.8 \times 10^{-13}$
Protactinium-231	$1.3 \times 10^{-3} / 1.9 \times 10^{-10}$	$2.0 \times 10^{-6} / 1.7 \times 10^{-13}$	$7.4 \times 10^{-6} / 5.8 \times 10^{-12}$	$1.3 \times 10^{-3} / 2.0 \times 10^{-10}$
Actinium-227	$5.3 \times 10^{-3} / 5.4 \times 10^{-10}$	$3.4 \times 10^{-6} / 5.0 \times 10^{-13}$	$7.8 \times 10^{-5} / 6.2 \times 10^{-11}$	$5.4 \times 10^{-3} / 6.0 \times 10^{-10}$
Thorium-232	$1.2 \times 10^{-4} / 1.3 \times 10^{-11}$	$7.9 \times 10^{-8} / 1.2 \times 10^{-14}$	$2.3 \times 10^{-9} / 1.7 \times 10^{-15}$	$1.2 \times 10^{-4} / 1.3 \times 10^{-11}$
Radium-228	$1.8 \times 10^{-5} / 1.3 \times 10^{-11}$	$2.4 \times 10^{-7} / 1.3 \times 10^{-13}$	$2.9 \times 10^{-5} / 2.3 \times 10^{-11}$	$4.7 \times 10^{-5} / 3.6 \times 10^{-11}$
Thorium-228	$4.9 \times 10^{-5} / 4.4 \times 10^{-11}$	$4.9 \times 10^{-8} / 3.9 \times 10^{-14}$	$4.9 \times 10^{-5} / 3.9 \times 10^{-11}$	$9.8 \times 10^{-5} / 8.3 \times 10^{-11}$
Route-Specific Total	$2.1 \times 10^{-2} / 9.0 \times 10^{-9}$	$3.3 \times 10^{-4} / 1.6 \times 10^{-10}$	$2.3 \times 10^{-2} / 1.9 \times 10^{-8}$	$4.5 \times 10^{-2} / 3 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite adult resident are based on the intake estimates in Table A.7; values are rounded to two significant figures except total risk, which is rounded to one significant figure. The basic exposure assumptions are described in Chapter 3 (including Tables 3.2 and 3.3)

TABLE A.14 Radiological Doses and Risks for an Offsite Child Resident from Particulates Released from the K-65 Residues[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
K-65 Residues				*Radionuclide-Specific*
Uranium-238	$4.8 \times 10^{-6} / 3.9 \times 10^{-12}$	$8.9 \times 10^{-9} / 6.0 \times 10^{-15}$	$2.1 \times 10^{-7} / 1.6 \times 10^{-13}$	$5.1 \times 10^{-6} / 4.0 \times 10^{-12}$
Uranium-234	$5.7 \times 10^{-6} / 4.6 \times 10^{-12}$	$9.0 \times 10^{-9} / 4.7 \times 10^{-15}$	$4.7 \times 10^{-10} / 3.4 \times 10^{-16}$	$5.7 \times 10^{-6} / 4.6 \times 10^{-12}$
Thorium-230	$5.0 \times 10^{-3} / 4.6 \times 10^{-10}$	$3.2 \times 10^{-6} / 4.9 \times 10^{-13}$	$1.2 \times 10^{-7} / 9.3 \times 10^{-14}$	$5.0 \times 10^{-3} / 4.6 \times 10^{-10}$
Radium-226	$4.6 \times 10^{-3} / 3.7 \times 10^{-9}$	$4.1 \times 10^{-5} / 2.0 \times 10^{-11}$	$1.2 \times 10^{-2} / 9.3 \times 10^{-9}$	$1.6 \times 10^{-2} / 1.3 \times 10^{-8}$
Lead-210	$4.8 \times 10^{-3} / 4.0 \times 10^{-9}$	$2.8 \times 10^{-4} / 1.4 \times 10^{-10}$	$8.2 \times 10^{-6} / 4.6 \times 10^{-12}$	$5.1 \times 10^{-3} / 4.2 \times 10^{-9}$
Uranium-235	$2.6 \times 10^{-7} / 2.1 \times 10^{-13}$	$4.4 \times 10^{-10} / 2.5 \times 10^{-16}$	$4.8 \times 10^{-8} / 3.8 \times 10^{-14}$	$3.1 \times 10^{-7} / 2.5 \times 10^{-13}$
Protactinium-231	$1.3 \times 10^{-3} / 1.9 \times 10^{-10}$	$2.0 \times 10^{-6} / 1.7 \times 10^{-13}$	$3.7 \times 10^{-6} / 2.9 \times 10^{-12}$	$1.3 \times 10^{-3} / 2.0 \times 10^{-10}$
Actinium-227	$5.3 \times 10^{-3} / 5.4 \times 10^{-10}$	$3.4 \times 10^{-6} / 5.0 \times 10^{-13}$	$3.9 \times 10^{-5} / 3.1 \times 10^{-11}$	$5.3 \times 10^{-3} / 5.7 \times 10^{-10}$
Thorium-232	$1.2 \times 10^{-4} / 1.3 \times 10^{-11}$	$7.9 \times 10^{-8} / 1.2 \times 10^{-14}$	$1.2 \times 10^{-9} / 8.7 \times 10^{-16}$	$1.2 \times 10^{-4} / 1.3 \times 10^{-11}$
Radium-228	$1.8 \times 10^{-5} / 1.3 \times 10^{-11}$	$2.4 \times 10^{-7} / 1.3 \times 10^{-13}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$	$3.3 \times 10^{-5} / 2.5 \times 10^{-11}$
Thorium-228	$4.9 \times 10^{-5} / 4.4 \times 10^{-11}$	$4.9 \times 10^{-8} / 3.9 \times 10^{-14}$	$2.5 \times 10^{-5} / 2.0 \times 10^{-11}$	$7.4 \times 10^{-5} / 6.4 \times 10^{-11}$
Route-Specific Total	$2.1 \times 10^{-2} / 9.0 \times 10^{-9}$	$3.3 \times 10^{-4} / 1.6 \times 10^{-10}$	$1.2 \times 10^{-2} / 9.3 \times 10^{-9}$	$3.3 \times 10^{-2} / 2 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite child resident are based on the intake estimates in Table A.8; values are rounded to two significant figures except total risk, which is rounded to one significant figure. The basic exposure assumptions are described in Chapter 3 (including Tables 3.2 and 3.3).

TABLE A.15 Radiological Intakes for a Remedial Action Worker from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
L-30, F-32, and L-50 Residues and Tower Soils				
Uranium-238	676	2.3×10^{-1}	1.1×10^{-2}	1.7×10^{-2}
Uranium-234	676	2.3×10^{-1}	1.1×10^{-2}	1.7×10^{-2}
Thorium-230	7,200	2.4	1.1×10^{-1}	1.8×10^{-1}
Radium-226	9,830	3.3	1.6×10^{-1}	2.4×10^{-1}
Lead-210	13,300	4.4	2.1×10^{-1}	3.3×10^{-1}
Uranium-235	49	1.6×10^{-2}	7.7×10^{-4}	1.2×10^{-3}
Protactinium-231	113	3.8×10^{-2}	1.8×10^{-3}	2.8×10^{-3}
Actinium-227	113	3.8×10^{-2}	1.8×10^{-3}	2.8×10^{-3}
Thorium-232	21	6.9×10^{-3}	3.3×10^{-4}	5.1×10^{-4}
Radium-228	21	6.9×10^{-3}	3.3×10^{-4}	5.1×10^{-4}
Thorium-228	21	6.9×10^{-3}	3.3×10^{-4}	5.1×10^{-4}

[a] These preliminary intake estimates for the hypothetical remedial action worker are rounded to two significant figures. See Chapter 3 (including Tables 3.2 and 3.3) for the preliminary conceptual assumptions underlying these estimates. The total amount of particulates assumed to be deposited over four combined excavation seasons (32 months) is adjusted to account for the fractional time during which waste group 2 would be excavated (two-thirds of a season), to calculate the deposition of particulates from these wastes. Exposure point concentrations are estimated by scaling the source concentrations from Table 2.2 (volume-weighted per the component wastes) to the deposited particulates, which are assumed to be uniformly mixed in the top 1 cm (0.4 in.) of soil with an estimated density of 1.8 g/cm^3. External gamma exposures from these deposited particulates are adjusted to account for the elapsed years during which the worker would be onsite (because the DCF is in units of per year), for an effective duration of 0.78 years.

TABLE A.16 Radiological Intakes for an Onsite Maintenance Worker from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
L-30, F-32, and L-50 Residues and Tower Soils				
Uranium-238	676	3.6	5.7×10^{-1}	5.2×10^{-3}
Uranium-234	676	3.6	5.7×10^{-1}	5.2×10^{-3}
Thorium-230	7,200	38	6.1	5.5×10^{-2}
Radium-226	9,830	52	8.3	7.6×10^{-2}
Lead-210	13,300	71	11	1.0×10^{-1}
Uranium-235	49	2.6×10^{-1}	4.1×10^{-2}	3.7×10^{-4}
Protactinium-231	113	6.0×10^{-1}	9.5×10^{-2}	8.7×10^{-4}
Actinium-227	113	6.0×10^{-1}	9.5×10^{-2}	8.7×10^{-4}
Thorium-232	21	1.1×10^{-1}	1.7×10^{-2}	1.6×10^{-4}
Radium-228	21	1.1×10^{-1}	1.7×10^{-2}	1.6×10^{-4}
Thorium-228	21	1.1×10^{-1}	1.7×10^{-2}	1.6×10^{-4}

[a] These preliminary intake estimates for a hypothetical onsite maintenance worker are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). Exposures to deposited particulates via incidental ingestion and external gamma irradiation would occur over the 10-year exposure duration, as adjusted to account for the deposition period (fractional excavation season). For external gamma, the deposition-adjusted concentration is further adjusted by dividing by the overall time onsite (total work hours divided by total hours per year) to align with the DCF (in units of per year), resulting in an effective duration of 1.6 years.

TABLE A.17 Radiological Intakes for an Onsite Trespasser from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
L-30, F-32, and L-50 Residues and Tower Soils				
Uranium-238	676	4.0×10^{-2}	1.3×10^{-2}	2.9×10^{-5}
Uranium-234	676	4.0×10^{-2}	1.3×10^{-2}	2.9×10^{-5}
Thorium-230	7,200	4.3×10^{-1}	1.3×10^{-1}	3.1×10^{-4}
Radium-226	9,830	5.8×10^{-1}	1.8×10^{-1}	4.2×10^{-4}
Lead-210	13,300	7.9×10^{-1}	2.5×10^{-1}	5.7×10^{-4}
Uranium-235	49	2.9×10^{-3}	9.1×10^{-4}	2.1×10^{-6}
Protactinium-231	113	6.7×10^{-3}	2.1×10^{-3}	4.8×10^{-6}
Actinium-227	113	6.7×10^{-3}	2.1×10^{-3}	4.8×10^{-6}
Thorium-232	21	1.2×10^{-3}	3.9×10^{-4}	8.8×10^{-7}
Radium-228	21	1.2×10^{-3}	3.9×10^{-4}	8.8×10^{-7}
Thorium-228	21	1.2×10^{-3}	3.9×10^{-4}	8.8×10^{-7}

[a] These preliminary intake estimates are for a hypothetical onsite trespasser assumed to be exposed to airborne releases and deposited particulates during excavation of waste group 2. Values are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). The onsite trespasser is assumed to spend 10% of the time 1 m (3 ft) from the uncovered wastes and the remainder of the time 100 m (330 ft) from the wastes. Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the onsite maintenance worker (Table A.16), except the overall exposure extends over 5 years (instead of 10) and the exposure time and frequency are lower, resulting in an effective duration of 0.011 years.

TABLE A.18 Radiological Intakes for an Offsite Outdoor Worker from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
L-30, F-32, and L-50 Residues and Tower Soils				
Uranium-238	676	1.5×10^{-2}	3.8×10^{-3}	3.5×10^{-5}
Uranium-234	676	1.5×10^{-2}	3.8×10^{-3}	3.5×10^{-5}
Thorium-230	7,200	1.7×10^{-1}	4.1×10^{-2}	3.7×10^{-4}
Radium-226	9,830	2.3×10^{-1}	5.6×10^{-2}	5.1×10^{-4}
Lead-210	13,300	3.0×10^{-1}	7.6×10^{-2}	6.9×10^{-4}
Uranium-235	49	1.1×10^{-3}	2.8×10^{-4}	2.5×10^{-6}
Protactinium-231	113	2.6×10^{-3}	6.4×10^{-4}	5.9×10^{-6}
Actinium-227	113	2.6×10^{-3}	6.4×10^{-4}	5.9×10^{-6}
Thorium-232	21	4.8×10^{-4}	1.2×10^{-4}	1.1×10^{-6}
Radium-228	21	4.8×10^{-4}	1.2×10^{-4}	1.1×10^{-6}
Thorium-228	21	4.8×10^{-4}	1.2×10^{-4}	1.1×10^{-6}

[a] These preliminary intake estimates are for a hypothetical offsite outdoor worker assumed to be 560 m (1,800 ft) east-southeast of the IWCS. Values are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). No respiratory protection is assumed for this outdoor worker, so inhalation exposures correspond to the excavation time, i.e., 8-hour work day and 5-day work weeks over the excavation period (two-thirds of an excavation season for waste group 2). Exposures to the deposited contaminants via incidental ingestion and external gamma irradiation are estimated for the 10-year exposure duration as described for the onsite maintenance worker (Table A.16, but all exposures are at this single offsite location), with the effective duration of 1.6 years.

TABLE A.19 Radiological Intakes for an Offsite Adult Resident from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
L-30, F-32, and L-50 Residues and Tower Soils				
Uranium-238	676	5.6×10^{-3}	1.7×10^{-3}	9.3×10^{-5}
Uranium-234	676	5.6×10^{-3}	1.7×10^{-3}	9.3×10^{-5}
Thorium-230	7,200	5.9×10^{-2}	1.8×10^{-2}	9.9×10^{-4}
Radium-226	9,830	8.1×10^{-2}	2.5×10^{-2}	1.3×10^{-3}
Lead-210	13,300	1.1×10^{-1}	3.3×10^{-2}	1.8×10^{-3}
Uranium-235	49	4.0×10^{-4}	1.2×10^{-4}	6.7×10^{-6}
Protactinium-231	113	9.3×10^{-4}	2.8×10^{-4}	1.5×10^{-5}
Actinium-227	113	9.3×10^{-4}	2.8×10^{-4}	1.5×10^{-5}
Thorium-232	21	1.7×10^{-4}	5.2×10^{-5}	2.8×10^{-6}
Radium-228	21	1.7×10^{-4}	5.2×10^{-5}	2.8×10^{-6}
Thorium-228	21	1.7×10^{-4}	5.2×10^{-5}	2.8×10^{-6}

[a] These preliminary intake estimates are for a hypothetical offsite adult resident assumed to be 660 m (2,200 ft) south-southwest of the IWCS. Values are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). The offsite adult resident is assumed to spend 2 hours a day outdoors and 22 hours a day indoors during the excavation season. The indoor concentration is assumed to be 50% of the outdoor concentration. Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the onsite maintenance worker (Table A.16, but all exposures are at this single location), except the exposure time is greater (24 hours a day instead of 8) as is the frequency (238 days instead of 170, from April through November including weekends); this results in an effective duration of 6.5 years. For external gamma exposures, no credit is taken for shielding by the structure.

TABLE A.20 Radiological Intakes for an Offsite Child Resident from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
L-30, F-32, and L-50 Residues and Tower Soils				
Uranium-238	676	5.6×10^{-3}	1.7×10^{-3}	4.6×10^{-5}
Uranium-234	676	5.6×10^{-3}	1.7×10^{-3}	4.6×10^{-5}
Thorium-230	7,200	5.9×10^{-2}	1.8×10^{-2}	4.9×10^{-4}
Radium-226	9,830	8.1×10^{-2}	2.5×10^{-2}	6.7×10^{-4}
Lead-210	13,300	1.1×10^{-1}	3.3×10^{-2}	9.1×10^{-4}
Uranium-235	49	4.0×10^{-4}	1.2×10^{-4}	3.3×10^{-6}
Protactinium-231	113	9.3×10^{-4}	2.8×10^{-4}	7.7×10^{-6}
Actinium-227	113	9.3×10^{-4}	2.8×10^{-4}	7.7×10^{-6}
Thorium-232	21	1.7×10^{-4}	5.2×10^{-5}	1.4×10^{-6}
Radium-228	21	1.7×10^{-4}	5.2×10^{-5}	1.4×10^{-6}
Thorium-228	21	1.7×10^{-4}	5.2×10^{-5}	1.4×10^{-6}

[a] These preliminary intake estimates are for the offsite child resident assumed to be about 660 m (2,200 ft) south-southwest of the IWCS. Values are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the offsite adult resident (Table A.19), except the overall duration is 5 years instead of 10, resulting in an effective duration of 3.3 years.

TABLE A.21 Radiological Doses and Risks for a Remedial Action Worker from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
L-30, F-32, and L-50 Residues and Tower Soils				*Radionuclide-Specific*
Uranium-238	$6.7 \times 10^{-3} / 5.3 \times 10^{-9}$	$1.9 \times 10^{-6} / 1.3 \times 10^{-12}$	$2.6 \times 10^{-3} / 1.9 \times 10^{-9}$	$9.3 \times 10^{-3} / 7.2 \times 10^{-9}$
Uranium-234	$7.9 \times 10^{-3} / 6.3 \times 10^{-9}$	$1.9 \times 10^{-6} / 1.0 \times 10^{-12}$	$5.7 \times 10^{-6} / 4.2 \times 10^{-12}$	$7.9 \times 10^{-3} / 6.3 \times 10^{-9}$
Thorium-230	$8.9 \times 10^{-1} / 8.2 \times 10^{-8}$	$8.9 \times 10^{-5} / 1.4 \times 10^{-11}$	$1.9 \times 10^{-4} / 1.5 \times 10^{-10}$	$8.9 \times 10^{-1} / 8.2 \times 10^{-8}$
Radium-226	$1.2 \times 10^{-1} / 9.3 \times 10^{-8}$	$1.6 \times 10^{-4} / 8.1 \times 10^{-11}$	$2.6 \times 10^{0} / 2.1 \times 10^{-6}$	$2.7 \times 10^{0} / 2.2 \times 10^{-6}$
Lead-210	$1.6 \times 10^{-1} / 1.4 \times 10^{-7}$	$1.5 \times 10^{-3} / 7.3 \times 10^{-10}$	$2.5 \times 10^{-3} / 1.4 \times 10^{-9}$	$1.7 \times 10^{-1} / 1.4 \times 10^{-7}$
Uranium-235	$5.1 \times 10^{-4} / 4.1 \times 10^{-10}$	$1.4 \times 10^{-7} / 7.5 \times 10^{-14}$	$8.3 \times 10^{-4} / 6.5 \times 10^{-10}$	$1.3 \times 10^{-3} / 1.1 \times 10^{-9}$
Protactinium-231	$2.0 \times 10^{-2} / 2.9 \times 10^{-9}$	$4.7 \times 10^{-6} / 4.1 \times 10^{-13}$	$4.9 \times 10^{-4} / 3.9 \times 10^{-10}$	$2.0 \times 10^{-2} / 3.3 \times 10^{-9}$
Actinium-227	$7.9 \times 10^{-2} / 8.1 \times 10^{-9}$	$8.0 \times 10^{-6} / 1.2 \times 10^{-12}$	$5.2 \times 10^{-3} / 4.1 \times 10^{-9}$	$8.5 \times 10^{-2} / 1.2 \times 10^{-8}$
Thorium-232	$2.8 \times 10^{-3} / 3.0 \times 10^{-10}$	$2.8 \times 10^{-7} / 4.4 \times 10^{-14}$	$2.3 \times 10^{-7} / 1.7 \times 10^{-13}$	$2.8 \times 10^{-3} / 3.0 \times 10^{-10}$
Radium-228	$4.1 \times 10^{-4} / 3.0 \times 10^{-10}$	$8.4 \times 10^{-7} / 4.7 \times 10^{-13}$	$2.9 \times 10^{-3} / 2.3 \times 10^{-9}$	$3.3 \times 10^{-3} / 2.6 \times 10^{-9}$
Thorium-228	$1.1 \times 10^{-3} / 1.0 \times 10^{-9}$	$1.7 \times 10^{-7} / 1.4 \times 10^{-13}$	$4.9 \times 10^{-3} / 4.0 \times 10^{-9}$	$6.1 \times 10^{-3} / 5.0 \times 10^{-9}$
Route-Specific Total	$1.3 \times 10^{0} / 3.4 \times 10^{-7}$	$1.8 \times 10^{-3} / 8.3 \times 10^{-10}$	$2.6 \times 10^{0} / 2.1 \times 10^{-6}$	$3.9 \times 10^{0} / 2 \times 10^{-6}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical remedial action are based on the intake estimates in Table A.15. Values are rounded to two significant figures except total risk, which is rounded to one significant figure. The inhalation estimates are from breathing contaminated air for 1 day based on an assumed lack of respiratory protection. The ingestion and external gamma irradiation estimates are for an exposure period of 5 years. The ingestion doses and cancer risks are based on the amount deposited on surface soil during excavation of these wastes, which is assumed to be uniformly mixed in the top 1 cm (0.4 in.) of soil. The external gamma doses and risks assume uniform contamination to an infinite depth (rather than being limited to the top cm), which overestimates the doses and risks from external gamma irradiation by about a factor of five.

TABLE A.22 Radiological Doses and Risks for an Onsite Maintenance Worker from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
L-30, F-32, and L-50 Residues and Tower Soils				*Radionuclide-Specific*
Uranium-238	$1.1 \times 10^{-1} / 8.5 \times 10^{-8}$	$1.0 \times 10^{-4} / 6.9 \times 10^{-11}$	$8.1 \times 10^{-4} / 5.9 \times 10^{-10}$	$1.1 \times 10^{-1} / 8.6 \times 10^{-8}$
Uranium-234	$1.3 \times 10^{-1} / 1.0 \times 10^{-7}$	$1.0 \times 10^{-4} / 5.4 \times 10^{-11}$	$1.8 \times 10^{-6} / 1.3 \times 10^{-12}$	$1.3 \times 10^{-1} / 1.0 \times 10^{-7}$
Thorium-230	$1.4 \times 10^{1} / 1.3 \times 10^{-6}$	$4.7 \times 10^{-3} / 7.2 \times 10^{-10}$	$5.9 \times 10^{-5} / 4.5 \times 10^{-11}$	$1.4 \times 10^{1} / 1.3 \times 10^{-6}$
Radium-226	$1.8 \times 10^{0} / 1.5 \times 10^{-6}$	$8.6 \times 10^{-3} / 4.3 \times 10^{-9}$	$8.0 \times 10^{-1} / 6.4\times 10^{-7}$	$2.7 \times 10^{0} / 2.1 \times 10^{-6}$
Lead-210	$2.6 \times 10^{0} / 2.2 \times 10^{-6}$	$7.8 \times 10^{-2} / 3.9 \times 10^{-8}$	$7.7 \times 10^{-4} / 4.3 \times 10^{-10}$	$2.7 \times 10^{0} / 2.2 \times 10^{-6}$
Uranium-235	$8.2 \times 10^{-3} / 6.5 \times 10^{-9}$	$7.2 \times 10^{-6} / 4.0 \times 10^{-12}$	$2.6 \times 10^{-4} / 2.0 \times 10^{-10}$	$8.4 \times 10^{-3} / 6.7 \times 10^{-9}$
Protactinium-231	$3.1 \times 10^{-1} / 4.6 \times 10^{-8}$	$2.5 \times 10^{-4} / 2.2 \times 10^{-11}$	$1.5 \times 10^{-4} / 1.2 \times 10^{-10}$	$3.1 \times 10^{-1} / 4.6 \times 10^{-8}$
Actinium-227	$1.3 \times 10^{0} / 1.3 \times 10^{-7}$	$4.3 \times 10^{-4} / 6.2 \times 10^{-11}$	$1.6 \times 10^{-3} / 1.3 \times 10^{-9}$	$1.3 \times 10^{0} / 1.3 \times 10^{-7}$
Thorium-232	$4.5 \times 10^{-2} / 4.8 \times 10^{-9}$	$1.5 \times 10^{-5} / 2.3 \times 10^{-12}$	$7.3 \times 10^{-8} / 5.4 \times 10^{-14}$	$4.5 \times 10^{-2} / 4.8 \times 10^{-9}$
Radium-228	$6.5 \times 10^{-3} / 4.8 \times 10^{-9}$	$4.4 \times 10^{-5} / 2.5 \times 10^{-11}$	$9.0 \times 10^{-4} / 7.2 \times 10^{-10}$	$7.5 \times 10^{-3} / 5.6 \times 10^{-9}$
Thorium-228	$1.8 \times 10^{-2} / 1.6 \times 10^{-8}$	$9.2 \times 10^{-6} / 7.4 \times 10^{-12}$	$1.5 \times 10^{-3} / 1.2 \times 10^{-9}$	$1.9 \times 10^{-2} / 1.7 \times 10^{-8}$
Route-Specific Total	$2.1 \times 10^{1} / 5.3 \times 10^{-6}$	$9.3 \times 10^{-2} / 4.4 \times 10^{-8}$	$8.1 \times 10^{-1} / 6.5 \times 10^{-7}$	$2.1 \times 10^{1} / 6 \times 10^{-6}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (after the slash) for the hypothetical maintenance worker are based on the intake estimates in Table A.16; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.23 Radiological Doses and Risks for an Onsite Trespasser from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
L-30, F-32, and L-50 Residues and Tower Soils				*Radionuclide-Specific*
Uranium-238	$1.2 \times 10^{-3} / 9.5 \times 10^{-10}$	$2.3 \times 10^{-6} / 1.5 \times 10^{-12}$	$4.5 \times 10^{-6} / 3.3 \times 10^{-12}$	$1.2 \times 10^{-3} / 9.5 \times 10^{-10}$
Uranium-234	$1.4 \times 10^{-3} / 1.1 \times 10^{-9}$	$2.3 \times 10^{-6} / 1.2 \times 10^{-12}$	$9.9 \times 10^{-9} / 7.3 \times 10^{-15}$	$1.4 \times 10^{-3} / 1.1 \times 10^{-9}$
Thorium-230	$1.6 \times 10^{-1} / 1.5 \times 10^{-8}$	$1.0 \times 10^{-4} / 1.6 \times 10^{-11}$	$3.3 \times 10^{-7} / 2.5 \times 10^{-13}$	$1.6 \times 10^{-1} / 1.5 \times 10^{-8}$
Radium-226	$2.1 \times 10^{-2} / 1.7 \times 10^{-8}$	$1.9 \times 10^{-4} / 9.5 \times 10^{-11}$	$4.4 \times 10^{-3} / 3.6 \times 10^{-9}$	$2.5 \times 10^{-2} / 2.0 \times 10^{-8}$
Lead-210	$2.9 \times 10^{-2} / 2.4 \times 10^{-8}$	$1.7 \times 10^{-3} / 8.5 \times 10^{-10}$	$4.3 \times 10^{-6} / 2.4 \times 10^{-12}$	$3.1 \times 10^{-2} / 2.5 \times 10^{-8}$
Uranium-235	$9.1 \times 10^{-5} / 7.2 \times 10^{-11}$	$1.6 \times 10^{-7} / 8.9 \times 10^{-14}$	$1.4 \times 10^{-6} / 1.1 \times 10^{-12}$	$9.2 \times 10^{-5} / 7.3 \times 10^{-11}$
Protactinium-231	$3.5 \times 10^{-3} / 5.1 \times 10^{-10}$	$5.6 \times 10^{-6} / 4.8 \times 10^{-13}$	$8.5 \times 10^{-7} / 6.7 \times 10^{-13}$	$3.5 \times 10^{-3} / 5.1 \times 10^{-10}$
Actinium-227	$1.4 \times 10^{-2} / 1.4 \times 10^{-9}$	$9.4 \times 10^{-6} / 1.4 \times 10^{-12}$	$9.0 \times 10^{-6} / 7.1 \times 10^{-12}$	$1.4 \times 10^{-2} / 1.4 \times 10^{-9}$
Thorium-232	$5.0 \times 10^{-4} / 5.3 \times 10^{-11}$	$3.3 \times 10^{-7} / 5.1 \times 10^{-14}$	$4.0 \times 10^{-10} / 3.0 \times 10^{-16}$	$5.0 \times 10^{-4} / 5.3 \times 10^{-11}$
Radium-228	$7.3 \times 10^{-5} / 5.4 \times 10^{-11}$	$9.9 \times 10^{-7} / 5.5 \times 10^{-13}$	$5.0 \times 10^{-6} / 4.0 \times 10^{-12}$	$7.9 \times 10^{-5} / 5.8 \times 10^{-11}$
Thorium-228	$2.0 \times 10^{-4} / 1.8 \times 10^{-10}$	$2.0 \times 10^{-7} / 1.6 \times 10^{-13}$	$8.5 \times 10^{-6} / 6.9 \times 10^{-12}$	$2.1 \times 10^{-4} / 1.8 \times 10^{-10}$
Route-Specific Total	$2.3 \times 10^{-1} / 6.0 \times 10^{-8}$	$2.1 \times 10^{-3} / 9.7 \times 10^{-10}$	$4.5 \times 10^{-3} / 3.6 \times 10^{-9}$	$2.4 \times 10^{-1} / 6 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical trespasser are based on the intake estimates in Table A.17; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.24 Radiological Doses and Risks for an Offsite Outdoor Worker from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
L-30, F-32, and L-50 Residues and Tower Soils				*Radionuclide-Specific*
Uranium-238	$4.6 \times 10^{-4} / 3.7 \times 10^{-10}$	$6.9 \times 10^{-7} / 4.7 \times 10^{-13}$	$5.5 \times 10^{-6} / 4.0 \times 10^{-12}$	$4.6 \times 10^{-4} / 3.7 \times 10^{-10}$
Uranium-234	$5.4 \times 10^{-4} / 4.3 \times 10^{-10}$	$7.0 \times 10^{-7} / 3.7 \times 10^{-13}$	$1.2 \times 10^{-8} / 8.9 \times 10^{-15}$	$5.4 \times 10^{-4} / 4.3 \times 10^{-10}$
Thorium-230	$6.1 \times 10^{-2} / 5.6 \times 10^{-9}$	$3.2 \times 10^{-5} / 4.9 \times 10^{-12}$	$4.0 \times 10^{-7} / 3.1 \times 10^{-13}$	$6.1 \times 10^{-2} / 5.6 \times 10^{-9}$
Radium-226	$8.0 \times 10^{-3} / 6.4 \times 10^{-9}$	$5.8 \times 10^{-5} / 2.9 \times 10^{-11}$	$5.4 \times 10^{-3} / 4.3 \times 10^{-9}$	$1.3 \times 10^{-2} / 1.1 \times 10^{-8}$
Lead-210	$1.1 \times 10^{-2} / 9.4 \times 10^{-9}$	$5.3 \times 10^{-4} / 2.6 \times 10^{-10}$	$5.2 \times 10^{-6} / 2.9 \times 10^{-12}$	$1.2 \times 10^{-2} / 9.6 \times 10^{-9}$
Uranium-235	$3.5 \times 10^{-5} / 2.8 \times 10^{-11}$	$4.8 \times 10^{-8} / 2.7 \times 10^{-14}$	$1.7 \times 10^{-6} / 1.4 \times 10^{-12}$	$3.7 \times 10^{-5} / 2.9 \times 10^{-11}$
Protactinium-231	$1.3 \times 10^{-3} / 2.0 \times 10^{-10}$	$1.7 \times 10^{-6} / 1.5 \times 10^{-13}$	$1.0 \times 10^{-6} / 8.2 \times 10^{-13}$	$1.3 \times 10^{-3} / 2.0 \times 10^{-10}$
Actinium-227	$5.4 \times 10^{-3} / 5.5 \times 10^{-10}$	$2.9 \times 10^{-6} / 4.2 \times 10^{-13}$	$1.1 \times 10^{-5} / 8.6 \times 10^{-12}$	$5.4 \times 10^{-3} / 5.6 \times 10^{-10}$
Thorium-232	$1.9 \times 10^{-4} / 2.1 \times 10^{-11}$	$1.0 \times 10^{-7} / 1.6 \times 10^{-14}$	$4.9 \times 10^{-10} / 3.7 \times 10^{-16}$	$1.9 \times 10^{-4} / 2.1 \times 10^{-11}$
Radium-228	$2.8 \times 10^{-5} / 2.1 \times 10^{-11}$	$3.0 \times 10^{-7} / 1.7 \times 10^{-13}$	$6.1 \times 10^{-6} / 4.9 \times 10^{-12}$	$3.5 \times 10^{-5} / 2.6 \times 10^{-11}$
Thorium-228	$7.6 \times 10^{-5} / 6.8 \times 10^{-11}$	$6.2 \times 10^{-8} / 5.0 \times 10^{-14}$	$1.0 \times 10^{-5} / 8.3 \times 10^{-12}$	$8.7 \times 10^{-5} / 7.7 \times 10^{-11}$
Route-Specific Total	$8.8 \times 10^{-2} / 2.3 \times 10^{-8}$	$6.3 \times 10^{-4} / 3.0 \times 10^{-10}$	$5.5 \times 10^{-3} / 4.4 \times 10^{-9}$	$9.5 \times 10^{-2} / 3 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite worker assumed to work at the adjacent landfill are based on the intake estimates in Table A.18; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.25 Radiological Doses and Risks for an Offsite Adult Resident from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
L-30, F-32, and L-50 Residues and Tower Soils				*Radionuclide-Specific*
Uranium-238	$1.7 \times 10^{-4} / 1.3 \times 10^{-10}$	$3.0 \times 10^{-7} / 2.0 \times 10^{-13}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$	$1.8 \times 10^{-4} / 1.4 \times 10^{-10}$
Uranium-234	$1.9 \times 10^{-4} / 1.6 \times 10^{-10}$	$3.1 \times 10^{-7} / 1.6 \times 10^{-13}$	$3.2 \times 10^{-8} / 2.3 \times 10^{-14}$	$1.9 \times 10^{-4} / 1.6 \times 10^{-10}$
Thorium-230	$2.2 \times 10^{-2} / 2.0 \times 10^{-9}$	$1.4 \times 10^{-5} / 2.1 \times 10^{-12}$	$1.1 \times 10^{-6} / 8.1 \times 10^{-13}$	$2.2 \times 10^{-2} / 2.0 \times 10^{-9}$
Radium-226	$2.9 \times 10^{-3} / 2.3 \times 10^{-9}$	$2.6 \times 10^{-5} / 1.3 \times 10^{-11}$	$1.4 \times 10^{-2} / 1.1 \times 10^{-8}$	$1.7 \times 10^{-2} / 1.4 \times 10^{-8}$
Lead-210	$4.1 \times 10^{-3} / 3.4 \times 10^{-9}$	$2.3 \times 10^{-4} / 1.1 \times 10^{-10}$	$1.4 \times 10^{-5} / 7.7 \times 10^{-12}$	$4.3 \times 10^{-3} / 3.5 \times 10^{-9}$
Uranium-235	$1.3 \times 10^{-5} / 1.0 \times 10^{-11}$	$2.1 \times 10^{-8} / 1.2 \times 10^{-14}$	$4.6 \times 10^{-6} / 3.6 \times 10^{-12}$	$1.7 \times 10^{-5} / 1.4 \times 10^{-11}$
Protactinium-231	$4.8 \times 10^{-4} / 7.1 \times 10^{-11}$	$7.4 \times 10^{-7} / 6.4 \times 10^{-14}$	$2.7 \times 10^{-6} / 2.2 \times 10^{-12}$	$4.9 \times 10^{-4} / 7.3 \times 10^{-11}$
Actinium-227	$2.0 \times 10^{-3} / 2.0 \times 10^{-10}$	$1.3 \times 10^{-6} / 1.8 \times 10^{-13}$	$2.9 \times 10^{-5} / 2.3 \times 10^{-11}$	$2.0 \times 10^{-3} / 2.2 \times 10^{-10}$
Thorium-232	$7.0 \times 10^{-5} / 7.4 \times 10^{-12}$	$4.4 \times 10^{-8} / 6.9 \times 10^{-15}$	$1.3 \times 10^{-9} / 9.7 \times 10^{-16}$	$7.0 \times 10^{-5} / 7.4 \times 10^{-12}$
Radium-228	$1.0 \times 10^{-5} / 7.5 \times 10^{-12}$	$1.3 \times 10^{-7} / 7.4 \times 10^{-14}$	$1.6 \times 10^{-5} / 1.3 \times 10^{-11}$	$2.6 \times 10^{-5} / 2.0 \times 10^{-11}$
Thorium-228	$2.7 \times 10^{-5} / 2.5 \times 10^{-11}$	$2.7 \times 10^{-8} / 2.2 \times 10^{-14}$	$2.7 \times 10^{-5} / 2.2 \times 10^{-11}$	$5.5 \times 10^{-5} / 4.7 \times 10^{-11}$
Route-Specific Total	$3.2 \times 10^{-2} / 8.3 \times 10^{-9}$	$2.8 \times 10^{-4} / 1.3 \times 10^{-10}$	$1.4 \times 10^{-2} / 1.2 \times 10^{-8}$	$4.6 \times 10^{-2} / 2 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite adult resident are based on the intake estimates in Table A.19; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.26 Radiological Doses and Risks for an Offsite Child Resident from Particulates Released from the Other High-Activity Residues (L and F) and Tower Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
L-30, F-32, and L-50 Residues and Tower Soils				*Radionuclide-Specific*
Uranium-238	$1.7 \times 10^{-4} / 1.3 \times 10^{-10}$	$3.0 \times 10^{-7} / 2.0 \times 10^{-13}$	$7.2 \times 10^{-6} / 5.3 \times 10^{-12}$	$1.7 \times 10^{-4} / 1.4 \times 10^{-10}$
Uranium-234	$1.9 \times 10^{-4} / 1.6 \times 10^{-10}$	$3.1 \times 10^{-7} / 1.6 \times 10^{-13}$	$1.6 \times 10^{-8} / 1.2 \times 10^{-14}$	$1.9 \times 10^{-4} / 1.6 \times 10^{-10}$
Thorium-230	$2.2 \times 10^{-2} / 2.0 \times 10^{-9}$	$1.4 \times 10^{-5} / 2.1 \times 10^{-12}$	$5.3 \times 10^{-7} / 4.0 \times 10^{-13}$	$2.2 \times 10^{-2} / 2.0 \times 10^{-9}$
Radium-226	$2.9 \times 10^{-3} / 2.3 \times 10^{-9}$	$2.6 \times 10^{-5} / 1.3 \times 10^{-11}$	$7.1 \times 10^{-3} / 5.7 \times 10^{-9}$	$1.0 \times 10^{-2} / 8.0 \times 10^{-9}$
Lead-210	$4.1 \times 10^{-3} / 3.4 \times 10^{-9}$	$2.3 \times 10^{-4} / 1.1 \times 10^{-10}$	$6.8 \times 10^{-6} / 3.8 \times 10^{-12}$	$4.3 \times 10^{-3} / 3.5 \times 10^{-9}$
Uranium-235	$1.3 \times 10^{-5} / 1.0 \times 10^{-11}$	$2.1 \times 10^{-8} / 1.2 \times 10^{-14}$	$2.3 \times 10^{-6} / 1.8 \times 10^{-12}$	$1.5 \times 10^{-5} / 1.2 \times 10^{-11}$
Protactinium-231	$4.8 \times 10^{-4} / 7.1 \times 10^{-11}$	$7.4 \times 10^{-7} / 6.4 \times 10^{-14}$	$1.4 \times 10^{-6} / 1.1 \times 10^{-12}$	$4.8 \times 10^{-4} / 7.2 \times 10^{-11}$
Actinium-227	$2.0 \times 10^{-3} / 2.0 \times 10^{-10}$	$1.3 \times 10^{-6} / 1.8 \times 10^{-13}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$	$2.0 \times 10^{-3} / 2.1 \times 10^{-10}$
Thorium-232	$7.0 \times 10^{-5} / 7.4 \times 10^{-12}$	$4.4 \times 10^{-8} / 6.9 \times 10^{-15}$	$6.5 \times 10^{-10} / 4.9 \times 10^{-16}$	$7.0 \times 10^{-5} / 7.4 \times 10^{-12}$
Radium-228	$1.0 \times 10^{-5} / 7.5 \times 10^{-12}$	$1.3 \times 10^{-7} / 7.4 \times 10^{-14}$	$8.0 \times 10^{-6} / 6.4 \times 10^{-12}$	$1.8 \times 10^{-5} / 1.4 \times 10^{-11}$
Thorium-228	$2.7 \times 10^{-5} / 2.5 \times 10^{-11}$	$2.7 \times 10^{-8} / 2.2 \times 10^{-14}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$	$4.1 \times 10^{-5} / 3.6 \times 10^{-11}$
Route-Specific Total	$3.2 \times 10^{-2} / 8.3 \times 10^{-9}$	$2.8 \times 10^{-4} / 1.3 \times 10^{-10}$	$7.2 \times 10^{-3} / 5.8 \times 10^{-9}$	$3.9 \times 10^{-2} / 1 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite child resident are based on the intake estimates in Table A.20; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.27 Radiological Intakes for a Remedial Action Worker from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
R-10 Pile and Other Contaminated Soils				
Uranium-238	4.1	1.5×10^{-3}	2.1×10^{-4}	3.2×10^{-4}
Uranium-234	4.1	1.5×10^{-3}	2.1×10^{-4}	3.2×10^{-4}
Thorium-230	24	8.8×10^{-3}	1.2×10^{-3}	1.9×10^{-3}
Radium-226	34	1.3×10^{-2}	1.7×10^{-3}	2.7×10^{-3}
Lead-210	50	1.9×10^{-2}	2.6×10^{-3}	4.0×10^{-3}
Uranium-235	0.25	9.4×10^{-5}	1.3×10^{-5}	2.0×10^{-5}
Protactinium-231	0.33	1.2×10^{-4}	1.7×10^{-5}	2.6×10^{-5}
Actinium-227	0.33	1.2×10^{-4}	1.7×10^{-5}	2.6×10^{-5}
Thorium-232	0.069	2.5×10^{-5}	3.5×10^{-6}	5.4×10^{-6}
Radium-228	0.069	2.5×10^{-5}	3.5×10^{-6}	5.4×10^{-6}
Thorium-228	0.069	2.5×10^{-5}	3.5×10^{-6}	5.4×10^{-6}

[a] These preliminary intake estimates for the remedial action worker during excavation of waste group 3 are rounded to two significant figures. Inhalation exposures are for 1 work day (8 hours) based on an assumed lack of respiratory protection. The total amount of deposited particulates (assumed to occur over 32 months, four excavation seasons) was adjusted to account for the fraction of time during which these wastes would be excavated to calculate the deposition associated with particulate releases. The source concentrations are scaled to the deposited particulates, which are assumed to be uniformly mixed in the top 1 cm (0.4 in.) of soil. For external gamma, the amount of deposited particulates is further scaled to the total hours per year (because the DCF is in units of per year), resulting in an effective duration of 0.78 years.

TABLE A.28 Radiological Intakes for an Onsite Maintenance Worker from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
R-10 Pile and Other Contaminated Soils				
Uranium-238	4.1	6.8×10^{-2}	1.2×10^{-2}	1.1×10^{-4}
Uranium-234	4.1	6.8×10^{-2}	1.2×10^{-2}	1.1×10^{-4}
Thorium-230	24	3.9×10^{-1}	7.0×10^{-2}	6.4×10^{-4}
Radium-226	34	5.6×10^{-1}	1.0×10^{-1}	9.2×10^{-4}
Lead-210	50	8.3×10^{-1}	1.5×10^{-1}	1.4×10^{-3}
Uranium-235	0.25	4.2×10^{-3}	7.5×10^{-4}	6.9×10^{-6}
Protactinium-231	0.33	5.5×10^{-3}	9.8×10^{-4}	9.0×10^{-6}
Actinium-227	0.33	5.5×10^{-3}	9.8×10^{-4}	9.0×10^{-6}
Thorium-232	0.069	1.1×10^{-3}	2.0×10^{-4}	1.9×10^{-6}
Radium-228	0.069	1.1×10^{-3}	2.0×10^{-4}	1.9×10^{-6}
Thorium-228	0.069	1.1×10^{-3}	2.0×10^{-4}	1.9×10^{-6}

[a] These preliminary intake estimates are for a hypothetical onsite maintenance worker assumed to be exposed to airborne releases and deposited particulates during excavation of waste group 3. Values are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). No respiratory protection is assumed, so inhalation exposures correspond to the timing of the excavation activities. Exposures to deposited contaminants via incidental ingestion and external gamma irradiation would occur over the 10-year duration, as adjusted to account for the deposition period for these wastes. For external gamma, the deposition-adjusted concentration is further adjusted by dividing by the total elapsed years during which this worker would be exposed (hours onsite divided by hours per year) to align with the DCF (in units of per year), resulting in an effective duration of 1.6 years.

TABLE A.29 Radiological Intakes for an Onsite Trespasser from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
R-10 Pile and Other Contaminated Soils				
Uranium-238	4.1	7.1×10^{-4}	2.6×10^{-4}	5.9×10^{-7}
Uranium-234	4.1	7.1×10^{-4}	2.6×10^{-4}	5.9×10^{-7}
Thorium-230	24	4.1×10^{-3}	1.5×10^{-3}	3.4×10^{-6}
Radium-226	34	5.9×10^{-3}	2.1×10^{-3}	4.9×10^{-6}
Lead-210	50	8.8×10^{-3}	3.2×10^{-3}	7.2×10^{-6}
Uranium-235	0.25	4.4×10^{-5}	1.6×10^{-5}	3.7×10^{-8}
Protactinium-231	0.33	5.8×10^{-5}	2.1×10^{-5}	4.8×10^{-8}
Actinium-227	0.33	5.8×10^{-5}	2.1×10^{-5}	4.8×10^{-8}
Thorium-232	0.069	1.2×10^{-5}	4.3×10^{-6}	9.9×10^{-9}
Radium-228	0.069	1.2×10^{-5}	4.3×10^{-6}	9.9×10^{-9}
Thorium-228	0.069	1.2×10^{-5}	4.3×10^{-6}	9.9×10^{-9}

[a] These preliminary intake estimates are for a hypothetical onsite trespasser assumed to be exposed to airborne releases and deposited particulates during excavation of waste group 3. Values are rounded to two significant figures. The basic assumptions underlying these calculations are given in Chapter 3 (including Tables 3.2 and 3.3). The trespasser is assumed to spend 10% of the time 1 m (3 ft) from the uncovered wastes and the remainder of the time 100 m (330 ft) from the wastes. Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the onsite maintenance worker (Table A.28), except the overall exposure extends over 5 years (instead of 10) and the exposure time and frequency are lower, resulting in an effective duration of 0.011 years.

TABLE A.30 Radiological Intakes for an Offsite Outdoor Worker from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
R-10 Pile and Other Contaminated Soils				
Uranium-238	4.1	4.6×10^{-4}	1.2×10^{-4}	1.1×10^{-6}
Uranium-234	4.1	4.6×10^{-4}	1.2×10^{-4}	1.1×10^{-6}
Thorium-230	24	2.7×10^{-3}	6.7×10^{-4}	6.1×10^{-6}
Radium-226	34	3.8×10^{-3}	9.5×10^{-4}	8.7×10^{-6}
Lead-210	50	5.7×10^{-3}	1.4×10^{-3}	1.3×10^{-5}
Uranium-235	0.25	2.9×10^{-5}	7.2×10^{-6}	6.5×10^{-8}
Protactinium-231	0.33	3.7×10^{-5}	9.3×10^{-6}	8.5×10^{-8}
Actinium-227	0.33	3.7×10^{-5}	9.3×10^{-6}	8.5×10^{-8}
Thorium-232	0.069	7.7×10^{-6}	1.9×10^{-6}	1.8×10^{-8}
Radium-228	0.069	7.7×10^{-6}	1.9×10^{-6}	1.8×10^{-8}
Thorium-228	0.069	7.7×10^{-6}	1.9×10^{-6}	1.8×10^{-8}

[a] These preliminary intake estimates are for a hypothetical offsite outdoor worker 560 m (1,800 ft) east-southeast of the IWCS. Values are rounded to two significant figures. The basic exposure and excavation assumptions are given in Chapter 3 (including Tables 3.2 and 3.3). No respiratory protection is assumed for this worker, so inhalation exposures correspond to the excavation activities, i.e., 8 hours a day, 5 days a week, over 1.6 excavation seasons. Exposures to deposited contaminants via incidental ingestion and external gamma irradiation are estimated for the 10-year overall duration as described for the onsite maintenance worker (Table A.28), but for exposures at this single offsite location, over an effective duration of 1.6 years.

TABLE A.31 Radiological Intakes for an Offsite Adult Resident from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
R-10 Pile and Other Contaminated Soils				
Uranium-238	4.1	1.7×10^{-4}	5.1×10^{-5}	2.8×10^{-6}
Uranium-234	4.1	1.7×10^{-4}	5.1×10^{-5}	2.8×10^{-6}
Thorium-230	24	9.7×10^{-4}	2.9×10^{-4}	1.6×10^{-5}
Radium-226	34	1.4×10^{-3}	4.2×10^{-4}	2.3×10^{-5}
Lead-210	50	2.1×10^{-3}	6.2×10^{-4}	3.4×10^{-5}
Uranium-235	0.25	1.0×10^{-5}	3.1×10^{-6}	1.7×10^{-7}
Protactinium-231	0.33	1.4×10^{-5}	4.1×10^{-6}	2.2×10^{-7}
Actinium-227	0.33	1.4×10^{-5}	4.1×10^{-6}	2.2×10^{-7}
Thorium-232	0.069	2.8×10^{-6}	8.5×10^{-7}	4.6×10^{-8}
Radium-228	0.069	2.8×10^{-6}	8.5×10^{-7}	4.6×10^{-8}
Thorium-228	0.069	2.8×10^{-6}	8.5×10^{-7}	4.6×10^{-8}

[a] These preliminary intake estimates are for a hypothetical offsite adult resident 660 m (2,200 ft) south-southwest of the IWCS. Values are rounded to two significant figures. The basic exposure and excavation assumptions are given in Chapter 3 (including Tables 3.2 and 3.3). The offsite adult resident is assumed to spend 2 hours a day outdoors and 22 hours a day indoors; the indoor concentration is assumed to be 50% of the outdoor concentration. Inhalation, incidental ingestion, and external gamma exposures are generally calculated as described for the onsite maintenance worker (Table A.28), with all exposures at this single location, and with a greater exposure time (24 hours a day instead of 8) and frequency (238 days instead of 170, from April through November including weekends); this results in an effective duration of 6.5 years. For external gamma exposures, no credit is taken for the shielding by the structure.

TABLE A.32 Radiological Intakes for an Offsite Child Resident from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Concentration (pCi/g)	Inhalation (pCi)	Ingestion (pCi)	External Gamma (pCi-yr/g)
R-10 Pile and Other Contaminated Soils				
Uranium-238	4.1	1.7×10^{-4}	5.1×10^{-5}	1.4×10^{-6}
Uranium-234	4.1	1.7×10^{-4}	5.1×10^{-5}	1.4×10^{-6}
Thorium-230	24	9.7×10^{-4}	2.9×10^{-4}	8.0×10^{-6}
Radium-226	34	1.4×10^{-3}	4.2×10^{-4}	1.1×10^{-5}
Lead-210	50	2.1×10^{-3}	6.2×10^{-4}	1.7×10^{-5}
Uranium-235	0.25	1.0×10^{-5}	3.1×10^{-6}	8.6×10^{-8}
Protactinium-231	0.33	1.4×10^{-5}	4.1×10^{-6}	1.1×10^{-7}
Actinium-227	0.33	1.4×10^{-5}	4.1×10^{-6}	1.1×10^{-7}
Thorium-232	0.069	2.8×10^{-6}	8.5×10^{-7}	2.3×10^{-8}
Radium-228	0.069	2.8×10^{-6}	8.5×10^{-7}	2.3×10^{-8}
Thorium-228	0.069	2.8×10^{-6}	8.5×10^{-7}	2.3×10^{-8}

[a] These preliminary intake estimates are for the hypothetical offsite child resident 660 m (2,200 ft) south-southwest of the IWCS. Values are rounded to two significant figures. The basic assumptions underlying these calculations are described in Chapter 3 (including Tables 3.2 and 3.3). Inhalation, incidental ingestion, and external gamma exposures are calculated as described for the adult resident (Table A.31), except the overall exposure duration is 5 years instead of 10, resulting in an effective duration of 3.3 years.

TABLE A.33 Radiological Doses and Risks for a Remedial Action Worker from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
R-10 Pile and Other Contaminated Soils				*Radionuclide-Specific*
Uranium-238	$4.5 \times 10^{-5} / 3.6 \times 10^{-11}$	$3.7 \times 10^{-8} / 2.5 \times 10^{-14}$	$5.0 \times 10^{-5} / 3.7 \times 10^{-11}$	$9.5 \times 10^{-5} / 7.3 \times 10^{-11}$
Uranium-234	$5.3 \times 10^{-5} / 4.2 \times 10^{-11}$	$3.8 \times 10^{-8} / 2.0 \times 10^{-14}$	$1.1 \times 10^{-7} / 8.1 \times 10^{-14}$	$5.3 \times 10^{-5} / 4.2 \times 10^{-11}$
Thorium-230	$3.3 \times 10^{-3} / 3.0 \times 10^{-10}$	$9.4 \times 10^{-7} / 1.4 \times 10^{-13}$	$2.0 \times 10^{-6} / 1.5 \times 10^{-12}$	$3.3 \times 10^{-3} / 3.0 \times 10^{-10}$
Radium-226	$4.4 \times 10^{-4} / 3.6 \times 10^{-10}$	$1.8 \times 10^{-6} / 8.9 \times 10^{-13}$	$2.8 \times 10^{-2} / 2.3 \times 10^{-8}$	$2.9 \times 10^{-2} / 2.3 \times 10^{-8}$
Lead-210	$6.9 \times 10^{-4} / 5.8 \times 10^{-10}$	$1.8 \times 10^{-5} / 8.8 \times 10^{-12}$	$3.0 \times 10^{-5} / 1.7 \times 10^{-11}$	$7.4 \times 10^{-4} / 6.0 \times 10^{-10}$
Uranium-235	$3.0 \times 10^{-6} / 2.4 \times 10^{-12}$	$2.3 \times 10^{-9} / 1.3 \times 10^{-15}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$	$1.7 \times 10^{-5} / 1.3 \times 10^{-11}$
Protactinium-231	$6.4 \times 10^{-5} / 9.4 \times 10^{-12}$	$4.4 \times 10^{-8} / 3.8 \times 10^{-15}$	$4.6 \times 10^{-6} / 3.6 \times 10^{-12}$	$6.8 \times 10^{-5} / 1.3 \times 10^{-11}$
Actinium-227	$2.6 \times 10^{-4} / 2.6 \times 10^{-11}$	$7.5 \times 10^{-8} / 1.1 \times 10^{-14}$	$4.9 \times 10^{-5} / 3.9 \times 10^{-11}$	$3.1 \times 10^{-4} / 6.5 \times 10^{-11}$
Thorium-232	$1.0 \times 10^{-5} / 1.1 \times 10^{-12}$	$3.0 \times 10^{-9} / 4.6 \times 10^{-16}$	$2.5 \times 10^{-9} / 1.9 \times 10^{-15}$	$1.0 \times 10^{-5} / 1.1 \times 10^{-12}$
Radium-228	$1.5 \times 10^{-6} / 1.1 \times 10^{-12}$	$8.9 \times 10^{-9} / 5.0 \times 10^{-15}$	$3.1 \times 10^{-5} / 2.5 \times 10^{-11}$	$3.2 \times 10^{-5} / 2.6 \times 10^{-11}$
Thorium-228	$4.1 \times 10^{-6} / 3.7 \times 10^{-12}$	$1.8 \times 10^{-9} / 1.5 \times 10^{-15}$	$5.2 \times 10^{-5} / 4.2 \times 10^{-11}$	$5.6 \times 10^{-5} / 4.6 \times 10^{-11}$
Route-Specific Total	$4.8 \times 10^{-3} / 1.4 \times 10^{-9}$	$2.1 \times 10^{-5} / 9.9 \times 10^{-12}$	$2.9 \times 10^{-2} / 2.3 \times 10^{-8}$	$3.3 \times 10^{-2} / 2 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical remedial action are based on the intake estimates in Table A.27; values are rounded to two significant figures except total risk, which is rounded to one significant figure. For inhalation and incidental ingestion, this worker is assumed to be without respiratory protection for 1 day during the waste excavation (1.6 seasons). For external gamma irradiation from deposited particulates, exposures are assumed to occur each work day over the 5-year period. The ingestion calculation assumes the deposited particulates are uniformly mixed in the top 1 cm (0.4 in.) of soil. The external gamma calculation assumes uniform contamination to an infinite depth (rather than being limited to the upper cm of soil). This assumption overestimates the actual doses and risks from external gamma irradiation by about a factor of five.

TABLE A.34 Radiological Doses and Risks for an Onsite Maintenance Worker from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
R-10 Pile and Other Contaminated Soils				*Radionuclide-Specific*
Uranium-238	$2.0 \times 10^{-3} / 1.6 \times 10^{-9}$	$2.2 \times 10^{-6} / 1.5 \times 10^{-12}$	$1.7 \times 10^{-5} / 1.3 \times 10^{-11}$	$2.0 \times 10^{-3} / 1.6 \times 10^{-9}$
Uranium-234	$2.4 \times 10^{-3} / 1.9 \times 10^{-9}$	$2.2 \times 10^{-6} / 1.2 \times 10^{-12}$	$3.8 \times 10^{-8} / 2.8 \times 10^{-14}$	$2.4 \times 10^{-3} / 1.9 \times 10^{-9}$
Thorium-230	$1.5 \times 10^{-1} / 1.3 \times 10^{-8}$	$5.5 \times 10^{-5} / 8.4 \times 10^{-12}$	$6.9 \times 10^{-7} / 5.3 \times 10^{-13}$	$1.5 \times 10^{-1} / 1.3 \times 10^{-8}$
Radium-226	$2.0 \times 10^{-2} / 1.6 \times 10^{-8}$	$1.0 \times 10^{-4} / 5.2 \times 10^{-11}$	$9.7 \times 10^{-3} / 7.8 \times 10^{-9}$	$3.0 \times 10^{-2} / 2.4 \times 10^{-8}$
Lead-210	$3.1 \times 10^{-2} / 2.6 \times 10^{-8}$	$1.0 \times 10^{-3} / 5.1 \times 10^{-10}$	$1.0 \times 10^{-5} / 5.7 \times 10^{-12}$	$3.2 \times 10^{-2} / 2.6 \times 10^{-8}$
Uranium-235	$1.3 \times 10^{-4} / 1.1 \times 10^{-10}$	$1.3 \times 10^{-7} / 7.4 \times 10^{-14}$	$4.8 \times 10^{-6} / 3.7 \times 10^{-12}$	$1.4 \times 10^{-4} / 1.1 \times 10^{-10}$
Protactinium-231	$2.8 \times 10^{-3} / 4.2 \times 10^{-10}$	$2.6 \times 10^{-6} / 2.2 \times 10^{-13}$	$1.6 \times 10^{-6} / 1.2 \times 10^{-12}$	$2.8 \times 10^{-3} / 4.2 \times 10^{-10}$
Actinium-227	$1.2 \times 10^{-2} / 1.2 \times 10^{-9}$	$4.4 \times 10^{-6} / 6.4 \times 10^{-13}$	$1.7 \times 10^{-5} / 1.3 \times 10^{-11}$	$1.2 \times 10^{-2} / 1.2 \times 10^{-9}$
Thorium-232	$4.6 \times 10^{-4} / 4.9 \times 10^{-11}$	$1.7 \times 10^{-7} / 2.7 \times 10^{-14}$	$8.5 \times 10^{-10} / 6.3 \times 10^{-16}$	$4.6 \times 10^{-4} / 4.9 \times 10^{-11}$
Radium-228	$6.7 \times 10^{-5} / 5.0 \times 10^{-11}$	$5.2 \times 10^{-7} / 2.9 \times 10^{-13}$	$1.0 \times 10^{-5} / 8.4 \times 10^{-12}$	$7.8 \times 10^{-5} / 5.8 \times 10^{-11}$
Thorium-228	$1.8 \times 10^{-4} / 1.6 \times 10^{-10}$	$1.1 \times 10^{-7} / 8.6 \times 10^{-14}$	$1.8 \times 10^{-5} / 1.4 \times 10^{-11}$	$2.0 \times 10^{-4} / 1.8 \times 10^{-10}$
Route-Specific Total	$2.2 \times 10^{-1} / 6.0 \times 10^{-8}$	$1.2 \times 10^{-3} / 5.8 \times 10^{-10}$	$9.8 \times 10^{-3} / 7.8 \times 10^{-9}$	$2.3 \times 10^{-1} / 7 \times 10^{-8}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical maintenance worker are based on the intake estimates in Table A.28; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.35 Radiological Doses and Risks for an Onsite Trespasser from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
R-10 Pile and Other Contaminated Soils				*Radionuclide-Specific*
Uranium-238	$2.1 \times 10^{-5} / 1.7 \times 10^{-11}$	$4.6 \times 10^{-8} / 3.1 \times 10^{-14}$	$9.2 \times 10^{-8} / 6.7 \times 10^{-14}$	$2.1 \times 10^{-5} / 1.7 \times 10^{-11}$
Uranium-234	$2.5 \times 10^{-5} / 2.0 \times 10^{-11}$	$4.7 \times 10^{-8} / 2.5 \times 10^{-14}$	$2.0 \times 10^{-10} / 1.5 \times 10^{-16}$	$2.5 \times 10^{-5} / 2.0 \times 10^{-11}$
Thorium-230	$1.5 \times 10^{-3} / 1.4 \times 10^{-10}$	$1.2 \times 10^{-6} / 1.8 \times 10^{-13}$	$3.6 \times 10^{-9} / 2.8 \times 10^{-15}$	$1.5 \times 10^{-3} / 1.4 \times 10^{-10}$
Radium-226	$2.1 \times 10^{-4} / 1.7 \times 10^{-10}$	$2.2 \times 10^{-6} / 1.1 \times 10^{-12}$	$5.2 \times 10^{-5} / 4.1 \times 10^{-11}$	$2.6 \times 10^{-4} / 2.1 \times 10^{-10}$
Lead-210	$3.2 \times 10^{-4} / 2.7 \times 10^{-10}$	$2.2 \times 10^{-5} / 1.1 \times 10^{-11}$	$5.4 \times 10^{-8} / 3.0 \times 10^{-14}$	$3.5 \times 10^{-4} / 2.8 \times 10^{-10}$
Uranium-235	$1.4 \times 10^{-6} / 1.1 \times 10^{-12}$	$2.8 \times 10^{-9} / 1.6 \times 10^{-15}$	$2.5 \times 10^{-8} / 2.0 \times 10^{-14}$	$1.4 \times 10^{-6} / 1.1 \times 10^{-12}$
Protactinium-231	$3.0 \times 10^{-5} / 4.4 \times 10^{-12}$	$5.5 \times 10^{-8} / 4.7 \times 10^{-15}$	$8.4 \times 10^{-9} / 6.6 \times 10^{-15}$	$3.0 \times 10^{-5} / 4.4 \times 10^{-12}$
Actinium-227	$1.2 \times 10^{-4} / 1.2 \times 10^{-11}$	$9.3 \times 10^{-8} / 1.4 \times 10^{-14}$	$8.9 \times 10^{-8} / 7.0 \times 10^{-14}$	$1.2 \times 10^{-4} / 1.2 \times 10^{-11}$
Thorium-232	$4.9 \times 10^{-6} / 5.2 \times 10^{-13}$	$3.7 \times 10^{-9} / 5.7 \times 10^{-16}$	$4.5 \times 10^{-12} / 3.4 \times 10^{-18}$	$4.9 \times 10^{-6} / 5.2 \times 10^{-13}$
Radium-228	$7.1 \times 10^{-7} / 5.2 \times 10^{-13}$	$1.1 \times 10^{-8} / 6.2 \times 10^{-15}$	$5.6 \times 10^{-8} / 4.5 \times 10^{-14}$	$7.7 \times 10^{-7} / 5.7 \times 10^{-13}$
Thorium-228	$1.9 \times 10^{-6} / 1.7 \times 10^{-12}$	$2.3 \times 10^{-9} / 1.8 \times 10^{-15}$	$9.5 \times 10^{-8} / 7.6 \times 10^{-14}$	$2.0 \times 10^{-6} / 1.8 \times 10^{-12}$
Route-Specific Total	$2.3 \times 10^{-3} / 6.3 \times 10^{-10}$	$2.6 \times 10^{-5} / 1.2 \times 10^{-11}$	$5.2 \times 10^{-5} / 4.2 \times 10^{-11}$	$2.3 \times 10^{-3} / 7 \times 10^{-10}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical trespasser are based on the intake estimates in Table A.29; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.36 Radiological Doses and Risks for an Offsite Outdoor Worker from Particulates Released from the R-10 Pile and Other Contaminated Soils[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
R-10 Pile and Other Contaminated Soils				*Radionuclide-Specific*
Uranium-238	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$	$2.1 \times 10^{-8} / 1.4 \times 10^{-14}$	$1.6 \times 10^{-7} / 1.2 \times 10^{-13}$	$1.4 \times 10^{-5} / 1.1 \times 10^{-11}$
Uranium-234	$1.6 \times 10^{-5} / 1.3 \times 10^{-11}$	$2.1 \times 10^{-8} / 1.1 \times 10^{-14}$	$3.6 \times 10^{-10} / 2.6 \times 10^{-16}$	$1.6 \times 10^{-5} / 1.3 \times 10^{-11}$
Thorium-230	$9.9 \times 10^{-4} / 9.1 \times 10^{-11}$	$5.2 \times 10^{-7} / 7.9 \times 10^{-14}$	$6.5 \times 10^{-9} / 5.0 \times 10^{-15}$	$9.9 \times 10^{-4} / 9.1 \times 10^{-11}$
Radium-226	$1.4 \times 10^{-4} / 1.1 \times 10^{-10}$	$9.9 \times 10^{-7} / 4.9 \times 10^{-13}$	$9.2 \times 10^{-5} / 7.4 \times 10^{-11}$	$2.3 \times 10^{-4} / 1.8 \times 10^{-10}$
Lead-210	$2.1 \times 10^{-4} / 1.8 \times 10^{-10}$	$9.9 \times 10^{-6} / 4.9 \times 10^{-12}$	$9.7 \times 10^{-8} / 5.4 \times 10^{-14}$	$2.2 \times 10^{-4} / 1.8 \times 10^{-10}$
Uranium-235	$9.1 \times 10^{-7} / 7.2 \times 10^{-13}$	$1.3 \times 10^{-9} / 7.0 \times 10^{-16}$	$4.5 \times 10^{-8} / 3.5 \times 10^{-14}$	$9.5 \times 10^{-7} / 7.5 \times 10^{-13}$
Protactinium-231	$1.9 \times 10^{-5} / 2.9 \times 10^{-12}$	$2.5 \times 10^{-8} / 2.1 \times 10^{-15}$	$1.5 \times 10^{-8} / 1.2 \times 10^{-14}$	$1.9 \times 10^{-5} / 2.9 \times 10^{-12}$
Actinium-227	$7.9 \times 10^{-5} / 8.0 \times 10^{-12}$	$4.2 \times 10^{-8} / 6.1 \times 10^{-15}$	$1.6 \times 10^{-7} / 1.3 \times 10^{-13}$	$7.9 \times 10^{-5} / 8.1 \times 10^{-12}$
Thorium-232	$3.2 \times 10^{-6} / 3.4 \times 10^{-13}$	$1.6 \times 10^{-9} / 2.6 \times 10^{-16}$	$8.0 \times 10^{-12} / 6.0 \times 10^{-18}$	$3.2 \times 10^{-6} / 3.4 \times 10^{-13}$
Radium-228	$4.6 \times 10^{-7} / 3.4 \times 10^{-13}$	$4.9 \times 10^{-9} / 2.8 \times 10^{-15}$	$1.0 \times 10^{-7} / 8.0 \times 10^{-14}$	$5.6 \times 10^{-7} / 4.2 \times 10^{-13}$
Thorium-228	$1.2 \times 10^{-6} / 1.1 \times 10^{-12}$	$1.0 \times 10^{-9} / 8.1 \times 10^{-16}$	$1.7 \times 10^{-7} / 1.4 \times 10^{-13}$	$1.4 \times 10^{-6} / 1.3 \times 10^{-12}$
Route-Specific Total	$1.5 \times 10^{-3} / 4.1 \times 10^{-10}$	$1.2 \times 10^{-5} / 5.5 \times 10^{-12}$	$9.3 \times 10^{-5} / 7.4 \times 10^{-11}$	$1.6 \times 10^{-3} / 5 \times 10^{-10}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite worker are based on the intake estimates in Table A.30; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.37 Radiological Doses and Risks from Particulates Released from the R-10 Pile and Other Contaminated Soils for an Offsite Adult Resident[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
R-10 Pile and Other Contaminated Soils				*Radionuclide-Specific*
Uranium-238	$4.9 \times 10^{-6} / 3.9 \times 10^{-12}$	$9.1 \times 10^{-9} / 6.1 \times 10^{-15}$	$4.3 \times 10^{-7} / 3.2 \times 10^{-13}$	$5.4 \times 10^{-6} / 4.3 \times 10^{-12}$
Uranium-234	$5.8 \times 10^{-6} / 4.6 \times 10^{-12}$	$9.2 \times 10^{-9} / 4.8 \times 10^{-15}$	$9.5 \times 10^{-10} / 7.0 \times 10^{-16}$	$5.8 \times 10^{-6} / 4.7 \times 10^{-12}$
Thorium-230	$3.6 \times 10^{-4} / 3.3 \times 10^{-11}$	$2.3 \times 10^{-7} / 3.5 \times 10^{-14}$	$1.7 \times 10^{-8} / 1.3 \times 10^{-14}$	$3.6 \times 10^{-4} / 3.3 \times 10^{-11}$
Radium-226	$4.9 \times 10^{-5} / 3.9 \times 10^{-11}$	$4.4 \times 10^{-7} / 2.2 \times 10^{-13}$	$2.4 \times 10^{-4} / 2.0 \times 10^{-10}$	$2.9 \times 10^{-4} / 2.3 \times 10^{-10}$
Lead-210	$7.6 \times 10^{-5} / 6.3 \times 10^{-11}$	$4.4 \times 10^{-6} / 2.1 \times 10^{-12}$	$2.6 \times 10^{-7} / 1.4 \times 10^{-13}$	$8.1 \times 10^{-5} / 6.6 \times 10^{-11}$
Uranium-235	$3.3 \times 10^{-7} / 2.6 \times 10^{-13}$	$5.5 \times 10^{-10} / 3.1 \times 10^{-16}$	$1.2 \times 10^{-7} / 9.4 \times 10^{-14}$	$4.5 \times 10^{-7} / 3.5 \times 10^{-13}$
Protactinium-231	$7.0 \times 10^{-6} / 1.0 \times 10^{-12}$	$1.1 \times 10^{-8} / 9.3 \times 10^{-16}$	$4.0 \times 10^{-8} / 3.1 \times 10^{-14}$	$7.1 \times 10^{-6} / 1.1 \times 10^{-12}$
Actinium-227	$2.8 \times 10^{-5} / 2.9 \times 10^{-12}$	$1.8 \times 10^{-8} / 2.7 \times 10^{-15}$	$4.2 \times 10^{-7} / 3.3 \times 10^{-13}$	$2.9 \times 10^{-5} / 3.2 \times 10^{-12}$
Thorium-232	$1.1 \times 10^{-6} / 1.2 \times 10^{-13}$	$7.2 \times 10^{-10} / 1.1 \times 10^{-16}$	$2.1 \times 10^{-11} / 1.6 \times 10^{-17}$	$1.1 \times 10^{-6} / 1.2 \times 10^{-13}$
Radium-228	$1.7 \times 10^{-7} / 1.2 \times 10^{-13}$	$2.2 \times 10^{-9} / 1.2 \times 10^{-15}$	$2.6 \times 10^{-7} / 2.1 \times 10^{-13}$	$4.3 \times 10^{-7} / 3.3 \times 10^{-13}$
Thorium-228	$4.5 \times 10^{-7} / 4.0 \times 10^{-13}$	$4.5 \times 10^{-10} / 3.6 \times 10^{-16}$	$4.5 \times 10^{-7} / 3.6 \times 10^{-13}$	$9.0 \times 10^{-7} / 7.6 \times 10^{-13}$
Route-Specific Total	$5.3 \times 10^{-4} / 1.5 \times 10^{-10}$	$5.1 \times 10^{-6} / 2.4 \times 10^{-12}$	$2.5 \times 10^{-4} / 2.0 \times 10^{-10}$	$7.8 \times 10^{-4} / 3 \times 10^{-10}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks for the hypothetical offsite adult resident are based on the intake estimates in Table A.31; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

TABLE A.38 Radiological Doses and Risks from Particulates Released from the R-10 Pile and Other Contaminated Soils for an Offsite Child Resident[a]

Radionuclide	Radiation Dose *(mrem)* / Cancer Risk			
	Inhalation	Ingestion	External Gamma	Total
R-10 Pile and Other Contaminated Soils				*Radionuclide-Specific*
Uranium-238	$4.9 \times 10^{-6} / 3.9 \times 10^{-12}$	$9.1 \times 10^{-9} / 6.1 \times 10^{-15}$	$2.2 \times 10^{-7} / 1.6 \times 10^{-13}$	$5.2 \times 10^{-6} / 4.1 \times 10^{-12}$
Uranium-234	$5.8 \times 10^{-6} / 4.6 \times 10^{-12}$	$9.2 \times 10^{-9} / 4.8 \times 10^{-15}$	$4.8 \times 10^{-10} / 3.5 \times 10^{-16}$	$5.8 \times 10^{-6} / 4.6 \times 10^{-12}$
Thorium-230	$3.6 \times 10^{-4} / 3.3 \times 10^{-11}$	$2.3 \times 10^{-7} / 3.5 \times 10^{-14}$	$8.6 \times 10^{-9} / 6.6 \times 10^{-15}$	$3.6 \times 10^{-4} / 3.3 \times 10^{-11}$
Radium-226	$4.9 \times 10^{-5} / 3.9 \times 10^{-11}$	$4.4 \times 10^{-7} / 2.2 \times 10^{-13}$	$1.2 \times 10^{-4} / 9.8 \times 10^{-11}$	$1.7 \times 10^{-4} / 1.4 \times 10^{-10}$
Lead-210	$7.6 \times 10^{-5} / 6.3 \times 10^{-11}$	$4.4 \times 10^{-6} / 2.1 \times 10^{-12}$	$1.3 \times 10^{-7} / 7.2 \times 10^{-14}$	$8.1 \times 10^{-5} / 6.5 \times 10^{-11}$
Uranium-235	$3.3 \times 10^{-7} / 2.6 \times 10^{-13}$	$5.5 \times 10^{-10} / 3.1 \times 10^{-16}$	$6.0 \times 10^{-8} / 4.7 \times 10^{-14}$	$3.9 \times 10^{-7} / 3.1 \times 10^{-13}$
Protactinium-231	$7.0 \times 10^{-6} / 1.0 \times 10^{-12}$	$1.1 \times 10^{-8} / 9.3 \times 10^{-16}$	$2.0 \times 10^{-8} / 1.6 \times 10^{-14}$	$7.0 \times 10^{-6} / 1.0 \times 10^{-12}$
Actinium-227	$2.8 \times 10^{-5} / 2.9 \times 10^{-12}$	$1.8 \times 10^{-8} / 2.7 \times 10^{-15}$	$2.1 \times 10^{-7} / 1.7 \times 10^{-13}$	$2.9 \times 10^{-5} / 3.1 \times 10^{-12}$
Thorium-232	$1.1 \times 10^{-6} / 1.2 \times 10^{-13}$	$7.2 \times 10^{-10} / 1.1 \times 10^{-16}$	$1.1 \times 10^{-11} / 8.0 \times 10^{-18}$	$1.1 \times 10^{-6} / 1.2 \times 10^{-13}$
Radium-228	$1.7 \times 10^{-7} / 1.2 \times 10^{-13}$	$2.2 \times 10^{-9} / 1.2 \times 10^{-15}$	$1.3 \times 10^{-7} / 1.1 \times 10^{-13}$	$3.0 \times 10^{-7} / 2.3 \times 10^{-13}$
Thorium-228	$4.5 \times 10^{-7} / 4.0 \times 10^{-13}$	$4.5 \times 10^{-10} / 3.6 \times 10^{-16}$	$2.2 \times 10^{-7} / 1.8 \times 10^{-13}$	$6.8 \times 10^{-7} / 5.8 \times 10^{-13}$
Route-Specific Total	$5.3 \times 10^{-4} / 1.5 \times 10^{-10}$	$5.1 \times 10^{-6} / 2.4 \times 10^{-12}$	$1.2 \times 10^{-4} / 9.8 \times 10^{-11}$	$6.6 \times 10^{-4} / 2 \times 10^{-10}$

[a] These preliminary estimates of radiation doses (in mrem) and cancer risks (separated by a slash) for the hypothetical offsite child resident are based on the intake estimates in Table A.32; values are rounded to two significant figures except total risk, which is rounded to one significant figure. See Chapter 3 (including Tables 3.2 and 3.3) for the basic assumptions underlying these calculations.

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APPENDIX B:

ESTIMATED CHEMICAL EXPOSURE LEVELS AND INTAKES, RISKS, AND HAZARD INDEXES, AND SUPPORTING INFORMATION FOR THE TOXICITY VALUES

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APPENDIX B:

ESTIMATED CHEMICAL EXPOSURE LEVELS AND INTAKES, RISKS, AND HAZARD INDEXES, AND SUPPORTING INFORMATION FOR THE TOXICITY VALUES

Chemical exposure levels and intakes, hazard indexes (HIs), and risks have been estimated for six hypothetical receptors (three onsite and three offsite) who are assumed to be exposed to contaminants dispersed in air and deposited on surface soil as a result of emissions from the Interim Waste Containment Structure (IWCS) during waste excavation, based on preliminary conceptual assumptions. These illustrative estimates are presented in Section B.1, and information about the chemical toxicity values that are used to estimate the hazard quotients and risks is presented in Section B.2. Health risk fact sheets for selected IWCS chemicals are included in Appendix C.

The estimated concentrations in air and surface soil resulting from deposition of airborne particulates are calculated as described in Chapter 3 (and as highlighted for the radionuclides in Appendix A). The intakes are calculated as described in Section 3.4, using the exposure factors presented in Table 3.2. Preliminary conceptual assumptions for waste excavation are summarized in Table 3.3. The risks and HIs are calculated as described in Section 5.1.2, using the chemical- and route-specific toxicity values from Tables 4.5 and 4.6, respectively. Eleven chemical contaminants are quantitatively assessed in this technical memorandum (TM): arsenic (As), barium (Ba), cobalt (Co), lead (Pb), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), uranium (U), vanadium (V), and polychlorinated biphenyls (PCBs). (Asbestos is addressed qualitatively because information is insufficient for a quantitative assessment at this time.) The illustrative risk and HI results for the six hypothetical receptors based on preliminary conceptual assumptions for waste excavation are compared to target levels for exposures to site contaminants identified in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (EPA 1990) (see Section 5.1).

An additional comparison to occupational limits is provided for the hypothetical worker scenarios in this TM. Three sets of occupational limits are commonly considered to guide planning for worker protection: (1) permissible exposure limits (PELs) developed by the U.S. Occupational Safety and Health Administration (OSHA), (2) recommended exposure limits (RELs) developed by the National Institute for Occupational Safety and Health (NIOSH), and (3) threshold limit values (TLVs) developed by the American Conference of Governmental Industrial Hygienists (ACGIH). These occupational limits serve as points of comparison for the airborne concentrations estimated in this TM for the hypothetical workers, to help identify situations where worker protection measures would be warranted, for incorporation in the upcoming FS. The PELs, RELs, and TLVs for the 11 IWCS chemicals are listed in Table B.1. The 8-hour time-weighted averages are listed where available; others (in parentheses) represent ceiling or 15-minute limits. Where values have been established for multiple forms of a given chemical, the lowest (most protective) relevant value is shown (e.g., metal fumes are not considered relevant to the chemical forms in the IWCS, so those limits would not be reflected here). In several cases the three values are the same.

TABLE B.1 Occupational Limits Used to Guide Worker Protection Measures[a]

Occupational Limit	Air Concentration *(µg/m³)*										
	As	**Ba**	**Co**	**Pb**	**Li**	**Mn**	**Mo**	**Ni**	**U**	**V**	**PCBs**
OSHA PEL	10	500	100	50	25	(5,000)	5,000	1,000	50	(500)	500
NIOSH REL	(2)	500	50	50	25	1,000	-	15	50	(50)	1
ACGIH TLV	10	500	20	50	25	200 / *20*	500	100	200	50	500

(Notes for Table B.1)

[a] Sources: ACGIH (2011), NIOSH (2010), OSHA (2011). The acronyms and abbreviations in this table are defined in the preceding text. The TLVs are health-based, while both the PELs and RELs incorporate the consideration of technological feasibility for controlling workplace exposures to those levels. Note that the TLVs and RELs reflect periodic updates that consider more recent toxicity information compared to the PELs, which as promulgated federal standards undergo a protracted revision process. The values in this table serve as points of comparison for the preliminary conceptual estimates of airborne concentrations for the hypothetical workers presented in this TM. Parentheses indicate ceiling or 15-minute average values. A dash indicates the REL is not available (see further notes from NIOSH for molybdenum below).

The values shown here are 8-hour time-weighted averages except for those in parentheses, which are 15-minute or ceiling values: (1) the arsenic REL, for which the value is a 15-minute ceiling for inorganic arsenic compounds, as As; (2) the manganese PEL (note that the REL above is indicated as the 8-hour time-weighted average for manganese compounds, notably the metal, and fume, as Mn; for manganese oxide, in 1988 NIOSH reviewed the PEL of 1,000 $\mu g/m^3$ proposed as an 8-hour time-weighted average for manganese tetroxide, as Mn, and questioned whether the value was adequate to protect workers from recognized health hazards, see the manganese oxide link in NIOSH [2010]); and (3) the vanadium PEL and REL (the REL is a 15-minute ceiling for vanadium dust, as V, and the PEL is a ceiling for respirable divanadium pentoxide dust; a PEL ceiling value the same as the REL shown above was previously proposed for vanadium dust including oxides, see the link for this chemical in NIOSH [2010]. As a note, the PEL for divanadium pentoxide fume is half the value shown for the dust, but the fume is not the form that would be present in the IWCS.)

When occupational exposure limits have been established for more than one form of a chemical (e.g., soluble vs. insoluble compounds), the lower relevant value is shown here. For example, the PEL and REL values for barium reflect the limit for soluble compounds other than the sulfate, as Ba (the REL applies to respirable fraction); the limit for the respirable sulfate is 10 times higher. Similarly, for uranium, the REL and PEL are for soluble compounds, as U (corresponding limits for insoluble compounds are higher, at 200 and 250 $\mu g/m^3$, respectively); the TLV applies to both soluble and insoluble compounds. For PCBs, the PEL and TLV are for Aroclor 1254 (the respective limits for Aroclor 1242 are twice the value shown above); the REL applies to Aroclor 1254, Aroclor 1242, and other PCBs.

For cobalt, the PEL and REL are for metal dust and fume, as Co (note fume is not the form that would be present in the IWCS), while the TLV is for cobalt and inorganic compounds, as Co; a PEL value the same as the REL above was previously proposed (see the link for this chemical in NIOSH [2010]). Similarly, for nickel, a lower PEL of 100 $\mu g/m^3$ was previously proposed for soluble compounds (see the link for this chemical in NIOSH [2010]); note these values for nickel do not apply to the carbonyl (the PEL and REL for that form, which is not expected to represent the IWCS wastes, is 7 $\mu g/m^3$).

For molybdenum, the PEL is for soluble compounds, as Mo; in 1988, NIOSH reviewed the proposed PEL of 1,000 $\mu g/m^3$ (as well as the higher PEL proposed for insoluble compounds) and questioned whether either value was adequate to protect workers from recognized health hazards (see the link for this chemical in NIOSH [2010]).

For the TLVs, the lithium value is for the hydride (as are the PEL and REL values); the TLV for molybdenum is for soluble compounds, as Mo; that shown for nickel is for soluble inorganic compounds, as Ni; the TLV for uranium is for soluble and insoluble compounds, as U; and that for vanadium is for the pentoxide, as V. For manganese, ACGIH (2011) identifies a notice of intended change of the TLV for elemental and inorganic compounds, as Mn, with the TV for the inhalable fraction identified as 200 $\mu g/m^3$, a lower value of 20 $\mu g/m^3$ is identified for the respirable fraction, as denoted in italics in Table B.1 above.

B.1 EXPOSURE LEVELS AND INTAKES, RISKS, AND HAZARD INDEXES

Preliminary estimates of chemical exposure levels and intakes, risks, and HIs have been developed for the six hypothetical receptors, three waste groups, and two endpoint categories (cancer risk and noncarcinogenic effects). These estimates address the excavation of each waste group from the IWCS based on preliminary conceptual assumptions. The results are summarized in three sets of tables at the end of this appendix, beginning with the K-65 residues (waste group 1) because these residues have the highest concentrations of radionuclides and are expected to be a focus of the upcoming feasibility study (FS). The estimates associated with excavating the K-65 residues are presented in Tables B.5 through B.16, those for excavating waste group 2 (the other high-activity residues and tower soils) are presented in Tables B.17 through B.28, and the results for the R-10 pile and other contaminated soils are given in Tables B.29 through B.40. As described for the radiological calculations in Chapter 3 and Appendix A, the calculations for waste groups 2 and 3 reflect volume-weighted average concentrations estimated for the IWCS chemicals (from the data in Table 2.3).

To the extent possible, the preliminary risk estimates in this TM are presented in a manner that would allow for scaling of certain results to accommodate different assumptions for exposure times, frequencies, and durations, and for some exposures (e.g., direct incidental ingestion) the waste groupings. For example, estimates for other waste combinations can be approximated by scaling from the illustrative results in this TM to account for differing emission rates, length of time assumed for excavating the wastes, and relative contaminant concentrations. This same scaling approach can also be applied to the individual components of those waste groups if/as indicated. (Illustrative contaminant information is provided for each of these waste components to accommodate various combinations, recognizing that the definitions of the waste groups and processing rates are expected to be refined as development of the FS proceeds.)

All preliminary estimates of risk and HI for the six illustrative receptors associated with particulate releases during excavation of the three waste groups are below the target levels of comparison from the NCP (EPA 1990; see Section 5.1). The highest estimates are for the maintenance worker during excavation of waste group 2. Based on the preliminary assumptions in this TM (and conservative assumptions for inhalation exposures and toxicity values), the estimated cancer risk is 3×10^{-7} with inhalation of cobalt, nickel and vanadium the main contributors. The estimated HI is 0.6, primarily from inhalation of cobalt, manganese, and nickel. The next highest estimates are for the hypothetical remedial action worker during excavation of these same wastes (group 2). The total risk and HI estimated for this hypothetical cleanup worker are lower than those for the maintenance worker by about a factor of ten, with an estimated risk of 3×10^{-8} and HI of 0.04. The risks and HIs for all other receptors from excavating the three waste groups are even lower (all are well below the NCP comparison levels).

Similarly, all estimated air concentrations for the hypothetical worker scenarios meet (are well below) the occupational exposure limits (see Table B.1). The highest estimated airborne concentrations are for the remedial action worker during excavation of waste group 2, and these concentrations are less than 1% of the most restrictive limits shown in Table B.1. The most limiting chemicals are cobalt, lead, and manganese. Thus, the airborne concentrations of chemical contaminants in the workplace are not expected to exceed occupational limits based on the conceptual assumptions reflected in this TM. It is important to emphasize that the use of common worker protection equipment and other protective measures (including to control the releases of airborne contaminants) is expected to minimize exposures to all radioactive and chemical contaminants in the IWCS for any remedy that involves excavating wastes from this interim storage structure.

B.2 SUPPORTING INFORMATION FOR STANDARD TOXICITY VALUES

The traditional (earlier) classification scheme for carcinogens is summarized in Section B.2.1, as is the updated U.S. Environmental Protection Agency (EPA) approach that incorporates narrative to characterize the weight of evidence for human carcinogenicity. The adjustment factors used to account for uncertainty and variability in deriving the toxicity values used to estimate the potential for noncarcinogenic effects are described in Section B.2.2.

B.2.1 Toxicity Values Used to Estimate Cancer Risk

The EPA historically derived slope factors (SFs) to estimate cancer risk for both oral and inhalation exposures. The SF is defined as the plausible upper-bound estimate of the probability of a (tumor) response per unit intake of a chemical over a lifetime. It is used to determine an upper-bound probability of an individual developing cancer in a lifetime as a result of exposure to a carcinogen (EPA 2011a).

A key assumption underlying the SF is that the dose-response relationship is linear in the low-dose portion of the curve. Under this assumption, the SF is constant and risk is directly related to the exposure

level. In fact, recent studies indicate that for some chemicals, a threshold exists such that exposures below a certain level do not appear to induce cancer. Nevertheless, the use of SFs that are based on the conservative (protective) assumption of a linear no-threshold dose-response relationship is the default approach for estimating chemical risks unless otherwise demonstrated by scientific evidence. Note that this same linear, no-threshold concept also underlies the radiological dose conversion factors and risk coefficients.

In deriving toxicity values to assess the cancer endpoint, a linearized multistage model is commonly applied to extrapolate dose-response data for a given chemical and exposure route (which are typically for relatively high exposure levels) to estimate risks at environmental (lower) exposure levels. For chemicals known or considered to be potential carcinogens by the oral route, EPA has established the oral SF that represents the calculated upper-bound probability of a person developing cancer over a lifetime as a result of ingesting that chemical; the SF is expressed in units of risk per mg/kg-d. For chemicals that are carcinogenic by the inhalation route, the EPA now defines an inhalation unit risk (IUR) by a similar method, but the toxicity value represents the (continuous) exposure level as a concentration rather than a dose. Thus, the IUR is expressed as risk per mg (or μg)/m^3. The approach used to address dermal exposure is similar to that used for ingestion, except that the intake is based on the amount of contaminant that penetrates the skin and is absorbed by the body rather than the administered dose (EPA 2004).

For years, the EPA followed the same traditional classification scheme as many other national and international organizations, which is illustrated in Table B.2.

TABLE B.2 Traditional Carcinogen Classification

Group	Human Carcinogen	Basis
A	Known	Sufficient evidence from epidemiological studies substantiated by causal association between exposure and carcinogenicity.
B1	Probable	Limited evidence of carcinogenicity in humans from available epidemiological data.
B2	Probable	Sufficient evidence of carcinogenicity in animals, but inadequate or no evidence in humans.
C	Possible	Limited evidence of carcinogenicity in animals.
D	Not classified	Inadequate evidence of carcinogenicity in animals to support classification.
E	No	No evidence of carcinogenicity in at least two adequate animal tests in different species or in both epidemiological and animal studies.

More recently, EPA has moved away from these traditional categories (A to E) in order to better accommodate evolving scientific data (EPA 2005a). Under the current approach, descriptors that characterize the weight of evidence for human carcinogenicity are to be captured in the narrative of risk assessments, to describe the potential for that chemical to cause cancer in humans and the conditions under which carcinogenic effects can be expressed (EPA 2005a). These descriptive categories are summarized in Table B.3.

TABLE B.3 Updated Descriptors for Evaluating Carcinogenic Potential

Descriptor	Basis
Carcinogenic to humans	Convincing epidemiologic evidence of causality (human exposure-cancer link) *or* strong epidemiological *and* extensive animal evidence *and* mode of action knowledge relevant to tumor progression
Likely to be carcinogenic to humans	Tumor effects *and* other key data adequate to demonstrate human carcinogenic potential
Suggestive evidence of carcinogenic potential	Human or animal data suggest carcinogenicity, but not sufficient for stronger conclusion
Inadequate information to assess potential	Data inadequate to assess
Not likely to be carcinogenic to humans	Robust data for deciding there is no basis for human cancer hazard concern

Supplemental guidance that considers increased susceptibility to cancer from early-life exposures was published following the release of the updated cancer guidelines (EPA 2005b). For chemicals whose mode of action is genotoxic/mutagenic (damages the genetic material, suggesting heritable harm), a conventional linear extrapolation to the low-dose region is applied. If a nonlinear mode of action is established for carcinogenicity, then the threshold-based method can be used, which follows the approach used to derive the reference concentration (RfC) and reference dose (RfD) for inhalation and oral exposures, respectively (EPA 2002, 2010). Depending on the case, both approaches could be applied.

B.2.2 General Approach for Deriving Reference Values to Assess Noncarcinogenic Effects

The historical approach for deriving RfCs for inhalation and RfDs for oral exposures focused on identifying a single effect level from a single study, to which default uncertainty factors were then applied to estimate a "reliably safe" exposure level for humans. The RfC and RfD represent estimates of the level to which a person could be exposed every day (for the RfC, continuously) that would not be expected to cause adverse health effects over a lifetime.

These reference values are based on the concept that a threshold exists for noncarcinogenic effects, i.e., adverse effects are only observed after exposures exceed a certain concentration or dose level. This threshold concept applies for many chemicals and is well illustrated by essential human nutrients (such as copper, manganese, nickel, and zinc), for which low doses are actually necessary for overall health, and adverse effects are only seen after the doses or concentrations increase above a "no adverse effect" level. Note that the determination of adversity (e.g., organ/system damage with functional impairment versus a slight biochemical change that may be reversible) requires judgment and consensus, and it is not always straightforward.

To derive a toxicity value for noncarcinogenic effects for a given chemical and exposure route, key studies are selected from a comprehensive review of the scientific literature to determine the no observed adverse effect level (NOAEL). The NOAEL corresponds to the highest experimental exposure level for which no statistically significant adverse health effects are reported. If the study data are inadequate for determining a NOAEL (e.g., if the lowest dose tested elicited a response considered adverse), then a lowest observed adverse effect level (LOAEL) would be used. The LOAEL represents the lowest daily dose administered over a lifetime that induces an observable adverse effect. To illustrate the relationship

between the LOAEL and NOAEL, if the LOAEL were an increase in the level of a liver enzyme, then the next lower dose at which no adverse effect was observed would be the NOAEL for that hepatic effect.

The toxic effect targeted by the NOAEL or LOAEL is referred to as the critical effect and represents a common foundation or point of departure (POD) for deriving the toxicity value. The preferred starting point is the NOAEL, but if no NOAEL is identified – e.g., if the "next lowest dose" from the LOAEL is the control group that received no exposure – then the LOAEL is used as the POD. The POD is then adjusted downward to represent a reliably safe level for the general public, including sensitive subgroups, for daily exposures over a lifetime. These downward adjustments are made by dividing the POD by uncertainty factors (UFs) that are designed to address limitations in the toxicity data. Previously referred to as safety factors, the UFs also account for variability.

An RfC or RfD can be derived from a NOAEL or LOAEL, or a benchmark dose (BMD), with UFs to account for:

1. Variation in susceptibility among members of the human population (interindividual or intraspecies variability);

2. Uncertainty in extrapolating from animal data to humans (interspecies uncertainty);

3. Uncertainty in extrapolating from data obtained in a study with less-than-lifetime exposure (e.g., extrapolating data from a subchronic study to address chronic exposure);

4. Uncertainty in extrapolating from a LOAEL rather than a NOAEL (to account for not knowing the demarcation for no adverse effects); and

5. Uncertainty associated with an incomplete database.

These five types of UFs are summarized in Table B.4.

TABLE B.4 Standard Factors to Adjust for Uncertainty and Variability

Symbol	Uncertainty or Variability Addressed
UF_H	Intraspecies or interindividual variability: variation in human susceptibility
UF_A	Interspecies uncertainty: extrapolating from animal to human data
UF_S	Duration uncertainty: extrapolating from a shorter-than-lifetime study, e.g., from subchronic to chronic
UF_L	Effect level uncertainty: extrapolating from a LOAEL to a NOAEL (where a NOAEL is not available)
UF_D	Database uncertainty: where data are insufficient (e.g., for reproductive and developmental studies)

A factor of 10 has typically been used for each of these UFs, to address both toxicokinetic and toxicodynamic considerations. Toxicokinetics addresses "ADME" – absorption, distribution, metabolism, and elimination – or more simply, what the body does to the chemical. That is, toxicokinetics addresses absorption of the chemical across the exchange boundary (e.g., gut, lung, or skin), its distribution in the body (e.g., via the bloodstream), its metabolism (e.g., in the liver following ingestion), and elimination (e.g., in urine, feces, sweat, exhaled air, or milk). Toxicodynamics addresses the mode of toxic action, or more simply what the chemical does to the body. This involves how the chemical exerts its toxic effect, from the genetic/molecular and cellular levels to the tissue and system levels.

As more information has evolved regarding the toxicokinetics and toxicodynamics of different chemicals via different exposure routes, the animal-to-human and intrahuman uncertainty factors can be split into toxicokinetic and toxicodynamic components to reflect existing knowledge in order to reduce overall uncertainty in the RfD. The default values for the toxicokinetic and toxicodynamic components of the uncertainty factors are each set at one-half an order of magnitude ($10^{0.5}$), or 3.16. The value 3 is used to avoid artificial precision, given the considerable uncertainty in risk calculations. The revised formula for calculating the RfD with the animal-to-human and sensitive-human uncertainty factors split into toxicokinetic and toxicodynamic factors is:

$$\text{RfD}\,(\text{mg/kg-d}) = \frac{D_c}{(AF_{ak} \times AF_{ad} \times AF_{hk} \times AF_{hd} \times UF)}$$

where:

D_c	=	critical dose (NOAEL, LOAEL, or BMD)
AF_{ak}	=	interspecies toxicokinetic adjustment factor
AF_{ad}	=	interspecies toxicodynamic adjustment factor
AF_{hk}	=	interindividual toxicokinetic adjustment factor
AF_{hd}	=	interindividual toxicodynamic adjustment factor
UF	=	aggregate uncertainty factor – to account for the rest (duration, effect level, database)

These factors are still commonly referred to as UFs, even though they account for both uncertainty and variability. This typical set is used by multiple organizations, with the terms having become somewhat more standardized since the EPA review of its RfD/RfC process (EPA 2002). If specific data are available, a UF of 10 can be split into its toxicokinetic and toxicodynamic components (e.g., for interspecies and intraspecies UFs), producing factors of 3 for each. For example, for a contact irritant, a factor of 3 could be used instead of 10 if the scientific data indicate little variability within and/or across species. The EPA recently released recommendations regarding the derivation of the oral RfD that harmonizes with the approach being applied to derive the oral SF (EPA 2011b). This approach reflects using the body weight raised to the ¾ power for interspecies extrapolation as the default approach, and reducing the default adjustment for interspecies variability from 10 to 3.

B.2.3 Benchmark Dose Method for Deriving Reference Values

In 1995, the EPA initiated a project to develop benchmark dose software (BMDS) that could incorporate more of the available toxicity data than the conventional approach (i.e., a single NOAEL or LOAEL value from a single study). The BMD is defined as the best estimate of the dose corresponding to the BMR, which is the predetermined change in the level of the target response compared to background. This method considers the shape of the dose-response curve rather than using a single dose level (e.g., NOAEL or LOAEL) as the starting point (EPA 2011c).

The BMD method involves fitting mathematical models to all of the dose-response data from within a study, and also from other studies, and then using the results to select the appropriate BMD for a specified benchmark response (BMR). For example, a given response target could be a 10% increase in the incidence of a particular lesion, or a 10% decrease in body weight gain. The Agency also conducted a review of the RfD/RfC approach (EPA 2002) and used recommendations from that review to guide the overall refinement of the derivation process for the toxicity values used to address the potential for noncarcinogenic effects. This evaluation included consideration of chemical-specific adjustment factors rather than default UFs when possible, i.e., when sufficient toxicokinetic and toxicodynamic (mode of action) data are available.

The main implementation issues for the BMD method include: (1) choice of the model; (2) choice of the BMR; and most importantly, (3) sufficient data. For the model, a number of options exist and a number of conditions must be considered. These include the need for different models to address quantal versus continuous endpoints (relevant to the given response), and the selection of specially defined models for certain types of data (e.g., developmental toxicity data with nested dichotomous responses).

For the BMR, the selection bases are not generally well developed. Guidance indicates that for quantal endpoints, a 10% risk should always be included among the BMRs for which BMDs are calculated, while for continuous endpoints a tiered approach can be applied, as follows.

1. If there is an accepted degree of change in an endpoint that is considered biologically significant (e.g., 10% change in body weight), that degree of change is considered the BMR.

2. If individual data are available and there is an accepted degree of change that is considered adverse on an individual basis, the individual data can be converted to quantal data based on that cutoff value.

3. As a default, EPA recommends that a change of one standard deviation from the control mean be considered adverse. As explained in guidance for the BMDS, this value was chosen based on the results of Crump (1995), who showed that if values beyond the 98th to 99th percentile of the control animals are considered "abnormal" a dose that causes the mean to shift by one standard deviation results in an excess risk of about 10%.

Note that choosing a change of one standard deviation as the BMR also roughly corresponds to assuming that the background rate of "abnormal" response is 5% and identifying the dose that would increase risk by about 20% (i.e., 20% excess risk). For endpoints that are mild and reversible, this choice may be the most reasonable.

The most difficult issue for estimating a BMD is the inherent data needs for this type of analysis. Many toxicity studies identify response information in a way that is not appropriately handled by the models for the following reasons. First, they are often expressed in terms of percent abnormality or some multiple thereof. For some, although it may be a continuous measure, the percent response has some features not shared by other continuous endpoints – including the constraint that percents must range from 0 to 100. The variability of observed percents (around a mean percent, such as for a given dose group) is not normally distributed.

Furthermore, variances for the estimates of percent response depend on the value being estimated (the variance is not independent of the mean being estimated). These features are not captured by the assumptions of the continuous models developed for the BMDS because those models do assume normality of the responses and do not constrain the magnitude of the responses to be between 0 and 100. For some percentage (considered to be in the range of 10% to 90%), an assumption of a normal distribution may be adequate, especially when the variances are relatively small and uniform over different dose groups. However, this condition is commonly not the case because the percents are often less than 10% with variances not constant over the different dose groups.

To address this problem, the dose-response data can be mathematically transformed, or models for variability other than normal distribution could be applied. Difficulties can nevertheless remain, e.g., for data reported as observed means and sample standard deviations, because unfortunately the typical transformations are applied to individual data points rather than to group means and standard deviations.

Thus, applying the BMD approach requires considerable data and judgment in selecting the appropriate BMR and curve-fitting model.

The EPA continues to refine the BMD process and software, including adding a multistage-cancer model in 2007 to calculate a cancer SF per the new EPA cancer guidelines (EPA 2011d). More recent evaluations that support newer toxicity values in the Integrated Risk Information System (IRIS, EPA 2011a) commonly reflect the BMD approach, which can combine information across studies and effect severities with consideration of mode of action, also considering whether the effects of concern are likely to be linear or nonlinear at low doses. Nevertheless, chemicals with limited toxicity data in a form not conducive to this type of evaluation (including transformation) are not good candidates for the BMD method. Therefore, although the BMD approach provides a more quantitative option for assessing dose-response data, in many cases the data needed will not be available such that the traditional NOAEL/LOAEL approach is better suited to the derivation of that toxicity value. In some cases, a combination of BMD and NOAEL evaluations may be considered in developing the toxicity value for a particular chemical.

In summary, the current standard chemical toxicity values are available from the IRIS database, which contains information for hundreds of chemicals (EPA 2011a). The IRIS database is the primary source of toxicity values used in this TM, as noted in Table 4.4. The chemical-specific toxicity values used to estimate cancer risk and the potential for noncarcinogenic effects from exposures to IWCS contaminants are summarized in Tables 4.5 and 4.6, respectively, together with an indication of the underlying uncertainty where available.

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TABLE B.5 Chemical Exposure Levels and Cancer Risks from the K-65 Residues for a Remedial Action Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (*mg/kg-d*)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	5.0×10^{-6}	2.8×10^{-13}	1.0×10^{-11}	1.6×10^{-11}	1.6×10^{-11}
Cobalt	2.0×10^{-3}	2.4×10^{-10}			2.4×10^{-10}
Lead	5.6×10^{-2}	8.8×10^{-12}	1.2×10^{-7}	1.0×10^{-9}	1.0×10^{-9}
Nickel	3.0×10^{-3}	9.4×10^{-12}			9.4×10^{-12}
Vanadium	2.0×10^{-3}	2.2×10^{-10}			2.2×10^{-10}
PCBs	5.0×10^{-5}	3.7×10^{-13}	1.0×10^{-10}	2.1×10^{-10}	2.1×10^{-10}
Route-Specific		4.7×10^{-10}		1.2×10^{-9}	2×10^{-9}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.6 Chemical Exposure Levels and Hazard Indexes from the K-65 Residues for a Remedial Action Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (*mg/kg-d*)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	5.0×10^{-6}	3.1×10^{-7}	1.0×10^{-11}	3.5×10^{-8}	3.4×10^{-7}
Barium			6.3×10^{-8}	3.1×10^{-7}	3.1×10^{-7}
Cobalt	2.0×10^{-3}	9.2×10^{-5}	4.2×10^{-9}	1.4×10^{-6}	9.3×10^{-5}
Lithium			2.1×10^{-10}	1.0×10^{-7}	1.0×10^{-7}
Manganese	1.0×10^{-4}	1.8×10^{-6}	2.1×10^{-10}	1.5×10^{-9}	1.8×10^{-6}
Molybdenum			2.1×10^{-8}	4.2×10^{-6}	4.2×10^{-6}
Nickel	3.0×10^{-3}	5.5×10^{-5}	6.3×10^{-9}	3.1×10^{-7}	5.5×10^{-5}
Uranium	3.8×10^{-3}	1.2×10^{-5}	8.0×10^{-9}	2.7×10^{-6}	1.4×10^{-5}
Vanadium	2.0×10^{-3}	1.8×10^{-5}	4.2×10^{-9}	4.7×10^{-7}	1.9×10^{-5}
PCBs			1.0×10^{-10}	5.2×10^{-6}	5.2×10^{-6}
Route-Specific		1.8×10^{-4}		1.5×10^{-5}	0.0002
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.7 Chemical Exposure Levels and Risks from the K-65 Residues for an Onsite Maintenance Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (*mg/kg-d*)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	1.4×10^{-7}	6.0×10^{-12}	1.5×10^{-12}	2.3×10^{-12}	8.3×10^{-12}
Cobalt	5.8×10^{-5}	5.0×10^{-9}			5.0×10^{-9}
Lead	1.6×10^{-3}	1.9×10^{-10}	1.7×10^{-8}	1.4×10^{-10}	3.3×10^{-10}
Nickel	8.6×10^{-5}	2.0×10^{-10}			2.0×10^{-10}
Vanadium	5.8×10^{-5}	4.6×10^{-9}			4.6×10^{-9}
PCBs	1.4×10^{-6}	8.0×10^{-12}	1.5×10^{-11}	3.0×10^{-11}	3.8×10^{-11}
Route-Specific		1.0×10^{-8}		1.8×10^{-10}	1×10^{-8}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for locations 50 m (160 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.5. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.8 Chemical Exposure Levels and Hazard Indexes from the K-65 Residues for an Onsite Maintenance Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (*mg/kg-d*)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	1.4×10^{-7}	6.5×10^{-6}	1.5×10^{-12}	5.0×10^{-9}	6.5×10^{-6}
Barium			9.0×10^{-9}	4.5×10^{-8}	4.5×10^{-8}
Cobalt	5.8×10^{-5}	0.0020	6.0×10^{-10}	2.0×10^{-7}	0.0020
Lithium			3.0×10^{-11}	1.5×10^{-8}	1.5×10^{-8}
Manganese	2.9×10^{-6}	3.9×10^{-5}	3.0×10^{-11}	2.1×10^{-10}	3.9×10^{-5}
Molybdenum			3.0×10^{-9}	6.0×10^{-7}	6.0×10^{-7}
Nickel	8.6×10^{-5}	0.0012	9.0×10^{-10}	4.5×10^{-8}	0.0012
Uranium	1.1×10^{-4}	2.5×10^{-4}	1.1×10^{-9}	3.8×10^{-7}	2.5×10^{-4}
Vanadium	5.8×10^{-5}	3.9×10^{-4}	6.0×10^{-10}	6.7×10^{-8}	3.9×10^{-4}
PCBs			1.5×10^{-11}	7.5×10^{-7}	7.5×10^{-7}
Route-Specific		0.0038		2.1×10^{-6}	0.004
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for locations 50 m (160 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.6. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.9 Chemical Exposure Levels and Risks from the K-65 Residues for an Onsite Trespasser[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)[c]	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	4.8×10^{-8}	7.6×10^{-14}	1.4×10^{-12}	2.1×10^{-12}	2.1×10^{-12}
Cobalt	1.9×10^{-5}	6.4×10^{-11}			6.4×10^{-11}
Lead	5.3×10^{-4}	2.4×10^{-12}	1.6×10^{-8}	1.3×10^{-10}	1.3×10^{-10}
Nickel	2.9×10^{-5}	2.6×10^{-12}			2.6×10^{-12}
Vanadium	1.9×10^{-5}	5.9×10^{-11}			5.9×10^{-11}
PCBs	4.8×10^{-7}	1.0×10^{-13}	1.4×10^{-11}	2.8×10^{-11}	2.8×10^{-11}
Route-Specific		1.3×10^{-10}		1.6×10^{-10}	3×10^{-10}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for locations 100 m (330 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.5. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.10 Chemical Exposure Levels and Hazard Indexes from the K-65 Residues for an Onsite Trespasser[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	4.8×10^{-8}	8.3×10^{-8}	1.4×10^{-12}	4.6×10^{-9}	8.7×10^{-8}
Barium			8.3×10^{-9}	4.1×10^{-8}	4.1×10^{-8}
Cobalt	1.9×10^{-5}	2.5×10^{-5}	5.5×10^{-10}	1.8×10^{-7}	2.5×10^{-5}
Lithium			2.8×10^{-11}	1.4×10^{-8}	1.4×10^{-8}
Manganese	9.5×10^{-7}	5.0×10^{-7}	2.8×10^{-11}	2.0×10^{-10}	5.0×10^{-7}
Molybdenum			2.8×10^{-9}	5.5×10^{-7}	5.5×10^{-7}
Nickel	2.9×10^{-5}	1.5×10^{-5}	8.3×10^{-10}	4.1×10^{-8}	1.5×10^{-5}
Uranium	3.6×10^{-5}	3.1×10^{-6}	1.1×10^{-9}	3.5×10^{-7}	3.5×10^{-6}
Vanadium	1.9×10^{-5}	5.0×10^{-6}	5.5×10^{-10}	6.1×10^{-8}	5.0×10^{-6}
PCBs			1.4×10^{-11}	6.9×10^{-7}	6.9×10^{-7}
Route-Specific		4.8×10^{-5}		1.9×10^{-6}	0.00005
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for locations 100 m (330 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.6. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.11 Chemical Exposure Levels and Risks from the K-65 Residues for an Offsite Outdoor Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (*mg/kg-d*)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	1.6×10^{-9}	1.5×10^{-14}	7.3×10^{-15}	1.1×10^{-14}	2.6×10^{-14}
Cobalt	6.4×10^{-7}	1.3×10^{-11}			1.3×10^{-11}
Lead	1.8×10^{-5}	4.8×10^{-13}	8.2×10^{-11}	7.0×10^{-13}	1.2×10^{-12}
Nickel	9.7×10^{-7}	5.1×10^{-13}			5.1×10^{-13}
Vanadium	6.4×10^{-7}	1.2×10^{-11}			1.2×10^{-11}
PCBs	1.6×10^{-8}	2.0×10^{-14}	7.3×10^{-14}	1.5×10^{-13}	1.7×10^{-13}
Route-Specific		2.6×10^{-11}		8.5×10^{-13}	3×10^{-11}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.12 Chemical Exposure Levels and Hazard Indexes from the K-65 Residues for an Offsite Outdoor Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (*mg/kg-d*)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	1.6×10^{-9}	1.7×10^{-8}	7.3×10^{-15}	2.4×10^{-11}	1.7×10^{-8}
Barium			4.4×10^{-11}	2.2×10^{-10}	2.2×10^{-10}
Cobalt	6.4×10^{-7}	5.0×10^{-6}	2.9×10^{-12}	9.7×10^{-10}	5.0×10^{-6}
Lithium			1.5×10^{-13}	7.3×10^{-11}	7.3×10^{-11}
Manganese	3.2×10^{-8}	1.0×10^{-7}	1.5×10^{-13}	1.0×10^{-12}	1.0×10^{-7}
Molybdenum			1.5×10^{-11}	2.9×10^{-9}	2.9×10^{-9}
Nickel	9.7×10^{-7}	3.0×10^{-6}	4.4×10^{-12}	2.2×10^{-10}	3.0×10^{-6}
Uranium	1.2×10^{-6}	6.3×10^{-7}	5.6×10^{-12}	1.9×10^{-9}	6.4×10^{-7}
Vanadium	6.4×10^{-7}	1.0×10^{-6}	2.9×10^{-12}	3.2×10^{-10}	1.0×10^{-6}
PCBs			7.3×10^{-14}	3.7×10^{-9}	3.7×10^{-9}
Route-Specific		9.7×10^{-6}		1.0×10^{-8}	0.00001
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.13 Chemical Exposure Levels and Risks from the K-65 Residues for an Offsite Adult Resident[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (*mg/kg-d*)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	1.5×10^{-9}	8.8×10^{-15}	2.3×10^{-15}	3.4×10^{-15}	1.2×10^{-14}
Cobalt	5.9×10^{-7}	7.4×10^{-12}			7.4×10^{-12}
Lead	1.7×10^{-5}	2.8×10^{-13}	2.6×10^{-11}	2.2×10^{-13}	4.9×10^{-13}
Nickel	8.9×10^{-7}	3.0×10^{-13}			3.0×10^{-13}
Vanadium	5.9×10^{-7}	6.8×10^{-12}			6.8×10^{-12}
PCBs	1.5×10^{-8}	1.2×10^{-14}	2.3×10^{-14}	4.6×10^{-14}	5.8×10^{-14}
Route-Specific		1.5×10^{-11}		2.7×10^{-13}	2×10^{-11}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.14 Chemical Exposure Levels and Hazard Indexes from the K-65 Residues for an Offsite Adult Resident[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (*mg/kg-d*)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	1.5×10^{-9}	9.6×10^{-9}	2.3×10^{-15}	7.7×10^{-12}	9.6×10^{-9}
Barium			1.4×10^{-11}	6.9×10^{-11}	6.9×10^{-11}
Cobalt	5.9×10^{-7}	2.9×10^{-6}	9.2×10^{-13}	3.1×10^{-10}	2.9×10^{-6}
Lithium			4.6×10^{-14}	2.3×10^{-11}	2.3×10^{-11}
Manganese	3.0×10^{-8}	5.7×10^{-8}	4.6×10^{-14}	3.3×10^{-13}	5.7×10^{-8}
Molybdenum			4.6×10^{-12}	9.2×10^{-10}	9.2×10^{-10}
Nickel	8.9×10^{-7}	1.7×10^{-6}	1.4×10^{-12}	6.9×10^{-11}	1.7×10^{-6}
Uranium	1.1×10^{-6}	3.6×10^{-7}	1.7×10^{-12}	5.8×10^{-10}	3.6×10^{-7}
Vanadium	5.9×10^{-7}	5.7×10^{-7}	9.2×10^{-13}	1.0×10^{-10}	5.7×10^{-7}
PCBs			2.3×10^{-14}	1.1×10^{-9}	1.1×10^{-9}
Route-Specific		5.6×10^{-6}		3.2×10^{-9}	0.000006
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.15 Chemical Exposure Levels and Risks from the K-65 Residues for an Offsite Child Resident[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	1.5×10^{-9}	8.8×10^{-15}	2.1×10^{-14}	3.2×10^{-14}	4.1×10^{-14}
Cobalt	5.9×10^{-7}	7.4×10^{-12}			7.4×10^{-12}
Lead	1.7×10^{-5}	2.8×10^{-13}	2.4×10^{-10}	2.0×10^{-12}	2.3×10^{-12}
Nickel	8.9×10^{-7}	3.0×10^{-13}			3.0×10^{-13}
Vanadium	5.9×10^{-7}	6.8×10^{-12}			6.8×10^{-12}
PCBs	1.5×10^{-8}	1.2×10^{-14}	2.1×10^{-13}	4.3×10^{-13}	4.4×10^{-13}
Route-Specific		1.5×10^{-11}		2.5×10^{-12}	2×10^{-11}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.16 Chemical Exposure Levels and Hazard Indexes from the K-65 Residues for an Offsite Child Resident[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	1.5×10^{-9}	9.6×10^{-9}	2.1×10^{-14}	7.1×10^{-11}	9.6×10^{-9}
Barium			1.3×10^{-10}	6.4×10^{-10}	6.4×10^{-10}
Cobalt	5.9×10^{-7}	2.9×10^{-6}	8.6×10^{-12}	2.9×10^{-9}	2.9×10^{-6}
Lithium			4.3×10^{-13}	2.1×10^{-10}	2.1×10^{-10}
Manganese	3.0×10^{-8}	5.7×10^{-8}	4.3×10^{-13}	3.1×10^{-12}	5.7×10^{-8}
Molybdenum			4.3×10^{-11}	8.6×10^{-9}	8.6×10^{-9}
Nickel	8.9×10^{-7}	1.7×10^{-6}	1.3×10^{-11}	6.4×10^{-10}	1.7×10^{-6}
Uranium	1.1×10^{-6}	3.6×10^{-7}	1.6×10^{-11}	5.4×10^{-9}	3.7×10^{-7}
Vanadium	5.9×10^{-7}	5.7×10^{-7}	8.6×10^{-12}	9.5×10^{-10}	5.8×10^{-7}
PCBs			2.1×10^{-13}	1.1×10^{-8}	1.1×10^{-8}
Route-Specific		5.6×10^{-6}		3.0×10^{-8}	0.000006
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.17 Chemical Exposure Levels and Cancer Risks from the Other High-Activity Residues (L and F) and Tower Soils for a Remedial Action Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (*mg/kg-d*)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	5.4×10^{-4}	3.0×10^{-11}	9.3×10^{-10}	1.4×10^{-9}	1.4×10^{-9}
Cobalt	1.1×10^{-1}	1.2×10^{-8}			1.2×10^{-8}
Lead	2.2×10^{-1}	3.5×10^{-11}	3.9×10^{-7}	3.3×10^{-9}	3.3×10^{-9}
Nickel	3.5×10^{-1}	1.1×10^{-9}			1.1×10^{-9}
Vanadium	4.5×10^{-2}	4.9×10^{-9}			4.9×10^{-9}
PCBs	1.3×10^{-3}	9.7×10^{-12}	2.3×10^{-9}	4.5×10^{-9}	4.6×10^{-9}
Route-Specific		1.8×10^{-8}		9.2×10^{-9}	3×10^{-8}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.18 Chemical Exposure Levels and Hazard Indexes from the Other High-Activity Residues (L and F) and Tower Soils for a Remedial Action Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (*mg/kg-d*)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	5.4×10^{-4}	4.9×10^{-5}	9.3×10^{-10}	3.1×10^{-6}	5.3×10^{-5}
Barium			2.9×10^{-7}	1.5×10^{-6}	1.5×10^{-6}
Cobalt	1.1×10^{-1}	0.0073	1.8×10^{-7}	6.1×10^{-5}	0.0074
Lithium			6.6×10^{-9}	3.3×10^{-6}	3.3×10^{-6}
Manganese	7.3×10^{-1}	0.020	1.3×10^{-6}	9.1×10^{-6}	0.020
Molybdenum			2.7×10^{-8}	5.4×10^{-6}	5.4×10^{-6}
Nickel	3.5×10^{-1}	0.0096	6.0×10^{-7}	3.0×10^{-5}	0.0096
Uranium	7.9×10^{-2}	3.7×10^{-4}	1.4×10^{-7}	4.6×10^{-5}	4.1×10^{-4}
Vanadium	4.5×10^{-2}	6.3×10^{-4}	7.9×10^{-8}	8.8×10^{-6}	6.4×10^{-4}
PCBs			2.3×10^{-9}	1.1×10^{-4}	1.1×10^{-4}
Route-Specific		0.038		2.8×10^{-4}	0.04
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.19 Chemical Exposure Levels and Risks from the Other High-Activity Residues (L and F) and Tower Soils for an Onsite Maintenance Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	2.5×10^{-5}	4.8×10^{-10}	1.4×10^{-10}	2.2×10^{-10}	6.9×10^{-10}
Cobalt	4.9×10^{-3}	2.0×10^{-7}			2.0×10^{-7}
Lead	1.0×10^{-2}	5.6×10^{-10}	6.0×10^{-8}	5.1×10^{-10}	1.1×10^{-9}
Nickel	1.6×10^{-2}	1.7×10^{-8}			1.7×10^{-8}
Vanadium	2.1×10^{-3}	7.8×10^{-8}			7.8×10^{-8}
PCBs	6.1×10^{-5}	1.5×10^{-10}	3.5×10^{-10}	7.1×10^{-10}	8.6×10^{-10}
Route-Specific		2.9×10^{-7}		1.4×10^{-9}	3×10^{-7}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for locations 50 m (160 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.17. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.20 Chemical Exposure Levels and Hazard Indexes from the Other High-Activity Residues (L and F) and Tower Soils for an Onsite Maintenance Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	2.5×10^{-5}	7.9×10^{-4}	1.4×10^{-10}	4.8×10^{-7}	7.9×10^{-4}
Barium			4.6×10^{-8}	2.3×10^{-7}	2.3×10^{-7}
Cobalt	4.9×10^{-3}	0.12	2.9×10^{-8}	9.5×10^{-6}	0.12
Lithium			1.0×10^{-9}	5.1×10^{-7}	5.1×10^{-7}
Manganese	3.4×10^{-2}	0.32	2.0×10^{-7}	1.4×10^{-6}	0.32
Molybdenum			4.2×10^{-9}	8.5×10^{-7}	8.5×10^{-7}
Nickel	1.6×10^{-2}	0.15	9.3×10^{-8}	4.7×10^{-6}	0.15
Uranium	3.7×10^{-3}	0.0058	2.1×10^{-8}	7.2×10^{-6}	0.0058
Vanadium	2.1×10^{-3}	0.010	1.2×10^{-8}	1.4×10^{-6}	0.010
PCBs			3.5×10^{-10}	1.8×10^{-5}	1.8×10^{-5}
Route-Specific		0.61		4.4×10^{-5}	0.6
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for locations 50 m (160 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.18. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.21 Chemical Exposure Levels and Risks from the Other High-Activity Residues (L and F) and Tower Soils for an Onsite Trespasser[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)[c]	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	8.8×10^{-6}	5.7×10^{-12}	1.3×10^{-10}	1.9×10^{-10}	2.0×10^{-10}
Cobalt	1.7×10^{-3}	2.3×10^{-9}			2.3×10^{-9}
Lead	3.7×10^{-3}	6.6×10^{-12}	5.3×10^{-8}	4.5×10^{-10}	4.6×10^{-10}
Nickel	5.7×10^{-3}	2.0×10^{-10}			2.0×10^{-10}
Vanadium	7.5×10^{-4}	9.3×10^{-10}			9.3×10^{-10}
PCBs	2.2×10^{-5}	1.8×10^{-12}	3.1×10^{-10}	6.2×10^{-10}	6.2×10^{-10}
Route-Specific		3.5×10^{-9}		1.3×10^{-9}	5×10^{-9}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for locations 100 m (330 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.17. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.22 Chemical Exposure Levels and Hazard Indexes from the Other High-Activity Residues (L and F) and Tower Soils for an Onsite Trespasser[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	8.8×10^{-6}	9.4×10^{-6}	1.3×10^{-10}	4.2×10^{-7}	9.8×10^{-6}
Barium			4.0×10^{-8}	2.0×10^{-7}	2.0×10^{-7}
Cobalt	1.7×10^{-3}	0.0014	2.5×10^{-8}	8.4×10^{-5}	0.0015
Lithium			9.0×10^{-10}	4.5×10^{-7}	4.5×10^{-7}
Manganese	1.2×10^{-2}	0.0038	1.7×10^{-7}	1.2×10^{-6}	0.0038
Molybdenum			3.7×10^{-9}	7.4×10^{-7}	7.4×10^{-7}
Nickel	5.7×10^{-3}	0.0018	8.2×10^{-8}	4.1×10^{-6}	0.0018
Uranium	1.3×10^{-3}	6.9×10^{-5}	1.9×10^{-8}	6.3×10^{-6}	7.6×10^{-5}
Vanadium	7.5×10^{-4}	1.2×10^{-4}	1.1×10^{-8}	1.2×10^{-6}	1.2×10^{-4}
PCBs			3.1×10^{-10}	1.6×10^{-5}	1.6×10^{-5}
Route-Specific		0.0072		1.1×10^{-4}	0.007
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for locations 100 m (330 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; the concentrations at 1 m (3 ft) from the exposed waste (10% of the time) are shown in Table B.18. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.23 Chemical Exposure Levels and Risks from the Other High-Activity Residues (L and F) and Tower Soils for an Offsite Outdoor Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	3.3×10^{-7}	2.1×10^{-12}	9.8×10^{-13}	1.5×10^{-12}	3.5×10^{-12}
Cobalt	6.5×10^{-5}	8.5×10^{-10}			8.5×10^{-10}
Lead	1.4×10^{-4}	2.4×10^{-12}	4.1×10^{-10}	3.5×10^{-12}	5.9×10^{-12}
Nickel	2.1×10^{-4}	7.4×10^{-11}			7.4×10^{-11}
Vanadium	2.8×10^{-5}	3.4×10^{-10}			3.4×10^{-10}
PCBs	8.0×10^{-7}	6.7×10^{-13}	2.4×10^{-12}	4.8×10^{-12}	5.5×10^{-12}
Route-Specific		1.3×10^{-9}		9.7×10^{-12}	1×10^{-9}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.24 Chemical Exposure Levels and Hazard Indexes from the Other High-Activity Residues (L and F) and Tower Soils for an Offsite Outdoor Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	3.3×10^{-7}	3.4×10^{-6}	9.8×10^{-13}	3.3×10^{-9}	3.4×10^{-6}
Barium			3.1×10^{-10}	1.5×10^{-9}	1.5×10^{-9}
Cobalt	6.5×10^{-5}	5.0×10^{-4}	1.9×10^{-10}	6.4×10^{-8}	5.0×10^{-4}
Lithium			6.9×10^{-12}	3.5×10^{-9}	3.5×10^{-9}
Manganese	4.5×10^{-4}	0.0014	1.3×10^{-9}	9.5×10^{-9}	0.0014
Molybdenum			2.9×10^{-11}	5.7×10^{-9}	5.7×10^{-9}
Nickel	2.1×10^{-4}	6.6×10^{-4}	6.3×10^{-10}	3.2×10^{-8}	6.6×10^{-4}
Uranium	4.9×10^{-5}	2.5×10^{-5}	1.5×10^{-10}	4.8×10^{-8}	2.5×10^{-5}
Vanadium	2.8×10^{-5}	4.3×10^{-5}	8.3×10^{-11}	9.2×10^{-9}	4.3×10^{-5}
PCBs			2.4×10^{-12}	1.2×10^{-7}	1.2×10^{-7}
Route-Specific		0.0026		3.0×10^{-7}	0.003
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.25 Chemical Exposure Levels and Risks from the Other High-Activity Residues (L and F) and Tower Soils for an Offsite Adult Resident[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	3.0×10^{-7}	1.2×10^{-12}	3.1×10^{-13}	4.6×10^{-13}	1.6×10^{-12}
Cobalt	5.9×10^{-5}	4.9×10^{-10}			4.9×10^{-10}
Lead	1.3×10^{-4}	1.4×10^{-12}	1.3×10^{-10}	1.1×10^{-12}	2.5×10^{-12}
Nickel	1.9×10^{-4}	4.3×10^{-11}			4.3×10^{-11}
Vanadium	2.6×10^{-5}	1.9×10^{-10}			1.9×10^{-10}
PCBs	7.4×10^{-7}	3.8×10^{-13}	7.5×10^{-13}	1.5×10^{-12}	1.9×10^{-12}
Route-Specific		7.3×10^{-10}		3.1×10^{-12}	7×10^{-10}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.26 Chemical Exposure Levels and Hazard Indexes from the Other High-Activity Residues (L and F) and Tower Soils for an Offsite Adult Resident[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	3.0×10^{-7}	2.0×10^{-6}	3.1×10^{-13}	1.0×10^{-9}	2.0×10^{-6}
Barium			9.7×10^{-11}	4.9×10^{-10}	4.9×10^{-10}
Cobalt	5.9×10^{-5}	2.9×10^{-4}	6.1×10^{-11}	2.0×10^{-8}	2.9×10^{-4}
Lithium			2.2×10^{-12}	1.1×10^{-9}	1.1×10^{-9}
Manganese	4.1×10^{-4}	8.0×10^{-4}	4.2×10^{-10}	3.0×10^{-9}	8.0×10^{-4}
Molybdenum			9.0×10^{-12}	1.8×10^{-9}	1.8×10^{-9}
Nickel	1.9×10^{-4}	3.8×10^{-4}	2.0×10^{-10}	9.9×10^{-9}	3.8×10^{-4}
Uranium	4.5×10^{-5}	1.4×10^{-5}	4.6×10^{-11}	1.5×10^{-8}	1.4×10^{-5}
Vanadium	2.6×10^{-5}	2.5×10^{-5}	2.6×10^{-11}	2.9×10^{-9}	2.5×10^{-5}
PCBs			7.5×10^{-13}	3.8×10^{-8}	3.8×10^{-8}
Route-Specific		0.0015		9.3×10^{-8}	0.002
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.27 Chemical Exposure Levels and Risks from the Other High-Activity Residues (L and F) and Tower Soils for an Offsite Child Resident[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	3.0×10^{-7}	1.2×10^{-12}	2.9×10^{-12}	4.3×10^{-12}	5.5×10^{-12}
Cobalt	5.9×10^{-5}	4.9×10^{-10}			4.9×10^{-10}
Lead	1.3×10^{-4}	1.4×10^{-12}	1.2×10^{-9}	1.0×10^{-11}	1.2×10^{-11}
Nickel	1.9×10^{-4}	4.3×10^{-11}			4.3×10^{-11}
Vanadium	2.6×10^{-5}	1.9×10^{-10}			1.9×10^{-10}
PCBs	7.4×10^{-7}	3.8×10^{-13}	7.0×10^{-12}	1.4×10^{-11}	1.4×10^{-11}
Route-Specific		7.3×10^{-10}		2.9×10^{-11}	8×10^{-10}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.28 Chemical Exposure Levels and Hazard Indexes from the Other High-Activity Residues (L and F) and Tower Soils for an Offsite Child Resident[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	3.0×10^{-7}	2.0×10^{-6}	2.9×10^{-12}	9.6×10^{-9}	2.0×10^{-6}
Barium			9.1×10^{-10}	4.5×10^{-9}	4.5×10^{-9}
Cobalt	5.9×10^{-5}	2.9×10^{-4}	5.7×10^{-10}	1.9×10^{-7}	2.9×10^{-4}
Lithium			2.0×10^{-11}	1.0×10^{-8}	1.0×10^{-8}
Manganese	4.1×10^{-4}	8.0×10^{-4}	3.9×10^{-9}	2.8×10^{-8}	8.0×10^{-4}
Molybdenum			8.4×10^{-11}	1.7×10^{-8}	1.7×10^{-8}
Nickel	1.9×10^{-4}	3.8×10^{-4}	1.8×10^{-9}	9.2×10^{-8}	3.8×10^{-4}
Uranium	4.5×10^{-5}	1.4×10^{-5}	4.3×10^{-10}	1.4×10^{-7}	1.5×10^{-5}
Vanadium	2.6×10^{-5}	2.5×10^{-5}	2.4×10^{-10}	2.7×10^{-8}	2.5×10^{-5}
PCBs			7.0×10^{-12}	3.5×10^{-7}	3.5×10^{-7}
Route-Specific		0.0015		8.7×10^{-7}	0.002
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.29 Chemical Exposure Levels and Cancer Risks from the R-10 Pile and Other Contaminated Soils for a Remedial Action Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (*mg/kg-d*)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	3.7×10^{-5}	2.1×10^{-12}	1.9×10^{-10}	2.8×10^{-10}	2.8×10^{-10}
Cobalt	1.9×10^{-3}	2.2×10^{-10}			2.2×10^{-10}
Lead	4.4×10^{-4}	6.8×10^{-14}	2.2×10^{-9}	1.9×10^{-11}	1.9×10^{-11}
Nickel	3.8×10^{-3}	1.2×10^{-11}			1.2×10^{-11}
Vanadium	3.8×10^{-3}	4.1×10^{-10}			4.1×10^{-10}
PCBs	1.5×10^{-3}	1.1×10^{-11}	7.3×10^{-9}	1.5×10^{-8}	1.5×10^{-8}
Route-Specific		6.5×10^{-10}		1.5×10^{-8}	2×10^{-8}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.30 Chemical Exposure Levels and Hazard Indexes from the R-10 Pile and Other Contaminated Soils for a Remedial Action Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (*mg/kg-d*)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	3.7×10^{-5}	1.4×10^{-6}	1.9×10^{-10}	6.3×10^{-7}	2.0×10^{-6}
Barium			6.4×10^{-8}	3.2×10^{-7}	3.2×10^{-7}
Cobalt	1.9×10^{-3}	5.3×10^{-5}	9.5×10^{-9}	3.2×10^{-6}	5.7×10^{-5}
Lithium			1.9×10^{-8}	9.3×10^{-6}	9.3×10^{-6}
Manganese	1.3×10^{-2}	1.5×10^{-4}	6.5×10^{-8}	4.7×10^{-7}	1.5×10^{-4}
Molybdenum			7.3×10^{-9}	1.5×10^{-6}	1.5×10^{-6}
Nickel	3.8×10^{-3}	4.3×10^{-5}	1.9×10^{-8}	9.6×10^{-7}	4.4×10^{-5}
Uranium	4.1×10^{-4}	7.6×10^{-7}	2.0×10^{-9}	6.8×10^{-7}	1.4×10^{-6}
Vanadium	3.8×10^{-3}	2.1×10^{-5}	1.9×10^{-8}	2.1×10^{-6}	2.3×10^{-5}
PCBs			7.3×10^{-9}	3.6×10^{-4}	3.6×10^{-4}
Route-Specific		2.7×10^{-4}		3.8×10^{-4}	0.0006
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.31 Chemical Exposure Levels and Risks from the R-10 Pile and Other Contaminated Soils for an Onsite Maintenance Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	2.6×10^{-6}	9.4×10^{-11}	3.2×10^{-11}	4.8×10^{-11}	1.4×10^{-10}
Cobalt	1.3×10^{-4}	9.9×10^{-9}			9.9×10^{-9}
Lead	3.0×10^{-5}	3.1×10^{-12}	3.7×10^{-10}	3.2×10^{-12}	6.2×10^{-12}
Nickel	2.6×10^{-4}	5.3×10^{-10}			5.3×10^{-10}
Vanadium	2.6×10^{-4}	1.8×10^{-8}			1.8×10^{-8}
PCBs	1.0×10^{-4}	4.8×10^{-10}	1.2×10^{-9}	2.5×10^{-9}	3.0×10^{-9}
Route-Specific		2.9×10^{-8}		2.5×10^{-9}	3×10^{-8}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for locations 50 m (160 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; concentrations at 1 m (3 ft) from the waste (10% of the time) are shown in Table B.29. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.32 Chemical Exposure Levels and Hazard Indexes from the R-10 Pile and Other Contaminated Soils for an Onsite Maintenance Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	2.6×10^{-6}	6.3×10^{-5}	3.2×10^{-11}	1.1×10^{-7}	6.3×10^{-5}
Barium			1.1×10^{-8}	5.5×10^{-8}	5.5×10^{-8}
Cobalt	1.3×10^{-4}	0.0024	1.6×10^{-9}	5.4×10^{-7}	0.0024
Lithium			3.2×10^{-9}	1.6×10^{-6}	1.6×10^{-6}
Manganese	9.0×10^{-4}	0.0066	1.1×10^{-8}	8.0×10^{-8}	0.0066
Molybdenum			1.2×10^{-9}	2.5×10^{-7}	2.5×10^{-7}
Nickel	2.6×10^{-4}	0.0019	3.3×10^{-9}	1.6×10^{-7}	0.0019
Uranium	2.8×10^{-5}	3.4×10^{-5}	3.5×10^{-10}	1.2×10^{-7}	3.4×10^{-5}
Vanadium	2.6×10^{-4}	9.5×10^{-4}	3.2×10^{-9}	3.6×10^{-7}	9.5×10^{-4}
PCBs			1.2×10^{-9}	6.2×10^{-5}	6.2×10^{-5}
Route-Specific		0.012		6.5×10^{-5}	0.01
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for locations 50 m (160 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; concentrations at 1 m (3 ft) from the waste (10% of the time) are shown in Table B.30. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.33 Chemical Exposure Levels and Risks from the R-10 Pile and Other Contaminated Soils for an Onsite Trespasser[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)[c]	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	9.8×10^{-7}	1.0×10^{-12}	2.7×10^{-11}	4.1×10^{-11}	4.2×10^{-11}
Cobalt	5.0×10^{-5}	1.1×10^{-10}			1.1×10^{-10}
Lead	1.1×10^{-5}	3.4×10^{-14}	3.2×10^{-10}	2.7×10^{-12}	2.7×10^{-12}
Nickel	1.0×10^{-4}	6.0×10^{-12}			6.0×10^{-12}
Vanadium	9.9×10^{-5}	2.0×10^{-10}			2.0×10^{-10}
PCBs	3.8×10^{-5}	5.4×10^{-12}	1.0×10^{-9}	2.1×10^{-9}	2.1×10^{-9}
Route-Specific		3.3×10^{-10}		2.1×10^{-9}	2×10^{-9}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for locations 100 m (330 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; concentrations at 1 m (3 ft) from the waste (10% of the time) are shown in Table B.29. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.34 Chemical Exposure Levels and Hazard Indexes from the R-10 Pile and Other Contaminated Soils for an Onsite Trespasser[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	9.8×10^{-7}	7.0×10^{-7}	2.7×10^{-11}	9.0×10^{-8}	7.9×10^{-7}
Barium			9.2×10^{-9}	4.6×10^{-8}	4.6×10^{-8}
Cobalt	5.0×10^{-5}	2.7×10^{-5}	1.4×10^{-9}	4.6×10^{-6}	3.1×10^{-5}
Lithium			2.7×10^{-9}	1.3×10^{-6}	1.3×10^{-6}
Manganese	3.4×10^{-4}	7.4×10^{-5}	9.4×10^{-9}	6.7×10^{-8}	7.4×10^{-5}
Molybdenum			1.0×10^{-9}	2.1×10^{-7}	2.1×10^{-7}
Nickel	1.0×10^{-4}	2.2×10^{-5}	2.8×10^{-9}	1.4×10^{-7}	2.2×10^{-5}
Uranium	1.1×10^{-5}	3.8×10^{-7}	2.9×10^{-10}	9.8×10^{-8}	4.8×10^{-7}
Vanadium	9.9×10^{-5}	1.1×10^{-5}	2.7×10^{-9}	3.0×10^{-7}	1.1×10^{-5}
PCBs			1.0×10^{-9}	5.2×10^{-5}	5.2×10^{-5}
Route-Specific		1.3×10^{-4}		5.9×10^{-5}	0.0002
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for locations 100 m (330 ft) from the exposed waste, where this receptor is assumed to spend 90% of the time; concentrations at 1 m (3 ft) from the waste (10% of the time) are shown in Table B.30. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.35 Chemical Exposure Levels and Risks from the R-10 Pile and Other Contaminated Soils for an Offsite Outdoor Worker[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	4.1×10^{-8}	6.4×10^{-13}	3.0×10^{-13}	4.6×10^{-13}	1.1×10^{-12}
Cobalt	2.1×10^{-6}	6.8×10^{-11}			6.8×10^{-11}
Lead	4.8×10^{-7}	2.1×10^{-14}	3.6×10^{-12}	3.0×10^{-14}	5.1×10^{-14}
Nickel	4.2×10^{-6}	3.6×10^{-12}			3.6×10^{-12}
Vanadium	4.2×10^{-6}	1.2×10^{-10}			1.2×10^{-10}
PCBs	1.6×10^{-6}	3.3×10^{-12}	1.2×10^{-11}	2.4×10^{-11}	2.7×10^{-11}
Route-Specific		2.0×10^{-10}		2.4×10^{-11}	2×10^{-10}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.36 Chemical Exposure Levels and Hazard Indexes from the R-10 Pile and Other Contaminated Soils for an Offsite Outdoor Worker[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	4.1×10^{-8}	4.3×10^{-7}	3.0×10^{-13}	1.0×10^{-9}	4.3×10^{-7}
Barium			1.0×10^{-10}	5.2×10^{-10}	5.2×10^{-10}
Cobalt	2.1×10^{-6}	1.6×10^{-5}	1.5×10^{-11}	5.1×10^{-9}	1.6×10^{-5}
Lithium			3.0×10^{-11}	1.5×10^{-8}	1.5×10^{-8}
Manganese	1.4×10^{-5}	4.5×10^{-5}	1.1×10^{-10}	7.6×10^{-10}	4.5×10^{-5}
Molybdenum			1.2×10^{-11}	2.4×10^{-9}	2.4×10^{-9}
Nickel	4.2×10^{-6}	1.3×10^{-5}	3.1×10^{-11}	1.6×10^{-9}	1.3×10^{-5}
Uranium	4.5×10^{-7}	2.3×10^{-7}	3.3×10^{-12}	1.1×10^{-9}	2.3×10^{-7}
Vanadium	4.2×10^{-6}	6.5×10^{-6}	3.1×10^{-11}	3.4×10^{-9}	6.5×10^{-6}
PCBs			1.2×10^{-11}	5.9×10^{-7}	5.9×10^{-7}
Route-Specific		8.1×10^{-5}		6.2×10^{-7}	0.00008
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. Intermediate values are given to two significant figures. Numbers may not sum exactly due to rounding.

TABLE B.37 Chemical Exposure Levels and Risks from the R-10 Pile and Other Contaminated Soils for an Offsite Adult Resident[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	3.8×10^{-8}	3.7×10^{-13}	9.6×10^{-14}	1.4×10^{-13}	5.1×10^{-13}
Cobalt	1.9×10^{-6}	3.9×10^{-11}			3.9×10^{-11}
Lead	4.5×10^{-7}	1.2×10^{-14}	1.1×10^{-12}	9.5×10^{-15}	2.2×10^{-14}
Nickel	3.9×10^{-6}	2.1×10^{-12}			2.1×10^{-12}
Vanadium	3.9×10^{-6}	7.2×10^{-11}			7.2×10^{-11}
PCBs	1.5×10^{-6}	1.9×10^{-12}	3.7×10^{-12}	7.4×10^{-12}	9.3×10^{-12}
Route-Specific		1.2×10^{-10}		7.6×10^{-12}	1×10^{-10}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.38 Chemical Exposure Levels and Hazard Indexes from the R-10 Pile and Other Contaminated Soils for an Offsite Adult Resident[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	3.8×10^{-8}	2.5×10^{-7}	9.6×10^{-14}	3.2×10^{-10}	2.5×10^{-7}
Barium			3.3×10^{-11}	1.6×10^{-10}	1.6×10^{-10}
Cobalt	1.9×10^{-6}	9.4×10^{-6}	4.8×10^{-12}	1.6×10^{-9}	9.4×10^{-6}
Lithium			9.5×10^{-12}	4.7×10^{-9}	4.7×10^{-9}
Manganese	1.3×10^{-5}	2.6×10^{-5}	3.3×10^{-11}	2.4×10^{-10}	2.6×10^{-5}
Molybdenum			3.7×10^{-12}	7.4×10^{-10}	7.4×10^{-10}
Nickel	3.9×10^{-6}	7.6×10^{-6}	9.8×10^{-12}	4.9×10^{-10}	7.6×10^{-6}
Uranium	4.2×10^{-7}	1.3×10^{-7}	1.0×10^{-12}	3.5×10^{-10}	1.3×10^{-7}
Vanadium	3.9×10^{-6}	3.7×10^{-6}	9.6×10^{-12}	1.1×10^{-9}	3.7×10^{-6}
PCBs			3.7×10^{-12}	1.9×10^{-7}	1.9×10^{-7}
Route-Specific		4.7×10^{-5}		2.0×10^{-7}	0.00005
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.39 Chemical Exposure Levels and Risks from the R-10 Pile and Other Contaminated Soils for an Offsite Child Resident[a]

Chemical	Inhalation		Incidental Ingestion		Combined Cancer Risk
	Air Concentration ($\mu g/m^3$)	Cancer Risk	Intake (mg/kg-d)	Cancer Risk	
K-65 Residues					*Chemical-Specific*
Arsenic	3.8×10^{-8}	3.7×10^{-13}	8.9×10^{-13}	1.3×10^{-12}	1.7×10^{-12}
Cobalt	1.9×10^{-6}	3.9×10^{-11}			3.9×10^{-11}
Lead	4.5×10^{-7}	1.2×10^{-14}	1.0×10^{-11}	8.9×10^{-14}	1.0×10^{-13}
Nickel	3.9×10^{-6}	2.1×10^{-12}			2.1×10^{-12}
Vanadium	3.9×10^{-6}	7.2×10^{-11}			7.2×10^{-11}
PCBs	1.5×10^{-6}	1.9×10^{-12}	3.5×10^{-11}	6.9×10^{-11}	7.1×10^{-11}
Route-Specific		1.2×10^{-10}		7.1×10^{-11}	2×10^{-10}
					Total Risk

[a] The combined risk across the chemicals and exposure routes is below the NCP target range for incremental risk from exposures to site contaminants. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

TABLE B.40 Chemical Exposure Levels and Hazard Indexes from the R-10 Pile and Other Contaminated Soils for an Offsite Child Resident[a]

Chemical	Inhalation		Incidental Ingestion		Hazard Index
	Air Concentration ($\mu g/m^3$)	Hazard Quotient	Intake (mg/kg-d)	Hazard Quotient	
K-65 Residues					*Chemical-Specific*
Arsenic	3.8×10^{-8}	2.5×10^{-7}	8.9×10^{-13}	3.0×10^{-9}	2.5×10^{-7}
Barium			3.0×10^{-10}	1.5×10^{-9}	1.5×10^{-9}
Cobalt	1.9×10^{-6}	9.4×10^{-6}	4.5×10^{-11}	1.5×10^{-8}	9.4×10^{-6}
Lithium			8.9×10^{-11}	4.4×10^{-8}	4.4×10^{-8}
Manganese	1.3×10^{-5}	2.6×10^{-5}	3.1×10^{-10}	2.2×10^{-9}	2.6×10^{-5}
Molybdenum			3.5×10^{-11}	6.9×10^{-9}	6.9×10^{-9}
Nickel	3.9×10^{-6}	7.6×10^{-6}	9.1×10^{-11}	4.6×10^{-9}	7.6×10^{-6}
Uranium	4.2×10^{-7}	1.3×10^{-7}	9.7×10^{-12}	3.2×10^{-9}	1.4×10^{-7}
Vanadium	3.9×10^{-6}	3.7×10^{-6}	9.0×10^{-11}	1.0×10^{-8}	3.7×10^{-6}
PCBs			3.5×10^{-11}	1.7×10^{-6}	1.7×10^{-6}
Route-Specific		4.7×10^{-5}		1.8×10^{-6}	0.00005
					Total HI

[a] The combined HI across the chemicals and exposure routes is below the NCP target level of 1, so no adverse noncarcinogenic effects are indicated. The air concentrations are for outdoor air; indoor concentrations are assumed to be half these estimates. (Intermediate values are given to two significant figures; numbers may not sum exactly due to rounding.)

APPENDIX C:

HEALTH RISK FACT SHEETS FOR SELECTED RADIONUCLIDES AND CHEMICALS AT NFSS

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APPENDIX C:

HEALTH RISK FACT SHEETS FOR SELECTED RADIONUCLIDES AND CHEMICALS AT NFSS

This appendix presents 24 fact sheets that support health risk evaluations for selected radionuclides and chemicals at the NFSS. This total includes two supporting summary tables for the radionuclides plus a figure that illustrates their distribution in the body. This set of fact sheets covers key contaminants at the IWCS and other selected radioisotopes likely present at the site, in addition to two further radionuclides (carbon-14 and potassium-40) as context for natural background. The information resources used to develop these sheets are provided in Peterson et al. (2011). The fact sheets are provided in the following order:

1. Eleven radiological fact sheets for specific IWCS contaminants and associated decay products, three more for naturally occurring radionuclides (carbon-14, potassium-40, and the natural decay series), and a general fact sheet on ionizing radiation:

    - Americium
    - Carbon-14
    - Cesium
    - Ionizing radiation
    - Natural decay series: uranium, radium, and thorium
    - Neptunium
    - Plutonium
    - Polonium
    - Potassium-40
    - Protactinium *(includes information for actinium)*
    - Radium *(includes information for radon and lead)*
    - Strontium *(includes information for yttrium)*
    - Technetium
    - Thorium
    - Uranium *(includes information on chemical toxicity)*

2. One fact sheet describing the radionuclide-specific information included in the set above, a figure that illustrates their internal distribution following intake, two summary tables:

    - Basic concepts for radioactive properties, internal distribution, and risk coefficients
    - Figure C.1: Initial radionuclide distribution in the body following intake
    - Table C.1: Radioactive properties
    - Table C.2: Mortality and morbidity risk coefficients

3. Five chemical fact sheets, including three for selected IWCS contaminants and two on mixtures, as context for the cumulative risk evaluation:

    - Arsenic
    - Lead
    - Polychorinated biphenyls (PCBs)
    - Basic concepts for mixtures
    - Mixtures of arsenic, cadmium, chromium, and lead

REFERENCE

J. Peterson, M. MacDonell, L. Haroun, R.D. Hildebrand, A. Taboas, and K. Keil, 2012, *Radiological and Chemical Fact Sheets to Support Health Risk Analyses for Contaminated Areas* (updates of the 2007 fact sheet report), prepared by Argonne National Laboratory, Environmental Science Division, in collaboration with R.D. Hildebrand, U.S. Department of Energy (DOE), Richland Operations Office; A. Taboas, DOE Chicago Operations Office, and K. Keil, U.S. Army Corps of Engineers, Buffalo District.

Americium

Symbol: **Am**

Atomic Number: **95**
(protons in nucleus)

Atomic Weight: **-**
(not naturally occurring)

What Is It? Americium is a malleable, silvery white metal that tarnishes slowly in dry air at room temperature. Americium does not occur naturally but is produced artificially by successive neutron capture reactions by plutonium isotopes. There are sixteen known isotopes of americium and all of them are radioactive. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) Americium-241 was first produced in 1944 in a nuclear reactor at the University of Chicago. Dr. Glenn Seaborg gave the new element its name in 1946 in honor of the continent on which it was discovered.

Of the sixteen radioactive isotopes, only three have half-lives long enough to warrant concern at Department of Energy (DOE) environmental management sites: americium-241, americium-242m, and americium-243. The half-lives of these three isotopes range from 150 to 7,400 years, while those of the other isotopes are less than a day. Americium-241 is generally the most prevalent isotope at DOE sites such as Hanford. It has a half-life of 430 years and decays by emitting an alpha particle with attendant gamma radiation. The other two isotopes typically represent less than a few percent of the total americium inventory at a site. Americium-242m (the "m" means metastable) has a half-life of 150 years, and it decays by isomeric transition. Americium-243 is generally not a major concern at DOE sites given its low abundance relative to americium-241 and low specific activity.

Radioactive Properties of Key Americium Isotopes and Associated Radionuclides

Isotope	Half-Life	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Am-241	430 yr	3.5	α	5.5	0.052	0.033
Am-242m	150 yr	9.8	IT	0.025	0.044	0.0051
Am-242	*16 hr*	*820,000*	*β, EC*	-	*0.18*	*0.018*
Am-243	7,400 yr	0.20	α	5.3	0.022	0.055
Np-239	*2.4 days*	*230,000*	*β*	-	*0.26*	*0.17*

IT = isomeric transition, EC = electron capture, Ci = curie, g = gram, and MeV = million electron volts; a dash means that the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Americium-242 decays by two means: by emitting a beta particle (83%) and by electron capture (17%). Certain properties of americium-242 and neptunium-239 are included here because these radionuclides accompany the americium decays. Values are given to two significant figures.

Where Does It Come From? Americium is a byproduct of plutonium production activities and results from the successive capture of neutrons by plutonium. The most common isotope is americium-241, a decay product of plutonium-241. When plutonium-239 absorbs two neutrons it produces plutonium-241, which decays by emitting a beta particle with a fairly short half-life of 14 years to generate americium-241. Americium-243 is produced in a similar manner from the decay of plutonium-243, which decays by emitting a beta particle with a half-life of 5 hours. Successive neutron absorptions of the isotope americium-241can produce both americium-242m and americium-243.

How Is It Used? The most common use of americium is in smoke detectors. These detectors rely on the alpha particle associated with the decay of americium-241 to ionize the air in a gap between two electrodes, causing a very small electrical current to flow between them. When smoke enters the space between the electrodes, the alpha radiation is absorbed by the soot particles, the current is interrupted, and the alarm is sounded. Alpha particles from smoke detectors do not themselves pose a health hazard, as they are absorbed in a few centimeters of air or by the structure of the detector. Americium is also used as a portable source for gamma radiography, for crystal research, and as target material in nuclear reactors or particle accelerators to produce even heavier elements. A common neutron source is composed of americium-241 and beryllium. The alpha particle given off during the radioactive decay of americium-241 is absorbed by beryllium-9, producing carbon-12 and a neutron. Such devices can be used for the nondestructive testing of machinery and equipment and for other industrial applications.

What's in the Environment? Atmospheric testing of nuclear weapons, which ceased worldwide by 1980, generated most environmental americium. Accidents and other releases from weapons production facilities have caused localized contamination. Americium oxide is the most common form in the environment. Average americium-241 levels in surface soil are about 0.01 picocuries (pCi)/g. Americium is typically quite insoluble, although a small fraction can become soluble through chemical and biological processes. It adheres very strongly to soil, with americium concentrations associated with sandy soil particles estimated to be 1,900 times higher than in interstitial water (the water in the pore spaces between the soil particles); it binds more tightly to loam and clay soils so those concentration ratios are even higher. At DOE sites such as Hanford, americium can be present in areas that contain waste from the processing of irradiated fuel.

What Happens to It in the Body? Americium can be taken into the body by eating food, drinking water, or breathing air. Gastrointestinal absorption from food or water is a likely source of internally deposited americium in the general population. After ingestion or inhalation, most americium is excreted from the body within a few days and never enters the bloodstream; only about 0.05% of the amount taken into the body by ingestion is absorbed into the blood. After leaving the intestine or lung, about 10% clears the body. The rest of what enters the bloodstream deposits about equally in the liver and skeleton where it remains for long periods of time, with biological retention half-lives of about 20 and 50 years, respectively (per simplified models that do not reflect intermediate redistribution). The amount deposited in the liver and skeleton depends on the age of the individual, with fractional uptake in the liver increasing with age. Americium in the skeleton is deposited uniformly on cortical and trabecular surfaces of bones and slowly redistributes throughout the volume of mineral bone over time.

What Are the Primary Health Effects? Americium is generally a health hazard only if it is taken into the body, although there is a small risk associated with the gamma rays emitted by neptunium-239, a radioactive decay product of americium-243. The main means of exposure are ingestion of food and water containing americium isotopes and inhalation of americium-contaminated dust. Ingestion is generally the exposure of concern unless there is a nearby source of contaminated airborne dust. Because americium is taken up in the body much more readily if inhaled rather than ingested, both exposure routes can be important. The major health concern is tumors resulting from the ionizing radiation emitted by americium isotopes deposited on bone surfaces and in the liver.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including americium *(see box at right).* While ingestion is generally the most common type of exposure, the risk coefficients for this route are much lower than those for inhalation. As for other nuclides, the coefficient for tap water is about 80% of that shown for dietary ingestion.

In addition to risks from internal exposures, there is an external gamma exposure risk associated with americium-243. To estimate a lifetime cancer mortality risk, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial average concentration of 1 pCi/g americium-243, then 3 of these 100,000 people would be predicted to incur a fatal cancer. (This is in comparison to the 20,000 people from the group predicted to die of cancer from all other causes per the U.S. average.) This risk is largely associated with the gamma ray emitted by its short-lived decay product neptunium-239. The external risk for the other two americium isotopes is less than 10% of that for americium-243 (see Table C.2).

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. These values include the contributions from the short-lived americium decay products. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Americium-241	2.4×10^{-8}	9.5×10^{-11}
Americium-242m	1.3×10^{-8}	6.8×10^{-11}
Americium-243	2.3×10^{-8}	9.8×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Carbon-14

Symbol:	**C(-14)**
Atomic Number: *(protons in nucleus)*	**6**
Atomic Weight: *(naturally occurring)*	**12**

What Is It? Carbon-14 is a naturally occurring radioactive isotope of carbon. (An isotope is a different form of an element that has the same number of protons in the nucleus but a different number of neutrons.) Carbon is widely distributed in nature and is present in all organic compounds. Natural forms include diamonds and graphite, which are among the hardest and softest minerals known, respectively. The nucleus of a carbon-14 atom contains six protons and eight neutrons. There are two stable (nonradioactive) isotopes of carbon: carbon-12, which has six protons and six neutrons, and carbon-13, which has six protons and seven neutrons. Carbon-12 comprises most (about 99%) of naturally occurring carbon, and carbon-13 accounts for about 1.1%. Naturally occurring carbon contains an extremely small fraction (about two trillionths) of radioactive carbon-14.

There are several radioactive isotopes of carbon in addition to carbon-14. These isotopes are very short-lived – with half-lives ranging from 20 minutes for carbon-11 to less than a second – so they are not a health concern for Department of Energy (DOE) environmental management sites. The half-life of carbon-14 is about 5,700 years, and it decays by emitting a beta particle with no attendant gamma radiation to produce nitrogen-14. Carbon-14 is an important radionuclide in the low-level radioactive wastes previously disposed of at Hanford.

Radioactive Properties of Carbon-14

Isotope	Half-Life *(yr)*	Natural Abundance *(%)*	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
					Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
C-14	5,700	<<1	4.5	β	-	0.049	-

Ci = curie, g = gram, and MeV = million electron volts; a dash means the entry is not applicable. (See companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for explanation of terms and interpretation of radiation energies.) Values are given to two significant figures.

Where Does It Come From? Carbon-14 is produced naturally in the upper atmosphere by the reaction of neutrons originating from cosmic rays with nitrogen and, to a lesser extent, with oxygen and carbon. The natural steady-state inventory of carbon-14 in the biosphere is about 300 million Ci, most of which is in the oceans. Large amounts of carbon-14 have also been released to the atmosphere as a result of nuclear weapons testing. Weapons testing through 1963 added about 9.6 million Ci, an increase of 3% above natural steady-state levels. Carbon-14 is also made commercially for use in medical or biological tracer research. Carbon-14 is produced in nuclear reactors by the capture of neutrons by nitrogen, carbon, or oxygen present as components of the fuel, moderator, or structural hardware. The contribution to the carbon-14 global inventory from commercial nuclear reactors and DOE facilities in the United States has been less than 600 Ci per year, or less than 1/500,000th of the natural steady-state level. Carbon-14 was produced at Hanford by neutron activation of carbon in graphite-moderated plutonium-production reactors in the 100 Area. Carbon-14 is present in the graphite moderator of these shutdown reactors and in certain wastes associated with previous reactor operations, as well as in wastes from ongoing decommissioning activities, including for spent graphite.

How Is It Used? Two main uses of carbon-14 are in diagnostic medical procedures and radiocarbon dating to determine the age of previously living animals and plants. In medicine, carbon-14 can be injected to study abnormalities of metabolism that underlie diabetes, gout, anemia, and acromegaly (adult "gigantism"), and to trace the metabolism of new drugs. However, its main use to date has been to determine the age of fossils and other dead organic material. All living organisms absorb carbon from the environment, which contains carbon-12 and carbon-14 in a fixed ratio. When an organism dies, it no longer takes in carbon through respiration so the amount of carbon-14 will decrease at a constant rate due to radioactive decay, resulting in a lower ratio of carbon-14 to carbon-12 over time. Because this is constant in all living organisms, one can determine when an organism died by measuring the ratio of these

two isotopes. Radiocarbon dating is considered one of the most reliable means of determining the age of artifacts containing plant or animal matter, including some prehistoric materials up to 50,000 years old.

What's in the Environment? Carbon-14 is present in the atmosphere, oceans, and all organic material, and it behaves in the environment in the same manner as other carbon isotopes. The largest source is in the upper atmosphere where nitrogen interacts with neutrons from cosmic rays, with about 38,000 Ci of carbon-14 being produced by this process each year. Carbon-14 occurs in the ratio of 6 picocuries (pCi) of carbon-14 per gram of total carbon, and it is assimilated into tissues of all plants and animals just like other carbon isotopes. The atmospheric inventory is estimated at 13 million Ci, and it is generally present as carbon dioxide with less than 1% in the form of carbon monoxide, methane, formaldehyde, and other molecules. Carbon-14 distributes throughout the atmosphere and surface ocean waters over a period of several years. Transfer to deep ocean waters proceeds much more slowly, taking hundreds to thousands of years. The carbon-14 concentration in the troposphere has been reported to be 3.4 pCi per kilogram of air, and its concentration in soil is about 0.2 pCi/g. Carbon-14 can be present at sites with graphite-moderated reactors. It is not a major contaminant in site groundwater due to its low leachability from graphite waste and limited presence in soil. Concentrations in sandy soil are estimated to be 5 times higher than in the interstitial water (in the pore spaces between the soil particles). Thus, carbon-14 that does leach from solids to soil can move downward fairly quickly with percolating water to groundwater.

What Happens to It in the Body? Carbon-14 can be taken into the body by drinking water, eating food, or breathing air. Carbon-14 is present in the human body at a level of about 0.1 microcurie (or 100,000 pCi) in adults, and it behaves in the same manner as other carbon isotopes. Most carbon-14 is almost completely absorbed upon ingestion, moving quickly from the gastrointestinal tract to the bloodstream. However, some carbon-containing compounds in food, such as cholesterol, fat-soluble vitamins, cellulose, and polysaccharides, may be less completely absorbed. The fractional uptake of carbon-14 by inhalation is strongly dependent on its chemical form. For carbon dioxide gas and organic compounds, essentially all inhaled carbon-14 is absorbed into the bloodstream, while for carbon monoxide gas the absorption fraction is about 40%. The absorption fraction for carbon-14 on inorganic particulate aerosols is significantly lower. The carbon-14 that enters the bloodstream after either ingestion or inhalation is quickly distributed to all organs and tissues of the body, as for other isotopes of carbon. Carbon-14 is eliminated from the body with a biological half-life of 40 days.

What Is the Primary Health Effect? Carbon-14 poses a health hazard only if it is taken into the body, because it decays by emitting a weak beta particle with no gamma radiation. The beta particle emitted by carbon-14 has low energy and cannot penetrate deeply into tissue or travel far in air. Carbon-14 behaves the same as ordinary carbon, both in the environment and in the human body. Hence, a significant fraction of the carbon-14 taken in by either ingestion or inhalation is absorbed into the bloodstream, where it is transferred to all organs of the body. The health hazard of carbon-14 is associated with cell damage caused by the ionizing radiation that results from radioactive decay, with the potential for subsequent cancer induction.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including carbon-14 *(see box at right).* Additional values are also available, including for inhalation of carbon-14 as a gaseous oxide, i.e., as carbon monoxide and carbon dioxide. As for other radionuclides, the risk coefficient for tap water is about 80% of that for dietary ingestion.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. The recommended default absorption type was used for inhalation as an organic particulate, and the dietary value was used for ingestion. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Carbon-14	6.5×10^{-12}	1.4×10^{-12}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Cesium

Symbol:	**Cs**
Atomic Number: *(protons in nucleus)*	**55**
Atomic Weight: *(naturally occurring)*	**133**

What Is It? Cesium is a soft, silvery white-gray metal that occurs in nature as cesium-133. The natural source yielding the greatest quantity of cesium is the rare mineral pollucite. American ores of pollucite, found in Maine and South Dakota, contain about 13% cesium oxide. Although it is a metal, cesium melts at the relatively low temperature of 28° C (82° F), so like mercury it is liquid at moderate temperatures. This most alkaline of metals reacts explosively when it comes in contact with cold water.

There are 11 major radioactive isotopes of cesium. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) Only three have half-lives long enough to warrant concern: cesium-134, cesium-135 and cesium-137. Each of these decays by emitting a beta particle, and their half-lives range from about 2 to 2 million years. The half-lives of the other cesium isotopes are less than two weeks. Of these three, the isotope of most concern for Department of Energy (DOE) environmental management sites and other areas is cesium-137 which has a half-life of 30 years. Its decay product, barium-137m (the "m" means metastable) stabilizes itself by emitting an energetic gamma ray with a half-life of about 2.6 minutes. It is this decay product that makes cesium an external hazard (that is, a hazard without being taken into the body). Cesium-135 and cesium-134 are typically of less concern because of their radiological decay characteristics. The very long half-life of cesium-135 means it has a very low specific activity, and the slow decay rate combined with its low decay energy contribute to its low hazard. Cesium-134 has a half-life of 2.1 years and decays by emitting a beta particle. The relatively small amount of cesium-134 produced more than 20 years ago would essentially be all gone today due to radioactive decay.

Radioactive Properties of Key Cesium Isotopes and an Associated Radionuclide

Isotope	Half-Life	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Cs-134	2.1 yr	1,300	β	-	0.16	1.6
Cs-135	2.3 million yr	0.0012	β	-	0.067	-
Cs-137	30 yr	88	β	-	0.19	-
Ba-137m (95%)	*2.6 min*	*540 million*	*IT*	-	*0.065*	*0.60*

IT = isomeric transition, Ci = curie, g = gram, and MeV = million electron volts; a dash indicates that the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Certain properties of barium-137m are included here because this radionuclide accompanies the cesium decays. Values are given to two significant figures.

Where Does It Come From? Cesium is naturally present as the isotope 133 in various ores and to a lesser extent in soil. The three radioactive cesium isotopes identified above are produced by nuclear fission. When an atom of uranium-235 (or other fissile nuclide) fissions, it generally splits asymmetrically into two large fragments – fission products with mass numbers in the range of about 90 and 140 – and two or three neutrons. (The mass number is the sum of the number of protons and neutrons in the nucleus of the atom.) Cesium radionuclides are such fission products, with cesium-135 and cesium-137 being produced with relatively high yields of about 7% and 6%, respectively. That is, about 7 atoms of cesium-135 and 6 atoms of cesium-137 are produced per 100 fissions. Cesium-137 is a major radionuclide in spent nuclear fuel, high-level radioactive wastes resulting from the processing of spent nuclear fuel, and radioactive wastes associated with the operation of nuclear reactors and fuel reprocessing plants.

How Is It Used? Cesium metal is used in photoelectric cells and various optical instruments, and cesium compounds are used in the production of glass and ceramics. Cesium-137 is also used in brachytherapy to treat various types of cancer. (Brachytherapy is a method of radiation treatment in which sealed sources are used to deliver a radiation dose at a distance of up to a few centimeters by surface, intracavitary, or interstitial application.)

What's in the Environment? Cesium-133 exists naturally as a stable isotope. The concentration of cesium in the earth's crust is 1.9 milligrams per kilogram (mg/kg), and the concentration in seawater is about 0.5 micrograms/kg. Cesium has been shown to biomagnify in aquatic food chains. Radioactive cesium is present in soil around the world largely as a result of fallout from past atmospheric nuclear weapons tests. The concentration of cesium-137 in surface soil from fallout ranges from about 0.1 to 1 picocurie (pCi)/g, averaging less than 0.4 pCi/g (or 0.3 billionth of a milligram per kilogram soil). Cesium is also present as a contaminant at certain locations, such as nuclear reactors and facilities that process spent nuclear fuel.

Cesium is generally one of the less mobile radioactive metals in the environment. It preferentially adheres quite well to soil, and the concentration associated with sandy soil particles is estimated to be 280 times higher than in interstitial water (water in the pore space between soil particles); concentration ratios are much higher (about 2,000 to more than 4,000) in clay and loam soils. Thus, cesium is generally not a major contaminant in groundwater at DOE sites or other locations.

What Happens to It in the Body? Cesium can be taken into the body by eating food, drinking water, or breathing air. After being taken in, cesium behaves in a manner similar to potassium and distributes uniformly throughout the body. Gastrointestinal absorption from food or water is the principal source of internally deposited cesium in the general population. Essentially all cesium that is ingested is absorbed into the bloodstream through the intestines. Cesium tends to concentrate in muscles because of their relatively large mass. Like potassium, cesium is excreted from the body fairly quickly. In an adult, 10% is excreted with a biological half-life of 2 days, and the rest leaves the body with a biological half-life of 110 days. Clearance from the body is somewhat quicker for children and adolescents. This means that if someone is exposed to radioactive cesium and the source of exposure is removed, much of the cesium will readily clear the body along the normal pathways for potassium excretion within several months.

What Are the Primary Health Effects? Cesium-137 presents an external as well as internal health hazard. The strong external gamma radiation associated with its short-lived decay product barium-137m makes external exposure a concern, and shielding is often needed to handle materials containing large concentrations of cesium. While in the body, cesium poses a health hazard from both beta and gamma radiation, and the main health concern is associated with the increased likelihood for inducing cancer.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including cesium *(see box at right)*. While the coefficients for ingestion are somewhat lower than for inhalation, ingestion is generally the most common means of entry into the body. Similar to other radionuclides, the risk coefficients for tap water are about 80% of those for dietary ingestion.

In addition to risks from internal exposures, there is a risk from external gamma exposure. Using the external gamma risk coefficient to estimate a lifetime cancer mortality risk, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial average concentration of 1 pCi/g cesium-137, then 6 of these 100,000 people would be predicted to incur a fatal cancer. (This is in comparison to about 20,000 people from the group predicted to die of cancer from all other causes per the general U.S. average.) This risk is largely associated with the gamma ray from barium-137m.

Radiological Risk Coefficients

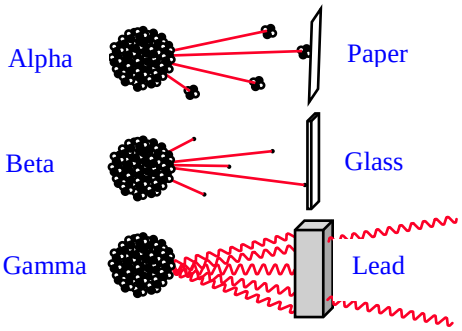
This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. The cesium-137 values include the contribution from the decay product barium-137m. (See text at left for information on the risk from external exposure.) Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Cesium-134	1.1×10^{-11}	3.5×10^{-11}
Cesium-135	1.3×10^{-12}	4.0×10^{-12}
Cesium-137	8.1×10^{-12}	2.6×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

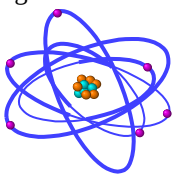
Ionizing Radiation

What Is It? Ionizing radiation is energy that is carried by any of several types of particles and rays (electromagnetic radiation) given off by radioactive material, X-ray machines, and nuclear reactions. This energy can knock electrons out of molecules with which they interact, thus creating ions. Non-ionizing radiation, such as that emitted by a laser, is different because it does not create ions when it interacts with matter but dissipates energy generally in the form of heat. The three main types of ionizing radiation are alpha particles, beta particles, and gamma rays.



An alpha particle consists of two protons and two neutrons and is identical to the nucleus of a helium atom. Because of its relatively large mass and charge, an alpha particle produces ions in a very localized area. An alpha particle loses some of its energy each time it produces an ion (its positive charge pulls electrons away from atoms in its path), finally acquiring two electrons from an atom at the end of its path to become a complete helium atom. An alpha particle has a short range (several centimeters) in air and cannot penetrate the outer layer of skin.

Beta particles can be either negative (negatron) or positive (positron). Negatrons are identical to electrons and originate in the nucleus of an atom that undergoes radioactive decay by changing a neutron into a proton. The only difference between a negative beta particle (negatron) and an electron is the ancestry. A beta particle originates in the nucleus whereas an electron is external to the nucleus. Unless otherwise specified, the term "beta particle" generally refers to a negatron. A positron is emitted from an atom that decays by changing a proton into a neutron. Beta particles are smaller and more penetrating than alpha particles, but their range in tissue is still quite limited. When its energy is spent, a negatron attaches itself to an atom and becomes an ordinary electron, while a positron collides with an ambient electron and the two particles annihilate each other, producing two gamma rays. When a negatron passes close to the nucleus of an atom, the strong attractive Coulomb force causes the beta particle to deviate sharply and lose energy at a rate proportional to the square of the acceleration. This energy manifests itself as photons termed Bremsstrahlung. The amount of beta energy converted into photons is directly proportional to the energy of the beta particle. This effect is only significant for high-energy beta particles generally passing through very dense materials such as lead, i.e., those with higher atomic numbers and so more protons in the nucleus.



Gamma rays are electromagnetic radiation given off by an atom as a means of releasing excess energy. They are bundles (quanta) of energy that have no charge or mass and can travel long distances through air (up to several hundred meters), body tissue, and other materials. A gamma ray can pass through a body without hitting anything, or it may hit an atom and give that atom all or part of its energy. This normally knocks an electron out of the atom, ionizing it. This electron then uses the energy it receives from the gamma ray to create additional ions by knocking electrons out of other atoms. Because a gamma ray is pure energy, it no longer exists once it loses all its energy. The capability of a gamma ray to do damage is a function of its energy, where the distance between ionizing events is large on the scale of the nucleus of a cell. Additional forms of ionizing radiation beyond the three types shown in the figure above include neutrons, protons, neutrinos, muons, pions, heavy charged particles, X-rays and others. Essentially all radioactive materials at the Hanford Site originated from neutron interactions with uranium fuel to produce plutonium. Byproducts of this process include fission products (most of which are in the high-level waste currently in on-site storage), activation products in the containment and reactor coolant materials, and various radioactive wastes. However, the radioactive hazards that remain at the Hanford Site are largely those associated with the three general types of radiation shown above, so the discussion here is limited to these three.

Where Does It Come From? All organisms are being exposed to ionizing radiation from natural sources all the time. Radiation doses are typically given in units of rem – an acronym for Roentgen equivalent man – or millirem (mrem), which is one one-thousandth of a rem. This unit was developed to allow for the consistent reporting of hazards associated with the various types and energies of radiation on the human body. The rem is the product of the absorbed dose in rads (i.e., the amount of energy imparted to tissue by the radiation, where 1 rad equals 0.01 joules/kg) and factors for the relative biological effectiveness (RBE) of the radiation. The RBE is directly related to the linear energy transfer (LET) or distance over which the radiation energy is imparted to the absorbing medium and is accounted for by a quality factor. For example, alpha particles are 20 times more hazardous than beta particles for the same energy deposition and hence have a quality factor of 20, whereas the quality factor for beta particles is one. The International Commission on Radiological Protection (ICRP) has developed a methodology for reporting the effective dose. This is the product of the dose (in rem or mrem) to individual tissues and the tissue-specific weighting factors (fractional values less than one) that indicate the total detriment to the body, including cancer induction from irradiation of that tissue, summed over all relevant tissues. By use of the effective dose, it is possible to compare the relative radiation hazards from various types of radiation that impact different organs of the body. The doses discussed below are effective doses.

The National Council on Radiation Protection and Measurements (NCRP) estimates the average annual dose to an individual in the United States is 620 mrem, evenly split between natural and man-made sources. Of the natural sources, about 37% is from radon gas decay products, 5% from cosmic radiation, 3% from terrestrial radiation, and 5% from internal sources such as potassium-40. Contributions from man-made sources include computed tomography (CT) scans (24%), nuclear medicine (12%), medical X-rays and fluoroscopies (12%), consumer products (2%), and radioactive fallout and nuclear power plants (<1%). These percentages are representative, and not all people are exposed to the same sources to the same degree. For reference, a typical chest X-ray produces a dose of about 2 mrem, and a person flying cross-country receives about 3 mrem.

How Is It Used? Radioactive materials and other sources of ionizing radiation are widely used to diagnose and treat diseases in human and veterinary medicine. CT scans and fluoroscopy procedures are common in medical diagnostics. Medical and dental X-rays are used to detect problems such as broken bones and dental cavities. Sealed radiation sources are used to deliver very high, localized radiation doses to treat certain types of cancers. Ionizing radiation also has a number of industrial and commercial uses. Radioactive sources are used in consumer products such as smoke detectors and to sterilize food products. Ionizing radiation is also used to test materials, inspect welds, generate heat and electricity for space travel, determine soil moisture content, and track the movement of various elements in the environment and human body (through use of radioactive tracers). Additional uses continue to be identified.

What's in the Environment? Exposure to background radiation and naturally occurring radioactive materials results in an annual dose of about 310 mrem/yr. Of this total, about one-third is due to external ionizing radiation, the main contributors being cosmic rays (33 mrem/yr), terrestrial gamma rays (21 mrem/yr), and radionuclides within the body other than radon-222 decay products (50 mrem/yr). Cosmic rays are produced when subatomic particles originating outside the solar system interact with particles in the upper atmosphere to produce gamma rays, neutrons and leptons that can reach and penetrate the earth's surface. It is these secondary particles and rays that produce the dose from cosmic radiation. Naturally occurring radioactive elements such as uranium, thorium and radium are present in soil, rock, water, and all other environmental media, and certain of these radionuclides (and their radioactive decay products) give off gamma rays as they undergo radioactive decay. The principal contributor to the dose from radionuclides in the body (other than radon-222 progeny) is potassium-40, which decays by emitting an energetic beta particle and gamma rays. About two-thirds of the natural background radiation dose (of 310 mrem/yr) is due to intake of radionuclides into the body. The largest contributor is inhalation of radon-220 and radon-222 gases and their short-lived radioactive decay products, which are charged particles that readily attach to airborne dust particles. Inhalation of radon gas contributes about 310 mrem/yr, and most of this dose is due to the short-lived radon-222 decay products polonium-218 and polonium-214. Ingestion of food and water containing naturally occurring radionuclides accounts for only a few mrem/yr.

What Are the Primary Health Effects? High doses of ionizing radiation can lead to effects such as skin burns, hair loss, birth defects, illness, cancer, and death, depending on the dose and the period of time over which it is received. Acute doses (such as from a serious accident involving nuclear materials) can result in damage to the blood-forming organs, gastrointestinal tract, and central nervous system. Very high doses, e.g., on the order of 500 rem (or 500,000 mrem) or more, can cause death in many (but not all) individuals, depending on the degree of medical intervention. The main health concern associated with radiation exposure is the induction of various cancers. Additional effects may include genetic mutations (although none have been observed in humans) and teratogenic effects such as mental retardation. The U.S. Environmental Protection Agency (EPA) has indicated that for radioactively contaminated Superfund sites, the risk from cancer is limiting and should be used as the sole basis for assessing radiation-related human health risks. The EPA noted that on average, about 50% of all cancers that can be induced by radiation (they can also be caused by other agents) are fatal, ranging from about 10% for thyroid cancer to 100% for liver cancer. Other EPA estimates for specific isotopes indicate the average may be higher, e.g., 60 to 70% or more.

What Happens to It in the Body? Radioactive materials can enter the body by inhalation, ingestion, or dermal absorption. In addition, gamma radiation external to the body can penetrate the skin and produce a dose in various tissues. Inhalation is the primary exposure mode for gaseous radionuclides (such as radon), and particulates near the source of an airborne release. A fractional amount of inhaled radionuclides is transferred from the lungs to the blood, where it distributes to other organs. The extent of absorption is strongly dependent on the radionuclide and its chemical form. Ingestion is the primary uptake mode for radionuclides in soil, water, and food, including those naturally occurring (such as radium and uranium in soil and groundwater) and man-made (such as plutonium from radioactive fallout). A fractional amount of ingested radionuclides is absorbed from the gastrointestinal tract into the blood while the rest clears the body through normal biological processes via urine and feces. As with inhalation, the extent of uptake depends on the radionuclide and its chemical form. The skin is generally an effective barrier against absorption of radionuclides, so dermal absorption is a very minor route of exposure. An exception to this is dermal absorption of tritiated water, i.e., water containing some amount of tritium (hydrogen-3) in place of a normal hydrogen atom in the water molecule, which is absorbed through the skin in the same manner as ordinary water.

What Is the Risk? While the EPA has developed lifetime cancer mortality risk coefficients for nearly all radionuclides, the agency has not developed a risk coefficient for ionizing radiation as a general category. A nominal mortality value of 6×10^{-7} incremental cancer risk per mrem has been identified for low-LET radiation delivered at a low dose and dose rate.

Natural Decay Series: Uranium. Radium. and Thorium

Uranium, radium, and thorium occur in three natural decay series, headed by uranium-238, thorium-232, and uranium-235, respectively. In nature, the radionuclides in these three series are approximately in a state of secular equilibrium, in which the activities of all radionuclides within each series are nearly equal.

Two conditions are necessary for secular equilibrium. First, the parent radionuclide must have a half-life much longer than that of any other radionuclide in the series. Second, a sufficiently long period of time must have elapsed, for example ten half-lives of the decay product having the longest half-life, to allow for ingrowth of the decay products *(see the companion fact sheet on Ionizing Radiation).* Under secular equilibrium, the activity of the parent radionuclide undergoes no appreciable changes during many half-lives of its decay products.

The radionuclides of the uranium-238, thorium-232, and uranium-235 decay series are shown in Figures C.2, C.3, and C.4, along with the major mode of radioactive decay for each. Radioactive decay occurs when an unstable (radioactive) isotope transforms to a more stable isotope, generally by emitting a subatomic particle such as an alpha or beta particle. Radionuclides that give rise to alpha and beta particles are shown in these figures, as are those that emit significant gamma radiation.

Gamma radiation is not a mode of radioactive decay (such as alpha and beta decay). Rather, it is a mechanism by which excess energy is emitted from certain radionuclides, i.e., as highly energetic electromagnetic radiation emitted from the nucleus of the atom. For simplicity, only significant gamma emissions associated with the major decay modes are shown in Figures C.2 through C.4; that is, radionuclides listed are those for which the radiation dose associated with gamma rays may pose a health concern. The gamma component is not shown for those radionuclides whose gamma emissions do not generally represent a concern.

Of the two conditions noted above for secular equilibrium, the first is generally met for the uranium-238, thorium-232 and uranium-235 decay series in naturally occurring ores. While the second condition may not be met for all ores or other deposits of uranium and thorium (given the extremely long half-lives for the radionuclides involved and the geological changes that occur over similar time scales), it is reasonable to assume secular equilibrium for naturally occurring ores to estimate the concentrations of the various daughter radionuclides that accompany the parent. The state of secular equilibrium in natural uranium and thorium ores is significantly altered when they are processed to extract specific radionuclides.

After processing, radionuclides with half-lives less than one year will reestablish equilibrium conditions with their longer-lived parent radionuclides within several years. For this reason, at processing sites what was once a single, long decay series (for example the series for uranium-238) may be present as several smaller decay series headed by the longer-lived decay products of the original series (that is, headed by uranium-238, uranium-234, thorium-230, radium-226, and lead-210 in the case of uranium-238). Each of these sub-series can be considered to represent a new, separate decay series. Understanding the physical and chemical processes associated with materials containing uranium, thorium, and radium is important when addressing associated radiological risks.

In the fact sheets developed for uranium, radium, and thorium, the contributions of radionuclides having half-lives less than one year were included in the risk coefficients. (Each fact sheet identifies which radionuclides are included in these coefficients.) In some situations, it may be necessary to add the radiological risk identified for a given radionuclide to that of its parent radionuclide to properly represent the total risk. For example, the radiological risk for thorium-232 is comprised of the risk for thorium-232 plus the risk for radium-228. Decay series information should be used together with the information in these fact sheets to ensure that the radiological risks associated with uranium, radium, and thorium are properly estimated and represented.

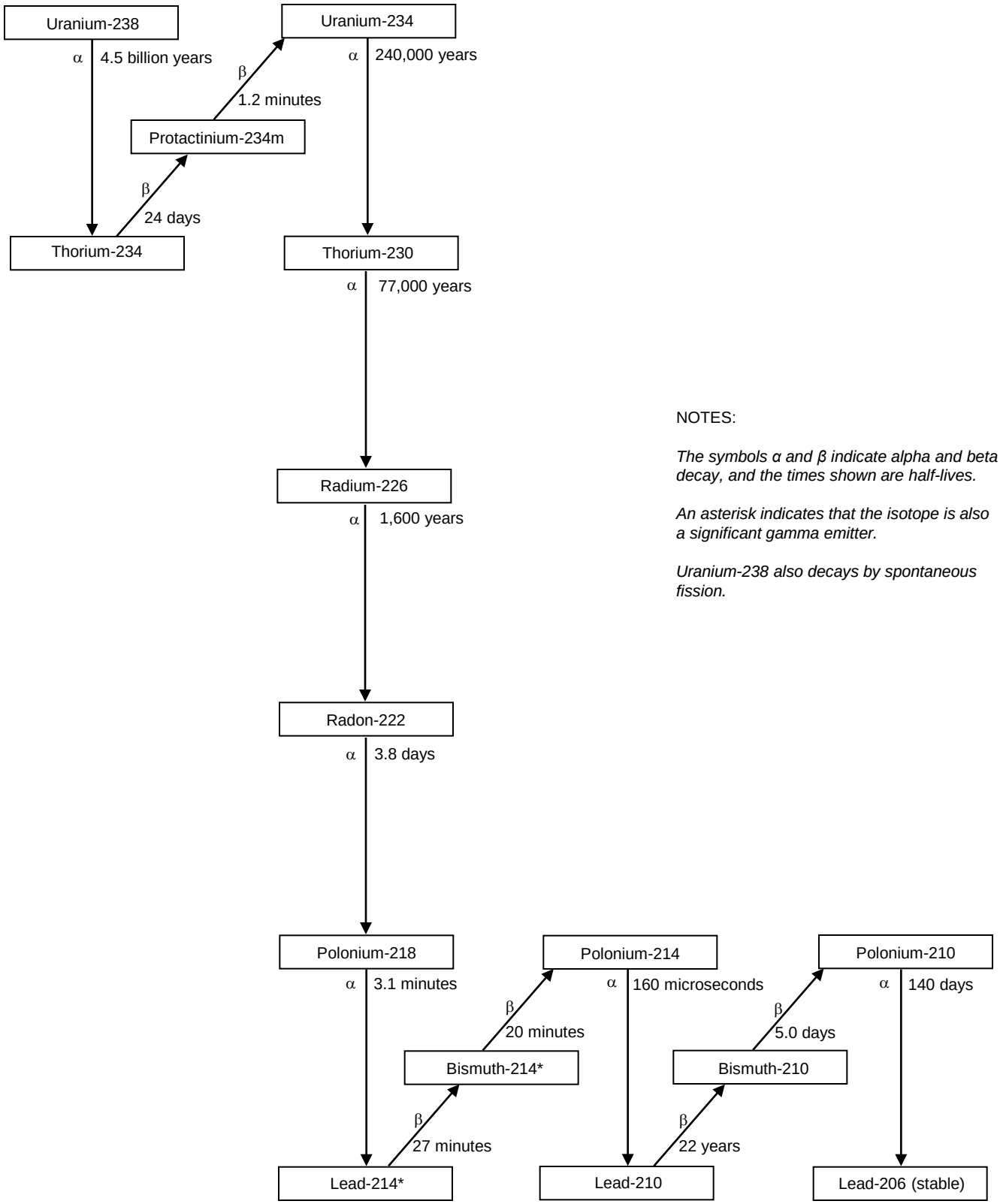
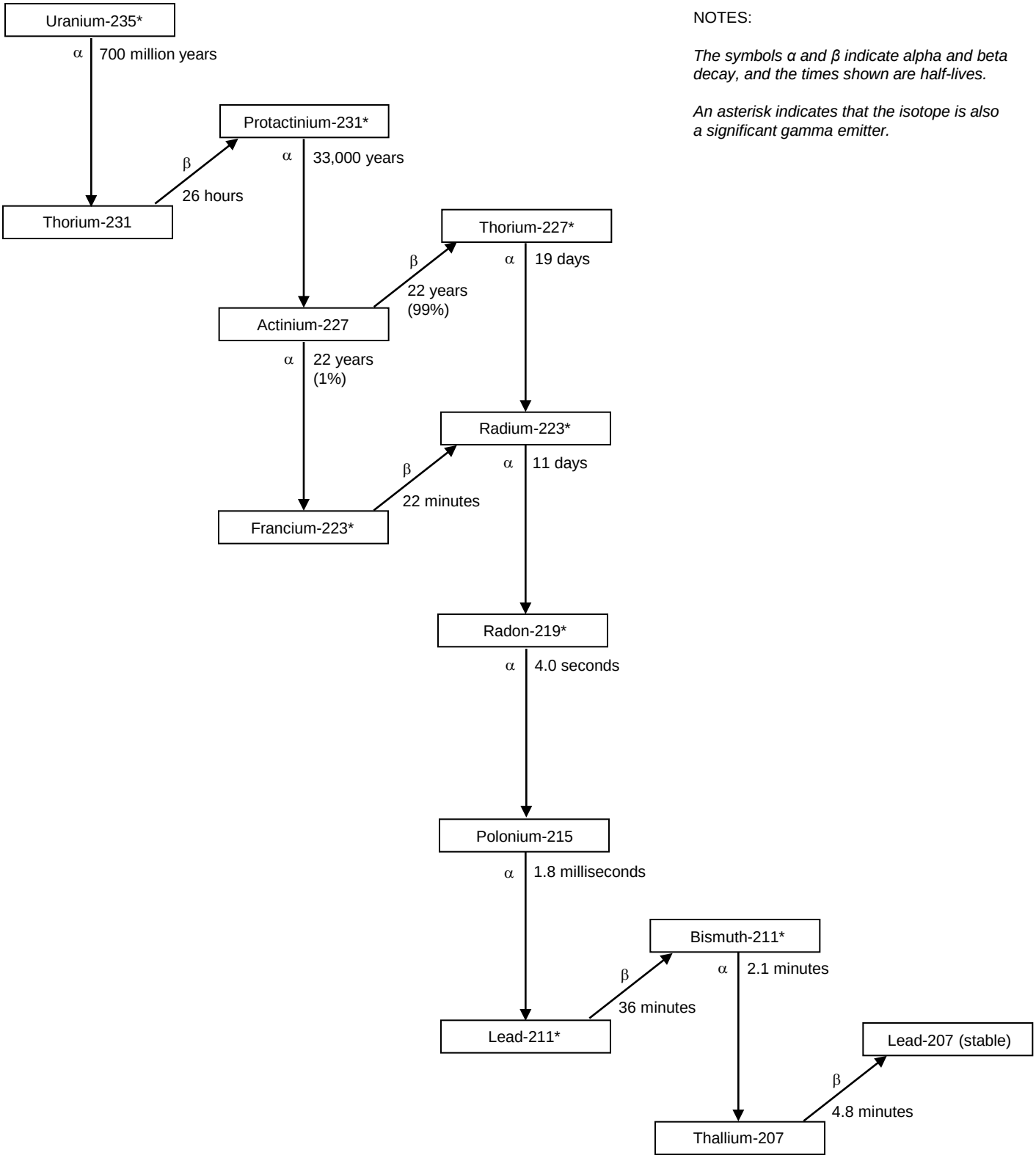


FIGURE N.1 Natural Decay Series: Uranium-238



NOTES:

The symbols α and β indicate alpha and beta decay, and the times shown are half-lives.

An asterisk indicates that the isotope is also a significant gamma emitter.

FIGURE N.2 Natural Decay Series: Uranium-235

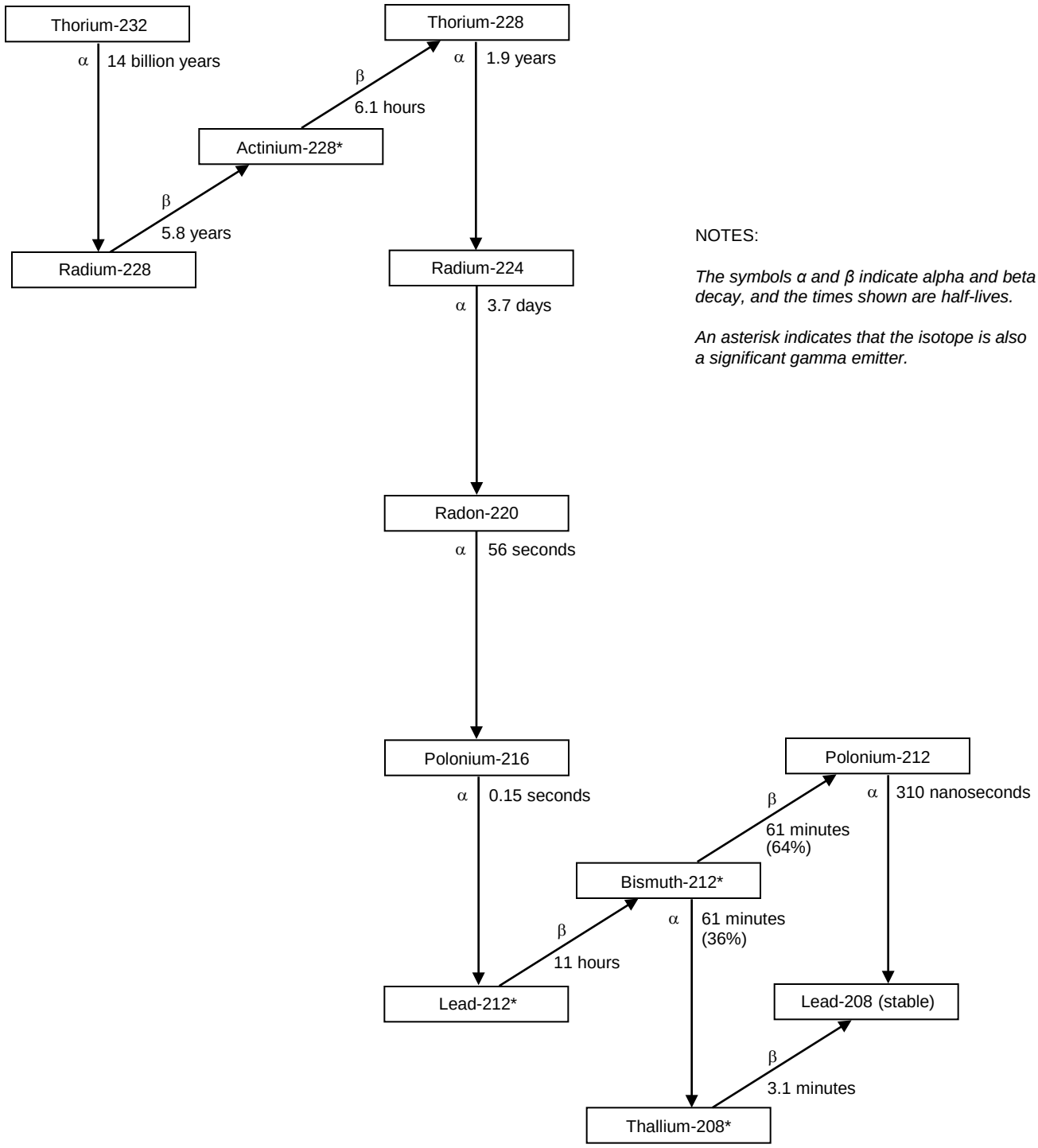


FIGURE N.3 Natural Decay Series: Thorium-232

Neptunium

Symbol:	**Np**
Atomic Number: *(protons in nucleus)*	**93**
Atomic Weight: *(not naturally occurring)*	**-**

What Is It? Neptunium is a ductile, silver-colored metal about twice as dense as lead. It does not occur naturally but is produced artificially by neutron capture reactions by uranium. There are seventeen known isotopes of neptunium, and all are radioactive. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) The first neptunium isotope to be identified was neptunium-239, which has a half-life of 2.4 days. This isotope was first produced in 1940 in a cyclotron at the University of California at Berkeley by bombarding uranium-238 with high-energy neutrons. Neptunium was the first transuranic element to be formed and was named for the planet Neptune.

Of the seventeen neptunium isotopes, only three have half-lives long enough to warrant concern at Department of Energy (DOE) environmental management sites: neptunium-235, neptunium-236, and neptunium-237. The half-lives of these three isotopes range from 1.1 to 2.1 million years, while those of the other isotopes are less than five days. Of the three, neptunium-237 is the most prevalent isotope at DOE sites such as Hanford. It has a half-life of 2.1 million years and decays by emitting an alpha particle. The other two isotopes typically represent less than a few percent of the total neptunium inventory at a site. Neptunium-235 has a half-life of 1.1 years and decays by electron capture; essentially all of this isotope that was produced more than 20 years ago has long since decayed away. Neptunium-236 has a half-life of 120,000 years and decays by emitting a beta particle and electron capture.

Radioactive Properties of Key Neptunium Isotopes and Associated Radionuclides

Isotope	Half-Life *(yr)*	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Np-235	1.1	1,400	EC	<	0.010	0.0071
Np-236	120,000	0.013	β, EC	-	0.21	0.14
Pu-236 (9%)	*2.9*	*540*	*α*	*5.8*	*0.013*	*0.0021*
Np-237	2.1 million	0.00071	α	4.8	0.070	0.035
Pa-233	*0.074*	*21,000*	*β*	-	*0.20*	*0.20*

EC = electron capture, Ci = curie, g = gram, and MeV = million electron volts; a "<" means the radiation energy is less than 0.001 MeV, and a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for explanation of terms and interpretation of radiation energies.) About 0.001% of the neptunium-235 decays are by alpha-particle emission. The isotope neptunium-236 decays both by emitting a beta particle (9%) and by electron capture (91%); another isotope of neptunium-236 with a half-life of 23 hours also exists. Certain properties of plutonium-236 and protactinium-233 are included here because these radionuclides accompany the neptunium decays. Values are given to two significant figures.

Where Does It Come From? Neptunium is a byproduct of plutonium production activities and results from the capture of neutrons by uranium isotopes, usually in a nuclear reactor. Neptunium isotopes can be formed by a variety of neutron capture and radioactive decay routes. Neptunium is present in spent nuclear fuel, high-level radioactive wastes resulting from the processing of spent nuclear fuel, and radioactive wastes associated with the operation of reactors and fuel reprocessing plants. Although neptunium is essentially not naturally present in the environment, very minute amounts may be associated with uranium ores.

How Is It Used? There are no major commercial uses of neptunium, although neptunium-237 is used as a component in neutron detection instruments. Neptunium-237 can also be used to make plutonium-238 (by absorption of a neutron). Neptunium is considered useable in nuclear weapons, although no country is known to have used it to make a nuclear explosive device.

What's in the Environment? Atmospheric testing of nuclear weapons, which ceased worldwide by 1980, generated most environmental neptunium. The level of neptunium in soil from fallout is quite low; for

example, the concentration of neptunium-237 is less than 1% of that for plutonium-239 (on the order of 0.0001 picocuries per gram, pCi/g). Accidents and other releases from weapons production facilities have caused localized contamination. Neptunium typically occurs in the environment as an oxide, although other forms can be present. It is generally more mobile than other transuranic elements such as plutonium, americium, and curium, and it can move down with percolating water to underlying layers of soil. Neptunium preferentially adheres to soil particles, with the concentration associated with sandy soil particles estimated to be about 5 times higher than in interstitial water (water in pore spaces between the soil particles); it bonds more tightly to clay soils, where concentration ratios are typically higher (55). Neptunium is readily taken up by plants, and plant concentrations are typically similar to soil concentrations.

What Happens to It in the Body? Neptunium can be taken into the body by eating food, drinking water, or breathing air. Gastrointestinal absorption from food or water is a likely source of internally deposited neptunium in the general population. After ingestion or inhalation, most neptunium is excreted from the body within a few days and never enters the bloodstream; only about 0.05% of the amount taken into the body by ingestion is absorbed into the blood. After leaving the intestine or lung, about 50% of the neptunium that does enter the bloodstream deposits in the skeleton, about 10% deposits in the liver, about 5% deposits in other soft tissues, and the rest is excreted, primarily in urine. The biological half-lives in the skeleton and liver are about 50 and 20 years, respectively. (This information is per simplified models that do not reflect intermediate redistribution.) The amount deposited in the liver and skeleton depends on the age of the individual, with fractional uptake in the liver increasing with age. Neptunium in the skeleton is deposited on bone surfaces and slowly redistributes throughout the bone volume over time.

What Is the Primary Health Effect? Neptunium is generally a health hazard only if it is taken into the body, although there is an external risk associated with the gamma rays emitted by neptunium-236 and neptunium-237 and its short-lived decay product protactinium-233. The main means of exposure are ingestion of food and water containing neptunium isotopes and inhalation of neptunium-contaminated dust. Ingestion is generally the exposure of concern unless there is a nearby source of contaminated airborne dust. Because neptunium is taken up in the body much more readily if inhaled rather than ingested, both exposure routes can be important. The major health concern is cancer resulting from the ionizing radiation emitted by neptunium isotopes deposited on bone surfaces and in the liver.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including neptunium *(see box at right)*. While ingestion is generally the most common route of exposure, the risk coefficients for this route are much lower than those for inhalation. Similar to other radionuclides, the risk coefficients for tap water are about 70 to 75% of those for dietary ingestion.

In addition to risks from internal exposures, there is an external gamma risk associated with exposure to neptunium-236 and neptunium-237. To estimate a lifetime cancer mortality risk, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial average concentration of 1 pCi/g, then 2 of these 100,000 people would be predicted to incur a fatal cancer if the soil contained neptunium-236, and 4 if it contained neptunium-237. (This is in comparison to the 20,000 people from the group predicted to die of cancer from all other causes per the U.S. average.) The external risk for neptunium-237 is largely due to its short-lived decay product protactinium-233.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. Values include contributions from the short-lived neptunium decay products. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Neptunium-235	1.0×10^{-12}	2.8×10^{-13}
Neptunium-236	7.3×10^{-10}	9.0×10^{-12}
Neptunium-237	1.6×10^{-8}	5.8×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Plutonium

Symbol:	**Pu**
Atomic Number: *(protons in nucleus)*	**94**
Atomic Weight: *(not naturally occurring)*	**-**

What Is It? Plutonium in its pure form is a very heavy, silver-colored, radioactive metal about twice as dense as lead. Essentially all the plutonium on earth has been created within the past six decades by human activities involving fissionable materials. Several plutonium isotopes exist, all of which are radioactive. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.)

The main plutonium isotopes at Department of Energy (DOE) environmental management sites are plutonium-238, plutonium-239, plutonium-240, and plutonium-241. Except for plutonium-241, these isotopes decay by emitting an alpha particle. Plutonium-241 decays by emitting a low-energy beta particle to americium-241, an alpha-emitting radionuclide with a half-life of 430 years that is much more radiotoxic than its parent. The maximum activity of americium-241 is about 3% of the initial activity of plutonium-241 and occurs 73 years later. An extremely small fraction of the decays of plutonium-236, plutonium-238, plutonium-240, and plutonium-242, are by spontaneous fission (SF), as are about 0.1% of the plutonium-244 decays. The higher activity isotopes (plutonium 242 and plutonium-244) are generally present in relatively low concentrations.

Radioactive Properties of Key Plutonium Isotopes

Isotope	Half-Life	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Pu-236	2.9 yr	540	α	5.8	0.013	0.0021
Pu-238	88 yr	17	α	5.5	0.011	0.0018
Pu-239	24,000 yr	0.063	α	5.1	0.0067	<
Pu-240	6,500 yr	0.23	α	5.2	0.011	0.0017
Pu-241	14 yr	100	β	<	0.0052	<
Pu-242	380,000 yr	0.0040	α	4.9	0.0087	0.0014
Pu-244	83,000,000 yr	0.000018	α	4.6	0.0071	0.0012
U-240	*14 hr*	*940,000*	*β*	-	*0.14*	*0.0076*
Np-240m	*7.4 min*	*110 million*	*β*	-	*0.68*	*0.34*

Ci = curie, g = gram, and MeV = million electron volts; a "<" means the radiation energy is less than 0.001 MeV, and a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) A very small fraction (about 0.002%) of the plutonium-241 decays are by alpha-particle emission to uranium-237. Certain properties of uranium-240 and neptunium-240m are included here because these radionuclides accompany the plutonium-244 decays. Values are given to two significant figures.

Where Does It Come From? Plutonium was first made in large quantities by American scientists in the 1940s as part of the Manhattan Project to create the atomic bomb, and this production continued through the Cold War. Plutonium is formed when the nucleus of a uranium atom captures one or more neutrons, changing the atomic structure and creating a new element. This process occurs in nuclear reactors and mainly involves transforming uranium-238 into plutonium. (Extremely small quantities of plutonium were created naturally in sustained underground nuclear reactions estimated to have occurred about 1.9 billion years ago in Gabon, Africa. This phenomenon occurred because concentrations of uranium-235 were much higher at that time. The current uranium-235 concentration, about 0.72%, will not sustain such natural reactions.)

How Is It Used? The nuclear properties of plutonium-239, as well as our ability to produce large amounts of nearly pure plutonium-239, led to its use in nuclear weapons and nuclear power. The fissioning of uranium-235 in the reactor of a nuclear power plant produces two to three neutrons, and these neutrons can be absorbed by uranium-238 to produce plutonium-239 and other isotopes. Plutonium-239 can also absorb neutrons and fission along with the uranium-235. Plutonium fissions provide about one-third of the total energy produced in a typical commercial nuclear power plant. The use of plutonium in power plants occurs without it ever being removed from the nuclear reactor fuel, i.e., it is fissioned in the same fuel rods in which it is produced. Another isotope, plutonium-238, is used as a heat source in radiothermal generators to produce electricity for a variety of purposes including unmanned spacecraft and interplanetary probes. The United States recovered or acquired about 110,000 kilograms (kg) of plutonium between 1944 and 1994, and about 100,000 kg remains in inventory. Of this amount, over 80% is in the form of weapons-grade plutonium, primarily plutonium-239. Plutonium was generated in production reactors at DOE's Hanford and Savannah River sites, and weapons components were produced at the Rocky Flats facility. Surplus plutonium is currently stored at the Pantex Plant and other sites.

What's in the Environment? Atmospheric testing of nuclear weapons, which ceased worldwide by 1980, generated most environmental plutonium. About 10,000 kg were released to the atmosphere during these tests. Average plutonium levels in surface soil from fallout range from about 0.01 to 0.1 picocurie per gram (pCi/g). Accidents and other releases from weapons production facilities have caused greater localized contamination.

The most common form in the environment is plutonium oxide. Plutonium is typically very insoluble, with the oxide being less soluble in water than ordinary sand (quartz). It adheres tightly to soil particles and tends to remain in the top few centimeters of soil as the oxide. In aquatic systems, plutonium tends to settle out and adhere strongly to sediments, again remaining in upper layers. Typically one part of plutonium will remain in solution for every 2,000 parts in sediment or soil. A small fraction of plutonium in soil can become soluble through chemical or biological processes, depending on its chemical form. While plutonium can bioconcentrate in aquatic organisms, data have not indicated that it biomagnifies in aquatic or terrestrial food chains.

What Happens to It in the Body? When plutonium is inhaled, a significant fraction can move from the lungs through the blood to other organs, depending on the solubility of the compound. Little plutonium (about 0.05%) is absorbed from the gastrointestinal tract after ingestion, and little is absorbed through the skin following dermal contact. After leaving the intestine or lung, about 10% clears the body. The rest of what enters the bloodstream deposits about equally in the liver and skeleton where it remains for long periods of time, with biological retention half-lives of about 20 and 50 years, respectively, per simplified models that do not reflect intermediate redistribution. The amount deposited in the liver and skeleton depends on the age of the individual, with fractional uptake in the liver increasing with age. Plutonium in the skeleton deposits on the cortical and trabecular surfaces of bones and slowly redistributes throughout the volume of mineral bone with time.

Plutonium metal*. Plutonium isotopes are primarily alpha-emitters so they pose little risk outside the body. Here the plastic bag, gloves, and outer (dead) layer of skin would each alone stop the emitted alpha particles from getting into the body.*

What Is the Primary Health Effect? Plutonium generally poses a health hazard only if it is taken into the body because all isotopes except plutonium-241 decay by emitting an alpha particle, and the beta particle emitted by plutonium-241 is of low energy. Minimal gamma radiation is associated with these radioactive decays. However, there is an external gamma radiation hazard associated with plutonium-244 from it short-lived decay product neptunium-240m. Inhaling airborne plutonium is the primary concern for all isotopes, and cancer resulting from the ionizing radiation is the health effect of concern. The ingestion hazard associated with common forms of plutonium is much lower than the inhalation hazard because absorption into the body after ingestion is quite low. Laboratory studies with experimental animals have shown that exposure to high levels of plutonium can cause decreased life spans, diseases of the respiratory tract, and cancer. The target tissues in those animals were the lungs and associated lymph nodes, liver, and bones. However, these observations in experimental animals have not been corroborated by epidemiological investigations in humans exposed to lower levels.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. These values include the contributions from short-lived plutonium decay products. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Plutonium-236	2.1×10^{-8}	6.9×10^{-11}
Plutonium-238	3.0×10^{-8}	1.3×10^{-10}
Plutonium-239	2.9×10^{-8}	1.3×10^{-10}
Plutonium-240	2.9×10^{-8}	1.3×10^{-10}
Plutonium-241	2.9×10^{-10}	5.8×10^{-12}
Plutonium-242	2.8×10^{-8}	1.3×10^{-10}
Plutonium-244	2.6×10^{-8}	1.4×10^{-10}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and accompanying Table C.2.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including plutonium (*see box at right).* While ingestion is generally the most common route of exposure, the risk coefficients for this route are much lower than those for inhalation. As for other radionuclides, the risk coefficients for tap water are about 80% of those for dietary ingestion. In addition to risks from internal exposures, there is an external gamma exposure risk associated with plutonium-244 and plutonium-241. To estimate a lifetime cancer mortality risk, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial concentration of 1 pCi/g of plutonium-244, then 7 of these 100,000 people would be predicted to incur a fatal cancer. (This is in comparison to the 20,000 people from this group predicted to die of cancer from all other causes per the U.S. average.) This external hazard is largely associated with the gamma rays emitted by its short-lived decay product neptunium-240m. The external gamma risk from plutonium-241 is about 25% of that for plutonium-244 (see Table C.2), and external gamma risk for the other plutonium isotopes is less than 1% of that for plutonium-244. As a note, for inhalation (the exposure of highest risk), breathing in 5,000 respirable plutonium particles of about 3 microns each is estimated to increase an individual's risk of incurring a fatal cancer about 1% above the U.S. average.

Polonium

Symbol: **Po**

Atomic Number: **84**
(protons in nucleus)

Atomic Weight: **210**
(naturally occurring)

What Is It? Polonium is a radioactive element that occurs naturally in very low concentrations in the earth's crust (at about one part in 10^{15}, or one millionth of a trillionth). Polonium was the first element discovered by Marie and Pierre Curie in 1898, while seeking the cause of radioactivity of pitchblende ore containing uranium. Polonium in its pure form is a low-melting, fairly volatile metal. Over 25 isotopes of polonium are known, with atomic masses ranging from 192 to 218 (isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) All polonium isotopes are radioactive, with only three having appreciable half-lives: polonium-208, polonium-209, and polonium-210.

Polonium-210, historically called "radium F," is the major naturally occurring isotope of polonium and the one most widely used. Polonium-210 is a radioactive decay product in the natural uranium-238 decay series; along with lead-210 it is one of two relatively long-lived decay products of radon-222. Polonium-210 has a half-life of 138 days, and it decays to stable lead-206 by emitting an alpha particle. One-thousandth of a gram (1 mg) of polonium-210 emits as many alpha particles as 5 g of radium-226. The energy released by its decay is so large (140 watts/g) that a capsule containing about half a gram reaches a temperature above 500ºC.

Radioactive Properties of Key Polonium Isotopes

Isotope	Half-Life	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Po-208	2.9 yr	590	α	5.1	<	<
Po-209	100 yr	17	α	4.9	<	<
Po-210	140 days	4,500	α	5.3	<	<

Ci = curie, g = gram, and MeV = million electron volts; a "<" means the radiation energy is less than 0.001 MeV. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Values are given to two significant figures. Polonium-210 is a decay product of radium-226 and is also shown on that fact sheet. The basic properties of polonium-208 and polonium-209 (which are not in the natural decay series) are also given here because they are included in the general discussion below.

Where Does It Come From? Because it is produced during the decay of naturally ubiquitous uranium-238, polonium-210 is widely distributed in small amounts in the earth's crust. Although it can be produced by the chemical processing of uranium ores or minerals, uranium ores contain less than 0.1 mg polonium-210 per ton. Originally, polonium-210 was obtained from the rich pitchblende ore found in Bohemia, but it can also be obtained from aged radium salts that contain about 0.2 mg per gram of radium. Although a number of other polonium isotopes are present in the natural decay series, their short half-lives preclude any appreciable concentrations.

Due to its scarcity, polonium-210 is usually produced artificially in a nuclear reactor by bombarding bismuth-209 (a stable isotope) with neutrons. This forms radioactive bismuth-210, which has a half-life of 5 days. Bismuth-210 decays to polonium-210 through beta decay. Milligram amounts of polonium-210 have been produced by this method. The longer-lived isotopes polonium-209 (half-life 103 years) and polonium-208 (half-life 2.9 years) are also produced in reactors or particle accelerators, but these are very expensive.

How Is It Used? Polonium-210 is used mainly in static eliminators, which are devices designed to eliminate static electricity in machinery where it can be caused by processes such as paper rolling, manufacturing sheet plastics, and spinning synthetic fibers. The polonium-210 is generally electroplated onto a backing foil and inserted into a brush, tube, or other holder. Alpha particles from the polonium ionize adjacent air, and the air ions then neutralize static electricity on the surfaces in contact with the air. These devices generally need to be replaced every year because of the short half-life of this radioisotope. Polonium-210 is also used in brushes to remove dust from photographic films and camera lenses. Static eliminators typically contain from tens to hundreds of mCi (thousandth of a curie) of radioactivity. Polonium-210 can also be combined with beryllium to produce neutron sources, and in fact it was used as neutron-producing initiators of at least the first generation of atomic weapons. In addition, polonium-210 has been investigated as a source for thermoelectric power devices for space applications.

What's in the Environment? Polonium-210 is naturally present in all environmental media at very low concentrations. In soils, the concentration is similar to that of uranium, averaging about 1 pCi/g (or one trillionth curie per gram). Because polonium-210 is produced from the decay of radon-222 gas, it can be found in the atmosphere from which it is deposited on the earth's surface. Average annual air concentrations range from 0.005 to 0.04 pCi/m^3. Polonium-210 is also emitted to the atmosphere during the calcining of phosphate rock as part of the production of elemental phosphorous. Although direct root uptake by plants is generally small, polonium-210 can be deposited on broad-leaved vegetables. Deposition from the atmosphere on tobacco leaves results in elevated concentrations of polonium-210 in tobacco smoke, resulting in greater intakes in smokers compared to non-smokers. It is estimated that the average Western diet includes from 1 to 10 pCi of polonium-210 per day. Polonium-210 can be significantly elevated in residents of northern lands who subsist on reindeer that consume lichens, which absorb trace elements from the atmosphere.

What Happens to It in the Body? Polonium can be taken into the body by eating food, drinking water, or breathing air. Between 50% and 90% of the polonium taken in by ingestion will promptly leave the body in feces. The fraction remaining in the body enters the bloodstream. In general, the spleen and kidneys concentrate polonium more than other tissues except for temporary deposition in the lung after inhalation of an insoluble form. It is estimated that approximately 45% of ingested polonium will be deposited in the spleen, kidneys, and liver, with 10% deposited in bone marrow and the remainder distributed throughout the body. The amount of polonium in the body will decrease with a half-time of 50 days.

Studies of smokers have shown that inhaled polonium can be highly localized in the lungs, with about twice as much polonium found in the ribs of smokers compared to nonsmokers. It is estimated that the dose to the skeleton is elevated about 30% in smokers. Another source of polonium-210 in the body is its gradual ingrowth from the decay of radium-226 and lead-210 deposited in bone. The average amount of polonium-210 in the body is approximately 1 nCi (one billionth of a curie).

What Are the Primary Health Effects? Polonium-210 is a health hazard only if it is taken into the body. External exposure is not a concern because polonium is an alpha emitter. The primary means of exposure are ingestion of food and water containing polonium-210 and inhalation of polonium-contaminated dust. Inhalation is of particular concern in the vicinity of a source of airborne dust, such as a phosphate plant, and in areas of high radon concentrations, or for cigarette smokers.

Substantial radiation doses from polonium can be expected in many tissues of the body; it supplies a more nearly whole-body dose than almost all other alpha emitters. Effects are more common in the kidney than the spleen, despite a higher dose in the spleen. The lymph nodes and liver can also be affected. Polonium that is inhaled, either from radon in the air or cigarette smoke, can be deposited on the mucous lining of the respiratory tract. When alpha particles are then emitted within the lung, the cells lining the airways can be damaged, potentially leading to lung cancer over time.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including polonium-210 *(see box at right).* Risk coefficients for inhalation are about 6 times higher than for dietary ingestion. Similar to other radionuclides, the risk coefficients for ingestion of tap water containing polonium-210 are about 75% of those shown for dietary ingestion. Polonium-210 poses no external risk when outside the body.

Radiological Risk Coefficients

This table provides risk coefficients for inhalation and absorption. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth). Other values, including for morbidity, are also available. No risk factors are available for Po-208 or Po-209.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Po-210	1.0×10^{-8}	1.6×10^{-9}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Potassium-40

Symbol:	**K(-40)**
Atomic Number: *(protons in nucleus)*	**19**
Atomic Weight: *(naturally occurring)*	**39**

What Is It? Potassium is a soft, silver-white metal. An important constituent of soil, it is widely distributed in nature and is present in all plant and animal tissues. Potassium-40 is a naturally occurring radioactive isotope of potassium. (An isotope is a different form of an element that has the same number of protons in the nucleus but a different number of neutrons.) Two stable (nonradioactive) isotopes of potassium exist, potassium-39 and potassium-41. Potassium-39 comprises most (about 93%) of naturally occurring potassium, and potassium-41 accounts for essentially all the rest. Radioactive postassium-40 comprises a very small fraction (about 0.012%) of naturally occurring potassium.

Several radioactive isotopes of potassium exist in addition to potassium-40. These isotopes all have half-lives of less than one day so they are not of concern for Department of Energy (DOE) environmental management sites such as Hanford. The half-life of potassium-40 is 1.3 billion years, and it decays to calcium-40 by emitting a beta particle with no attendant gamma radiation (89% of the time) and to the gas argon-40 by electron capture with emission of an energetic gamma ray (11% of the time). Potassium-40 is an important radionuclide in terms of the dose associated with naturally occurring radionuclides.

Radioactive Properties of Potassium-40

Isotope	Half-Life *(yr)*	Natural Abundance *(%)*	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
					Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
K-40	1.3 billion	0.012	0.0000071	β, EC	-	0.52	0.16

EC = electron capture, Ci = curie, g = gram, and MeV = million electron volts; a dash means that the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for explanation of terms and interpretation of radiation energies.) Potassium-40 decays by both emitting a beta particle (89%) and electron capture (11%). Values are given to two significant figures.

Where Does It Come From? Potassium-40 is present as a very small fraction of naturally occurring potassium, which is an element found in large amounts throughout nature. Potassium is the seventh most abundant element in the crust of the earth and the sixth most abundant element in solution in the oceans. It is present in mineral waters and brines, and in various minerals such as carnallite, feldspar, saltpeter, greensand, and sylvite. Potassium is an important constituent of fertile soil and is an essential nutrient for plant growth and in the human diet.

How Is It Used? Potassium metal, which is so soft it can be cut with a knife, is used in photoelectric cells. Potassium is one of the most reactive metals in nature, and it forms a number of compounds that have many commercial uses. For example, the white solid potassium bromide is used in photography, engraving, and lithography. The red crystal potassium chromate and yellow crystal potassium bichromate are powerful oxidizing agents used in matches and fireworks, and they are also used to dye textiles and tan leather. The white crystal potassium iodide is very soluble in water and is used in photography to prepare gelatin emulsions. It is also used in medicine to treat rheumatism and overactive thyroid glands. Potassium nitrate is a white solid used in matches, explosives, and fireworks, and it is also used to pickle meat. The purple crystal potassium permanganate is used as a disinfectant and germicide and as an oxidizing agent in various chemical reactions. The white solid potassium carbonate is used to make glass and soft soap. The white solids potassium sulfate and potassium chloride are used to fertilize soil, because potassium (along with nitrogen and phosphorous) is an essential element for plant growth. Potassium is also an essential element for humans, as a key electrolyte for maintaining basic cardiovascular functions; many people take potassium supplements as capsules or tablets. There are no specific commercial or medical uses associated with the radioactive properties of potassium-40.

What's in the Environment? Potassium is present in the earth's crust, oceans, and all organic material. Its concentration in the earth's crust is about 15,000 milligrams per kilogram (mg/kg) or 1.5%, and its concentration in seawater is about 416 mg per liter (mg/L). Because potassium-40 represents 0.012% of naturally occurring potassium, its concentration in the earth's crust is about 1.8 mg/kg, or 13 picocurie per gram (pCi/g). Potassium binds preferentially to soil, with the concentration associated with sandy soil particles estimated to be 15 times higher than in the interstitial water (in pore spaces between soil particles); it binds more tightly to loam and clay soil, so those concentration ratios are higher (above 50). Together with nitrogen and phosphorous, potassium is a major soil fertilizer, so levels of potassium-40 in soils are strongly influenced by fertilizer use; it is estimated that about 3,000 Ci of potassium-40 are added annually to U.S. soils. Potassium-40 behaves in the environment the same as other potassium isotopes, being assimilated into the tissues of all plants and animals through normal biological processes. It is the predominant radioactive component in human tissues and in most food. For example, milk contains about 2,000 pCi/L of natural potassium-40.

What Happens to It in the Body? Potassium-40 can be taken into the body by drinking water, eating food, or breathing air. Once taken in, potassium-40 behaves in the body in the same manner as other potassium isotopes. Humans require potassium to sustain biological processes, with most (including potassium-40) being almost completely absorbed upon ingestion, moving quickly from the gastrointestinal tract to the bloodstream. The potassium-40 that enters the bloodstream after ingestion or inhalation is quickly distributed to all organs and tissues. Potassium-40 is eliminated from the body with a biological half-life of 30 days. The potassium content of the body is under strict homeostatic control (in which the amount retained is actively regulated by the body to achieve the normal range required for system functions), and it is not influenced by variations in environmental levels. Hence, the potassium-40 content in the body is constant, with an adult male having about 0.1 microcurie or 100,000 pCi. Each year this isotope delivers an effective dose equivalent of about 14 millirem to adults.

What Is the Primary Health Effect? Potassium-40 can present both an external and an internal health hazard. The strong gamma radiation associated with the electron-capture decay process (which occurs 11% of the time) makes external exposure to this isotope a concern. While in the body, potassium-40 poses a health hazard from both the beta particles and gamma rays. Potassium-40 behaves the same as ordinary potassium, both in the environment and within the human body – it is an essential element for both. Hence, what is taken in is readily absorbed into the bloodstream and distributed throughout the body, with homeostatic controls regulating how much is retained or cleared. The health hazard of potassium-40 is associated with cell damage caused by the ionizing radiation that results from radioactive decay, with the general potential for subsequent cancer induction.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including potassium-40 *(see box at right).* While ingestion is generally the most common type of exposure, the risk coefficients for this route are lower than those for inhalation. As for other radionuclides, the risk coefficient for tap water is about 70% of that for dietary ingestion. In addition to risks from internal exposures, an external gamma exposure risk also exists for potassium-40. To estimate a lifetime cancer mortality risk, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial average concentration of 1 pCi/g potassium-40, then 4 of these 100,000 people would be predicted to incur a fatal cancer over their lifetime. (This is in comparison to the 20,000 people from the group predicted to die of cancer from all other causes per the U.S. average.)

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Maximum values are given for inhalation since no default absorption types were provided, and dietary values were used for ingestion. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Potassium-40	2.1×10^{-10}	2.2×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Protactinium

Symbol: **Pa**

Atomic Number: **91**
(protons in nucleus)

Atomic Weight: **231**
(naturally occurring)

What Is It? Protactinium is a malleable, shiny, silver-gray radioactive metal that does not tarnish rapidly in air. It has a density greater than that of lead and occurs in nature in very low concentrations as a decay product of uranium. There are three naturally occurring isotopes, with protactinium-231 being the most abundant. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) The other two naturally occurring isotopes are protactinium-234 and protactinium-234m (the "m" meaning metastable), both of which have very short half-lives (6.7 hours and 1.2 minutes, respectively) and occur in extremely low concentrations. Protactinium was first identified in 1913 by Kasimir Fajans and O.H. Gohring (as the isotope protactinium-234m), and protactinium-231 was identified in 1917. The name comes from the Greek work *protos* (meaning first) and the element actinium, because protactinium is the precursor of actinium.

Of the 20 known isotopes of protactinium, only protactinium-231 has a half-life greater than one year and is a concern for Department of Energy (DOE) environmental management sites. The half-lives of all other protactinium isotopes are less than a month. Protactinium-231 is a decay product of uranium-235 and is present at sites that processed uranium ores and associated wastes. This isotope decays by emitting an alpha particle with a half-life of 33,000 years to actinium-227, which has a half-life of 22 years and decays by emitting an alpha or beta particle. Actinium-227 and all of its decay products are included in the list of radionuclides associated with protactinium-231 in the table to the right for completeness, as these radionuclides are typically present with protactinium-231. Much of the hazard associated with protactinium-231 is attributable to actinium-227.

Radioactive Properties of the Key Protactinium Isotope and Associated Radionuclides

Isotope	Half-Life	Natural Abun-dance (%)	Specific Activity (Ci/g)	Decay Mode	Radiation Energy (MeV)		
					Alpha (α)	Beta (β)	Gamma (γ)
Pa-231	33,000 yr	>99	.048	α	5.0	0.065	0.048
Ac-227	*22 yr*		*73*	*α, β*	*0.068*	*0.016*	*<*
Th-227 (99%)	*19 days*		*31,000*	*α*	*5.9*	*0.053*	0.11
Fr-223 (1%)	*22 min*		*39 million*	*β*	*-*	*0.40*	*0.059*
Ra-223	*11 days*		*52,000*	*α*	*5.7*	*0.076*	*0.13*
Rn-219	*4.0 sec*		*13 billion*	*α*	*6.8*	*0.0063*	*0.056*
Po-215	*0.0018 sec*		*30 trillion*	*α*	*7.4*	*<*	*<*
Pb-211	*36 min*		*25 million*	*β*	*-*	*0.46*	*0.051*
Bi-211	*2.1 min*		*420 million*	*α, β*	*6.6*	*0.010*	*0.047*
Tl-207	*4.8 min*		*190 million*	*β*	*-*	*0.49*	*0.0022*

Ci = curie, g = gram, and MeV = million electron volts; a "<" means the radiation energy is less than 0.001 MeV, and a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Thorium-227 decays by both emitting an alpha particle (1%) and a beta particle (99%). Certain properties of additional radionuclides are included here because they accompany the protactinium decays. Values are given to two significant figures.

Where Does It Come From? Protactinium is widely distributed in very small amounts in the earth's crust, and it is one of the rarest and most expensive naturally occurring elements. It is present in uranium ores at a concentration of about 1 part protactinium to 3 million parts uranium. Of the three naturally occurring isotopes, protactinium-231 is a decay product of uranium-235, and protactinium-234 and protactinium-234m are decay products of uranium-238. Essentially all (99.8%) of the decays of thorium-234, which is the immediate decay product of uranium-238, are to protactium-234m; only about 0.2% are to protactinium-234. *(See the companion fact sheets on Uranium and Natural Decay Series for additional information.)*

How Is It Used? There are no industrial or commercial uses of protactinium due to its scarcity, expense, and radiotoxicity. Its only uses are associated with basic scientific research activities.

What's in the Environment? Protactinium is naturally present in soil, rocks, surface water, groundwater, plants, and animals in very low concentrations – on the order of one part per trillion, or 0.1 picocuries (pCi)/g. Higher levels are present in uranium ores and other geologic materials. Essentially all naturally occurring protactinium is present as protactinium-231. Protactinium preferentially adheres quite well to soil, and the concentration associated with sandy soil particles is typically 550 times higher than in interstitial water (water in the pore space between the soil particles); concentration ratios are even higher (about 2,000 and above) for loam and clay soils. Protactinium is generally not a major contaminant at DOE sites and is not a concern for groundwater.

What Happens to It in the Body? Protactinium can be taken into the body by eating food, drinking water, or breathing air. When protactinium is inhaled, a significant fraction can move from the lungs through the blood to other organs, depending on the solubility of the compound. Gastrointestinal absorption from food or water is a likely source of internally deposited protactinium in the general population. Most of the protactinium taken in by ingestion will promptly leave the body in feces; only about 0.05% of the amount ingested is absorbed from the gastrointestinal tract into the bloodstream. After leaving the intestine or lung, about 40% of the protactinium that does enter the bloodstream deposits in the skeleton, about 15% deposits in the liver, about 2% deposits in the kidneys, and the rest is excreted. The biological half-life in the skeleton is about 50 years. Of the protactinium deposited in the liver, 70% is assumed to be retained with a biological half-life of 10 days, with the remaining 30% having a biological half-life of 60 days. Of the protactinium deposited in the kidneys, 20% is assumed to be retained with a biological half-life of 10 days, with the remaining 80% having a biological half-life of 60 days. (This information is per simplified models that do not reflect intermediate redistribution.)

What Are the Primary Health Effects? Protactinium is generally a health hazard only if it is taken into the body, although there is a small external risk associated with the gamma rays emitted by protactinium-231 and a number of short-lived decay products of actinium-227. The main means of exposure are ingestion of food and water containing protactinium and inhalation of protactinium-contaminated dust. Ingestion is generally the exposure of concern unless there is a nearby source of contaminated airborne dust. Because protactinium is taken up in the body much more readily if inhaled rather than ingested, both exposure routes can be important. The major health concern is cancer resulting from the ionizing radiation emitted by protactinium deposited in the skeleton, liver, and kidneys. The health risks associated with protactinium-234m are included with those for uranium-238 *(see the companion fact sheet on Uranium)*. Protactinium-234m decays by emitting an energetic beta particle so precautions against this radiation are needed when handling uranium; for example, heavy rubber gloves are worn to protect the hands and forearms.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including protactinium *(see box at right)*. The inhalation risk factor for protactinium-231 represents one of the largest risk factors for any radionuclide. Actinium-227 and its decay products account for more than 80% of this inhalation risk. While the risk factor for ingestion is much lower than for inhalation, ingestion is generally the most common means of entry into the body. Similar to other radionuclides, the risk coefficient for tap water is about 75% of that shown for dietary ingestion.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and absorption. Maximum values are given for inhalation as no default absorption types were provided, and dietary values were used for ingestion. These values include the contributions from the actinium-227 and its short-lived decay products. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Pa-231	2.0×10^{-7}	6.0×10^{-10}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and accompanying Table C.2.

In addition to risks from internal exposures, there is a risk from external gamma exposure to protactinium-231. Using the external gamma risk coefficients to estimate lifetime cancer mortality risks, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial average concentration of 1 pCi/g protactinium-231, then 8 of these 100,000 people would be predicted to incur a fatal cancer. (This is in comparison to the 20,000 people from this group predicted to die of cancer from all other causes per the U.S. average.) As for internal exposures, much of this risk is from actinium-227 and its decay products.

Radium

Symbol: **Ra**

Atomic Number: **88**
(protons in nucleus)

Atomic Weight: **226**
(naturally occurring)

What Is It? Radium is a radioactive element that occurs naturally in very low concentrations (about one part per trillion) in the earth's crust. Radium in its pure form is a silvery-white heavy metal that oxidizes immediately upon exposure to air. Radium has a density about one-half that of lead and exists in nature mainly as radium-226, although several additional isotopes are present. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) Radium was first discovered in 1898 by Marie and Pierre Curie, and it served as the basis for identifying the activity of various radionuclides. One curie of activity is approximately equal to the rate of radioactive decay of one gram (g) of radium-226.

Of the 25 isotopes of radium, only two – radium-226 and radium-228 – have half-lives greater than one year and are of concern for Department of Energy environmental management sites. Radium-226 is a radioactive decay product in the uranium-238 decay series and is the precursor of the gas radon-222. Radium-228 is a radioactive decay product in the thorium-232 decay series. Both isotopes give rise to many additional short-lived radionuclides, resulting in a wide spectrum of alpha, beta and gamma radiations. Lead-210 has a 22-year half-life, and is included in the list of radionuclides associated with radium-226 as this isotope and its short-lived decay products are typically present with radium-226. The half-life of radium-226 is 1,600 years, and it decays by emitting an alpha particle. Radium-228 has a much shorter half-life (5.8 years) and decays by emitting a beta particle. Radium-226 poses a long-term hazard due to its long half-life, while radium-228 poses a long-term hazard only if its parent (thorium-232) is present.

Radioactive Properties of Key Radium Isotopes and Associated Radionuclides

Isotope	Half-Life	Natural Abundance (%)	Specific Activity (Ci/g)	Decay Mode	Radiation Energy (MeV)		
					Alpha (α)	Beta (β)	Gamma (γ)
Ra-226	1,600 yr	>99	1.0	α	4.8	0.0036	0.0067
Rn-222	*3.8 days*		*160,000*	α	*5.5*	<	<
Po-218	*3.1 min*		*290 million*	α	*6.0*	<	<
Pb-214	*27 min*		*33 million*	β	-	*0.29*	*0.25*
Bi-214	*20 min*		*45 million*	β	-	*0.66*	*1.5*
Po-214	*0.00016 sec*		*330 trillion*	α	*7.7*	<	<
Pb-210	*22 yr*		*77*	β	-	*0.038*	*0.0048*
Bi-210	*5.0 days*		*130,000*	β	-	*0.39*	-
Po-210	*140 days*		*4,500*	α	*5.3*	<	<
Ra-228	5.8 yr	<<1	280	β	-	0.017	<
Ac-228	*6.1 hr*		*2.3 million*	β	-	*0.48*	*0.97*
Th-228	*1.9 yr*		*830*	α	*5.4*	*0.021*	0.0033
Ra-224	*3.7 days*		*160,000*	α	*5.7*	*0.0022*	*0.010*
Rn-220	*56 sec*		*930 million*	α	*6.3*	<	<
Po-216	*0.15 sec*		*350 billion*	α	*6.8*	<	<
Pb-212	*11 hr*		*1.4 million*	β	-	*0.18*	*0.15*
Bi-212	*61 min*		*15 million*	α, β	*2.2*	*0.47*	*0.19*
Po-212 (64%)	*0.00000031 sec*		*180,000 trillion*	α	*8.8*	-	-
Tl-208 (36%)	*3.1 min*		*300 million*	β	-	*0.60*	*3.4*

Ci = curie, g = gram, and MeV = million electron volts; a "<" means the radiation energy is less than 0.001 MeV, and a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Bismuth-212 decays by both emitting an alpha particle (36%) and a beta particle (64%). Certain properties of additional radionuclides are included here because they accompany the radium decays. Values are given to two significant figures.

Where Does It Come From? Radium is widely distributed in small amounts in the earth's crust. It is present in all uranium and thorium minerals; its concentration in uranium ores is about one part radium to 3 million parts uranium. The chemical properties of radium are similar to those of barium, and the two substances are removed from uranium ore by precipitation and other chemical processes. Originally, radium was obtained from the rich pitchblende ore found in Bohemia. The carnotite sands of Colorado furnish some radium, but richer ores are found in the Republic of Zaire and the Great Lakes Region of Canada. Radium is a major contaminant in mine and milling wastes, such as uranium mill tailings, and is present in various radioactive wastes associated with past uranium processing activities.

How Is It Used? Radium-226 is the only radium isotope used commercially. Historically, the main use of radium has been as a component in luminous paint used on the dials of watches, clocks, and other instruments, although it is no longer used for

this purpose. Radium is currently used in brachytherapy to treat various types of cancer. (Brachytherapy is a method of radiation treatment in which sealed sources are used to deliver a radiation dose at a distance of up to a few centimeters by surface, intracavitary, or interstitial application.)

What's in the Environment? Essentially all naturally occurring radium is present as radium-226. Radium exists naturally in soil, rocks, surface water, groundwater, plants, and animals in generally low concentrations – on the order of one part per trillion, or 1 picocurie (pCi)/g. Higher levels are present in uranium ores and other geologic materials. Because of the separation process used to extract uranium from ores, radium-226 is a major contaminant in uranium mill tailings. The concentration of radium in plants is typically about 0.03 (or 3%) of that in soil. However, Brazil nuts in areas of high natural radium have much higher (orders of magnitude) concentration ratios. The average concentration of radium in food has been estimated at less than 0.01 to 0.03 pCi/g. Radium preferentially adheres well to soil particles, with concentrations in sandy soil generally on the order of 500 times higher than in interstitial water (water in the pore spaces between soil particles); it is even less mobile in clay soils, with concentration ratios over 9,000. The maximum contaminant level developed by the U.S. Environmental Protection Agency for radium (as radium-226 and radium-228, combined) in drinking water supplies is 5 pCi per liter (pCi/L).

What Happens to It in the Body? Radium can be taken into the body by eating food, drinking water, or breathing air. Most of the radium taken in by ingestion (about 80%) will promptly leave the body in feces. The remaining 20% enters the bloodstream and is carried to all parts of the body. Inhaled radium can remain in the lungs for several months and will gradually enter the bloodstream and be carried throughout the body. The metabolic behavior of radium in the body is similar to that of calcium. For this reason, an appreciable fraction is preferentially deposited in bone and teeth. The amount in bone decreases with time from the exposure, generally dropping below 10% in a few months to 1% and less in a few years. Release from the bone is slow, so a portion of inhaled and ingested radium will remain in the bones throughout a person's lifetime.

What Are the Primary Health Effects? Radium poses an external as well as an internal health hazard. The strong external gamma radiation associated with several short-lived decay products of radium-226 and radium-228 makes external exposure a concern, and shielding is often needed to handle waste and other materials containing large concentrations of these radionuclides. The majority of epidemiological data on the health effects of radium-226 and radium-228 in humans comes from studies of radium dial painters, radium chemists, and technicians exposed through medical procedures in the early 1900s. These studies, as well as studies on experimental animals, indicate that chronic exposure to radium can induce bone sarcomas. The minimum latency period is seven years after the first exposure, but tumors can continue to appear throughout a lifetime.

The inhalation risk is associated primarily with radium decay products, i.e., radon and its short-lived daughters. Each of the two radium isotopes decays into a gaseous radon isotope. Radon-222 is a short-lived decay product of radium-226, and radon-220 is a short-lived decay product of radium-228. The primary hazard associated with radon arises from the inhalation of its short-lived decay products, which are charged ions that readily attach to dust particles. These particles can be inhaled into the lungs and deposited on the mucous lining of the respiratory tract. Unattached decay products tend to be inhaled deeper into the lungs where the residence time is longer. When alpha particles are then emitted within the lung, the cells lining the airways can be damaged, potentially leading to lung cancer over time.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including radium *(see box at right).* The ingestion and inhalation coefficients for radium-226 and radium-228 are generally comparable. While ingestion is the most common means of radium entry into the body, risk coefficients for that exposure route are lower than for inhalation. Similar to other radionuclides, the risk coefficients for tap water are about 75% of those shown for dietary ingestion.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and absorption. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. These values include the contributions from the short-lived radium decay products. (See text for information on the external exposure pathway.) Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Ra-226	2.4×10^{-8}	2.9×10^{-9}
Ra-228	9.0×10^{-8}	1.3×10^{-9}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

In addition to risks from internal exposures, a risk from external gamma exposure is associated with these two isotopes. Using the external gamma risk coefficients to estimate lifetime cancer mortality risks, if it is assumed that 100,000 persons were continuously exposed to a thick layer of soil with an initial average concentration of 1 pCi/g, then 40 of these 100,000 people would be predicted to incur a fatal cancer if the soil contained radium-226, and 7 if it contained radium-228. (This is in comparison to the 20,000 people from the group predicted to die of cancer from all other causes per the U.S. average.) These risks are associated with the gamma rays emitted by various decay products of these two radium isotopes.

Strontium

What Is It? Strontium is a soft, silver-gray metal that occurs in nature as four stable isotopes. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) Strontium-88 is the most prevalent form, comprising about 83% of natural strontium. The other three stable isotopes and their relative abundance are strontium-84 (0.6%), strontium-86 (9.9%), and strontium-87 (7.0%). Strontium is present in nature chiefly as celestite ($SrSO_4$) and strontianite ($SrCO_3$), and it comprises about 0.025% of the earth's crust.

Symbol: **Sr**

Atomic Number: **38**
(protons in nucleus)

Atomic Weight: **88**
(naturally occurring)

Sixteen major radioactive isotopes of strontium exist, but only strontium-90 has a half-life sufficiently long (29 years) to warrant concern for nuclear facilities such as the Department of Energy Hanford site. The half-lives of all other strontium radionuclides are less than 65 days. Strontium-90 decays to yttrium-90 by emitting a beta particle, and yttrium-90 decays by emitting a more energetic beta particle with a half-life of 64 hours to zirconium-90. The main health concerns for strontium-90 are related to the energetic beta particle from yttrium-90.

Radioactive Properties of the Key Strontium Isotope and an Associated Radionuclide

Isotope	Half-Life	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Sr-90	29 yr	140	β	-	0.20	-
Y-90	*64 hr*	*550,000*	*β*	-	*0.94*	<

Ci = curie, g = gram, and MeV = million electron volts; a dash means the entry is not applicable, and a "<" means the radiation energy is less than 0.001 MeV. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Properties of yttrium-90 are included here because this radionuclide accompanies strontium decays. Values are given to two significant figures.

Where Does It Come From? While four stable isotopes of strontium occur naturally, strontium-90 is produced by nuclear fission. When an atom of uranium-235 (or other fissile nuclide) fissions, it generally splits asymmetrically into two large fragments – fission products with mass numbers in the range of about 90 and 140 – and two or three neutrons. (The mass number is the sum of the number of protons and neutrons in the nucleus of the atom.) Strontium-90 is such a fission product, and it is produced with a yield of about 6%. That is, about six atoms of strontium-90 are produced per 100 fissions. Strontium-90 is a major radionuclide in spent nuclear fuel, high-level radioactive wastes resulting from processing spent nuclear fuel, and radioactive wastes associated with the operation of reactors and fuel reprocessing plants.

How Is It Used? Strontium has a variety of commercial and research uses. It has been used in certain optical materials, and it produces the red flame color of pyrotechnic devices such as fireworks and signal flares. Strontium has also been used as an oxygen eliminator in electron tubes and to produce glass for color television tubes. In addition, strontium-90 has been used as an isotopic energy source in various governmental research applications, including in radiothermal generators to produce electricity for a variety of purposes including devices to power remote weather stations, navigational buoys, and satellites.

What's in the Environment? Beyond the four stable isotopes naturally present in soil, strontium-90 is also present in surface soil around the world as a result of fallout from past atmospheric nuclear weapons tests. Current strontium-90 levels in surface soil typically range from 0.01 to 1 picocurie per gram (pCi/g), reflecting various rainfall and wind patterns, elevation, and terrain; most levels fall between 0.05 and 0.5 pCi/g, with 0.1 pCi/g as a general average. Strontium-90 is relatively mobile and can move down through soil with percolating water to groundwater. Environmental transport of strontium is strongly influenced by its chemical form. Strontium preferentially adheres to soil particles, and the amount in sandy soil is typically about 15 times higher than in interstitial

water (in the pore spaces between soil particles); concentration ratios are typically higher (110) in clay soil. As a note, many years ago the U.S. Environmental Protection Agency (EPA) established a maximum contaminant level for strontium-90 in public drinking water supplies. That value based on extant dosimetry models is 8 pCi per liter (pCi/L). The value using current, improved dosimetry models would be 36 pCi/L.

What Happens to It in the Body? Strontium can be taken into the body by eating food, drinking water, or breathing air. Gastrointestinal absorption from food or water is the principal source of internally deposited strontium in the general population. On average, 30 to 40% of ingested strontium is absorbed into the bloodstream. The amount absorbed tends to decrease with age, and is higher (about 60%) in children in their first year of life. Adults on fasting and low-calcium diets can also increase intestinal absorption to these levels, as the body views strontium as a replacement for calcium. Strontium behaves similarly to calcium (although it is not homeostatically controlled, i.e., the body does not actively regulate levels within the cells), but living organisms generally use and retain it less effectively. For adults, about 31% of the activity entering the blood (plasma) from the gastrointestinal tract is retained by bone surfaces; the remainder goes to soft tissues or is excreted in urine and feces. Much of the activity initially deposited on bone surfaces is returned to plasma within a few days based on an updated biokinetic model that accounts for redistribution in the body. About 8% of the ingested activity remains in the body after 30 days, and this decreases to about 4% after 1 year. This activity is mainly in the skeleton.

What Are the Primary Health Effects? Strontium is a health hazard only if it is taken into the body. External gamma exposure is not a major concern because strontium-90 emits no gamma radiation and its decay product yttrium-90 emits only a small amount. Strontium-90 concentrates in bone surfaces and bone marrow, and its relatively long radioactive half-life (29 years) make it one of the more hazardous products of radioactive fallout. The health effects associated with strontium-90 were studied concurrent with development of the atomic bomb during World War II by the Manhattan Engineer District. Bone tumors and tumors of the blood-cell forming organs are the main health concern. These tumors are associated with the beta particles emitted during the radioactive decay of strontium-90 and yttrium-90.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including strontium-90 *(see box at right)*. Most of the risk is associated with the high-energy beta particle emitted by yttrium-90. Although the risk coefficient for ingestion is lower than for inhalation, ingestion is generally the most common way this radioisotope enters the body. Similar to other radionuclides, the risk coefficient for tap water is about 80% of that for dietary ingestion. In addition to potential radiogenic effects, strontium has been shown to inhibit calcification and cause bone deformities in animals, notably at high doses. The EPA toxicity value for estimating the potential for non-cancer effects from oral exposure is termed a reference dose (RfD), which is an estimate of the highest dose that can be taken in every day without causing an adverse non-cancer effect. The RfD for ingested strontium *(see box at right)* based on rachitic bone effects was developed by studying test animals given relatively high doses over their lifetimes, then adjusting and normalizing those results to a milligram per kilogram per day (mg/kg-day) basis for humans. A noncancer toxicity value for inhalation exposure has not been developed.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. The recommended default absorption type was used for inhalation, and the dietary value was used for ingestion. These values include the contribution from the decay product yttrium-90. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Strontium-90	1.0×10^{-10}	7.5×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Chemical Toxicity Value
Non-Cancer Effect: *Oral RfD*
0.6 mg/kg-day

Technetium

Symbol:	**Tc**
Atomic Number: *(protons in nucleus)*	**43**
Atomic Weight: *(not naturally occurring)*	**-**

What Is It? Technetium is a silvery gray metal that looks like platinum and tarnishes slowly in moist air. Essentially all the technetium on earth has been created by human activities involving fissionable materials. Taking its name from the Greek work *technetos* meaning artificial, it was first produced in 1937 by bombarding molybdenum with deuterons (a form of hydrogen with a neutron in the nucleus) in a cyclotron.

There are no stable, i.e., nonradioactive, isotopes of technetium. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) Of the ten major radioactive isotopes, only three – technetium-97, technetium-98 and technetium-99 – have half-lives sufficiently long to warrant concern over time. The half-lives of the other isotopes are less than 90 days. Only one of the three long-lived isotopes, technetium-99, is produced in sufficient quantities to be of concern at Department of Energy (DOE) environmental management sites such as Hanford. This fission product decays by emitting a beta particle to produce the stable isotope ruthenium-99. The very long half-life (and thus low specific activity) of technetium-99 limits its radioactive hazards.

Technetium-98 also decays by emitting a beta particle while technetium-97 decays by electron capture. These two radionuclides have very long half-lives (in excess of a million years). An additional radionuclide, technetium-99m (the "m" means metastable), is used in medical diagnostic procedures. This isotope has a half-life of about six hours and is a decay product of molybdenum-99, a radionuclide with a half-life of 66 hours that also decays by emitting a beta particle.

Radioactive Properties of Key Technetium Isotopes

Isotope	Half-Life *(yr)*	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Tc-97	2.6 million	0.0014	EC	-	0.0056	0.011
Tc-98	4.2 million	0.00088	β	-	0.16	1.4
Tc-99	210,000	0.017	β	-	0.10	-

EC = electron capture, Ci = curie, g = gram, and MeV = million electron volts; a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Values are given to two significant figures.

Where Does It Come From? Technetium is produced as a result of nuclear transformations, typically in a nuclear reactor. When an atom of a fissile nuclide such as uranium-235 fissions, it generally splits asymmetrically into two large fragments – fission products with mass numbers in the range of about 90 and 140 – and two or three neutrons. (The mass number is the sum of the number of protons and neutrons in the nucleus of the atom.) Technetium-99 and molybdenum-99 are two such fission products, with a relatively high yield of about 6%. That is, about six atoms of each isotope are produced per 100 fissions. Technetium-99m is a short-lived decay product of molybdenum-99. (An extremely small amount of technetium was created naturally in sustained underground nuclear reactions estimated to have occurred about 1.9 billion years ago in Gabon, Africa. This phenomenon occurred because much higher concentrations of uranium-235 were present at that time; the current uranium-235 concentration, about 0.72%, will not sustain such natural reactions.) Technetium-99 is a key radionuclide in spent nuclear fuel, high-level radioactive wastes resulting from processing spent fuel, and radioactive wastes associated with operating nuclear reactors and fuel reprocessing plants.

How Is It Used? Technetium is a very good corrosion inhibitor for steel, and protection can be achieved by adding only very small amounts during production. However, this use is limited by the

radioactive nature of technetium. Technetium-99m is commonly used in nuclear medicine as a radioactive tracer. In this application, the radionuclide is chemically attached to a drug chosen for its tendency to collect in specific organs of the body, and the solution is then injected into the patient. After a short time (its half-life is only 6 hours), an image is collected with a radiosensitive detector for analysis. This technique is very useful in identifying cancer metastases in locations distant from primary tumors.

What's in the Environment? Technetium is not a naturally occurring element. Technetium-99 is present in soil due to fallout from past atmospheric nuclear weapons tests. Estimated concentrations in surface soil are very low, on the order of 0.0001 picocuries per gram (pCi/g), due to its low specific activity. Technetium-99 is very mobile in the environment, especially under aerobic conditions (i.e., where oxygen is present). From the surface it can move rapidly downward with percolating water because most technetium compounds do not bind well to soil particles. The concentration associated with sandy soil particles is estimated at 0.1 of that in interstitial water (in the pore spaces between the soil particles), although technetium binds more tightly to clay soils (with concentration ratios 10 times higher). For this reason, technetium-99 has been found in groundwater at several DOE sites.

What Happens to It in the Body? Technetium pertechnetate (TcO_4) is readily taken up from the intestines and lungs following ingestion or inhalation, with about 50 to 80% of the amount ingested being transferred to the bloodstream. After reaching the blood, about 4% of the technetium pertechnetate deposits in the thyroid where it is retained with a biological half-life of 0.5 days; the other two organs to which this isotope preferentially distributes are the stomach wall (10%) and liver (3%). The rest of what enters the blood is uniformly distributed throughout all other organs and tissues with a short residence time. Of the amount that reaches body tissues, half is excreted in urine and half is excreted in feces. For the technetium that is distributed to organs other than the thyroid, about 75% leaves the body with a biological half-life of 1.6 days, 20% clears with a half-life of 3.7 days, and 5% clears with a half-life of 22 days. (This information is per simplified models that do not reflect intermediate redistribution.)

What Are the Primary Health Effects? Technetium-99 is a health hazard only if it is taken into the body. It does not pose an external hazard because it decays by emitting a relatively low-energy beta particle with no gamma radiation. The main concern is cancer induction from the beta particles associated with its radioactive decay. Technetium can concentrate in several organs depending on its chemical form, so there is no primary organ of concern. This is one reason why the short-lived isotope technetium-99m has such wide usage in nuclear medicine as a diagnostic tool. The low energy of the beta particle, the lack of significant gamma or X-rays, and the rapid excretion of technetium-99 from the body limit the potential for health effects.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including technetium *(see box at right)*. While the coefficients for ingestion are somewhat lower than for inhalation, ingestion is generally the most common means of entry into the body. Similar to other radionuclides, the risk coefficients for tap water are about 70% of those for dietary ingestion.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Technetium-97	7.6×10^{-13}	2.3×10^{-13}
Technetium-98	2.6×10^{-11}	6.0×10^{-12}
Technetium-99	1.3×10^{-11}	2.3×10^{-12}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Thorium

Symbol: **Th**

Atomic Number: **90**
(protons in nucleus)

Atomic Weight: **232**
(naturally occurring)

What Is It? Thorium is a radioactive element that occurs naturally in low concentrations (about 10 parts per million) in the earth's crust. It is about three times as abundant as uranium and about as abundant as lead or molybdenum. Thorium in its pure form is a silvery-white heavy metal that is about as dense as lead. In nature, almost all thorium is thorium-232, although several additional isotopes can be present in small amounts. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) Thorium is a soft, ductile metal that is pyrophoric in powdered form. When heated in air, thorium turnings ignite and burn brilliantly with a white light.

Of the 26 known isotopes of thorium, only 12 have half-lives greater than one second, and of these only 3 have half-lives sufficiently long to warrant a concern. These key isotopes decay very slowly by emitting an alpha particle. The half-lives of thorium-232 and thorium-230, the isotopes of most concern, are very long. Their low specific activity means these two isotopes are not highly radioactive. Both thorium-232 and thorium-230 are present in soil and ores in secular equilibrium with radium-228 and radium-226, respectively. The health risks for these two radium isotopes (shown in the Radium fact sheet) must be added to those shown here to estimate the total risk. Thorium-229 is not generally associated with nuclear fuel cycle activities previously performed by the Department of Energy (DOE), and hence is not a radionuclide of concern at DOE environmental management sites. The health risks associated with thorium-228, which has a half-life of 1.9 years, are commonly included with those for radium-228 because thorium-228 cannot persist for an extended period of time in the absence of radium-228. *(See the companion fact sheet for Radium.)*

Radioactive Properties of Key Thorium Isotopes and Associated Radionuclides

Isotope	Half-Life	Natural Abundance *(%)*	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
					Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Th-232	14 billion yr	>99	0.00000011	α	4.0	0.012	0.0013
Th-230	77,000 yr	<<1	0.020	α	4.7	0.015	0.0016
Th-229	7,300 yr	<<1	0.22	α	4.9	0.12	0.096
Ra-225	*15 days*		*40,000*	*β*	-	*0.11*	*0.014*
Ac-225	*10 days*		*59,000*	*α*	*5.8*	*0.022*	*0.018*
Fr-221	*4.8 min*		*180 million*	*α*	*6.3*	*0.010*	*0.031*
At-217	*0.032 sec*		*1.6 trillion*	*α*	*7.1*	<	<
Bi-213	*46 min*		*20 million*	*α, β*	*0.13*	*0.44*	*0.13*
Po-213 (98%)	*0.0000042 sec*		*13,000 trillion*	*α*	*8.4*	-	-
Tl-209 (2%)	*2.2 min*		*410 million*	*β*	-	*0.69*	*2.0*
Pb-209	*3.3 hr*		*4.7 million*	*β*	-	*0.20*	-

Ci = curie, g = gram, and MeV = million electron volts; a "<" means the radiation energy is less than 0.001 MeV, and a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for explanation of terms and interpretation of radiation energies.) Bismuth-213 decays by both emitting an alpha particle (2%) and a beta particle (98%). Certain properties of additional radionuclides are included here because they accompany the thorium decays. Values are to two significant figures.

Where Does It Come From? Thorium is widely distributed in small amounts in the earth's crust. The chief commercial source is monazite sands in the United States (in North Carolina, South Carolina, Idaho, Colorado, Montana, and Florida) as well as in Brazil, India, Australia, and South Africa. The concentration of thorium oxide in monazite sands is about 3 to 10%. Thorium is also found in the minerals thorite (thorium silicate) and thorianite (mixed thorium and uranium oxides). The isotope thorium-230, a decay product of uranium-238, is found in uranium deposits as well as in uranium mill tailings.

How Is It Used? The principal use of thorium has been in the preparation of the Welsbach mantle for portable gas lanterns. These mantles contain thorium oxide with about 1% cerium oxide and other ingredients, and they glow with a dazzling light when heated in a gas flame. Thorium is an important alloying element in magnesium and is used to coat tungsten wire for components of electronic equipment. Thorium can also be added to ceramic items such as crucibles to make them more heat resistant, as well as to refractive glass to allow for smaller and more accurate camera lenses. In addition, thorium is used in welding rods and electric bulb filaments to improve product performance.

Thorium can also be used as a fuel in nuclear reactors. While thorium-232 itself is not fissile, it transforms into the fissile isotope uranium-233 upon absorption of a neutron. Although use of the thorium-232/uranium-233 fuel cycle has been demonstrated in pilot-scale studies, it has not been proven to be economically or technically viable for use in commercial nuclear power plants.

What's in the Environment? Thorium is naturally present in soil, rocks, surface water, groundwater, plants, and animals at low concentrations, on the order of ten parts per million. Higher levels are present in certain geological materials such as monzanite sands. Essentially all naturally occurring thorium is present as thorium-232. Thorium-230 is a radioactive decay product of uranium-238 and is found in low concentrations in uranium deposits and mill tailings. In its natural state, thorium occurs as an oxide (ThO_2), phosphate ($ThPO_4$), and silicate ($ThSiO_4$). Thorium preferentially adheres very tightly to soil particles, with concentrations in sandy soil generally more than 3,000 times higher than in interstitial water (water in the pore spaces between soil particles); it is even less mobile in clay soils, with concentration ratios over 5,000. The concentration of thorium in plants is typically about 0.0042 (or 0.42%) of that in soil. Data have not indicated that it biomagnifies in terrestrial or aquatic food chains. Because of its low solubility, thorium is not generally a major groundwater contaminant at DOE sites.

What Happens to It in the Body? Thorium can be taken into the body by eating food, drinking water, or breathing air. Most thorium that is inhaled or ingested in food and water is excreted within a few days, with only a small fraction being absorbed into the bloodstream. Gastrointestinal absorption from food or water is the principal source of internally deposited thorium in the general population. About 0.02 to 0.05% of the amount ingested is absorbed into the bloodstream through the intestines. Of the amount entering the blood, about 70% deposits in bone where it is retained with a biological half-life of about 22 years, 4% deposits in the liver where it is retained with a biological half-life of 700 days, and 16% is uniformly distributed to all other organs and tissues of the body where it is cleared with a biological half-life of 700 days. (per simplified models that do not reflect intermediate redistribution). Most of the remaining 10% is directly excreted. Thorium is predominantly deposited on the endosteal surfaces of mineral bone and only slowly redistributes throughout the bone volume.

What Are the Primary Health Effects? Thorium is generally a health hazard only if it is taken into the body. External gamma exposure is not a major concern because thorium emits only a small amount of gamma radiation. Although thorium-229 has a much higher gamma component than either thorium-232 or thorium-230, thorium-229 comprises a very small fraction of natural thorium. (Note that if significant concentrations of radium occur along with thorium, which is common, the external gamma dose associated with the radium must also be addressed.) The major means of exposure to thorium are ingestion of food and water containing thorium and inhalation of thorium-contaminated dust. Ingestion is generally the main exposure concern, unless there is a nearby source of airborne dust containing thorium such as uranium mill tailings. Thorium is taken up in the body much more readily if inhaled rather than ingested (see table below), so both exposure routes can be important. The main health concern for environmental exposures is generally bone cancer.

Most of the human data for thorium exposure comes from diagnostic studies. Colloidal thorium-232 dioxide (Thorotrast) was injected into patients as a radiographic contrast medium between 1928 and 1955. The epidemiological data from these studies show that the primary health effects of high doses of injected Thorotrast are blood disorders and liver tumors. Some evidence of increased incidence of lung, pancreatic, and hematopoietic cancers was found in workers occupationally exposed to thorium via inhalation. However, these workers were also exposed to several other toxic agents, so direct causation cannot be inferred. Few data are available regarding the health effects associated with low (e.g., environmental) levels of exposure from either inhalation or ingestion.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including thorium *(see box at right).* The risk coefficients for the isotopes of most concern (thorium-230 and thorium-232) are similar. While the coefficients for thorium-229 are about five to eight times higher, this isotope is generally not of concern at DOE sites. The risk coefficients for ingestion, the most common type of exposure, are much lower than those for inhalation for all three isotopes. Similar to other radionuclides, the risk coefficients for tap water are nearly 80% of those for dietary ingestion.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. These values include the contributions from the short-lived thorium decay products. Risks are for lifetime cancer mortality per unit intake (picocurie, pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Th-229	2.2×10^{-7}	4.7×10^{-10}
Th-230	2.7×10^{-8}	8.0×10^{-11}
Th-232	4.1×10^{-8}	9.1×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Uranium

Symbol: **U**

Atomic Number: **92**
(protons in nucleus)

Atomic Weight: **238**
(naturally occurring)

What Is It? Uranium is a radioactive element that occurs naturally in low concentrations (a few parts per million, ppm) in soil, rock, surface water, and groundwater. It is the heaviest naturally occurring element, with an atomic number of 92. Uranium in its pure form is a silver-colored heavy metal that is nearly twice as dense as lead. In nature, uranium exists as several isotopes: primarily uranium-238, uranium-235, and a very small amount of uranium-234. (Isotopes are different forms of an element that have the same number of protons in the nucleus but a different number of neutrons.) In a typical sample of natural uranium, almost all the mass (99.27%) consists of atoms of uranium-238. Less than 1% (about 0.72%) of the mass consists of atoms of uranium-235, and a very small amount (0.0055% by mass) is uranium-234.

Uranium decays very slowly by emitting an alpha particle. The main uranium isotope (uranium-238) has a half-life of about 4.5 billion years and has a very low specific activity, i.e., it is not very radioactive. The very long half-lives of these three uranium isotopes are the reason why uranium still exists on earth. Three additional isotopes (uranium-232, uranium-233, and uranium-236) do not occur naturally but they can be produced by nuclear transformations (e.g., in a reactor). These three isotopes also decay by emitting an alpha particle.

Radioactive Properties of Key Uranium Isotopes and Associated Radionuclides

Isotope	Half-Life	Natural Abundance *(% by mass)*	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
					Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
U-232	72 yr	0	22	α	5.3	0.017	0.0022
U-233	160,000 yr	0	0.0098	α	4.8	0.0061	0.0013
U-234	240,000 yr	0.0055	0.0063	α	4.8	0.013	0.0017
U-235	700 million yr	0.72	0.0000022	α	4.4	0.049	0.16
Th-231	*26 hr*		*540,000*	*β*	-	*0.17*	*0.026*
U-236	23 million yr	0	0.000065	α	4.5	0.011	0.0016
U-238	4.5 billion yr	>99	0.00000034	α	4.2	0.010	0.0014
Th-234	*24 days*		*23,000*	*β*	-	*0.060*	*0.0093*
Pa-234m	*1.2 min*		*690 million*	*β*	-	*0.82*	*0.012*

Ci = curie, g = gram, and MeV = million electron volts; a dash means the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for an explanation of terms and interpretation of radiation energies.) Properties of thorium-231, thorium-234, and protactinium-234m are included here because these radionuclides accompany the uranium decays. Values are given to two significant figures. (Note: on an activity basis, the natural abundance of U -238:U-235:U-234 in the earth's crust is about 1.0:0.046:1.0.)

Where Does It Come From? While small amounts of natural uranium are found almost everywhere in soil, rock, and water, uranium ores are found in just a few places – usually in hard rock or sandstone, in deposits normally covered with earth and vegetation. Uranium has been mined in the southwest United States, Canada, Australia, parts of Europe, the former Soviet Union, Namibia, South Africa, Niger, and elsewhere. It is a contaminant at many Department of Energy sites (including Hanford) and other facilities that used natural uranium, including mining, milling, and production facilities.

How Is It Used? For many years, uranium was used to color ceramic glazes, producing colors that ranged from orange-red to lemon yellow. It was also used for tinting in early photography. The radioactive properties of uranium were not recognized until 1896, and its potential for use as an energy source was not realized until the middle of the 20th century. In nuclear reactors, uranium serves as both a source of neutrons (via the fission process) and a target material for producing plutonium. (Plutonium-239 is produced when uranium-238 absorbs a neutron.) Today, its primary use is as fuel in nuclear power reactors to generate electricity. Uranium is also used in small nuclear reactors to produce isotopes for medical and industrial purposes around the world. Natural uranium must be enriched in the isotope uranium-235 for use as a nuclear fuel in light-water reactors, and this enrichment has generally been achieved by gaseous diffusion techniques. Highly enriched uranium is a primary component of certain nuclear weapons. A byproduct of the enrichment process is depleted uranium, i.e., uranium depleted in the isotope 235.

What's in the Environment? Uranium is naturally present in all environmental media at very low concentrations (a few parts per million). Higher levels are present in certain areas, including those with natural uranium ores such as in the southwestern United States. In its natural state, uranium occurs as an oxide ore, U_3O_8. Additional compounds that may be present include other oxides (UO_2, UO_3) as well as fluorides, carbides or carbonates, silicates, vanadates, and phosphates. In addition to the three naturally occurring isotopes, uranium-232, uranium-233, and uranium-236 are present at Hanford. At that site, uranium-233 was produced in targets and disposed of in the 300 Area; uranium-236 measurements in groundwater there have been used to distinguish the presence of natural uranium from uranium associated with reprocessed

spent nuclear fuel. The environmental transport of uranium is strongly influenced by its chemical form. It is generally one of the more mobile radioactive metals and can move down through soil with percolating water to underlying groundwater. Uranium preferentially adheres to soil particles, with a soil concentration typically about 35 times higher than that in the interstitial water (the water between the soil particles); concentration ratios are usually much higher for clay soils (e.g., 1,600). Uranium can bioconcentrate in certain food crops and in terrestrial and aquatic organisms. However, data do not indicate that it biomagnifies in terrestrial or aquatic food chains. The U.S. Environmental Protection Agency (EPA) established a maximum contaminant level (MCL) for uranium in drinking water of 0.030 milligram per liter (mg/L). This equates to about 27 picocuries (pCi)/L (corresponding to a U-234:U-238 ratio of 1.64) considering the ratio of isotopes typically present in drinking water sources.

What Happens to It in the Body? Uranium can be taken into the body by eating food, drinking water, or breathing air. Gastrointestinal absorption from food or water is the main source of internally deposited uranium in the general population. After ingestion, most uranium is excreted within a few days and never enters the bloodstream. The small fraction (0.2 to 5%) that is absorbed into the bloodstream is deposited preferentially in bone (about 22%) and kidneys (about 12%), with the rest being distributed throughout the body (12%) and excreted. Most of what goes to the kidneys leaves within a few days (in urine), while that deposited in bone can remain for many years. After inhalation, generally only a small fraction penetrates to the lung's alveolar region, where it can remain for years and from which it can also enter the bloodstream.

What Are the Primary Health Effects? Uranium is a health hazard only if it is taken into the body. External exposure is generally not a major concern because uranium emits only a small amount of low-energy gamma radiation. While uranium-235 has a much higher gamma component than either uranium-234 or uranium-238, uranium-235 only comprises about 2% of the total activity of natural uranium. The primary means of exposure are ingestion of food and water containing uranium isotopes and inhalation of uranium-contaminated dust. Ingestion is usually the exposure of concern unless there is a nearby source of airborne dust, such as a uranium mine or mill. Because common forms are absorbed much more readily if inhaled rather than ingested, both exposure routes can be important. The main health concern is kidney damage caused by the chemical toxicity of soluble uranium compounds. That effect can be reversible depending on the level of exposure. (Uranium has also been implicated in reproductive effects in laboratory animals and developmental effects in young animals, but it is not known if these problems exist for humans.) A second concern is for uranium deposited in bone, which can lead to bone cancer from the ionizing radiation associated with its radioactive decay products.

What Is the Risk? Lifetime cancer mortality risk coefficients have been calculated for nearly all radionuclides, including uranium *(see box at right).* Although ingestion is generally the common means of entry, these risk coefficients are much lower than those for inhalation so both exposure routes need to be considered. Similar to other radionuclides, the risk coefficients for tap water are about 75% of those for dietary ingestion. On an activity (curie) basis, the risk coefficients are essentially the same for all uranium isotopes (although the factor for ingesting uranium-232 is somewhat higher), so the risk is essentially independent of the ratio of various isotopes in a compound. For this reason, the risk from exposure to depleted uranium is essentially the same as for enriched uranium on an activity basis. Uranium-235 also poses an external gamma exposure risk. To estimate the lifetime cancer mortality risk from that exposure, if it is assumed that 100,000 people were continuously exposed to a thick layer of soil with an initial concentration of 1 pCi/g uranium-235, then 3 of those 100,000 people would be predicted to incur a fatal cancer. (This is in comparison to about 20,000 people from that group estimated to die of cancer from all other causes based on the general U.S. average.) Uranium can also kidney damage due to its chemical toxicity. The standard toxicity value used to estimate the potential for non-cancer effects following ingestion is the EPA reference dose (RfD), which is an estimate of the dose that can be taken in every day over a lifetime without causing an adverse health effect. In addition to the RfD shown above (which is being reviewed as part of ongoing updates), EPA more recently derived a value of 0.0006 mg/kg-day in developing the drinking water MCL. These values are developed by analyzing the biological effects of test animals given relatively large amounts of uranium, then adjusting and normalizing to a mg/kg-day basis for humans.

Radiological Risk Coefficients

This table provides selected risk coefficients for inhalation and ingestion. Recommended default absorption types were used for inhalation, and dietary values were used for ingestion. These values include contributions from short-lived uranium decay products. Risks are for lifetime cancer mortality per unit intake (pCi), averaged over all ages and both genders (10^{-9} is a billionth, and 10^{-12} is a trillionth). Other values, including for morbidity, are also available.

Isotope	Lifetime Cancer Mortality Risk	
	Inhalation (pCi^{-1})	Ingestion (pCi^{-1})
Uranium-232	1.8×10^{-8}	2.7×10^{-10}
Uranium-233	1.1×10^{-8}	6.3×10^{-11}
Uranium-234	1.1×10^{-8}	6.1×10^{-11}
Uranium-235	9.5×10^{-9}	6.2×10^{-11}
Uranium-236	9.9×10^{-9}	5.8×10^{-11}
Uranium-238	8.8×10^{-9}	7.5×10^{-11}

For more information, see the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients and the accompanying Table C.2.

Chemical Toxicity Value
Non-Cancer Effect: ***Oral RfD*** *(soluble salts)*
0.003 mg/kg-day

Radioactive Properties, Internal Distribution, and Risk Coefficients

The fact sheets for the individual radionuclides contain summary-level information on the radioactive properties of the major isotopes of concern at Department of Energy (DOE) environmental management sites such as Hanford, as well as information on the potential health risks associated with exposure to these radionuclides. This information was developed using standard references and publications. The fact sheets are intentionally brief and it is not possible to include all relevant information associated with the highlights summarized in these sheets. This companion fact sheet has been prepared to provide additional context to assist the reader in understanding the basis of the information presented in the individual fact sheets and to allow for proper interpretation of the radionuclide-specific data.

Radioactive Properties. Each radionuclide fact sheet contains a table that summarizes the key properties of the various radioactive isotopes of that element. The information provided in that table includes the radioactive half-life, specific activity, radioactive decay modes, and the average energy of the emitted radiations. To simplify the presentation, all values have been rounded to two significant figures. Much of the information was obtained from Appendix G of Federal Guidance Report (FGR) Number 13 of the Environmental Protection Agency (EPA), *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, 402-R-99-001 (September 1999). These data were also checked with the more detailed decay information in International Commission on Radiological Protection (ICRP) Report 38, *Radionuclide Transformations, Energy and Intensity of Emissions* (1983). The ICRP report is a major source of the information given in Appendix G of FGR Number 13.

Half-Life. The radioactive half-life is the length of time for a given amount of radioactive material to decrease to one half its initial amount by radioactive decay. Half-lives are constant for each radionuclide and can range from less than a second to billions of years. Only those radionuclides with half-lives longer than about one year are of concern for DOE environmental management sites, as shorter-lived radionuclides will have already decayed away to innocuous levels because production activities involving radioactive materials at major sites such as Hanford ceased more than ten years ago.

Specific Activity. The specific activity is the activity per mass and is given in units of curies (Ci) per gram in the individual fact sheets. For reference, the specific activity of radium-226 is about 1 Ci per gram, and for context 1 gram of material is about 0.035 ounce. The specific activities in the fact sheets (in units of curies per gram) were calculated using the following equation given in the Health Physics and Radiological Health Handbook (1992, p. 264). Specific Activity = $A_{Ra\text{-}226} \times T_{Ra\text{-}226} / A_i \times T_i$ where $A_{Ra\text{-}22a} = 226$, the atomic weight of radium-226; $T_{Ra\text{-}226} = 1{,}600$, the value used for the half-life of radium-226, in years (to two significant figures); A_i = the atomic weight of the isotope; and T_i = half-life of the isotope in years. The specific activity can be expressed in international units by multiplying the value in the fact sheet by 3.7×10^{10} becquerels (Bq) per Ci.

Decay Mode. The radioactive decay modes identified in the fact sheets include beta-particle emission, alpha-particle emission, isomeric transition (IT), electron capture (EC), and spontaneous fission (SF). The companion fact sheet on *Ionizing Radiation* contains additional information on the first two decay modes. The IT decay mode is a process whereby a nucleus in an elevated energy state (typically a metastable isotope designated by the letter "m") releases excess energy by emitting a gamma ray. The product of the decay is not a new isotope, but rather the same isotope in a reduced (more stable) energy configuration. The EC decay mode is a process in which an inner-shell electron orbiting the nucleus of an atom is "captured" by the nucleus where it combines with a proton to become a neutron, and excess energy is given off in the form of gamma rays. An outer-shell electron fills the "hole" left in the inner shell, and the excess energy associated with the movement of an outer-shell electron to an inner shell is given off as X-rays. The SF decay mode is a process in which an unstable nucleus splits (fissions) into two smaller products without needing additional neutrons to initiate the process, i.e., it is spontaneous. For simplicity, only the major decay modes are shown in the fact sheets; decay modes that occur less than 1% of the time are not included. Report 38 of the ICRP includes a very detailed accounting of all decay modes for each radionuclide and can be consulted for additional information.

In addition to the radioactive decay modes discussed above, there are additional mechanisms by which unstable atoms release energy. Internal conversion is a process in which the excess energy of a nucleus in an excited state is transferred to an electron orbiting the nucleus, which results in the electron being emitted from the atom. This process competes with gamma-ray emission as a mechanism for releasing excess energy from the nucleus, such as occurs during IT decay. Both internal conversion and EC result in a "hole" in the inner shell of orbital electrons, which is filled by an outer-shell electron with excess energy given off in the form of X-rays. These X-rays can interact with other orbital electrons, transferring sufficient energy to them to result in the emission of additional electrons. Such emitted electrons generated by interactions with X-rays are termed Auger electrons and have very little kinetic energy.

Decay Energy. The average energy reported for individual isotopes in the fact sheets represents the energy of the indicated radiation multiplied by the fractional yield for the given decay mode. That is, the energy reported for the various types of radiation represents the average energy per decay of the radionuclide. The energy of the radiation is given in units of million electron volts (MeV). One MeV is equal to 0.16 trillionth of a joule. The following two examples are provided to illustrate how this information should be interpreted.

Consider a radionuclide that decays by emitting an alpha particle with two different energies: half the time the energy is 5 MeV and the other half of the time the energy is 6 MeV. The energy reported for the alpha particle decay in this case would be 5.5 MeV. Consider a second example in which a radionuclide decays half the time by emitting a beta particle with an average energy of 0.5 MeV, and the other half of the time it decays by emitting an alpha particle with an energy of 6 MeV. The energy of the beta particle would be reported as 0.25 MeV (half of 0.5 MeV), and the energy of the alpha particle would be given as 3 MeV (half of 6 MeV). As a note, the average energy of a beta particle is typically about one-third the maximum energy (which is often the energy reported in radionuclide charts), or about 30% of the maximum for negatrons and 40% for positrons. (See the companion fact sheet on *Ionizing Radiation* for a discussion of negatrons and positrons.) The summary-level tables in the individual radionuclide fact sheets include the contributions of all primary (alpha and beta particles and gamma rays) and secondary (X-rays and Auger electrons) radiations.

The average energy reported for gamma rays in the fact sheets includes the contributions of X-rays and has been adjusted to account for the fractional yield. The only difference between these two types of electromagnetic radiation is their origin, and hence energy. Gamma rays originate in the nucleus as a means of releasing excess energy from the atom, while X-rays are emitted when electrons outside the nucleus move from higher to lower energy states. Radionuclides having gamma-ray energies less than 0.03 MeV per decay, considering the fractional yield (as described above), generally do not present a health concern from external gamma exposure. The average energy per decay reported for beta particles includes the contributions of all electrons and positrons regardless of their origin (internal or external to the nucleus). The average energy per decay reported for alpha particles does not include the contribution of the recoiling atom (which is typically quite small, e.g., a few percent of the total energy associated with the alpha-decay process).

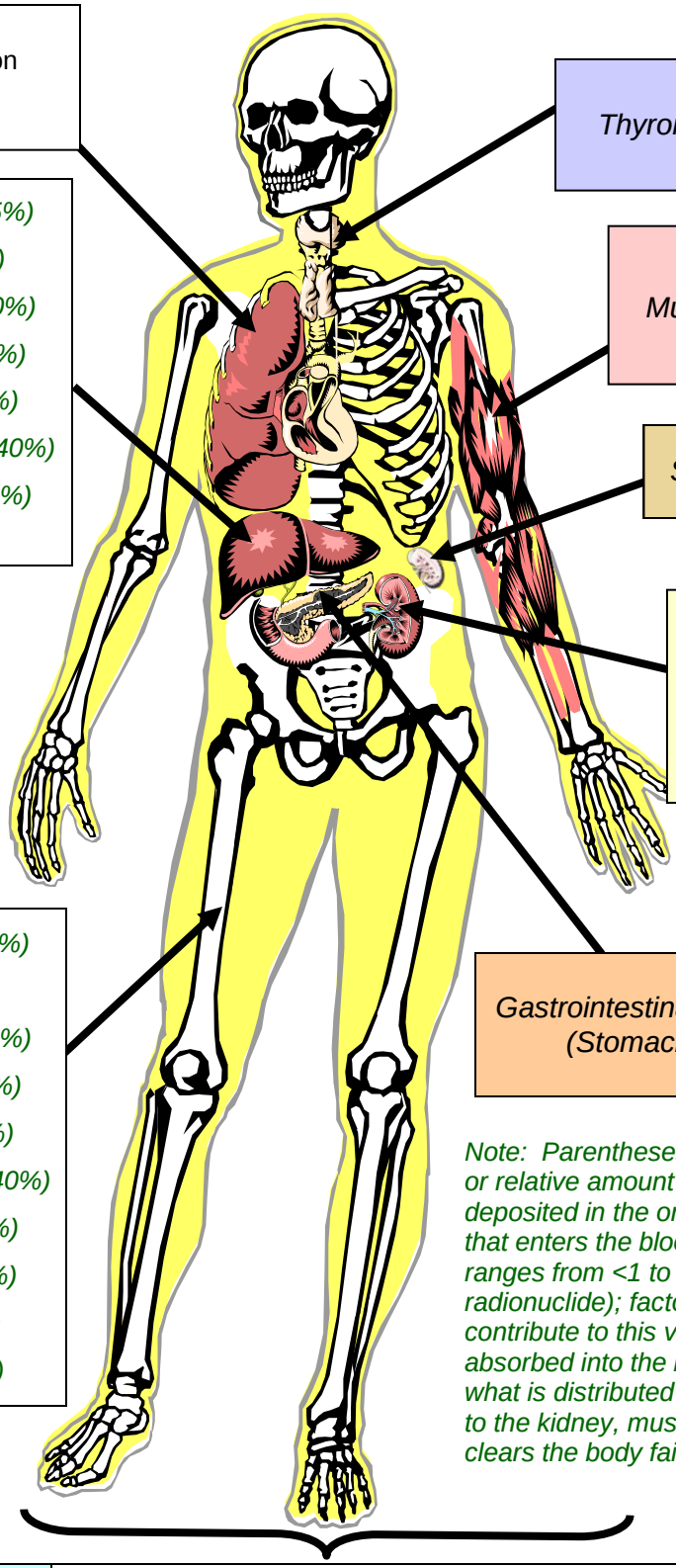
Some radionuclides decay into short-lived daughters that always accompany the parent. (The term *parent* is used to describe the original isotope, and *daughter* is used for the decay product.) For example, strontium-90 decays to yttrium-90 by emitting a beta particle with a 29-year half-life. The daughter yttrium-90 quickly decays by emitting a beta particle, with a half-life of 64 hours. So for all practical purposes, each decay of strontium-90 can be considered to yield two beta particles, one for strontium-90 and one for yttrium-90. Short-lived decay products need to be considered when estimating the potential health effects of exposures to radionuclides. To facilitate this consideration, the radioactive properties of both the parent and its short-lived daughter(s) are presented in the individual radionuclide fact sheets.

Internal Distribution. To estimate the human health risks associated with radionuclides, it is necessary to follow the movement of the isotopes from intake through excretion. These isotopes constantly emit radiation at a rate proportional to their specific activity as they pass through the body irradiating various organs. Some radionuclides very quickly deposit in one or two organs; others deposit more slowly throughout the entire body. Various models and computer codes have been developed by the ICRP, EPA, and other national and international organizations to estimate internal radiation doses and risks from intake of radionuclides. These models are based on extensive animal and human data and can be quite complex. A number of codes and models were considered by the EPA in developing the risk coefficients presented in FGR Number 13, as illustrated by the references in that document. The risk coefficients were calculated used the DCAL (Dose and Risk Calculation) software developed by Oak Ridge National Laboratory for the EPA. The DCAL is a comprehensive system for calculating radiation dose and risk coefficients using age-dependent models that incorporate information developed by the ICRP and other organizations on the distribution and retention of radionuclides by various organs in the body. The initial distribution of selected radionuclides in the body is shown in Figure C.1 of the accompanying distribution fact sheet.

Risk Coefficients. The EPA has developed mortality risk coefficients for nearly all radionuclides to estimate the lifetime risk of incurring a fatal cancer from environmental exposures using the DCAL software as described in FGR Number 13. These coefficients have been calculated by state-of-the-art methods and computer models that take into account age and gender dependence of intake, metabolism, dosimetry, and radiogenic risk, as well as competing causes of death, to estimate health risks from internal and external exposures. The values are given per unit uptake (picocurie, pCi) averaged over all ages and both genders. (For context, 10^{-9} is a billionth, 10^{-12} is a trillionth, and a pCi is a trillionth of a Ci.) To convert to standard international units, the given values should be multiplied by 27 pCi/Bq.

Each radionuclide fact sheet contains a table with selected mortality risk coefficients for inhalation and ingestion, which are also summarized in Table C.2. These values include the contributions from short-lived decay products, as identified on the radioactive properties summary table described above (e.g., the value for strontium-90 includes the contribution from yttrium-90). For inhalation, the values correspond to the recommended default absorption type for particulates, except as otherwise noted (e.g., the tritium values are for tritiated water). For ingestion, the dietary values shown are the highest for ingestion exposures; the values for tap water ingestion vary by radionuclide and are typically 70 to 80% of those for dietary intake. Coefficients are also available to estimate the risk of incurring all types of cancer (morbidity risk coefficients), and these values also vary by radionuclide. For most radionuclides, the ingestion mortality coefficients are on the order of 60 to 80% of the morbidity values, with iodine an exception at about 10%. For inhalation the percentages are a bit higher, ranging from 70% (for cesium and tritium) to nearly 100% (for uranium-234 and uranium-238), with the mortality coefficient for iodine again much lower at about 10%. For major gamma-emitting radionuclides, risk coefficients are shown in Table C.2 and risk text is included in the fact sheet.

FIGURE C.1 Initial Distribution of Selected Radionuclides in the Body



Lung	Radium / Radon *(inhaled)*
Liver	Americium *(45%)* Lead *(10-15%)* Neptunium *(10%)* Plutonium *(45%)* Polonium *(15%)* Protactinium *(40%)* Technetium *(3%)* Thorium *(4%)*
Bone	Americium *(45%)* Lead *(50-90%)* Neptunium *(50%)* Plutonium *(45%)* Polonium *(10%)* Protactinium *(40%)* Radium *(1-30%)* Strontium *(15%)* Thorium *(70%)* Uranium *(22%)*
Thyroid	Iodine *(30%)* Technetium *(4%)*
Muscle	Cesium *(slightly more than, but comparable to, all body tissues)*
Spleen	Polonium *(15%)*
Kidney	Polonium*(15%)* Protactinium *(2%)* Strontium *(see below)* Uranium *(12%)*
Gastrointestinal Tract (Stomach)	Technetium *(10%)*

Note: Parentheses indicate approximate percent or relative amount generally distributed to/ deposited in the organ/system, of the fraction that enters the bloodstream after intake (which ranges from <1 to ~100% depending on the radionuclide); factors such as age and diet contribute to this variability. The remaining amount absorbed into the blood is excreted. Much of what is distributed throughout the body (including to the kidney, muscle, and other soft tissues) also clears the body fairly quickly.

Throughout Body	Carbon-14 *(100%)*	Potassium-40 *(100%)*	Technetium *(83%)*
	Cesium *(100%)*	Radium *(6-20%)*	Thorium *(16%)*
	Neptunium *(5%)*	Strontium *(37%)*	Uranium *(12%)*
	Polonium *(45%)*		

TABLE C.1 Summary Radioactive Properties for Selected Radionuclides[a]

Isotope	Half-Life	Specific Activity *(Ci/g)*	Decay Mode	Radiation Energy *(MeV)*		
				Alpha *(α)*	Beta *(β)*	Gamma *(γ)*
Americium-241	430 yr	3.5	α	5.5	0.052	0.033
Americium-242m	150 yr	9.8	IT	0.025	0.044	0.0051
Americium-242	*16 hr*	*820,000*	*β, EC*	-	*0.18*	*0.018*
Americium-243	7,400 yr	0.20	α	5.3	0.022	0.056
Neptunium-239	*2.4 days*	*230,000*	*β*	-	*0.26*	*0.17*
Carbon-14[e]	5.700 yr	4.5	β	-	0.049	-
Cesium-134	2.1 yr	1,300	β	-	0.16	1.6
Cesium-135	2.3 million yr	0.0012	β	-	0.067	-
Cesium-137	30 yr	88	β	-	0.19	-
Barium-137m (95%)	*2.6 min*	*540 million*	*IT*	-	*0.065*	*0.60*
Neptunium-235	1.1 yr	1,400	EC	<0.001	0.010	0.0071
Neptunium-236	120,000 yr	0.013	β, EC	-	0.21	0.14
Plutonium-236 (9%)	*2.9 yr*	*540*	*α*	*5.8*	*0.013*	*0.0021*
Neptunium-237	2.1 million yr	0.00071	α	4.8	0.070	0.035
Protactinium-233	*27 days*	*21,000*	*β*	-	*0.20*	*0.20*
Plutonium-236	2.9 yr	540	α	5.8	0.013	0.0021
Plutonium-238	88 yr	17	α	5.5	0.011	0.0018
Plutonium-239	24,000 yr	0.063	α	5.1	0.0067	<0.001
Plutonium-240	6,500 yr	0.23	α	5.2	0.011	0.0017
Plutonium-241	14 yr	100	β	<0.001	0.0052	<0.001
Plutonium-242	380,000 yr	0.0040	α	4.9	0.0087	0.0014
Plutonium-244	83 million yr	0.000018	α	4.6	0.0071	0.0012
Uranium-240	*14 hr*	*940,000*	*β*	-	*0.14*	*0.0076*
Neptunium-240m	*7.4 min*	*110 million*	*β*	-	*0.68*	*0.34*
Polonium-208	2.9 yr	590	α	5.1	<0.001	<0.001
Polonium-209	100 yr	17	α	4.9	<0.001	<0.001
Polonium-210	140 days	4,500	α	5.3	<0.001	<0.001
Potassium-40[e]	1.3 billion yr	0.0000071	β, EC	-	0.52	0.16
Protactinium-231[e]	33,000 yr	0.048	α	5.0	0.065	0.048
Actinium-227[e]	*22 yr*	*73*	*α, β*	*0.068*	*0.016*	*<0.001*
Thorium-227[e] (99%)	*19 days*	*31,000*	*α*	*5.9*	*0.053*	*0.11*
Francium-223[e] (1%)	*22 min*	*39 million*	*β*	-	*0.40*	*0.059*
Radium-223[e]	*11 days*	*52,000*	*α*	*5.7*	*0.076*	*0.13*
Radon-219[e]	*4.0 sec*	*13 billion*	*α*	*6.8*	*0.0063*	*0.056*
Polonium-215[e]	*0.0018 sec*	*30 trillion*	*α*	*7.4*	*<0.001*	*<0.001*
Lead-211[e]	*36 min*	*25 million*	*β*	-	*0.46*	*0.051*
Bismuth-211[e]	*2.1 min*	*420 million*	*α*	*6.6*	*0.010*	*0.047*

Isotope	Half-Life	Specific Activity (Ci/g)	Decay Mode	Radiation Energy (MeV)		
				Alpha (α)	Beta (β)	Gamma (γ)
Thallium-207[e]	*4.8 min*	*190 million*	*β*	-	*0.49*	*0.0022*
Radium-226[e]	1600 yr	1.0	α	4.8	0.0036	0.0067
Radon-222[e]	*3.8 days*	*160,000*	*α*	*5.5*	*<0.001*	*<0.001*
Polonium-218[e]	*3.1 min*	*290 million*	*α*	*6.0*	*<0.001*	*<0.001*
Lead-214[e]	*27 min*	*33 million*	*β*	-	*0.29*	*0.25*
Bismuth-214[e]	*20 min*	*45 million*	*β*	-	*0.66*	*1.5*
Polonium-214[e]	*0.00016 sec*	*330 trillion*	*α*	*7.7*	*<0.001*	*<0.001*
Lead-210[e]	*22 yr*	*77*	*β*	-	*0.038*	*0.0048*
Bismuth-210[e]	*5.0 days*	*130,000*	*β*	-	*0.39*	-
Polonium-210[e]	*140 days*	*4,500*	*α*	*5.3*	*<0.001*	*<0.001*
Radium-228[e]	5.8 yr	280	β	-	0.017	<0.001
Actinium-228[e]	*6.1 hr*	*2.3 million*	*β*	-	*0.48*	*0.97*
Thorium-228[e]	*1.9 yr*	*830*	*α*	*5.4*	*0.021*	*0.0033*
Radium-224[e]	*3.7 days*	*160,000*	*α*	*5.7*	*0.0022*	*0.010*
Radon-220[e]	*56 sec*	*930 million*	*α*	*6.3*	*<0.001*	*<0.001*
Polonium-216[e]	*0.15 sec*	*350 billion*	*α*	*6.8*	*<0.001*	*<0.001*
Lead-212[e]	*11 hr*	*1.4 million*	*β*	-	*0.18*	*0.15*
Bismuth-212[e]	*61 min*	*15 million*	*α, β*	*2.2*	*0.47*	*0.19*
Polonium-212[e] *(64%)*	*0.00000031 sec*	*180,000 trillion*	*α*	*8.8*	-	-
Thallium-208[e] *(36%)*	*3.1 min*	*300 million*	*β*	-	*0.60*	*3.4*
Strontium-90	29 yr	140	β	-	0.20	-
Yttrium-90	*64 hr*	*550,000*	*β*	-	*0.94*	*<0.001*
Technetium-97	2.6 million	0.0014	EC	-	0.0056	0.011
Technetium-98	4.2 million	0.00088	β	-	0.16	1.4
Technetium-99	210,000	0.017	β	-	0.10	-
Thorium-229	7,300 yr	0.22	α	4.9	0.12	0.096
Radium-225	*15 days*	*40,000*	*β*	-	*0.11*	*0.014*
Actinium-225	*10 days*	*59,000*	*α*	*5.8*	*0.022*	*0.018*
Francium-221	*4.8 min*	*180 million*	*α*	*6.3*	*0.010*	*0.031*
Astatine-217	*0.032 sec*	*1.6 trillion*	*α*	*7.1*	*<0.001*	*<0.001*
Bismuth-213	*46 min*	*20 million*	*α, β*	*0.13*	*0.44*	*0.13*
Polonium-213 (98%)	*0.0000042 sec*	*13,000 trillion*	*α*	*8.4*	-	-
Thallium-209 (2%)	*2.2 min*	*410 million*	*β*	-	*0.69*	*2.0*
Lead-209	*3.3 hr*	*4.7 million*	*β*	-	*0.20*	-
Thorium-230[e]	77,000 yr	0.020	α	4.7	0.015	0.0016
Thorium-232[e]	14 billion yr	0.00000011	α	4.0	0.012	0.0013
Uranium-232	72 hr	22	α	5.3	0.017	0.0022
Uranium-233	160,000 yr	0.0098	α	4.8	0.0061	0.0013

Isotope	**Half-Life**	**Specific Activity** *(Ci/g)*	**Decay Mode**	**Radiation Energy** *(MeV)*		
				Alpha *(α)*	**Beta** *(β)*	**Gamma** *(γ)*
Uranium-234[e]	240,000 yr	0.0063	α	4.8	0.013	0.0017
Uranium-235[e]	700 million yr	0.0000022	α	4.4	0.049	0.16
Thorium-231[e]	*26 hr*	*540,000*	*β*	-	*0.17*	*0.026*
Uranium-236	23 million yr	0.000065	α	4.5	0.011	0.0016
Uranium-238[n]	4.5 billion yr	0.00000034	α	4.2	0.010	0.0014
Thorium-234[e]	*24 days*	*23,000*	*β*	-	*0.060*	*0.0093*
Protactinium-234m[e]	*1.2 min*	*690 million*	*β*	-	*0.82*	*0.012*

[a] This table summarizes key radioactive properties of selected radionuclides (shaded) and their associated decay products, which are indicated in italics. Values are given to two significant figures.

An "e" indicates the isotope exists naturally in the environment. A dash means the entry is not applicable,

EC = electron capture, IT = isomeric transition, Ci = curie, g = gram, and MeV = million electron volts. See the radionuclide-specific fact sheets for further information, and the companion fact sheet on *Radioactive Properties, Internal Distribution, and Risk Coefficients* for an explanation of terms and interpretation of radiation energies.

TABLE C.2 Mortality and Morbidity Risk Coefficients for Selected Radionuclides[a]

Isotope	Lifetime Cancer Risk					
	Mortality			Morbidity		
	Inhalation	Ingestion	External	Inhalation	Ingestion	External
Americium-241	2.4×10^{-8}	9.5×10^{-11}	1.9×10^{-8}	2.8×10^{-8}	1.3×10^{-10}	2.8×10^{-8}
Americium-242m	1.3×10^{-8}	6.8×10^{-11}	2.4×10^{-8}	1.6×10^{-8}	9.0×10^{-11}	3.6×10^{-8}
Americium-243	2.3×10^{-8}	9.8×10^{-11}	4.3×10^{-7}	2.7×10^{-8}	1.4×10^{-10}	6.4×10^{-7}
Carbon-14	6.5×10^{-12}	1.4×10^{-12}	-	7.1×10^{-12}	2.0×10^{-12}	-
Cesium-134	1.1×10^{-11}	3.5×10^{-11}	4.8×10^{-6}	1.7×10^{-11}	5.1×10^{-11}	7.1×10^{-6}
Cesium-135	1.3×10^{-12}	4.0×10^{-12}	-	1.9×10^{-12}	5.9×10^{-12}	-
Cesium-137	8.1×10^{-12}	2.6×10^{-11}	1.7×10^{-6}	1.2×10^{-11}	3.7×10^{-11}	2.6×10^{-6}
Neptunium-235	1.0×10^{-12}	2.8×10^{-13}	-	1.2×10^{-12}	5.1×10^{-13}	-
Neptunium-236	7.3×10^{-10}	9.0×10^{-12}	2.2×10^{-7}	8.1×10^{-10}	1.4×10^{-11}	3.3×10^{-7}
Neptunium-237	1.6×10^{-8}	5.8×10^{-11}	5.4×10^{-7}	1.8×10^{-8}	9.1×10^{-11}	8.0×10^{-7}
Plutonium-236	2.1×10^{-8}	6.9×10^{-11}	-	2.3×10^{-8}	9.9×10^{-11}	-
Plutonium-238	3.0×10^{-8}	1.3×10^{-10}	-	3.6×10^{-8}	1.7×10^{-10}	-
Plutonium-239	2.9×10^{-8}	1.3×10^{-10}	-	3.3×10^{-8}	1.7×10^{-10}	-
Plutonium-240	2.9×10^{-8}	1.3×10^{-10}	-	3.3×10^{-8}	1.7×10^{-10}	-
Plutonium-241	2.9×10^{-10}	5.8×10^{-12}	2.6×10^{-7}	3.4×10^{-10}	9.4×10^{-12}	3.8×10^{-7}
Plutonium-242	2.8×10^{-8}	1.3×10^{-10}	-	3.1×10^{-8}	1.7×10^{-10}	-
Plutonium-244	2.6×10^{-8}	1.4×10^{-10}	1.0×10^{-6}	2.9×10^{-8}	1.9×10^{-10}	1.5×10^{-6}
Polonium-210	1.0×10^{-8}	1.6×10^{-9}	-	1.1×10^{-8}	2.3×10^{-9}	-
Potassium-40	2.1×10^{-10}	2.2×10^{-11}	5.4×10^{-7}	2.2×10^{-10}	3.4×10^{-11}	8.0×10^{-7}
Protactinium-231	2.0×10^{-7}	6.0×10^{-10}	1.1×10^{-6}	2.3×10^{-7}	8.8×10^{-10}	1.6×10^{-6}
Radium-226	2.4×10^{-8}	2.9×10^{-9}	5.8×10^{-6}	2.5×10^{-8}	4.0×10^{-9}	8.5×10^{-6}
Radium-228	9.0×10^{-8}	1.3×10^{-9}	8.4×10^{-6}	9.7×10^{-8}	1.9×10^{-9}	1.2×10^{-5}
Strontium-90	1.0×10^{-10}	7.5×10^{-11}	-	1.1×10^{-10}	9.5×10^{-11}	-
Technetium-97	7.6×10^{-13}	2.3×10^{-13}	-	8.5×10^{-13}	3.9×10^{-13}	-
Technetium-98	2.6×10^{-11}	6.0×10^{-12}	4.4×10^{-6}	3.0×10^{-11}	1.0×10^{-11}	6.5×10^{-6}
Technetium-99	1.3×10^{-11}	2.3×10^{-12}	-	1.4×10^{-11}	4.0×10^{-12}	-
Thorium-229	2.2×10^{-7}	4.7×10^{-10}	7.9×10^{-7}	2.3×10^{-7}	7.2×10^{-10}	1.5×10^{-6}
Thorium-230	2.7×10^{-8}	8.0×10^{-11}	-	3.4×10^{-8}	1.2×10^{-10}	-
Thorium-232	4.1×10^{-8}	9.1×10^{-11}	-	4.3×10^{-8}	1.3×10^{-10}	-
Uranium-232	1.8×10^{-8}	2.7×10^{-10}	-	2.0×10^{-8}	3.9×10^{-10}	-
Uranium-233	1.1×10^{-8}	6.3×10^{-11}	-	1.2×10^{-8}	9.7×10^{-11}	-
Uranium-234	1.1×10^{-8}	6.1×10^{-11}	-	1.1×10^{-8}	9.6×10^{-11}	-
Uranium-235	9.5×10^{-9}	6.2×10^{-11}	3.7×10^{-7}	1.0×10^{-8}	9.8×10^{-11}	5.4×10^{-7}
Uranium-236	9.9×10^{-9}	5.8×10^{-11}	-	1.1×10^{-8}	9.0×10^{-11}	-
Uranium-238	8.8×10^{-9}	7.5×10^{-11}	7.8×10^{-8}	9.4×10^{-9}	1.2×10^{-10}	1.1×10^{-7}

[a] This table provides selected risk coefficients for inhalation and dietary ingestion of various radionuclides, and for external gamma irradiation where that entry is appropriate (Source: *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, Federal Guidance Report 13, EPA 402-R-99-001, September 1999). Shading is used to distinguish between radionuclides. The mortality risk represents the lifetime risk of incurring a fatal cancer, and the morbidity risk represents the risk of incurring all cancers (fatal and non-fatal). Values are averaged over all ages and both genders. (For context, 10^{-9} is a billionth, 10^{-12} is a trillionth, and a pCi is a picocurie, or a trillionth of a curie.) To convert to standard international units, multiply by 27 pCi per becquerel (Bq). Values shown here include the contributions from short-lived decay products, as indicated in the radionuclide-specific fact sheets. (For example, strontium-90 includes the contribution from yttrium-90.)

For ingestion and inhalation, units are risk per pCi. For inhalation, the values corresponding to the recommended default absorption type for particulates are shown; the maximum value is given if no absorption type was recommended. For ingestion, the dietary values shown are the highest for ingestion exposures; values for tap water ingestion are typically 70 to 80% of those for diet.

For external exposure, risk coefficients are given for those radionuclides having gamma-ray energies in excess of 0.03 MeV per decay, accounting for the fraction of time that the radioactive decay results in the emission of gamma rays. A dash indicates the radionuclide or its decay products does not emit significant gamma radiation *(*see the companion fact sheet on *Radioactive Properties, Internal Distribution, and Risk Coefficients).* Units for external gamma risk coefficients shown in the table are risk per pCi/g soil for one year of exposure.

Arsenic

Symbol:	**As**
Atomic Number: *(protons in nucleus)*	**33**
Atomic Weight:	**75**

What Is It? Inorganic and organic arsenic occur naturally in the environment, with inorganic forms being most abundant. Inorganic arsenic is associated with other metals in igneous and sedimentary rocks, and it also occurs in combination with many other elements, especially oxygen, chlorine, and sulfur. Organic arsenic contains carbon and hydrogen. Both inorganic and organic forms exist naturally in soils, plants, animals, and humans. Most pure, inorganic arsenic compounds are white or colorless powders with no specific smell or taste. Because it is an element, arsenic does not degrade nor can it be destroyed.

How Is It Used? Arsenic has been recognized as a poison since ancient times. In past centuries it was used to treat syphilis, and decades ago it was a common active ingredient in pesticides and was also a common wood preservative. Today, about 90% of arsenic produced is used as a wood preservative (chromated copper arsenate).

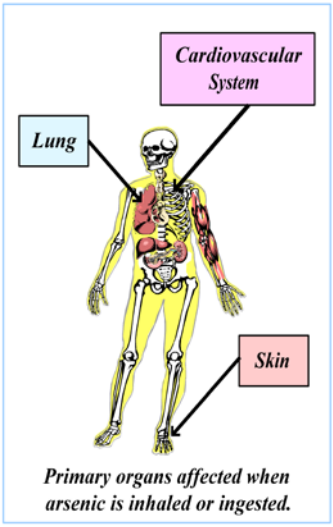
Although organic arsenicals continue to be used as pesticides, primarily on cotton, inorganic compounds can no longer be used. Arsenic is also used as a feed additive for poultry and swine and in cattle and sheep dips to control lice and ticks. In addition, arsenic is used in alloys (primarily in lead-acid batteries for automobiles) and in semiconductors and light-emitting diodes.

What's in the Environment? Arsenic occurs everywhere in the environment. Weathering of rock is the major natural source of inorganic arsenic, and it is also released by human activities. For example, arsenic is emitted as a fine dust when arsenic-containing ores are heated at smelters to process copper or lead. The concentration of arsenic in the earth's crust ranges from 2 to 5 milligrams per kilogram (mg/kg), or parts per million (ppm). The mean natural soil concentration is 5 mg/kg, and it ranges from about 1 to 40 mg/kg. Water-soluble arsenites (the trivalent form, As III) and arsenates (the pentavalent form, As V) are the most common forms. Arsenites especially can be relatively mobile, with a typical concentration associated with soil particles estimated to be 10 to 200 times higher than in the interstitial water (water in the pore spaces between the soil particles). Levels in U.S. drinking water generally average 2 µg/liter, or 2 parts per billion (ppb). Bacteria, fungi, and some plants methylate inorganic arsenic, converting it to organic compounds. Many methylated forms are volatile, such as dimethylarsine. Aquatic organisms in particular can accumulate nontoxic, organic forms of arsenic; for example, levels of arsenobetaine in shrimp are often high. However, the typical ratio of the arsenic concentration in plants to that in soil is low, estimated at 0.006 (or 0.6%).

What Happens to It in the Body? Arsenic can be taken in by eating food, drinking water, or breathing air, and to a limited degree via skin contact. Diet is the primary source of arsenic exposure for most people. Children, and to a lesser extent adults, can also be exposed by ingesting soil. When ingested, dissolved arsenic compounds are readily absorbed (80-90%) through the gastrointestinal tract and distributed in the blood to the liver, kidney, lung, spleen, aorta, and skin. Two processes are involved in arsenic metabolism: (1) oxidation/reduction reactions that interconvert arsenate and arsenite, and (2) methylation of arsenite to form monomethyl arsenic acid and dimethyl arsenic acid. The methylated forms are less toxic and more easily excreted in the urine. Most arsenic is eliminated in the urine within a week (75-90%, depending on the compound), especially from the liver, kidney, and spleen, while that in the skin, brain, skeleton, and especially hair and nails, remains somewhat longer. When arsenic is inhaled and deposited in the lungs, about 80% is absorbed into the bloodstream and distributes throughout the body as above. Arsenic in soil or dissolved in water does not readily penetrate the skin (less than 1% to 3% is estimated to be absorbed, respectively), so dermal exposures are not typically a concern.

What Are the Primary Health Effects? Depending on the amount ingested, arsenic can be beneficial (animal studies suggest that low levels of arsenic in the diet are essential) or adverse (high levels can be toxic). The acute lethal dose to humans can be about 2 to 20 mg/kg body weight per day (mg/kg-day). Ingesting high doses of arsenic irritates the stomach and intestines, with symptoms including nausea, vomiting, diarrhea and liver swelling. However, wide recognition of its toxicity makes arsenic poisoning today very rare. Ingesting small amounts over time produces chronic effects such as skin darkening and formation of corns, damage to peripheral nerves, cardiovascular system effects, hair and appetite loss, and mental disorders. Effects from inhaling arsenic

dust include respiratory irritation, rhinitis, pharyngitis, laryngitis, and sometimes nasal perforation. Skin contact with inorganic arsenic dusts can cause dermatitis, allergic hypersensitivity, and conjunctivitis. Occupational exposure studies show a correlation between chronic arsenic exposure and lung cancer. Arsenic can also cause reproductive/developmental effects, including spontaneous abortions and reduced birth weights. Epidemiological studies indicate an association between arsenic concentrations in drinking water and increased incidences of skin, liver, kidney, lung, and bladder cancers. Studies also show an association between inhaling arsenic and lung cancer. From these data, the U.S. Environmental Protection Agency (EPA) has classified inorganic arsenic as a known human carcinogen. Limited information is available on the joint toxicity of arsenic with other chemicals. For neurological effects, arsenic and lead together can cause effects higher than one alone (greater than additive toxicity), whereas these metals are less toxic to the kidney and hematopoietic (blood-forming) system together rather than alone. The joint toxicity of arsenic and cadmium on the kidney, hematopoietic system, and male reproductive system is also predicted to be less than additive. Additional context for joint toxicity is given in the fact sheet on chemical mixtures.

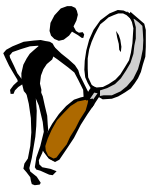


What Is the Risk? The EPA has developed toxicity values *(see box below)* to estimate the risk of getting cancer or other noncancer health effects as a result of ingesting or inhaling inorganic arsenic. These values have been developed based on studies of workers exposed to arsenic in occupational settings, workers applying arsenical pesticides, and populations who drink water containing naturally high concentrations of arsenic. The slope factor is a toxicity value used to estimate the risk of getting cancer from oral exposures, and the value for estimating the risk of cancer following inhalation exposure is called the inhalation unit risk (UR). The UR is an estimate of the chance a person will get cancer from continuous exposure to the chemical in air at a unit concentration, e.g., 1 mg per cubic meter air (m^3). The oral slope factor can be converted to a drinking water unit risk by assuming a 70-kilogram (kg) adult drinks 2 liters (L) of water daily. The EPA estimates a person would have a one-in-a-million chance of developing cancer if the level of inorganic arsenic in their lifetime water supply was 0.02 µg/L. Similarly, using the inhalation UR, EPA estimates a person would have a one-in-a-million chance of getting cancer if exposed daily over a lifetime to 0.0002 µg/m^3 inorganic arsenic in air. The EPA toxicity value used to estimate the potential for noncancer effects following ingestion is the reference dose (RfD), which is an estimate of the dose that can be taken in every day over a lifetime without causing adverse noncancer health effects. To illustrate how the RfD is applied, a 150-pound (lb) person could ingest 0.02 mg arsenic every day without expecting any adverse effects (2.2 lb = 1 kg, or 1,000 g, or 1 million mg). The toxicity value for noncancer effects from inhalation, a reference concentration (RfC), has not been developed. EPA has reviewed existing toxicity values in light of more recent data and released a public draft report in 2010 with draft updates.

Chemical Toxicity Values		
Cancer Risk		**Noncancer Effect**
Oral Slope Factor	***Inhalation Unit Risk***	***Oral Reference Dose***
1.5 per mg/kg-d	4.3 per mg/m^3	0.0003 mg/kg-day

What Are Current Limits for Environmental Releases and Human Exposure? To help track facility releases to the environment, the Superfund amendments for emergency planning and community right-to-know require immediate reporting of a release of 1 lb (0.454 kg) or more of any arsenic compound in a 24-hour period; normal releases are reported annually and entered into the national Toxics Release Inventory. For drinking water, EPA revised its maximum contaminant level from 0.05 to 0.01 mg/L in 2001, with a goal of 0. The Occupational Safety and Health Administration basic standard for inorganic and organic arsenic in workplace air is 0.01 mg/m^3.

Where Can I Find More Information? More information on arsenic can be found in the primary information source for this overview, the Toxicological Profile for Arsenic, prepared by the Agency for Toxic Substances and Disease Registry (ATSDR) (http://www.atsdr.cdc.gov/toxprofiles/index.asp), the ATSDR ToxFAQs (http://www.atsdr.cdc.gov/toxfaqs/index.asp), information developed for the EPA Integrated Risk Information System (http://www.epa.gov/iris, with 2010 draft review at http://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=219111), and the National Library of Medicine Hazardous Substances Data Bank (http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB).



Lead

Symbol:	**Pb**
Atomic Number: *(protons in nucleus)*	**82**
Atomic Weight: *(naturally occurring)*	**207**

What Is It? Lead is an element found naturally in rocks, soil, plants and animals. It typically occurs in combination with other elements as lead salts, some of which are soluble in water. The pure metallic form of lead is bluish-gray, but metallic lead rarely occurs naturally. Lead does not evaporate, but it can be present in air as particles. Because it is an element, lead does not degrade nor can it be destroyed. Several radioactive isotopes are naturally present in the environment, with lead-210 being the isotope of most concern. (Information on radioactive isotopes is presented in the companion fact sheets for radium, thorium, and natural decay series.)

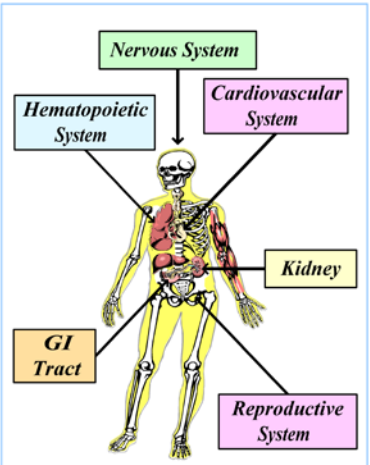
How Is It Used? Lead has been used for thousands of years for a variety of purposes. Today, its major use is in the production of certain types of batteries. Lead is also used to make ammunition, metal products (sheet metal, solder, and pipes), medical equipment (radiation shields and surgical equipment), paints, ceramic glazes, caulking, scientific equipment (circuit boards for computers), and high-precision glass for lasers and other optical equipment. In recent years, the amount used in products such as paints and ceramics has decreased significantly to help minimize exposures of people and animals. Tetraethyl and tetramethyl lead (volatile organic forms) were used for many years in gasoline to increase octane rating. In the United States, this use was phased out during the 1980s, and lead was banned from use in gasoline for transportation in 1996.

What's in the Environment? Lead occurs everywhere in the environment. Concentrations in U.S. soil typically range from less than 10 to 30 milligrams of lead per kilogram of soil (mg/kg). However, amounts in the top layers vary widely and can be much higher due to human activities. For example, concentrations near roadways can be 30 to 2,000 mg/kg higher than natural levels due to past use of leaded gasoline. In air, concentrations typically range from 0.001 to 0.002 microgram per cubic meter ($\mu g/m^3$) in remote areas and from 0.2 to 0.4 $\mu g/m^3$ in urban areas. Levels in surface water and groundwater typically range from 5 to 30 µg/liter. Lead is relatively immobile in soil but can leach to groundwater over time. Concentrations in sandy soil particles are estimated to be 270 times higher than in the water in pore spaces between the soil particles; it binds even more tightly to clay and loam soils, with concentration ratios of about 500 to more than 16,000. Reported concentrations of lead in various foods range from 0.002 to 0.65 mg/kg, with higher levels generally found in vegetables. The typical ratio of the concentration of lead in plants to that in the soil on which they grow is estimated at roughly 0.04 (or 4%).

What Happens to It in the Body? Lead can be taken in by eating food, drinking water, or breathing air. Children, and to a lesser extent, adults, can also be exposed by ingesting soil. Lead can also be absorbed through the skin, although this is usually a less important route of exposure. If air containing lead particles is inhaled, particles deposited in the lungs can lead to about 90% being absorbed. Particles deposited in the upper parts of the lung are usually coughed up and swallowed, while those deposited deep in the lungs can dissolve, allowing lead to enter the bloodstream. If lead is swallowed with food, the amount absorbed into the bloodstream is about 10 to 15% in a typical adult; however, about 60 to 80% is absorbed in adults who have not eaten for a day. In general, if adults and children ingest the same amount of lead, children will absorb a higher percentage (about 50%). After lead enters the bloodstream, it travels to three main compartments: blood, soft tissue, and bone. About 95% and 73% of lead in the body is stored in bones and teeth for adults and children, respectively. Lead has a half-life in blood of about 1 month, whereas lead in bone has a half-life of greater than 20 years. Inorganic lead is not metabolized in the body, but it can be conjugated with glutathione. About 75% of absorbed lead is excreted in urine and about 25% in feces; lead can also be excreted in breast milk.

What Are the Primary Health Effects? Lead can affect almost every organ and system in the body, including the gastrointestinal tract, the hematopoietic system (blood-forming tissues), cardiovascular system, central and peripheral nervous systems, kidneys, immune system, and reproductive system. Young and unborn children are extremely sensitive. Exposure of pregnant women to high levels can result in premature births and smaller babies, followed by learning difficulties and reduced growth. The latter effects are also seen in young children exposed to lead after birth, as are effects on other organ systems. In adults, peripheral nerve damage has been observed at 40 to 60 micrograms of lead per deciliter of blood (µg/dL) anemia at 80 µg/dL, and encephalopathy at 100 µg/dL. Although studies indicate that lead acetate and lead phosphate cause cancer in laboratory animals, we do not know

if lead can cause cancer in humans after being ingested or inhaled. On the basis of the animal studies, the U.S. Environmental Protection Agency (EPA) has classified lead as a probable human carcinogen. The joint toxicity of lead with other chemicals, including essential nutrients, has been studied more extensively than for most chemicals. Depending on the endpoint and chemical, the joint toxicity can be additive, higher than additive, or less than additive. For example, higher toxicity to the nervous system is predicted in combination with arsenic, cadmium, or manganese. In contrast, kidney toxicity is predicted to be less than additive for these same metal pairs. Zinc can protect against lead toxicity by reversing its enzyme-inhibiting effects, whereas iron deficiency appears to increase the gastrointestinal absorption of lead leading to increased toxicity to the hematopoietic system as well as other effects. Additional information is provided in the companion fact sheet on chemical mixtures.

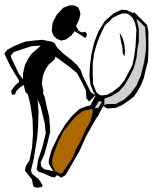


Organs and systems affected when lead is taken in through food, water, or air.

What Is the Risk? Unlike most other chemicals, the potential for adverse health effects from inorganic lead is based on predicted or measured levels of lead in blood rather than on toxicity values. The EPA developed a mathematical model (the Integrated Exposure Uptake Biokinetic Model, IEUBK), to predict concentrations of lead in the blood of children resulting from exposure to lead in soil, air, drinking water, food, and other sources. Predicted blood-lead concentrations have often been compared to a concentration of 10 µg/dL to evaluate the health risk to children. Using the IEUBK Model, the EPA estimated the blood concentration of lead in children could exceed 10 µg/dL if the concentration of lead in soil at residences exceeds 400 mg of lead per kg of soil. Similarly, EPA used the Adult Lead Model to predict a soil concentration of 800 mg/kg that would be protective of the fetus of a female worker in an occupational setting and would also protect adult male or female workers. The EPA subsequently developed an All Ages Lead Model, and a draft integrated science assessment was released in May 2011 to support the national ambient air quality standard. Certain lead compounds have been shown to cause cancer in animals, and lead is considered "reasonably anticipated to be a human carcinogen." (For radioactive isotopes of lead, the cancer risks are included in the risks for radium and thorium as indicated in those fact sheets.) The EPA has not established a cancer toxicity value because of difficulties accounting for pre-existing body burdens and other influences (also note people are more sensitive to the noncancer effects). The organic compound tetraethyl lead is very toxic, and a standard EPA toxicity value is available to estimate the potential for noncancer effects from exposure to this form. The EPA value used to estimate the potential for noncancer effects following ingestion is the reference dose (RfD), which is an estimate of the dose that can be taken in every day over a lifetime without causing adverse health effects. The RfD for tetraethyl lead is 0.0000001 mg/kg-day; this was developed by studying test animals given relatively high doses and then adjusting and normalizing to a mg/kg-day basis for humans. A standard inhalation toxicity value for noncancer effects, the EPA reference concentration, has not been established for tetraethyl lead or other forms.

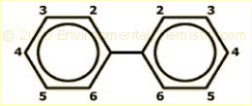
What Are Current Limits for Environmental Releases and Human Exposures? To help track facility releases to the environment, the Superfund amendments addressing emergency planning and community right-to-know require releases of eleven lead compounds to air, water, or land be reported annually and entered into a nationwide Toxics Release Inventory. For lead arsenate, a release above 1 lb (0.454 kg) must be reported immediately, while for other lead compounds the amount is 10 lb (4.54 kg). The EPA requires that lead in air not exceed 0.15 µg/m^3 as a rolling three-month average. The drinking water action level for lead is 15 µg/L. The EPA defines hazardous concentrations of lead as: 40 µg per square foot (ft^2) in dust on floors and 250 µg/ft^2 for interior window sills of homes; 400 mg/kg in bare soil in children's play areas; and 1,200 mg/kg in bare soil in other parts of the yard. For the workplace, the Occupational Safety and Health Administration has established a permissible exposure limit (PEL) of 0.05 mg/m^3 for lead (metal) and inorganic compounds (as lead). Many other regulations and recommendations have been developed for lead to protect workers and public health.

Where Can I Find More Information? More information can be found in the primary information source for this overview: the toxicological profile prepared by the Agency for Toxic Substances and Disease Registry (ATSDR) (via http://www.atsdr.cdc.gov/toxprofiles/index.asp). Other online sources include the ATSDR ToxFAQs (http://www.atsdr.cdc.gov/toxfaqs/index.asp), EPA's Integrated Risk Information System (http://www.epa.gov/iris), the National Library of Medicine Hazardous Substances Data Bank (http://www.toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB), and the draft EPA integrated science assessment (http://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=226323).



Polychlorinated Biphenyls (PCBs)

General PCB Structure



Chlorine atoms can be located in any of the numbered positions.

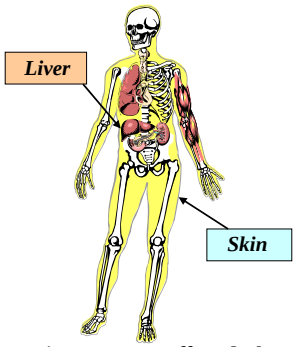
What Are They? Polychlorinated biphenyls (PCBs) are a family of 209 chlorinated hydrocarbon compounds (known as congeners) with the same general chemical structure. In the United States, commercial mixtures of these man-made chemicals were commonly sold under the trade name Aroclor, including Aroclors 1248, 1254, and 1260. For most Aroclors, the last two digits indicate the approximate percent of chlorine (e.g., Aroclor 1254 is 54% chlorine by weight.) The PCBs are nonflammable, colorless to light yellow oily liquids or waxy solids that have no odor or taste. They break down very slowly in the environment (with half-lives of months to years) and tend to cycle between air, water, and soil. (The chemical half-life is the time it takes half the initial amount to be broken down.) They can travel long distances in air and water and are found all over the world, including remote areas such as the Arctic.

How Are They Used? The production of PCBs ended in the United States in 1997 due to concerns over their environmental persistence and possible health and ecological effects. Previously, these compounds were used in hundreds of commercial and industrial applications due to their chemical stability, high heat capacity, low flammability, and insulating properties. Prior to 1974, PCBs were used in both closed and open system applications, with the latter including flame-retardants, inks, adhesives, dyes, paints, plasticizers, and fluorescent lighting fixtures. After 1974, the use of PCBs was restricted to closed system applications such as coolants and lubricants in transformers, capacitors, and other electrical equipment. PCBs are still found in closed systems, where, for example, the volume of PCBs can range from only a few milliliters in small capacitors to over several thousand liters in large capacitors.

What's in the Environment? PCBs are found throughout the environment, although concentrations within the United States have been decreasing over time because of restrictions on their use and disposal. They have been released into air, water, and soil from contaminated facilities, including from incineration of PCB-containing wastes, leakage of old electrical equipment and improper disposition of spills. PCBs do not degrade easily, so they tend to persist in the environment as they cycle among air, water and soil. Their movement among these media depends on factors such as their degree of chlorination and climatic conditions. Low-chlorinated PCBs can volatilize from water and soil into air, with the highest release rates occurring in the summer due to warmer temperatures. These lighter PCBs can be found far away from their original points of release. The low-chlorinated PCBs are also more reactive in the atmosphere and can be degraded to carboxylic acids in the presence of highly reactive molecules. Highly chlorinated PCBs can stick tightly to airborne particulates, but they do not tend to travel as far as lighter PCBs. PCBs can remain in the air for long periods of time, with half-lives ranging from months to years. In the United States, the average concentration in air ranges from about 0.02 to 3.36 nanograms per cubic meter (1 nanogram is a billionth of gram), with the highest concentrations found in urban areas. Highly chlorinated PCBs also stick strongly to sediments and soils, especially those with high organic content. Because of their strong affinity for soil, PCBs typically do not migrate readily to groundwater. Concentrations in soil are typically less than 100 micrograms per kg (μg/kg), but concentrations can be more than 10,000 times higher in very contaminated soils. PCBs are widely detected in surface waters in the low parts per trillion range. Similar to air, the half-lives of PCBs in soil or water ranges from months to years. Of particular concern is bioaccumulation, which can lead to PCB concentrations in fish and animals high in the food chain much greater than concentrations in fish or animals lower in the food chain. Levels of PCBs in fish have been found in the parts per million (ppm) range, while levels in meat and dairy products are typically in the low parts per billion range.

What Happens to Them in the Body? PCBs can be taken into the body primarily by eating contaminated food or breathing contaminated air, and to a more limited degree through ingestion of or dermal contact with contaminated water or soil. When PCBs are ingested, up to 100% can be absorbed into the blood; the amount absorbed following inhalation is not known. PCBs tend to accumulate in tissues with high concentrations of lipids and fats and can remain in the body for a long time. The tissues with the highest PCB concentrations are adipose, blood, brain, liver, and lungs. Due to the complex structure and number of different congeners, PCBs can undergo a variety of metabolic reactions. The rate of metabolism is generally lower for the more highly chlorinated congeners, but the number and position of the chlorine atoms is also important. These compounds are excreted in feces and urine. Some metabolites may be as harmful or more harmful than the unchanged congener. Reported half-lives of PCB mixtures in the body range from more than 2 to 8 years.

What Are the Primary Health Effects? The most commonly observed effects in people exposed to relatively high concentrations of PCBs (primarily workers) are skin conditions such as chloracne and rashes and effects on liver function. Liver effects are more severe in people with impaired liver function, such as alcoholics. Studies in animals indicate that exposure to PCBs can harm the liver, thyroid, and immune and endocrine systems. Women exposed to large amounts of PCBs during pregnancy were found to have children with lower birth weights, abnormal behavior, irregular development of the immune system, and other effects. Because PCBs concentrate in breast milk, nursing infants can be at higher risk depending on exposure levels. In animals, PCBs have been shown to reduce conception rates and live birth rates. Animal studies also indicate that exposure to relatively low levels over a long time (years) can result in liver and possibly other cancers, with suggestive evidence from human studies. The U.S. Environmental Protection Agency (EPA) and International Agency for Research on Cancer have determined that PCBs are probably carcinogenic to humans.



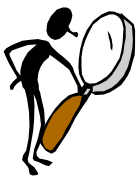
Primary organs affected when PCBs are inhaled or ingested.

What Is the Risk? The EPA has developed toxicity values (*see box below)* to estimate the risk of getting cancer or other adverse noncancer health effects as a result of ingesting or inhaling PCBs. The toxicity values were developed based on studies of animals exposed to PCB mixtures and individual PCB congeners. The toxicity value for estimating the risk of getting cancer following oral or inhalation exposure is a unit risk (UR). The UR is an estimate of the chance that a person will get cancer from continuous exposure to a chemical in water at a unit concentration of 1 microgram per liter (µg/L) or in air at a unit concentration, e.g., 1 µg per cubic meter (µg/m^3). Because PCBs are mixtures with different toxicities that are also subject to different environmental processes (e.g., volatilization and degradation), EPA developed a range of values, corresponding to high, low, and lowest risk and persistence conditions. The criteria for selecting the appropriate value depend on the available information and exposure context. For example, the high value is used to evaluate food chain exposure and soil ingestion, and the low value is typically used to evaluate inhalation of volatile congeners. To illustrate how the UR can be applied, using the middle tier slope factors, a person would have a one-in-a-million chance of developing cancer if exposed daily over a lifetime to water containing 0.1 µg/L, or air containing 0.01 µg/m^3 of PCBs. The standard toxicity value used to estimate the potential for noncancer effects following ingestion is the EPA reference dose (RfD), which is an estimate of the dose that can be taken in every day over a lifetime without causing adverse noncancer effects. Using the RfD, a 150-pound (lb) person could safely ingest 0.001 mg of Aroclor 1254 or 0.005 mg of Aroclor 1016 every day without expecting any adverse effects. The EPA is currently reviewing toxicity information to consider scientific studies conducted since these values were established.

Chemical Toxicity Values			
Cancer Risk		**Noncancer Effect:** ***Oral Reference Dose***	
Oral Unit Risk	***Inhalation Unit Risk***	**Aroclor 1016**	**Aroclor 1254**
1×10^{-5} per µg/L *(upper bound)* ---------- Slope factor for high risk and persistence: 2 per mg/kg per day *(upper bound)* 1 per mg/kg per day *(central estimate)*	1×10^{-4} per µg/m^3 *(upper bound)*	0.00007 mg/kg-day	0.00002 mg/kg-day

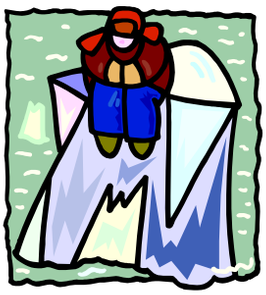
What Are Current Limits for Environmental Releases and Human Exposures? To help track facility releases to the environment, the Superfund amendments that address emergency planning and community right-to-know require immediate reporting of a release of 1 lb (0.45 kg) or more of PCBs to air, water, or land, and also require that normal releases be reported annually and entered into a nationwide Toxics Release Inventory. For drinking water supplies, the EPA has established a maximum contaminant level of 0.5 µg/L, with a goal of zero. For air in the workplace, the Occupational Safety and Health Administration has identified limits of 1 mg/m^3 and 0.5 mg/m^3 for PCBs containing 42% and 54% chlorine, respectively, for an 8-hour work day over 40-hour work weeks. The Food and Drug Administration and Federal Insecticide, Fungicide, and Rodenticide Act have set tolerance levels for PCBs in consumer products such as milk and manufactured dairy products (1.5 ppm), poultry (3 ppm), eggs (0.3 ppm), animal feed for food producing livestock (0.2 ppm), fish and shellfish (2 ppm), infant and junior foods (0.2 ppm), and paper (10 ppm).

Where Can I Find More Information? More information relevant to PCBs can be found in the Toxicological Profile prepared by the Agency for Toxic Substances and Disease Registry (ATSDR, http://www.atsdr.cdc.gov/toxprofiles/index.asp) and ToxFAQs (http://www.atsdr.cdc.gov/toxfaqs/index.asp), EPA Integrated Risk Information System (http://www.epa.gov/iris), and recent World Health Organization and EPA reports on toxic equivalency factors and the associated index chemical tetrachlorodibenzo-p-dioxin (such as http://www.who.int/ipcs/assessment/tef_update/en/, http://www.epa.gov/raf/hhtefguidance/, and http://www.epa.gov/superfund/health/contaminants/dioxin/dioxinsoil.html).



Basic Concepts for Mixtures Risk Assessment

Why Are Mixtures an Issue? Every day we are exposed to different combinations of chemicals in our homes, at work, in food, and in the environment (air, water, and soil). These mixtures can be composed of tens, hundreds, or even thousands of different chemicals. To further complicate matters, each chemical could have several toxic effects, ranging from cancer to different kinds of noncancer or *systemic* effects. A question commonly asked is: How could the combined chemicals affect my health? Risk assessment has historically looked at effects from single chemicals then simply added the risks together, so in a way this is looking at the "tip of the iceberg" for chemical mixtures. To better evaluate the many cumulative exposures and effects that could be possible, approaches are being developed to assess risks more comprehensively. The U.S. Environmental Protection Agency (EPA) first published risk assessment guidelines for mixtures in 1986, with an update in 2000. The Agency formally defined a cumulative risk policy and offered planning and scoping guidance in 1997, and a cumulative risk assessment framework was published in 2003 following extensive input from many people. Three types of cumulative risk "icebergs" are worth noting: interactions, exposures, and effects.

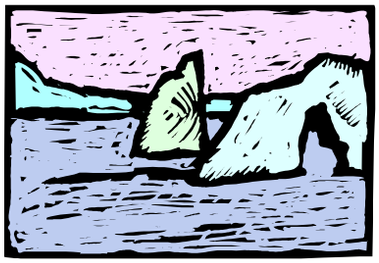


What Are Toxic Interactions? We might understand the toxic effects of certain chemicals in the mixtures to which we are exposed, but we simply don't have this information for all possible mixtures. Where appropriate data exist for the mixture itself, such as diesel exhaust or cigarette smoke, it is evaluated as a whole mixture. Where such data are not available, information about the individual chemicals in the mixture is used, considering their proportions and relative toxicities. We usually assume each chemical would cause the same harm regardless of whether it was in a mixture or by itself. Thus, *dose addition* is our basic assumption, where the toxicity of a mixture is predicted by adding the toxicities caused by the doses of its individual chemicals, as adjusted to account for their relative toxicities. For example, if a mixture has two chemicals in equal amounts and the first is twice as toxic as the second, the toxicity of the mixture would be the same as adding three doses of the first. The special case where the chemicals are toxicologically independent (i.e., cause harm in different ways) is described by *response addition*. Here, the combined toxic response is the same as if the responses caused by the individual chemicals were added. For instance, tranquilizers and alcohol both depress the central nervous system but by different means. If a person is exposed to both, the effect on the central nervous system is the same as the sum of the effects caused by each separately.

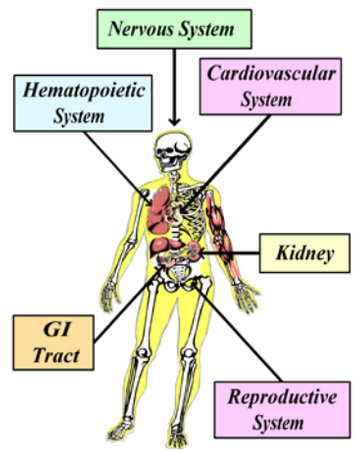
In fact, the toxicity of a mixture might be lower or higher than predicted from the known effects of each chemical acting alone. The influence one chemical has on the toxic effect of another is called a *toxic interaction*. The EPA mixtures guidance identifies toxic interaction as being something other than our default assumption of simple addition. Four types of interactions have been defined, relative to dose addition (see box). A *synergistic* interaction can be illustrated by alcohol and the solvent carbon tetrachloride, each of which harms the liver. Exposure to both damages the liver much more than predicted by simple dose addition. An *antagonistic* interaction can be illustrated by arsenic and lead. Exposure to both causes less harm to the kidney and blood than predicted by dose addition. *Potentiation* can be illustrated by carbon tetrachloride and isopropanol, which is rubbing alcohol (also found in perfume) and is not considered a liver toxin. Inside the body, isopropanol interacts with carbon tetrachloride and causes it to damage the liver more than it would have alone. *Inhibition* is the basis of some antidotes, where you take a dose of a chemical that does not harm you to reduce the harmful effect of another. When risks are estimated by assuming only dose or response addition without considering toxic interactions, perhaps only the tip of the iceberg is being addressed.

Interaction	Definition
Synergism	The combined effect of two or more chemicals is > predicted by dose addition
Antagonism	The combined effect of two or more chemicals is < predicted by dose addition
Potentiation	Exposure to one chemical that is not toxic itself increases the toxicity of second chemical when exposed to both
Inhibition	Exposure to one chemical at a nontoxic dose decreases the toxic effect of another

What Are Mixture Exposures? Some mixtures are manufactured before they are released to the environment (like a specific pesticide formulation), while others are formed during combustion (such as in our car engines) or by other chemical transformations. Chemical interactions in the environment can alter the composition and behavior of a mixture over time. We are exposed to mixtures everywhere. For example, when we breathe outside we can be taking in a mixture of all the air emissions from point sources (such as chimneys and smokestacks) and mobile sources (such as cars, buses, and planes) in the area. This led many federal programs to look more closely at cumulative exposures at the community scale, beginning in the 1990s, by studying releases alone or by combining modeling with emissions measurements. For example, a regional air impact modeling initiative (RAIMI) launched by EPA in 1999 considers risks at the neighborhood level from exposure to multiple air contaminants from multiple sources and pathways; the initial RAIMI study was completed for an area in Jefferson County, Texas. This type of integrated assessment has been pursued under several national programs. These include the Cumulative Exposure Project (CEP), the National-Scale Air Toxics Assessment (NATA), the Residual Risk Report to Congress, and the Integrated Urban Air Toxics Strategy. These types of assessments look at combined doses from many sources rather than only considering the chemicals from a single location. A fuller look at this second exposure "iceberg" considers lifestyle-related exposures, such as to household pesticides and cigarettes.



What Are Mixture Effects? In addition to considering the combination of chemicals in environmental mixtures and the many ways we can be exposed to them, we also have to realize that each chemical in a mixture could cause multiple health effects. Under the classic risk assessment approach, the *critical* or *primary effect* is generally the most sensitive effect (that first seen as the dose is increased above the level where no adverse effects are observed), and it is often determined from animal studies; this generally serves as the basis for the toxicity value we use to estimate human health risks. However, virtually all chemicals can also have *secondary effects*, which do not occur until we are exposed to larger amounts. Information about primary effects and some secondary effects is contained in EPA's Integrated Risk Information System (IRIS) and in the Agency for Toxic Substances and Disease Registry (ATSDR) toxicological and interaction profiles, each of which are available on-line. As science progresses, we will continue to improve our ability to evaluate the role of secondary effects. This is important because in theory, risks calculated based only on critical effects might not be considered a problem if the chemicals in a mixture each impact different organs (e.g., liver) or systems (e.g., nervous system) at tolerable levels. However, the evaluation of possible adverse health effects should extend beyond the chemicals' primary targets to also consider their cumulative impact on other organs or systems that could be harmed as exposures increase. This requires an extensive toxicity evaluation. In a sense, assessing only the primary effects might miss important cumulative secondary effects – a third "iceberg" to keep in mind.



Where Is the Science Taking Us? In the past, risk assessments have typically evaluated risks from distinct chemicals, operations, processes, waste streams, or contaminated media. As assessment methods keep pace with emerging scientific knowledge, EPA and others will continue to further evaluate contributions from (1) other pollutants and processes beyond those at the facility being assessed, (2) many sources of a single pollutant in a given community, and (3) the combination of sources, chemicals, and exposures that affect a given community. Interactions among chemicals and the cumulative result of secondary effects are being considered as part of these enhanced assessments. Additional research will better illuminate the often "hidden" components of cumulative health risk from environmental exposures.

Where Can I Find More Information? Key sources include: the EPA mixtures guidance (http://www.epa.gov/ncea/raf/pdfs/chem_mix/chem_mix_08_2001.pdf), cumulative risk framework (http://cfpub.epa.gov/ncea/raf/recordisplay.cfm?deid=54944.), IRIS (http://www.epa.gov/iris), and cumulative risk resource document (http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=190187), as well as ATSDR interaction profiles (http://www.atsdr.cdc.gov/interactionprofiles/index.asp).

Mixtures of Arsenic, Cadmium, Chromium, and Lead

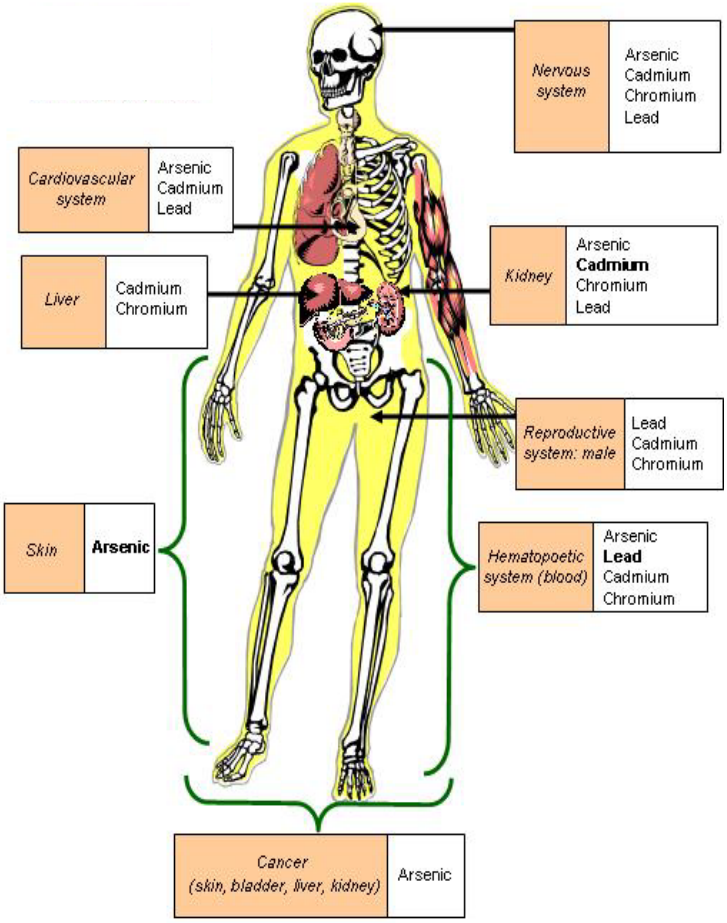
(This fact sheet summarizes information for combinations of metals in this set, with a focus on ingestion of inorganic forms, to support analyses at contaminated sites. Companion fact sheets provide chemical-specific information on common use, general environmental levels, and toxicity, also by other routes.)

Do These Metals Naturally Coexist? Arsenic, cadmium, chromium, and lead all occur naturally in the environment and are found in all materials – soils, plants, animals, and humans – typically as salts. These metals cannot be destroyed, nor do they degrade; however they can be converted to organic forms by biological action both in the environment and within the body. (This fact sheet focuses on inorganic forms.)

What Common Uses Could Result in a Combined Presence? These metals share many industrial uses, including in metallurgy. Arsenic and cadmium are byproducts of lead production, and various combinations are used in materials and processes as highlighted at right. The Agency for Toxic Substances Disease Registry (ATSDR) has identified these four metals as soil contaminants at about 15% of the waste sites reviewed. Amounts and proportions of each vary in content and concentration across different sites.

Uses	Combinations
Metal products, alloys	All four
Dyes, pigments, paints	Chromium, cadmium, lead
Batteries	Cadmium; lead and arsenic
Anti-corrosion/rust coat	Chromium and arsenic
Solder	Lead and arsenic
Wood preservative	Arsenic and chromium

What Health Effects Are Indicated? Chronic oral exposures often represent a route of concern for contaminated sites as contaminants can migrate to groundwater over time. Thus, this fact sheet focuses on ingestion-related effects. Key organs or systems affected by intermediate (subchronic) to long-term (chronic) oral exposures to the individual metals are highlighted at right. Shown are the critical organs and systems (where the first adverse effect is observed, in bold) and those affected at higher levels that are common across two or more metals, or that are known to be affected by another metal in the mixture. (No critical effect has been defined for chromium by the oral route; the respiratory system is the primary target for inhalation.)



Primary Organs/Systems Affected Following Ingestion

What Are The Joint Toxicities? Joint toxicity refers to the outcome of two or more chemicals acting together; three categories of joint toxicity are: greater than additive (synergism and potentiation); additive (no interaction); and less than additive (antagonism and inhibition). Additivity is the default assumption for evaluating health effects of multiple chemicals. Toxicological interactions can either increase or decrease

the apparent toxicity of a mixture relative to that expected from simple addition. No specific health study has been conducted for the quaternary mixture of arsenic, cadmium, chromium, and lead. A few studies have investigated the effects of three metals in combination, but most have studied pairs within this set. The lead-cadmium pair has been studied most, including in human epidemiological studies and oral animal studies. Data from key studies as given in the ATSDR interaction profile are summarized in the table below. These data reflect higher exposures than environmental levels.

Joint Toxicity for Selected Organ/System Endpoints Following Ingestion

Endpoint	*Arsenic* on			*Cadmium* on			*Chromium* on			*Lead* on		
	Cd	Cr	Pb	As	Cr	Pb	As	Cd	Pb	As	Cd	Cr
Nervous system			↑			↑				↑	↔	
Kidney	↔	↓	↓	↔	↔	↓	↓	↔		↓	↔	
Hematological system	↓		↓	↓		↓				↓	↔	
Reproductive: male	↓			*na*		↑	*na*			*na*	↑	
Skin	*na*	*na*	*na*		*na*	*na*	↑	*na*	*na*		*na*	
Cancer	*na*	*na*	*na*		*na*	*na*	↑	*na*	*na*		*na*	*na*

As = arsenic, Cd = cadmium, Cr = chromium, Pb = lead; ↑ = interactive effects are more than additive or one metal enhances an effect induced only by the other metal; ↓ = interactive effects are less than additive or one metal protects against an effect induced only by the other metal; ↔ = results are inconclusive or do not suggest that effects are more or less than additive; blank = relevant information is not available; na = not applicable because oral exposure to this metal is not indicated to cause that health endpoint. Note that for the cardiovascular system, results were inconclusive or unavailable for all pairs.

For neurological effects, the predicted direction of joint toxic action for the mixture is greater than additive for several pairs (arsenic-lead, cadmium-lead, lead-arsenic), which indicates the health hazard of those mixtures might be somewhat greater than that estimated by endpoint-specific hazard indices for this endpoint; the same higher-than-additive effect is indicated for the male reproductive system (testes) for cadmium and lead acting on each other. In contrast, for effects on the kidney and blood, the predicted direction of joint toxic action is less than additive for several metal pairs, indicating that the health hazard might be somewhat less than estimated by endpoint-specific hazard indices.

What Is the Joint Risk? No specific data exist to quantify the joint risk of mixtures of arsenic, lead, cadmium and chromium. Endpoints of potential concern for this mixture include critical effects of the individual metals as well as the common targets of toxicity that might become significant due to additivity (considering secondary effects) or certain interactions, as indicated in the table above (noting again that additional interactions protect against other adverse effects). The ATSDR recommends using a hazard index method with the target-organ toxicity dose (TTD) modification and qualitative weight-of-evidence (WOE) method to assess the additive and interactive actions of the mixture components. These methods are suggested only when exposures are significant, i.e., only if the hazard quotients for two or more metals are 0.1 or greater. If only one or none of the metals have a hazard quotient at or above that level, then no further assessment of joint toxic action is needed because additivity and/or interactions are unlikely to result in a significant health hazard.

Where Can I Find More Information? More information can be found in the primary information source for this overview, the interaction profile for arsenic, cadmium, chromium and lead prepared by ATSDR (http://www.atsdr.cdc.gov/interactionprofiles/ip04.html). Additional information can be found in the companion fact sheets for each of these metals and their respective information sources.

APPENDIX D:

ILLUSTRATIVE DOSE AND RISK ESTIMATES FOR WASTE EXCAVATION WITHOUT ANY ENGINEERING CONTROLS

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APPENDIX D:

ILLUSTRATIVE DOSE AND RISK ESTIMATES FOR WASTE EXCAVATION WITHOUT ANY ENGINEERING CONTROLS

This appendix supplements the illustrative estimates presented in the body of this technical memorandum (TM) and Appendices A and B, to help further support engineering planning for the development and evaluation of alternatives in the feasibility study (FS) for the Interim Waste Containment Structure (IWCS). Conceptual planning information to be outlined in the FS will include measures for assuring protection of workers and the public during remedial action activities at the IWCS. The estimates that have been presented in this TM represent preliminary calculations of doses and risks based on early conceptual assumptions for waste excavation. Absent project-specific information (given the early stage of the FS planning process), those evaluations reflect general assumptions from two main sources: (1) generic emission estimates and efficiencies of standard control measures based on common soil excavation activities, combined with practical context from other cleanup projects that have involved excavation; and (2) engineering design and implementation data for a U.S. Department of Energy (DOE) cleanup project at the Fernald site that involved removing wastes similar to those in the IWCS, including lessons learned (see USACE 2011).

To help assure that all potential releases and exposures that might impact workers or the public are considered in conceptual planning for the excavation alternatives to be presented in the FS, an additional set of example calculations is provided in this appendix. The intent of these supplemental calculations is simply to illustrate the imaginary case for which it is assumed no engineering controls are used during waste excavation, so that any potential issues warranting engineering controls are flagged for incorporation in the FS planning process. In reality, the IWCS wastes would never be excavated without engineering controls, given that such controls are routinely applied even for minor construction projects involving excavation of clean soil. Thus, the calculations in this appendix are offered to help indicate the types of contaminants and conditions for which controls would be particularly important, as well as indicating the general degree of control warranted, to help guide the conceptual engineering plans being developed for the FS. (For example, the identification and evaluation of control technologies and associated costs are not part of the scope of this TM, but those aspects are to be addressed in the FS – and the preliminary risk estimates in this TM can help frame those evaluations.)

The calculations in this appendix correspond to the results presented in Sections 5.2 and 6.4 of this TM, which reflect general assumptions for engineering controls to would reduce airborne releases of particulates and radon-222 (Rn-222) gas during waste excavation. Those preliminary estimates are based on the early conceptual planning assumptions described in Section 3.3. The supplemental estimates in this appendix assume no engineering controls are used during excavation, to offer bounding context for upcoming planning for the FS. The K-65 residues and other high-activity residues represent the main health concern at the IWCS because those wastes pose the greatest potential for impacting workers and members of the general public. The lower-contaminated wastes that comprise the rest of the materials DOE placed in the IWCS from past cleanup of the site and vicinity are also considered in this TM. Other than assuming no engineering controls are used to limit releases and exposures, the supplemental calculations in this appendix reflect the same general assumptions that underlie the estimates in the body of this report and Appendices A and B. These additional estimates can help facilitate the development of reasonable conceptual engineering information on which to base the alternative-specific evaluations of dose and risk (and other factors) to be incorporated in the FS.

No specific results are presented for the six hypothetical receptors in Section 5.2 for direct (and air-scattered or skyshine) gamma radiation exposures as the wastes are uncovered at the IWCS. The evaluation of gamma irradiation in that section is limited to exposures to airborne particulates estimated

to be deposited on surface soil following airborne releases during excavation. Selected gamma radiation exposures to the IWCS contents are provided in Table 5.4 for a limited set of hypothetical situations that involve cap breaches with at least some part of the IWCS wastes being uncovered. Those situations were postulated to support planning for the FS, and the preliminary estimates in that table are based on idealized exposure situations as illustrated in two graphs in Section 4.1.4 (Figures 4.3 and 4.5), which were developed using standard computer models specifically designed for such evaluations.

Beyond those selected example estimates, gamma irradiation from direct exposures to the IWCS wastes as they are uncovered was not quantified for the six hypothetical receptors because such exposures are highly dependent on a number of factors that have not yet been defined as part of planning for the IWCS FS. These factors include the use of permanent shielding (such as surrounding an excavation area), temporary shielding (to protect specific workers or other individuals), the conceptual approach used to remove the wastes and any inherent shielding this may provide (such as various types of large equipment), the specific locations and length of time workers could be exposed to these wastes, any shielding inherent to the waste containers or processing vessels, and more. Thus, to provide such estimates would be premature (and possibly misleading) without having appropriate conceptual engineering information regarding the approach envisioned for retrieving the wastes. Such an evaluation would only be possible when sufficient engineering planning information is available for the FS.

In contrast to the basic estimates presented elsewhere in this report, this appendix provides illustrative estimates of potential doses and risks for an imaginary case without any engineering controls, so direct and skyshine gamma irradiation associated with uncovering and removing the wastes can be hypothetically assessed under these "pretend" conditions as follows. For these calculations, it is assumed that the six illustrative receptors are exposed to the IWCS contents with no protective shielding (it is important to emphasize the highly speculative nature of these example calculations recognizing that the wastes would not in fact be excavated without any controls). The dose estimates are based on the graph in Figure 4.3. A number of assumptions underlie this figure, as described in Section 4.1.4, which may or may not be relevant to the conceptual engineering information developed as part of planning for the IWCS FS. Therefore, caution should be used in extending these results beyond their intended purpose.

Several basic results tables from Sections 5.2 and 6.4 are repeated in this appendix, with simple scaling adjustments to "undo" the emission reductions reflected in those tables per basic engineering controls that would limit particulate and gaseous releases to the atmosphere. In addition, estimates of the gamma irradiation doses from direct exposures to the IWCS contents as well as external gamma doses from deposited particulates (following airborne releases) are provided (again emphasizing that this information is offered solely to assist the development of conceptual engineering information for the FS analyses). Such exposures would not in fact occur, as the U.S. Army Corps of Engineers is fully committed to ensuring that any exposures to contaminants associated with activities at the IWCS and overall site are in accordance with Federal and state requirements for protection of workers and members of the public, and that any such site-related releases and exposures are maintained at levels as low as reasonably achievable.

Illustrative results for the radioactive contaminants are given in Section D.1, and those for the chemical contaminants are given in Section D.2. These example estimates parallel the results in Section 5.2, as adjusted to not account for the reductions that would in practice be achieved by engineering controls that would be applied to limit releases and exposures. An overall summary of these estimates is given in Section D.3, which parallels the results presented in Section 6.4 (which assume engineering controls during waste excavation). Other underlying assumptions remain the same, such as the duration of the excavation for each waste group (as described in Section 3.3.1 and highlighted in Table 3.3).

A brief discussion of the approach used to develop these companion "uncontrolled" estimates from the information provided in parallel tables within Sections 5.2 and 6.4 is summarized in Sections D.1 through

D.3, followed by the tabulated results. In many cases, the original results are simply multiplied by the scaling factors used to reflect control efficiencies in the preliminary representative estimates in the body of this TM. For example, particulate emissions for the K-65 residues (group 1) are assumed to be reduced by a factor of 100 based on the use of an engineered containment system (as supported by USACE 2011). For the corresponding estimate in this appendix, the original preliminary estimate is simply multiplied by 100. The basic scaling factors assumed for the main calculations in this TM are highlighted in Table 3.3.

D.1 RADIOACTIVE CONTAMINANTS

The example "uncontrolled" estimates for radioactive contaminants are presented for particulate emissions in Section D.1.1, for Rn-222 gas emissions in Section D.1.2, and for external gamma radiation from the IWCS wastes in Section D.1.3. The same basic exposure scenarios are evaluated for the six hypothetical receptors as described in Sections 3.2 and 3.3, except for assuming no engineering controls are used to limit contaminant releases and associated exposures. The results for these three sets of exposure estimates are combined and discussed in Section D.1.4.

D.1.1 Particulate Emissions

Preliminary estimates of radiation doses and cancer risks from particulates released during waste excavation assuming engineering controls are in place are presented in Table 5.2. The three types of exposures considered for these particulates are: inhalation of particulates carried in the passing plume, incidental ingestion of soil on which the airborne particulates are deposited, and direct gamma radiation from the deposited radionuclides.

For those original estimates, particulate releases are assumed to be reduced by a factor of 100 for the K-65 residues (waste group 1) based on the use of an engineered containment system. Particulate releases for the other two waste groups are assumed to be reduced by a factor of 4 based on the use of water sprays 4 times daily (see Section 3.3.2). To calculate the radiation doses and risks without these controls, the results for the K-65 residues are simply multiplied by 100, and the results for the other two waste groups are multiplied by 4. These "uncontrolled" estimates are presented in Table D.1.

D.1.2 Rn-222 Gas Emissions

The approach used to estimate Rn-222 gas emissions is described in Section 3.3.2, and the preliminary estimates of radiation doses and cancer risks associated with these releases are given in Table 5.3. These doses and cancer risks are largely attributable to inhalation of the attached (to particulate matter) and unattached short-lived Rn-222 decay products. These decay products are charged ions that can attach very quickly to particulate matter in the atmosphere and could then be readily inhaled. The approach used to calculate the inhalation doses and risks for Rn-222 is described in Section 4.1.2; it is based on calculating the concentration of Rn-222 progeny in the unit of working level (WL) and calculating exposures in the unit of working-level month (WLM).

The results presented in Table 5.3 address the excavation of all three wastes groups from the IWCS. About 95% of the current Rn-222 inventory in the IWCS contents is attributable to the K-65 residues (waste group 1), and 5% is associated with waste group 2. The wastes in group 3 represent a very small fraction of the total Rn-222 inventory in the IWCS contents, and the potential health effects of Rn-222 gas emitted from these wastes are considered to be accounted for (far outweighed by) the estimates provided for waste groups 1 and 2.

There are two mechanisms by which Rn-222 gas can be released to the atmosphere during waste excavation from the IWCS: (1) steady releases associated with exposed wastes having elevated

concentrations of radium-226 (Ra-226), and (2) puff releases as the wastes are disturbed during retrieval. Both mechanisms are addressed in this TM.

No controls are assumed for the steady releases in this TM. Rather, it was conservatively assumed that an area of 100 m^2 (120 yd^2) of IWCS wastes would represent the example area from which Rn-222 could be released during excavation of each waste group (based on the area assumption used in the radon assessment TM, USACE [2012]). This is considered a very conservative approach. The total amount of Rn-222 gas estimated to be released from this area during waste excavation activities is 130 curies (Ci), as described in Section 3.3.2. This amount represents the steady release of Rn-222 gas.

The puff releases account for the release of Rn-222 gas from the interstitial spaces in the IWCS wastes as they are disturbed. To be conservative, it is assumed that all the Rn-222 gas in these interstitial spaces (about 500 Ci) could be released during waste removal. For the main estimates in this TM, a control system is assumed to mitigate these puff releases, with an assumed efficiency of 90% (that is, the system is assumed to remove 90% of the Rn-222 gas released from the interstitial spaces during waste excavation). Because 90% of this gas is assumed to be captured by the radon control system, only 10% (or 50 Ci) would be released to the atmosphere by this mechanism. This represents the Rn-222 puff releases with use of a radon control system. Note the conservatism of these estimates is supported by the Fernald data, which indicate a substantially higher removal efficiency (USACE 2011).

Hence, the total Rn-222 release with engineering controls in place is estimated to be 180 Ci, as given in Section 3.3.2. Of this total, 130 Ci are from steady releases and 50 Ci are from puff releases. Again, these are very conservative estimates, and the actual Rn-222 releases would be expected to be much lower. Moreover, it is expected that this potentially significant exposure pathway will be analyzed in more detail in the FS when conceptual engineering information is available regarding the planned approach for retrieving the wastes and controlling airborne emissions including Rn-222 gas.

If it is assumed that no engineering controls would be used to limit Rn-222 gas emissions, the puff releases would increase to 500 Ci (the total inventory of Rn-222 gas in the interstitial spaces of the IWCS contents). With this assumption, the total amount of Rn-222 released during waste retrieval would be 630 Ci. This total consists of 130 Ci from steady releases (no controls were conservatively assumed for these releases in the estimates given in Section 3.3.2) and 500 Ci from puff releases.

Therefore, under the imaginary assumption of waste excavation without any engineering controls, the amount of Rn-222 released increases by a factor of 3.5 compared with the estimate that reflects reasonable but conservative assumptions regarding the control efficiency, i.e., 630 Ci divided by 180 Ci. To calculate the radiation doses and risks without any engineering controls for the Rn-222 gas emissions, the results given in Table 5.3 are simply multiplied by a factor of 3.5. These “uncontrolled” estimates are given in Table D.2.

D.1.3 External Gamma Irradiation

As explained in Section D.1.1, for the six hypothetical receptors evaluated in this TM, external gamma irradiation is only quantified for exposures to deposited particulates following assumed releases during waste excavation. The estimates for direct exposures associated with the IWCS wastes as they are uncovered and excavated were deferred until conceptual engineering information becomes available on which to base those estimates. Instead, a set of hypothetical situations that involve uncovering and disturbing the wastes at the IWCS was considered, as presented in Table 5.4. To provide additional information to support the FS, a companion set of calculations that assume no engineering controls (such as shielding) is presented in this appendix.

If an individual were to stand on top of uncovered K-65 residues, the gamma radiation dose rate is estimated to be about 600 mrem/hr (see Section 4.1.1). This exposure clearly needs to be avoided, and design controls are assumed to be developed and applied to prevent such situations. If anyone were to stand near the K-65 residues (waste group 1) and the other high-activity wastes (group 2) during excavation, they could incur high doses if engineering controls were not in place. These gamma radiation doses are very dependent on the specific location of the individual relative to the exposed wastes and the time of exposure. The same parameters given in Table 3.2 are used in the illustrative "uncontrolled" calculations presented in this appendix.

The assumed source-receptor geometry is a key consideration in developing these estimates. For this evaluation, it is assumed that the source (the exposed residues and wastes) can be reasonably represented by a right circular cylinder with a volume of 100 m^3 (130 yd^3). This represents the amount of waste that is assumed to be uncovered at the IWCS at any one time based on early conceptual assumptions (because project-specific planning information is not yet available for the FS). The total volume of the K-65 residues is about 3,000 m^3 (4,000 yd^3), as indicated in Table 2.2. Thus, the volume of 100 m^3 (130 yd^3) represents about 3% of the total volume of K-65 residues in the IWCS, which is considered a reasonable estimate for this highly speculative calculation. For the other two waste groups, this assumed source volume represents a lower percentage of the total waste volume for each group.

This volumetric source is assumed to be located in the center of the excavation area for each of the three waste groups. The excavation areas assumed for this TM (as described in Section 3.3.1 and highlighted in Table 3.3) are: 500 m^2 (600 yd^2) for the K-65 residues (waste group 1); 1,000 m^2 (1,200 yd^2) for waste group 2; and 2,000 m^2 (2,400 yd^2) for waste group 3. Circular geometry is used for this calculation, which means that the distance from the edge of the excavation to the center of the source is about 13 m (14 yd) for waste group 1, 18 m (20 yd) for waste group 2, and 25 m (28 yd) for waste group 3.

The normalized gamma dose rates are shown in Figure 4.3 for various source volumes. The dose rates are plotted based on the distance from the edge of the source. For a source volume of 100 m^3 (130 yd^3), the edge of the source is about 2.5 m (2.8 yd) from the center for the right circular cylindrical geometry used to develop Figure 4.3. This distance must be subtracted from the values listed above to estimate the distance from the edge of the source to the edge of the excavation for the calculations in this appendix. These resultant distances are then added to those identified for the exposure locations for the six illustrative receptors in Section 3.4.1 for this calculation. Those distances are shown in Table D.3.

For each receptor, the gamma dose rate (in mrem/hr) is obtained by using the normalized direct gamma dose rate from Figure 4.3 for a source volume of 100 m^3 (130 yd^3) at the appropriate distance, and multiplying this value by the average Ra-226 concentration (in pCi/g) for each of the three waste groups. These gamma dose rates at the various receptor locations are shown in Table D.3. The gamma dose rate is then multiplied by the time of exposure assumed for each receptor for each waste group. As described in Section 3.3.1, the conceptual estimates for the excavation periods (exposure durations) are 170 days for waste group 1, 112 days for waste group 2, and 275 days for waste group 3. The worker exposure time is assumed to be 8 hours for each work day. The skyshine component would be much lower than the direct component because no shielding is assumed, so it is not quantified in this appendix.

Even though this calculation assumes no engineering controls, the exposure time for each of the six receptors for each waste group is taken to be the period during which those waste materials are assumed to be excavated. That is, the exposure is limited to 8 hours per day for the number of excavation days for each waste group. Gamma exposures are not assumed to occur during nighttime hours for any receptor. This assumption assures consistency with the results summarized in Section 5.2 and allows the impact of the assumption of no shielding for direct gamma radiation to be assessed. The results of this calculation are given in Table D.3.

For the three hypothetical onsite receptors, the gamma radiation doses exceed the "uncontrolled" estimates for deposited airborne radionuclides (given in Table D.1) by factors of about 10 to 60. As expected, the highest values are for the K-65 residues. For the three hypothetical offsite receptors, the gamma radiation doses from deposited particulates following airborne releases are generally comparable (for the outdoor worker) or higher (for the two residential receptors). This result likely reflects the conservatism used in calculating air dispersion and particulate deposition near the IWCS, and in the approach used to calculate the gamma radiation doses from the deposited radionuclides. The assumptions used for those calculations are described in Chapter 3.

D.1.4 Combined Pathways

The estimated "uncontrolled" radiological doses and cancer risks for inhalation, incidental ingestion of deposited particulates, and external gamma irradiation (from direct exposures to the wastes and particulates deposited following airborne releases) are summarized in Tables D.4 and D.5. Table D.4 summarizes the information for the three types of releases evaluated in this appendix: particulate emissions, Rn-222 gas emissions, and external gamma irradiation. Table D.5 presents the results in the same format used for Table 5.6 to facilitate comparisons with those original estimates that reflect early conceptual assumptions for engineering controls.

As expected, certain doses and cancer risks estimated for the imaginary case of waste excavation without any engineering controls are quite high, especially for potential onsite receptors including the two hypothetical workers. These results further confirm how imperative it is to apply appropriate engineering controls during any waste retrieval activities involving the K-65 residues (group 1) or other high-activity residues and other more highly contaminated wastes (group 2) to reduce potential radiation exposures and health risks to workers and members of the general public, and to assure that levels meet regulatory standards and are as low as reasonably achievable. The doses and risks for waste group 3 indicate that minimal controls are needed to maintain radiation doses and risks to low levels, other than adhering to good housekeeping and health physics practices.

D.2 CHEMICAL CONTAMINANTS

The results for the chemical contaminants are limited to particulate emissions from the IWCS wastes during excavation. The results presented in this appendix reflect the same exposure assumptions as described for the six hypothetical receptors in Sections 3.2 and 3.3, except that no engineering controls are assumed to be applied during the excavation to protect workers and the general public.

The preliminary estimates of hazard indexes (HIs) and cancer risks associated with particulate releases during excavation of each of the three waste groups – assuming basic engineering controls are in place – are presented in Tables 5.7 and 5.8. As described for the radioactive particulate releases, these particulate releases are assumed to be reduced by a factor of 100 for the K-65 residues (group 1) based on the use of an engineered containment system; the releases for the other two waste groups are assumed to be reduced by a factor of 4 based on the use of water sprays 4 times daily (see Section 3.3.2). To calculate the HIs and risks under the imaginary case of excavation without any controls, the original preliminary results for the K-65 residues are simply multiplied by 100, and the results for the other two groups are multiplied by 4. These "uncontrolled" estimates are given in Tables D.6 and D.7, following the same format used for Tables 5.7 and 5.8 to facilitate comparisons with those original results.

For the unrealistic case that assumes no engineering controls, the estimated HI is 3 for the hypothetical maintenance worker from excavation of all wastes combined (the segregated HI is slightly above 1). The HIs for the other five receptors are less than 1, and the cancer risks for all six hypothetical receptors are

within or below the target levels that serve as points of comparison for the estimates in this TM. Waste group 2 represents the largest contributor to this elevated HI, and waste groups 1 and 2 both contribute comparably to the estimated cancer risks. These results largely reflect the assumptions for the chemical characteristics of these wastes in this TM. The lack of definitive chemical waste characterization data translates to substantial uncertainty in these results. In any case, the estimated chemical risks are much lower than the radiological risks, and measures taken to reduce radiological doses and risks to workers and members of the general public would also serve to reduce exposure levels and risks for the chemical contaminants.

D.3 COMBINED RESULTS

The basic risk and HI estimates in this TM (presented in the body of the report and Appendices A and B) assume practical engineering controls are used during waste excavation to limit contaminant releases from the IWCS. Those illustrative estimates reflect control assumptions based on information from other excavation and cleanup projects (pending project-specific information), and they are summarized in Section 6.4; see Tables 6.3 and 6.4 for the results organized by waste group and for all wastes combined.

The same general format is used in this appendix, with corresponding values simply scaled to reflect the imaginary case in which these wastes are assumed to be excavated without any engineering controls. The results for each waste group are presented in Tables D.8, and the estimates for excavating all wastes are summarized in Table D.9.

For onsite exposures, the risks estimated for both hypothetical workers (remedial action and maintenance) for "uncontrolled" excavation of all IWCS wastes exceed the NCP target range that serves as a point of comparison in this TM. The risk estimate for the hypothetical trespasser is within this target range. The highest risk is for the remedial action worker, at 3×10^{-2}, largely from direct gamma radiation because no shielding is assumed to be used when the wastes are uncovered and excavated. Regarding the potential for noncarcinogenic effects, the estimated HI for the maintenance worker is 3, with a segregated HI slightly above the comparison level of 1. The estimated HIs for all other hypothetical receptors are below this target level.

Offsite, the risks estimated for all three hypothetical receptors are within the target range. As for the onsite estimates, radionuclides are the dominant contributors, with chemicals contributing less than 1% to the total risk for each receptor (see Table D.9). The estimated HIs for the hypothetical offsite worker and resident adult and child are all below 1, as indicated above.

In addition to assuming engineering controls are in place to limit emissions, the main estimates in this TM also assume the remedial action worker wears respiratory protection equipment for all but 1 day during the excavation of each waste group. Thus, this receptor is assumed to inhale and incidentally ingest contaminants on this day for each waste group. In contrast, the remedial action worker would be exposed to direct gamma from deposited radionuclides for the entire time onsite. The supplemental estimates tabulated in this appendix reflect this same assumption, to facilitate comparisons with the main results.

An additional calculation is provided here to illustrate what the impact would be if the remedial action worker never wore any respiratory protection equipment. The inhalation and ingestion estimates would increase by a factor that reflects the number of days estimated to remove each waste group from the IWCS (see Table 3.3) – i.e., by a factor of 170 for the K-65 residues (waste group 1), 112 for waste group 2, and 275 for waste group 3. These scaled estimates are then added to the estimates for external gamma radiation exposures presented in Section D.1.3. The resultant dose estimate for the hypothetical remedial action worker is 68,000 mrem (68 rem), and the corresponding cancer risk is 5×10^{-2}. Again, most of this dose and risk is from external gamma radiation.

The parallel calculation for chemical exposures indicates the cancer risk for the completely unprotected worker would be 6×10^{-5}, and the HI would be 20. Although the latter exceeds the target level of comparison, the radiological risks would dominate (with chemicals contributing less than 1% to the overall risk).

The supplemental calculations in this appendix indicate that control measures should be applied during any activities that involve uncovering, disturbing, and/or excavating the IWCS wastes (notably the high-activity wastes) to assure protection of onsite workers and other individuals who might be onsite during this time.

D.4 REFERENCES

USACE (U.S. Army Corps of Engineers), 2011, *Waste Disposal Options and Fernald Lessons Learned Technical Memorandum for the Niagara Falls Storage Site, Lewiston, New York*, prepared by Science Applications International Corporation, Dublin, OH, for USACE Buffalo District, Buffalo, NY (July); http://www.lrb.usace.army.mil/fusrap/nfss/nfss-feasstudy-techmemo-wdoandfll-2011-07.pdf; available via http://www.lrb.usace.army.mil/fusrap/nfss/#Documents *(page last updated September 30, accessed December 6).*

USACE, 2012, *Radon Assessment Technical Memorandum for the Niagara Falls Storage Site, Lewiston, New York*, prepared by Science Applications International Corporation, Dublin, OH, for USACE Buffalo District, Buffalo, NY (January); http://www.lrb.usace.army.mil/fusrap/nfss/nfss-feasstudy-techmemo-radon-2012-01.pdf, available via http://www.lrb.usace.army.mil/fusrap/nfss/#Documents *(accessed February 6)*.

TABLE D.1 Illustrative Radiological Doses and Risks from Particulates Estimated to Be Released If Wastes Were Hypothetically Excavated without Any Engineering Controls[a]

Scenario	Exposure Route							
	Inhalation of Particulates		Incidental Ingestion of Particulates		External Gamma Radiation		Total	
	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk
***Waste Group 1:* K-65 Residues**								
Onsite: dispersed contaminants								
Remedial action worker	**110**	5×10^{-5}	0.32	2×10^{-7}	**630**	$\mathbf{5 \times 10^{-4}}$	**740**	$\mathbf{6 \times 10^{-4}}$
Maintenance worker	**2,300**	$\mathbf{1 \times 10^{-3}}$	15	7×10^{-6}	**180**	$\mathbf{1 \times 10^{-4}}$	**2,500**	$\mathbf{1 \times 10^{-3}}$
Trespasser	**28**	1×10^{-5}	0.36	2×10^{-7}	1.1	8×10^{-7}	**29**	1×10^{-5}
Offsite: dispersed contaminants								
Outdoor worker	5.9	2×10^{-6}	0.075	4×10^{-8}	0.88	7×10^{-7}	6.9	3×10^{-6}
Adult resident	2.1	9×10^{-7}	0.033	2×10^{-8}	2.3	2×10^{-6}	4.5	3×10^{-6}
Child resident	2.1	9×10^{-7}	0.033	2×10^{-8}	1.2	9×10^{-7}	3.3	2×10^{-6}
***Waste Group 2:* Other High-Activity Residues (L and F) and Tower Soils**								
Onsite: dispersed contaminants								
Remedial action worker	5.2	1×10^{-6}	0.0070	3×10^{-9}	10	8×10^{-6}	16	1×10^{-5}
Maintenance worker	**82**	2×10^{-5}	0.37	2×10^{-7}	3.2	3×10^{-6}	**86**	2×10^{-5}
Trespasser	0.92	2×10^{-7}	0.0082	4×10^{-9}	0.018	1×10^{-8}	0.94	3×10^{-7}
Offsite: dispersed contaminants								
Outdoor worker	0.35	9×10^{-8}	0.0025	1×10^{-9}	0.022	2×10^{-8}	0.38	1×10^{-7}
Adult resident	0.13	3×10^{-8}	0.0011	5×10^{-10}	0.058	5×10^{-8}	0.19	8×10^{-8}
Child resident	0.13	3×10^{-8}	0.0011	5×10^{-10}	0.029	2×10^{-8}	0.16	6×10^{-8}
***Waste Group 3:* R-10 Pile and Other Contaminated Soils**								
Onsite: dispersed contaminants								
Remedial action worker	0.019	5×10^{-9}	0.000084	4×10^{-11}	0.11	9×10^{-8}	0.13	1×10^{-7}
Maintenance worker	0.86	2×10^{-7}	0.0048	2×10^{-9}	0.039	3×10^{-8}	0.91	3×10^{-7}
Trespasser	0.0090	3×10^{-9}	0.00010	5×10^{-11}	0.00021	2×10^{-10}	0.0094	3×10^{-9}
Offsite: dispersed contaminants								
Outdoor worker	0.0059	2×10^{-9}	0.000046	2×10^{-11}	0.00037	3×10^{-10}	0.0063	2×10^{-9}
Adult resident	0.0021	6×10^{-10}	0.000020	1×10^{-11}	0.00098	8×10^{-10}	0.0031	1×10^{-9}
Child resident	0.0021	6×10^{-10}	0.000020	1×10^{-11}	0.00049	4×10^{-10}	0.0026	1×10^{-9}

[a] The estimated radiological doses and cancer risks from particulate emissions shown here for hypothetical waste excavation without any engineering controls are obtained by scaling from the results given in Table 5.2, with radiation doses and risks for waste group 1 multiplied by 100 and the doses and risks for waste groups 2 and 3 multiplied by 4. The radiation dose is given to two significant figures, and the risk is given to one significant figure. The values in bold exceed the comparison levels used in this TM (see Section 5.1). See the footnotes for Table 5.2 for additional explanations of the approach used to develop these estimates.

TABLE D.2 Illustrative Radiological Doses and Risks from Estimated Rn-222 Gas Emissions If Wastes Were Hypothetically Excavated without Any Engineering Controls[a]

Scenario	**Rn-222 Concentration** *(pCi/L)*	**Working-Level Ratio** *(WLR)*	**Exposure** *(WLM)*	**Dose** *(mrem)*	**Cancer Risk**
Onsite					
Remedial action worker	860	0.11	0.058	33	3×10^{-5}
Maintenance worker	9.2	0.16	1.1	**640**	$\mathbf{6 \times 10^{-4}}$
Trespasser	2.7	0.22	0.014	8.2	8×10^{-6}
Offsite					
Outdoor worker	8.1×10^{-2}	0.29	2.5×10^{-3}	1.4	1×10^{-6}
Adult resident	7.4×10^{-2}	0.30	1.8×10^{-3}	1.3	9×10^{-7}
Child resident	7.4×10^{-2}	0.30	1.8×10^{-3}	1.3	9×10^{-7}

[a] The estimated radiological doses and cancer risks from Rn-222 gas emissions shown here for hypothetical waste excavation without any engineering controls are obtained by scaling from the results given in Table 5.3, with the concentrations, exposures, radiation doses, and risks multiplied by 3.5 (see text for the determination of this factor). The WLR is not impacted by increasing the amount of Rn-222 gas released because it is simply a function of the distance from the release location (see Figure 4.1). These example Rn-222 concentrations (in pCi/L), exposures (in WLM), and doses (in mrem) are given to two significant figures, and the risk is given to one significant figure. The values in bold exceed the comparison levels used in this TM (see Section 5.1). See the footnotes for Table 5.3 for additional explanations of these terms and the approach used to develop these estimates.

TABLE D.3 Illustrative Radiological Doses and Risks from External Gamma Radiation for Hypothetical Waste Excavation without Any Engineering Controls[a]

Scenario	Receptor Distance *(m)*	Distance from Edge of Source *(m)*[b]	Normalized Dose Rate *(mrem/hr per 1,000 pCi/g)*[c]	Average Ra-226 Concentration *(pCi/g)*[d]	Dose Rate *(mrem/hr)*	Exposure Period *(hr)*[e]	Dose *(mrem)*	Risk[f]
***Waste Group 1:* K-65 Residues**								
Onsite: dispersed contaminants								
Remedial action worker	1	11	6.0×10^{-2}	520,000	31	1,360	**42,000**	**3×10^{-2}**
Maintenance worker	1 / 50	11 / 60	6.0×10^{-2} / 2.0×10^{-3}	520,000	31 / 1.0	136 / 1,224	**5,500**	**4×10^{-3}**
Trespasser	1 / 100	11 / 110	6.0×10^{-2} / 6.0×10^{-4}	520,000	31 / 0.31	2 / 18	**68**	5×10^{-5}
Offsite: dispersed contaminants								
Outdoor worker	560	570	2.0×10^{-6}	520,000	1.0×10^{-3}	1,360	1.4	1×10^{-6}
Adult resident	660	670	9.0×10^{-7}	520,000	4.7×10^{-4}	1,360	0.64	5×10^{-7}
Child resident	660	670	9.0×10^{-7}	520,000	4.7×10^{-4}	1,360	0.64	5×10^{-7}
***Waste Group 2:* Other High-Activity Residues (L and F) and Tower Soils**								
Onsite: dispersed contaminants								
Remedial action worker	1	16	3.0×10^{-2}	9,830	0.29	896	**260**	**2×10^{-4}**
Maintenance worker	1 / 50	16 / 65	3.0×10^{-2} / 1.5×10^{-3}	9,830	0.29 / 0.015	90 / 806	**38**	3×10^{-5}
Trespasser	1 / 100	16 / 120	3.0×10^{-2} / 5.0×10^{-4}	9,830	0.29 / 0.0049	1.3 / 12	0.44	4×10^{-7}
Offsite: dispersed contaminants								
Outdoor worker	560	580	2.0×10^{-6}	9,830	2.0×10^{-5}	896	0.018	1×10^{-8}
Adult resident	660	680	9.0×10^{-7}	9,830	8.8×10^{-6}	896	0.0079	6×10^{-9}
Child resident	660	680	9.0×10^{-7}	9,830	8.8×10^{-6}	896	0.0079	6×10^{-9}
***Waste Group 3:* R-10 Pile and Other Contaminated Soils**								
Onsite: dispersed contaminants								
Remedial action worker	1	24	1.0×10^{-2}	34	3.4×10^{-4}	2,200	0.75	6×10^{-7}
Maintenance worker	1 / 50	24 / 73	1.0×10^{-2} / 1.0×10^{-3}	34	3.4×10^{-4}/ 3.4×10^{-5}	220 / 1,980	0.14	1×10^{-7}
Trespasser	1 / 100	24/ 120	1.0×10^{-2} / 5.0×10^{-4}	34	3.4×10^{-4}/ 1.7×10^{-5}	3.2 / 29	0.0016	1×10^{-9}
Offsite: dispersed contaminants								
Outdoor worker	560	580	2.0×10^{-6}	34	6.8×10^{-8}	2,200	1.5×10^{-4}	1×10^{-10}
Adult resident	660	680	9.0×10^{-7}	34	3.1×10^{-8}	2,200	6.7×10^{-5}	5×10^{-11}
Child resident	660	680	9.0×10^{-7}	34	3.1×10^{-8}	2,200	6.7×10^{-5}	5×10^{-11}

[a] The estimated radiological doses and risks shown here are estimated to result from external gamma radiation exposures during hypothetical waste excavation without any engineering controls. Radiation doses are given to two significant figures and risks are given to one significant figure. Two entries are provided for the maintenance worker and trespasser because exposures for these two hypothetical receptors are assumed to occur at two distances from the excavation area. The doses and risks for the two residential scenarios account for time spent indoors and outdoors, with no credit taken for shielding by the structure while indoors. The values in bold exceed the comparison levels used in this TM (see Section 5.1).

[b] This entry gives the distance from the edge of the exposed gamma radiation source (assumed to be a right circular cylinder with a volume of 100 m^3 [130 yd^3]), for consistency with the manner in which the normalized gamma dose rates are presented in Figure 4.3.

[c] These values are obtained from Figure 4.3 for the indicated distances.

[d] The estimated concentrations of Ra-226 in the IWCS wastes are given in Table 2.2. The value used for the K-65 residues reflects the concentration in that table, while the values for waste groups 2 and 3 represent volume-weighted averages to account for the different concentrations in the wastes comprising each of these groups.

[e] The exposure period is the preliminary conceptual estimate of the total hours to excavate the given waste group. Exposures are assumed to occur during the eight hours of each work day during the excavation period, corresponding to the time when the wastes would be uncovered.

[f] The radiological cancer risk is calculated by multiplying the dose (in mrem) by the cancer risk factor of 8×10^{-7} cancers per mrem (see Section 4.1.3).

TABLE D.4 Illustrative Radiological Doses and Risks for Hypothetical Waste Excavation without Any Engineering Controls[a]

Scenario	Exposure Route							
	Particulate Emissions		Rn-222 Gas Emissions		External Gamma Radiation		Total	
	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk	Dose *(mrem)*	Risk
***Waste Group 1:* K-65 Residues**								
Onsite: dispersed contaminants								
Remedial action worker	**740**	**6×10^{-4}**	31	3×10^{-5}	**42,000**	**3×10^{-2}**	**43,000**	**3×10^{-2}**
Maintenance worker	**2,500**	**1×10^{-3}**	**610**	**6×10^{-4}**	**5,500**	**4×10^{-3}**	**8,600**	**6×10^{-3}**
Trespasser	**29**	1×10^{-5}	7.8	7×10^{-6}	**68**	5×10^{-5}	**100**	7×10^{-5}
Offsite: dispersed contaminants								
Outdoor worker	6.9	3×10^{-6}	1.4	1×10^{-6}	1.4	1×10^{-6}	9.7	6×10^{-6}
Adult resident	4.5	3×10^{-6}	1.2	9×10^{-7}	0.64	5×10^{-7}	6.4	4×10^{-6}
Child resident	3.3	2×10^{-6}	1.2	9×10^{-7}	0.64	5×10^{-7}	5.2	3×10^{-6}
***Waste Group 2:* Other High-Activity Residues (L and F) and Tower Soils**								
Onsite: dispersed contaminants								
Remedial action worker	16	1×10^{-5}	1.6	2×10^{-6}	**260**	**2×10^{-4}**	**280**	**2×10^{-4}**
Maintenance worker	**86**	2×10^{-5}	32	3×10^{-5}	**38**	3×10^{-5}	**160**	9×10^{-5}
Trespasser	0.94	3×10^{-7}	0.41	4×10^{-7}	0.44	4×10^{-7}	1.8	1×10^{-6}
Offsite: dispersed contaminants								
Outdoor worker	0.38	1×10^{-7}	0.072	7×10^{-8}	0.018	1×10^{-8}	0.47	2×10^{-7}
Adult resident	0.19	8×10^{-8}	0.066	5×10^{-8}	0.0079	6×10^{-9}	0.26	1×10^{-7}
Child resident	0.16	6×10^{-8}	0.066	5×10^{-8}	0.0079	6×10^{-9}	0.23	1×10^{-7}
***Waste Group 3:* R-10 Pile and Other Contaminated Soils**								
Onsite: dispersed contaminants								
Remedial action worker	0.13	1×10^{-7}			0.75	6×10^{-7}	0.88	7×10^{-7}
Maintenance worker	0.91	3×10^{-7}			0.14	1×10^{-7}	1.1	4×10^{-7}
Trespasser	0.0094	3×10^{-9}			0.0016	1×10^{-9}	0.011	4×10^{-9}
Offsite: dispersed contaminants								
Outdoor worker	0.0063	2×10^{-9}			1.5×10^{-4}	1×10^{-10}	0.0064	2×10^{-9}
Adult resident	0.0031	1×10^{-9}			6.7×10^{-5}	5×10^{-11}	0.0032	1×10^{-9}
Child resident	0.0026	1×10^{-9}			6.7×10^{-5}	5×10^{-11}	0.0027	1×10^{-9}

[a] This table summarizes the radiation doses and risks from Tables D.1, D.2, and D.3 for the three waste groups. The radiation dose is given to two significant figures and the risk is given to one significant figure. The values in bold exceed the comparison levels used in this TM (see Section 5.1). The values for particulate emissions include the contributions from external gamma radiation associated with the deposited radionuclides (from Table D.1); the values for Rn-222 gas emissions are from Table D.2, and the values for external gamma are from direct exposures as the wastes are excavated (from Table D.3). Gray shading for Rn-222 emissions under waste group 3 indicates the doses and risks were not quantified for this waste group because essentially all the Rn-222 gas emissions are associated with waste groups 1 and 2.

TABLE D.5 Illustrative Radiological Doses and Risks for Hypothetical Waste Excavation without Any Engineering Controls[a]

Scenario	Estimated Radiological Doses and Cancer Risks							
	Waste Group 1 **K-65 Residues**		***Waste Group 2*** **L-30, F-32, L-50 Residues and Tower Soils**		***Waste Group 3*** **R-10 Pile and Other Contaminated Soils**		***Total*** **All Wastes**	
	Dose *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**	**Dose** *(mrem)*	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	**43,000**	**3×10^{-2}**	**280**	**2×10^{-4}**	0.88	7×10^{-7}	**43,000**	**3×10^{-2}**
Maintenance worker	**8,600**	**6×10^{-3}**	**160**	9×10^{-5}	1.1	4×10^{-7}	**8,800**	**6×10^{-3}**
Trespasser	**100**	7×10^{-5}	1.8	1×10^{-6}	0.011	4×10^{-9}	**110**	8×10^{-5}
Offsite: dispersed contaminants								
Outdoor worker	9.7	6×10^{-6}	0.47	2×10^{-7}	0.0064	2×10^{-9}	10	6×10^{-6}
Adult resident	6.4	4×10^{-6}	0.26	1×10^{-7}	0.0032	1×10^{-9}	6.6	4×10^{-6}
Child resident	5.2	3×10^{-6}	0.23	1×10^{-7}	0.0027	1×10^{-9}	5.4	3×10^{-6}
Onsite: direct waste exposures								
External gamma (8 hr)	**2,000**	**2×10^{-3}**	38	3×10^{-5}	0.13	1×10^{-7}	**2,000**	**2×10^{-3}**
Incidental ingestion (100 mg)	**430**	**2×10^{-4}**	11	5×10^{-6}	0.041	2×10^{-8}	**440**	**2×10^{-4}**
Combined direct exposures	***2,400***	***2×10^{-3}***	*49*	*4×10^{-5}*	*0.17*	*1×10^{-7}*	***2,500***	***2×10^{-3}***

[a] This table summarizes the radiation doses and risks from Table D.4 for the three waste groups in the same format used for Table 5.6 to facilitate comparisons. (See the footnotes of Table 5.6 for additional information.) These results assume no engineering controls are used to control releases during waste excavation. The radiation dose is given to two significant figures and the risk is rounded to one significant figure. The values in bold exceed the comparison levels used in this TM (see Section 5.1). The direct waste exposure information presented in Table 5.6 is repeated here for completeness (see footnote b of Table 5.6 for a description of these scenarios).

TABLE D.6 Illustrative Chemical Hazard Indexes and Risks for Hypothetical Waste Excavation without Any Engineering Controls[a]

Scenario	Exposure Route					
	Inhalation of Particulates		Incidental Ingestion		Total	
	Hazard Index	Risk	Hazard Index	Risk	Hazard Index	Risk
***Waste Group 1:* K-65 Residues**						
Onsite: dispersed contaminants						
Remedial action worker	0.018	5×10^{-8}	0.0015	1×10^{-7}	0.02	2×10^{-7}
Maintenance worker	0.38	1×10^{-6}	2.1×10^{-4}	2×10^{-8}	0.4	1×10^{-6}
Trespasser	0.0048	1×10^{-8}	1.9×10^{-4}	2×10^{-8}	0.005	3×10^{-8}
Offsite: dispersed contaminants						
Outdoor worker	9.7×10^{-4}	3×10^{-9}	1.0×10^{-6}	9×10^{-11}	0.001	3×10^{-9}
Adult resident	5.6×10^{-4}	1×10^{-9}	3.2×10^{-7}	3×10^{-11}	0.0006	2×10^{-9}
Child resident	5.6×10^{-4}	1×10^{-9}	3.0×10^{-6}	2×10^{-10}	0.0006	2×10^{-9}
***Waste Group 2:* Other High-Activity Residues (L and F) and Tower Soils**						
Onsite: dispersed contaminants						
Remedial action worker	0.15	7×10^{-8}	0.0011	4×10^{-8}	0.2	1×10^{-7}
Maintenance worker	**2.4**	1×10^{-6}	1.8×10^{-4}	6×10^{-9}	**2**	1×10^{-6}
Trespasser	0.029	1×10^{-8}	4.6×10^{-4}	5×10^{-9}	0.03	2×10^{-8}
Offsite: dispersed contaminants						
Outdoor worker	0.010	5×10^{-9}	1.2×10^{-6}	4×10^{-11}	0.01	5×10^{-9}
Adult resident	0.0060	3×10^{-9}	3.7×10^{-7}	1×10^{-11}	0.006	3×10^{-9}
Child resident	0.0060	3×10^{-9}	3.5×10^{-6}	1×10^{-10}	0.006	3×10^{-9}
***Waste Group 3:* R-10 Pile and Other Contaminated Soils**						
Onsite: dispersed contaminants						
Remedial action worker	0.0011	3×10^{-9}	0.0015	6×10^{-8}	0.003	6×10^{-8}
Maintenance worker	0.048	1×10^{-7}	2.6×10^{-4}	1×10^{-8}	0.05	1×10^{-7}
Trespasser	5.4×10^{-4}	1×10^{-9}	2.4×10^{-4}	9×10^{-9}	0.0008	1×10^{-8}
Offsite: dispersed contaminants						
Outdoor worker	3.3×10^{-4}	8×10^{-10}	2.5×10^{-6}	1×10^{-10}	0.0003	9×10^{-10}
Adult resident	1.9×10^{-4}	5×10^{-10}	7.8×10^{-7}	3×10^{-11}	0.0002	5×10^{-10}
Child resident	1.9×10^{-4}	5×10^{-10}	7.3×10^{-6}	3×10^{-10}	0.0002	7×10^{-10}

[a] The estimated HIs and risks from particulate emissions given in this table for hypothetical waste excavation without any engineering controls are obtained from the results in Table 5.7, with the original estimates for waste group 1 multiplied by 100 and the original estimates for the waste groups 2 and 3 multiplied by 4. The pathway-specific HIs are given to two significant figures and the total HI is given to one significant figure, as is the cancer risk. The values in bold exceed the comparison levels used in this TM (see Section 5.1). See the footnotes of Table 5.7 for additional explanations of these terms and the approach used to develop these estimates.

TABLE D.7 Illustrative Chemical Hazard Indexes and Risks for Hypothetical Waste Excavation without Any Engineering Controls[a]

Scenario	Estimated Chemical Hazard Indexes and Cancer Risks							
	Waste Group 1		***Waste Group 2***		***Waste Group 3***		***Total***	
	K-65 Residues		**L-30, F-32, L-50 Residues and Tower Soils**		**R-10 Pile and Other Contaminated Soils**		**All Wastes**	
	Hazard Index	**Risk**	**Hazard Index**	**Risk**	**Hazard Index**	**Risk**	**Hazard Index**	**Risk**
Onsite: dispersed contaminants								
Remedial action worker	0.02	2×10^{-7}	0.2	1×10^{-7}	0.003	6×10^{-8}	0.2	3×10^{-7}
Maintenance worker	0.4	1×10^{-6}	**2**	1×10^{-6}	0.05	1×10^{-7}	**3**	2×10^{-6}
Trespasser	0.005	3×10^{-8}	0.03	2×10^{-8}	0.0008	1×10^{-8}	0.04	6×10^{-8}
Offsite: dispersed contaminants								
Outdoor worker	0.001	3×10^{-9}	0.01	5×10^{-9}	0.0003	9×10^{-10}	0.01	9×10^{-9}
Adult resident	0.0006	2×10^{-9}	0.006	3×10^{-9}	0.0002	5×10^{-10}	0.007	5×10^{-9}
Child resident	0.0006	2×10^{-9}	0.006	3×10^{-9}	0.0002	7×10^{-10}	0.007	5×10^{-9}
Onsite: direct waste exposure								
Incidental ingestion (100 mg)	**10**	$\mathbf{8 \times 10^{-4}}$	**9**	$\mathbf{3 \times 10^{-4}}$	**4**	$\mathbf{1 \times 10^{-4}}$	**20**	$\mathbf{1 \times 10^{-3}}$

[a] This table summarizes the HIs and risks from Table D.6 for the three waste groups in the same format used for Table 5.8, to facilitate comparisons. (See the footnotes of Table 5.8 for additional information.) These results assume no engineering controls are used to control releases during waste excavation. The HIs and risks are given to one significant figure. The values in bold exceed the comparison levels used in this TM (see Section 5.1). The direct waste exposure information given in Table 5.8 is repeated here for completeness (see footnote b of Table 5.8 for a description of this scenario).

TABLE D.8 Summary of Illustrative Hazard Indexes and Risks for Hypothetical Waste Excavation without Any Engineering Controls[a]

Scenario	Estimated Cancer Risks and Chemical Hazard Indexes										
	Waste Group 1			***Waste Group 2***			***Waste Group 3***			***Total***	
	K-65 Residues			**L-30, F-32, L-50 Residues and Tower Soils**			**R-10 Pile and Other Contaminated Soils**			**Combined Wastes**	
	Radiological Risk	**Chemical Risk**	**Hazard Index**	**Radiological Risk**	**Chemical Risk**	**Hazard Index**	**Radiological Risk**	**Chemical Risk**	**Hazard Index**	**Total Risk**	**Total HI**
Onsite: dispersed contaminants											
Remedial action worker	$\mathbf{3 \times 10^{-2}}$	2×10^{-7}	0.02	$\mathbf{2 \times 10^{-4}}$	1×10^{-7}	0.2	7×10^{-7}	6×10^{-8}	0.003	$\mathbf{3 \times 10^{-2}}$	0.2
Maintenance worker	$\mathbf{6 \times 10^{-3}}$	1×10^{-6}	0.4	9×10^{-5}	1×10^{-6}	**2**	4×10^{-7}	1×10^{-7}	0.05	$\mathbf{6 \times 10^{-3}}$	**3**
Trespasser	7×10^{-5}	3×10^{-8}	0.005	1×10^{-6}	2×10^{-8}	0.03	4×10^{-9}	1×10^{-8}	0.0008	8×10^{-5}	0.04
Offsite: dispersed contaminants											
Outdoor worker	6×10^{-6}	3×10^{-9}	0.001	2×10^{-7}	5×10^{-9}	0.01	2×10^{-9}	9×10^{-10}	0.0003	6×10^{-6}	0.01
Adult resident	4×10^{-6}	2×10^{-9}	0.0006	1×10^{-7}	3×10^{-9}	0.006	1×10^{-9}	5×10^{-10}	0.0002	4×10^{-6}	0.007
Child resident	3×10^{-6}	2×10^{-9}	0.0006	1×10^{-7}	3×10^{-9}	0.006	1×10^{-9}	7×10^{-10}	0.0002	3×10^{-6}	0.007
Onsite: direct waste exposures											
Incidental ingestion (100 mg)	$\mathbf{2 \times 10^{-4}}$	$\mathbf{8 \times 10^{-4}}$	**10**	5×10^{-6}	$\mathbf{3 \times 10^{-4}}$	**9**	2×10^{-8}	$\mathbf{1 \times 10^{-4}}$	**4**	$\mathbf{1 \times 10^{-3}}$	**20**
External gamma (8 hr)	$\mathbf{2 \times 10^{-3}}$			3×10^{-5}			1×10^{-7}			$\mathbf{2 \times 10^{-3}}$	
Combined direct exposures	$\mathbf{2 \times 10^{-3}}$	$\mathbf{8 \times 10^{-4}}$	**10**	4×10^{-5}	$\mathbf{3 \times 10^{-4}}$	**9**	1×10^{-7}	$\mathbf{1 \times 10^{-4}}$	**4**	$\mathbf{3 \times 10^{-3}}$	**20**

[a] This table summarizes information from Tables D.5 and D.7 for the three waste groups in the same format as given in Table 6.3. The footnotes given for Tables 5.6 and 5.8 can be reviewed for additional information, and these results do not reflect any credit for the use of engineering controls. All values are given to one significant figure, and the entries in bold exceed the comparison levels used in this TM (see Section 5.1). The direct waste exposure information given in Tables 5.6 and 5.8 is repeated here for completeness (see footnote b of these two tables for additional information on these estimates). Gray shading indicates the entry is not relevant.

TABLE D.9 Summary of Illustrative Hazard Indexes and Risks for Hypothetical Excavation of all Wastes without Any Engineering Controls[a]

Scenario	Hazard Index	Chemical Risk	Radiological Risk	Combined Cancer Risk
Onsite: dispersed particulates				
Remedial action worker	0.2	3×10^{-7}	$\mathbf{3 \times 10^{-2}}$	$\mathbf{3 \times 10^{-2}}$
Maintenance worker	**3**	2×10^{-6}	$\mathbf{6 \times 10^{-3}}$	$\mathbf{6 \times 10^{-3}}$
Trespasser	0.04	6×10^{-8}	8×10^{-5}	8×10^{-5}
Offsite: dispersed particulates				
Outdoor worker	0.01	9×10^{-9}	6×10^{-6}	6×10^{-6}
Adult resident	0.007	5×10^{-9}	4×10^{-6}	4×10^{-6}
Child resident	0.007	5×10^{-9}	3×10^{-6}	3×10^{-6}
Onsite: direct waste exposures				
Incidental ingestion (100 mg)	**20**	$\mathbf{1 \times 10^{-3}}$	$\mathbf{2 \times 10^{-4}}$	$\mathbf{1 \times 10^{-3}}$
External gamma (8 hr)			$\mathbf{2 \times 10^{-3}}$	$\mathbf{2 \times 10^{-3}}$
Combined direct exposures	***20***	$\boldsymbol{1 \times 10^{-3}}$	$\boldsymbol{2 \times 10^{-3}}$	$\boldsymbol{3 \times 10^{-3}}$

[a] This table summarizes information from Tables D.5, D.7, and D.8 for the three waste groups in the same format as Table 6.4. The footnotes for Tables 5.6 and 5.8 provide general context, but these estimates assume no engineering controls are applied, to help demonstrate the need for these controls (as for any such excavation project). Values are rounded to one significant figure, and entries in bold exceed the comparison levels used in this TM (see Section 5.1). Gray shading indicates the entry is not relevant.