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Off-Site Population Radiological Dose and Risk Assessment for Potential Airborne Emissions from the Weldon Spring Site

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The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Some acronyms used in tables or equations only are defined in the respective tables or equations.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

BA	baseline assessment
CDE	committed dose equivalent
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EDE	effective dose equivalent
EPA	U.S. Environmental Protection Agency
FS	feasibility study
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act of 1969, as amended
NESHAPs	National Emission Standards for Hazardous Air Pollutants
NRC	U.S. Nuclear Regulatory Commission
RI	remedial investigation

UNITS OF MEASURE

°C	degrees Celsius
Ci	curie
cm	centimeter
cm^3	cubic centimeter
d	day
h	hour
ha	hectare
kg	kilogram
km	kilometer
km^2	square kilometer
L	liter
m	meter
m^2	square meter
MeV	million electron volt
mi	mile
mrem	millirem
rem	roentgen-equivalent man
s	second
yr	year

OFF-SITE POPULATION RADIOLOGICAL DOSE AND RISK ASSESSMENT FOR POTENTIAL AIRBORNE EMISSIONS FROM THE WELDON SPRING SITE

by

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ABSTRACT

Radiological doses and health risks to the population around the Weldon Spring site from potential airborne emissions during remedial action at the chemical plant area of the site have been assessed with the Clean Air Act Assessment Package-1988 computer code. Two treatment options are being considered for waste produced by site cleanup activities: chemical stabilization/solidification and vitrification. Over the entire cleanup period of 7 years, the collective dose received by the people who live within 80 km (50 mi) of the site (about 3 million persons) is estimated to be about 34 person-rem for the chemical stabilization/solidification option and 32 person-rem for the vitrification option. By comparison, the same population is expected to receive about 6×10^6 person-rem from natural background radiation during that time. If only the population within a reasonable radius of impact is considered (about 10,700 persons live within 5 km [3 mi] of the site), the remedial action activities are estimated to result in about 5 person-rem over the entire cleanup period; the same population is expected to receive about 20,000 person-rem from natural background radiation during that time. Because the doses are low, no cancers or genetic effects are expected to occur among the population around the Weldon Spring site as a result of exposures resulting from potential radioactive releases to the atmosphere during remediation of the chemical plant area.

1 INTRODUCTION

The Weldon Spring site is located in St. Charles County, Missouri, about 48 km (30 mi) west of St. Louis (Figure 1). The site became contaminated as a result of processing and disposal activities that took place from the 1940s through the 1960s, and it is listed on the National Priorities List of the U.S. Environmental Protection Agency (EPA). The U.S. Department of Energy (DOE) is responsible for cleanup activities at the site under its Environmental Restoration and Waste Management Program.

The Weldon Spring site consists of two noncontiguous areas: an 88-ha (217-acre) chemical plant area and a 3.6-ha (9-acre) limestone quarry. The chemical plant area is about 3.2 km (2 mi) southwest of the junction of Missouri (State) Route 94 and U.S. 40/61, and the

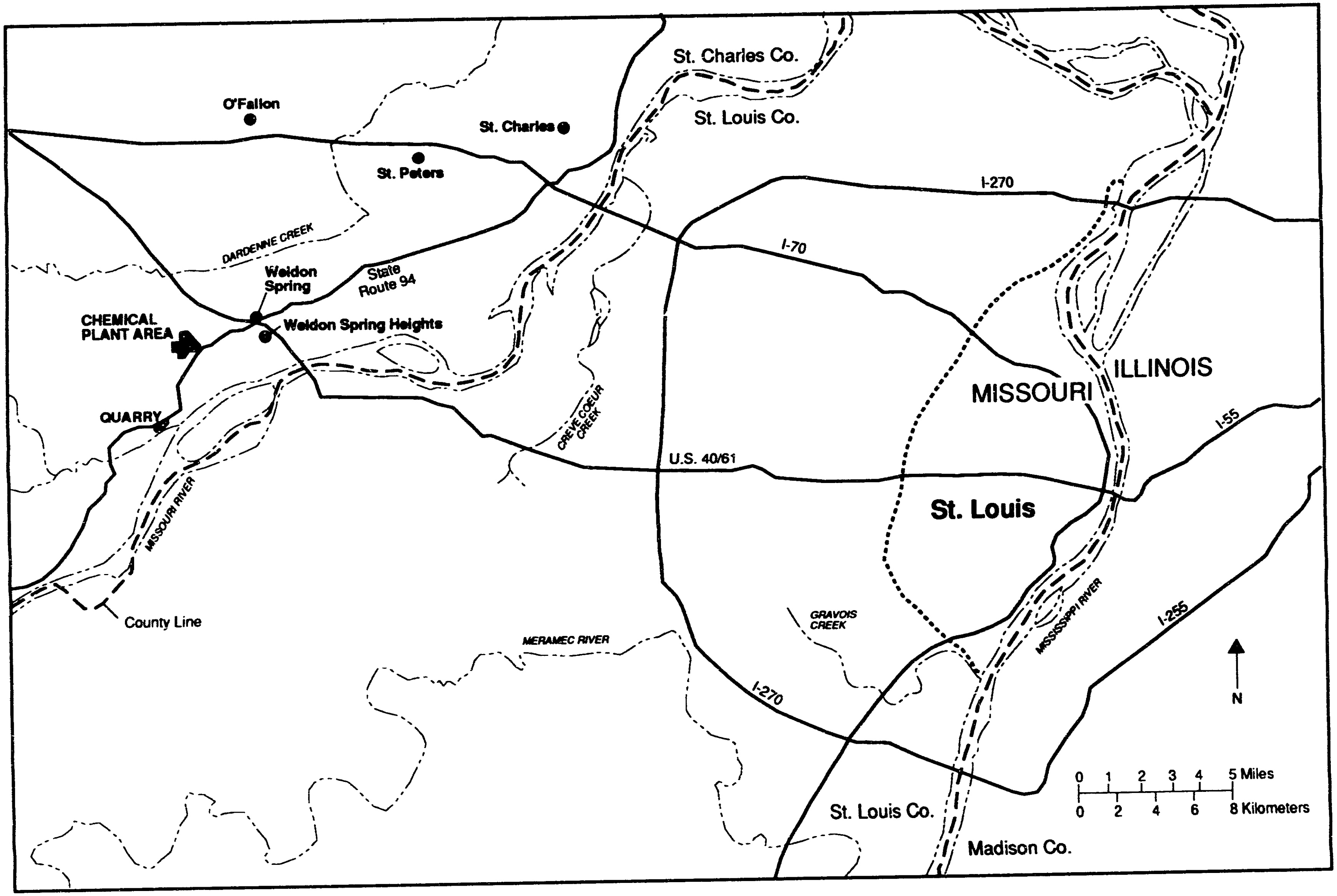

Figure 1 Location of the Weldon Spring Site (Source: DOE 1992a)

quarry is about 6.4 km (4 mi) south-southwest of the chemical plant area. Both locations are accessible from State Route 94 and are fenced and closed to the public. Explosives were produced at the chemical plant during the 1940s, and uranium and thorium materials were processed during the 1950s and 1960s. During the latter operational period, waste slurries at the chemical plant area were piped to four retention ponds, referred to as raffinate pits; various solid wastes (i.e., process residues and decontamination material that included soil, rubble, metal debris, and equipment) were disposed of in the quarry between 1942 and 1969.

In accordance with the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended, a remedial investigation/feasibility study (RI/FS) process has been performed for the chemical plant area of the Weldon Spring site. The RI/FS package comprises four documents: an RI report (DOE 1992d), a baseline assessment (BA) (DOE 1992a), an FS report (DOE 1992b), and a proposed plan (DOE 1992c). These documents were prepared in accordance with CERCLA requirements, incorporating values associated with the National Environmental Policy Act (NEPA). As part of the FS, the radiological impacts to the population near the site from potential airborne releases during the remedial action period have been assessed. The results of this assessment are summarized in the FS. This report describes the calculations performed and provides additional information associated with these analyses.

Radiological doses were calculated with Version 1.0 of the CAP88-PC personal computer code (EPA 1992), and the risks to human health were calculated by multiplying the doses obtained from CAP88-PC with risk factors used by the EPA (1989a). The assessment covered the two proposed options for waste treatment: chemical stabilization/solidification and vitrification. Potential doses and health risks were calculated for the off-site population within an 80-km (50-mi) radius of the site. From the results of these calculations, a radius of reasonable impact was inferred and the health risks to the population within this radius were calculated.

The methods used to estimate the collective radiological doses to members of the general public for this report differ somewhat from those used to estimate the doses to specific individual receptors in the BA and FS. The radiological doses presented herein are based on the methodology provided in the CAP88-PC computer code, whereas the doses in the BA and FS are largely based on the methodology given in the *Risk Assessment Guidance for Superfund* (EPA 1989b). However, these methodological differences are small and do not affect the results and conclusions given in the various documents developed for the Weldon Spring site. The population doses presented in this document are based on 1990 census data.

2 METHODOLOGY

The CAP88-PC computer code is a personal-computer version of the Clean Air Act Assessment Package-1988 (CAP-88) (Beres 1990), which is one of the codes specified by the EPA in Title 40, Code of Federal Regulations, Part 61, Subpart H (40 CFR Part 61, Subpart H), for demonstrating compliance with the National Emission Standards for Hazardous Air Pollutants (NESHAPs). The CAP88-PC computer code was developed by the EPA's Office of Radiation Programs (EPA 1992). This code comprises a set of subprograms, databases, and associated utility programs that implement a mathematical model for assessing dose and health risk from radionuclide emissions to the atmosphere. The code evaluates the environmental transport of radionuclides released to the atmosphere and estimates health impacts from the following pathways: inhalation, ingestion, and external gamma irradiation from air immersion and the ground surface. Results are tabulated for individuals residing at specified locations and for regional populations.

2.1 ENVIRONMENTAL TRANSPORT

The CAP88-PC program models environmental transport in a manner similar to that documented in its predecessor model, AIRDOS-EPA (Moore et al. 1979). The CAP88-PC program uses a modified Gaussian plume equation to estimate the average dispersion of radionuclides released from as many as six sources. The sources may be either elevated stacks or uniform area sources, such as a pile of uranium mill tailings. Plume rises can be calculated by assuming either a momentum-driven or buoyancy-driven plume. The assessment areas encompass a circular grid within a given radius around the modeled facility.

The CAP88-PC program computes radionuclide concentrations in air, rates of deposition on ground surfaces, concentrations in food, and intake rates for humans from inhalation of air and ingestion of food produced in the assessment area. The radionuclide concentrations in produce, leafy vegetables, milk, and meat consumed by humans are estimated by coupling the output of the atmospheric transport models with the terrestrial food chain models given in Regulatory Guide 1.109 of the U.S. Nuclear Regulatory Commission (NRC 1977).

2.2 ESTIMATION OF DOSE AND HEALTH RISK

Dose conversion factors in CAP88-PC are provided for intakes of radionuclides by ingestion and inhalation and also for external gamma irradiation from air immersion and the ground surface. Factors are further broken down by particle size, solubility class, and digestion transfer factors. These factors are generated with the RADRISK computer program (Dunning et al. 1980; Begovich et al. 1981).

In CAP88-PC, dose and health risk are estimated by the DARTAB program (Begovich et al. 1981), which combines the inhalation and ingestion intake rates and the air and ground surface concentrations with the dose and risk factors from the RADRISK database. The effective dose equivalent is calculated with the weighting factors given in Publication 26 of the International Commission on Radiological Protection (1977). The CAP88-PC code lists the dose and risk to individuals residing at the specified locations and to the collective population. Doses and risks are further tabulated as a function of radionuclide, pathway, location, and organ. More information concerning CAP88-PC and its methodology is given in the *User's Guide for CAP88-PC* (EPA 1992) and the reports of Beres (1990) and the Radiation Shielding Information Center (1987).

For this assessment, the CAP88-PC code was used to calculate the doses received by selected hypothetical off-site individuals and the collective population. The risks in terms of cancer induction and genetic effects among the exposed population were calculated as follows. The cancer risk was calculated by multiplying the collective committed effective dose equivalent (CEDE) by the risk factor of 6×10^{-4}/person-rem (EPA 1989a). The genetic effects, defined as the number of severe physical or mental defects in the offspring of exposed persons, were calculated by multiplying the sum of the collective committed dose equivalent (CDE) to gonads and the collective external effective dose equivalent (EDE) by the risk factor of 2.6×10^{-4}/person-rem (EPA 1989a).

3 INPUT PARAMETERS AND ASSUMPTIONS

Site-specific data used as input to the CAP88-PC code are given in Table 1. The 80-km (50-mi) off-site population distribution and wind frequency data used are provided in Tables 2 and 3. The average year and maximum year atmospheric releases of radionuclides (source terms) were calculated for each of the two waste treatment options. The average year releases for each radionuclide were determined by dividing the total release of radionuclides by 7, the number of years estimated for completion of cleanup activities. The radionuclide source terms used in the assessment are listed in Table 4. Only the principal radionuclides in the uranium-238, uranium-235, and thorium-232 decay series have been included in the source terms (see the discussion in Section 2.3.2.1 of the BA [DOE 1992a]). Analyses performed with the CAP-88 code (before the CAP88-PC code was available) for the assessment reported in this document showed that the short-lived decay products in these decay series (except for the daughters of radon-222, which are accounted for in both CAP-88 and CAP88-PC) contributed less than 10% to the total CEDE.

The input parameters other than the radionuclide source terms are listed in Table 5; these parameters are CAP88-PC default values. A more complete description of CAP88-PC input parameters and the default values assigned to these parameters in the code are provided in EPA (1992).

TABLE 1 CAP88-PC Input Parameters for Releases from the Weldon Spring Site

Parameter	Value
Radionuclide release data	
Stack (release) height	10 m
Period of long-term buildup activity in the soil	40 years
Release rate of radionuclides to the atmosphere	See Table 4
Meteorological data	
Rainfall rate	95 cm/yr
Average temperature	13°C
Height of tropospheric mixing layer	900 m
Height for wind speed measurements	10 m
Joint wind frequency data	See Table 3
Receptor data	
Inhalation rate of humans	8.3×10^5 cm^3/h
Total population	2,922,000
Population distribution	See Table 2
Rate of ingestion by humans[a]	
Produce	105 kg/yr
Milk	140 L/yr
Meat	35 kg/yr
Leafy vegetables	14 kg/yr
Source of food for individual's diet[a,b]	
Milk	
At location of individual	75%
Within assessment area	0
Outside assessment area	25%
Meat	
At location of individual	75%
Within assessment area	0
Outside assessment area	25%
Vegetables	
At location of individual	40%
Within assessment area	0
Outside assessment area	60%

[a] As recommended by the EPA (1991). Leafy vegetables were assumed to constitute 20% of the EPA-recommended vegetable component (NRC 1977).

[b] Assessment area is defined as an 80-km (50-mi) radius around the release point.

TABLE 2 Distribution of the Population within a 50-Mile Radius of the Weldon Spring Site

Wind Direction	Population per Sector[a]									
	0-1	1-2	2-3	3-4	4-5	5-10	10-20	20-30	30-40	40-50
N	73	220	367	513	660	5,501	11,619	3,361	3,793	3,794
NNW	73	220	367	513	660	5,501	10,554	4,626	5,984	4,388
NW	73	220	367	513	660	5,501	13,106	4,623	5,973	4,397
WNW	73	220	367	513	660	5,501	7,316	4,423	3,906	3,832
W	73	220	367	513	660	5,501	5,461	4,618	5,912	4,296
WSW	73	220	367	513	660	5,501	7,258	7,980	9,500	4,811
SW	73	220	367	513	660	5,501	10,498	8,475	11,865	9,286
SSW	73	220	367	513	660	4,309	5,176	8,475	9,564	4,711
S	73	220	367	720	2,026	14,787	35,168	18,399	22,880	11,689
SSE	73	220	369	2,352	3,575	29,791	72,099	25,586	35,034	38,143
SE	73	220	530	2,780	3,575	29,791	103,546	63,510	9,027	10,584
ESE	73	220	371	2,123	3,573	29,791	119,163	497,757	45,254	66,709
E	73	220	367	513	992	10,951	115,628	663,537	48,873	61,633
ENE	73	220	367	513	660	5,501	69,893	150,550	68,722	48,746
NE	73	220	367	513	660	5,501	20,635	19,380	13,961	9,436
NNE	73	220	367	513	660	5,501	7,300	4,268	5,951	5,142

[a] Each sector is expressed as a range of miles from the release point for the population within 80 km (50 mi) from the site. The population file consists of 10 radial sectors in each of 16 directions from the release point. Each entry is the population for a given sector in a particular direction away from the release point. All entries are based on 1990 census data and assume that the population is uniformly distributed within each county. This approach overestimates the actual population living within 5 km (3 mi) of the site.

TABLE 3 Joint Wind Frequency Data File[a]

Wind Direction	Stability Class	Wind Frequency at Wind Speed Bin					
		1.5 knots	5.0 knots	8.5 knots	13.5 knots	19.0 knots	23.0 knots
N	A	0.00054	0.00068	0.00000	0.00000	0.00000	0.00000
NNE	A	0.00066	0.00057	0.00000	0.00000	0.00000	0.00000
NE	A	0.00032	0.00091	0.00000	0.00000	0.00000	0.00000
ENE	A	0.00037	0.00160	0.00000	0.00000	0.00000	0.00000
E	A	0.00033	0.00114	0.00000	0.00000	0.00000	0.00000
ESE	A	0.00010	0.00126	0.00000	0.00000	0.00000	0.00000
SE	A	0.00005	0.00068	0.00000	0.00000	0.00000	0.00000
SSE	A	0.00033	0.00114	0.00000	0.00000	0.00000	0.00000
S	A	0.00034	0.00126	0.00000	0.00000	0.00000	0.00000
SSW	A	0.00003	0.00046	0.00000	0.00000	0.00000	0.00000
SW	A	0.00006	0.00080	0.00000	0.00000	0.00000	0.00000
WSW	A	0.00003	0.00034	0.00000	0.00000	0.00000	0.00000
W	A	0.00018	0.00080	0.00000	0.00000	0.00000	0.00000
WNW	A	0.00014	0.00023	0.00000	0.00000	0.00000	0.00000
NW	A	0.00025	0.00011	0.00000	0.00000	0.00000	0.00000
NNW	A	0.00025	0.00011	0.00000	0.00000	0.00000	0.00000
N	B	0.00130	0.00285	0.00000	0.00000	0.00000	0.00000
NNE	B	0.00062	0.00183	0.00000	0.00000	0.00000	0.00000
NE	B	0.00061	0.00171	0.00000	0.00000	0.00000	0.00000
ENE	B	0.00123	0.00194	0.00000	0.00000	0.00000	0.00000
E	B	0.00101	0.00400	0.00000	0.00000	0.00000	0.00000
ESE	B	0.00031	0.00091	0.00000	0.00000	0.00000	0.00000
SE	B	0.00043	0.00091	0.00000	0.00000	0.00000	0.00000
SSE	B	0.00051	0.00205	0.00000	0.00000	0.00000	0.00000
S	B	0.00069	0.00468	0.00000	0.00000	0.00000	0.00000
SSW	B	0.00049	0.00171	0.00000	0.00000	0.00000	0.00000
SW	B	0.00032	0.00103	0.00000	0.00000	0.00000	0.00000
WSW	B	0.00014	0.00194	0.00000	0.00000	0.00000	0.00000
W	B	0.00065	0.00228	0.00000	0.00000	0.00000	0.00000
WNW	B	0.00036	0.00171	0.00000	0.00000	0.00000	0.00000
NW	B	0.00037	0.00183	0.00000	0.00000	0.00000	0.00000
NNW	B	0.00068	0.00103	0.00000	0.00000	0.00000	0.00000
N	C	0.00069	0.00434	0.00274	0.00000	0.00000	0.00000
NNE	C	0.00059	0.00228	0.00046	0.00000	0.00000	0.00000
NE	C	0.00112	0.00331	0.00103	0.00011	0.00000	0.00000
ENE	C	0.00087	0.00308	0.00034	0.00000	0.00000	0.00000
E	C	0.00153	0.00445	0.00068	0.00000	0.00000	0.00000
ESE	C	0.00105	0.00194	0.00091	0.00000	0.00000	0.00000
SE	C	0.00160	0.00342	0.00091	0.00000	0.00000	0.00000
SSE	C	0.00158	0.00537	0.00171	0.00000	0.00000	0.00000
S	C	0.00174	0.00868	0.00594	0.00000	0.00000	0.00000
SSW	C	0.00066	0.00365	0.00194	0.00000	0.00000	0.00000
SW	C	0.00080	0.00411	0.00126	0.00000	0.00000	0.00000
WSW	C	0.00085	0.00514	0.00240	0.00000	0.00000	0.00000
W	C	0.00091	0.00400	0.00342	0.00000	0.00000	0.00000
WNW	C	0.00062	0.00285	0.00240	0.00000	0.00000	0.00000
NW	C	0.00069	0.00194	0.00183	0.00000	0.00000	0.00000
NNW	C	0.00126	0.00365	0.00251	0.00000	0.00000	0.00000
N	D	0.00562	0.01518	0.01119	0.00068	0.00000	0.00000
NNE	D	0.00413	0.01142	0.00639	0.00011	0.00000	0.00000
NE	D	0.00460	0.01119	0.00571	0.00034	0.00000	0.00000

TABLE 3 (Cont.)

Wind Direction	Stability Class	Wind Frequency at Wind Speed Bin					
		1.5 knots	5.0 knots	8.5 knots	13.5 knots	19.0 knots	23.0 knots
ENE	D	0.00392	0.00685	0.00126	0.00023	0.00000	0.00000
E	D	0.00649	0.01358	0.00194	0.00080	0.00000	0.00000
ESE	D	0.00479	0.00879	0.00228	0.00000	0.00011	0.00000
SE	D	0.00749	0.01221	0.00285	0.00000	0.00000	0.00000
SSE	D	0.00768	0.02500	0.00731	0.00011	0.00000	0.00000
S	D	0.01022	0.04669	0.02249	0.00342	0.00000	0.00000
SSW	D	0.00573	0.02683	0.01655	0.00297	0.00000	0.00000
SW	D	0.00493	0.00902	0.00605	0.00240	0.00000	0.00000
WSW	D	0.00329	0.00993	0.00445	0.00354	0.00011	0.00000
W	D	0.00473	0.01632	0.01507	0.00685	0.00023	0.00000
WNW	D	0.00578	0.01233	0.01541	0.00753	0.00046	0.00000
NW	D	0.00437	0.01484	0.01495	0.00616	0.00091	0.00000
NNW	D	0.00493	0.01404	0.01244	0.00285	0.00000	0.00000
N	E	0.00000	0.01176	0.00320	0.00000	0.00000	0.00000
NNE	E	0.00000	0.00491	0.00114	0.00000	0.00000	0.00000
NE	E	0.00000	0.00491	0.00068	0.00000	0.00000	0.00000
ENE	E	0.00000	0.00194	0.00000	0.00000	0.00000	0.00000
E	E	0.00000	0.00411	0.00023	0.00000	0.00000	0.00000
ESE	E	0.00000	0.00491	0.00023	0.00000	0.00000	0.00000
SE	E	0.00000	0.01084	0.00080	0.00000	0.00000	0.00000
SSE	E	0.00000	0.01301	0.00114	0.00000	0.00000	0.00000
S	E	0.00000	0.02705	0.00582	0.00000	0.00000	0.00000
SSW	E	0.00000	0.01564	0.00365	0.00000	0.00000	0.00000
SW	E	0.00000	0.00811	0.00114	0.00000	0.00000	0.00000
WSW	E	0.00000	0.00479	0.00160	0.00000	0.00000	0.00000
W	E	0.00000	0.00947	0.00274	0.00000	0.00000	0.00000
WNW	E	0.00000	0.00788	0.00297	0.00000	0.00000	0.00000
NW	E	0.00000	0.01005	0.00354	0.00000	0.00000	0.00000
NNW	E	0.00000	0.00776	0.00183	0.00000	0.00000	0.00000
N	F	0.00501	0.00011	0.00000	0.00000	0.00000	0.00000
NNE	F	0.00396	0.00023	0.00000	0.00000	0.00000	0.00000
NE	F	0.00505	0.00023	0.00000	0.00000	0.00000	0.00000
ENE	F	0.00392	0.00011	0.00000	0.00000	0.00000	0.00000
E	F	0.00673	0.00057	0.00000	0.00000	0.00000	0.00000
ESE	F	0.00563	0.00011	0.00000	0.00000	0.00000	0.00000
SE	F	0.01018	0.00068	0.00000	0.00000	0.00000	0.00000
SSE	F	0.00606	0.00046	0.00000	0.00000	0.00000	0.00000
S	F	0.01316	0.00205	0.00000	0.00000	0.00000	0.00000
SSW	F	0.00952	0.00228	0.00000	0.00000	0.00000	0.00000
SW	F	0.00587	0.00034	0.00000	0.00000	0.00000	0.00000
WSW	F	0.00563	0.00011	0.00000	0.00000	0.00000	0.00000
W	F	0.01290	0.00046	0.00000	0.00000	0.00000	0.00000
WNW	F	0.00752	0.00148	0.00000	0.00000	0.00000	0.00000
NW	F	0.00901	0.00046	0.00000	0.00000	0.00000	0.00000
NNW	F	0.00548	0.00011	0.00000	0.00000	0.00000	0.00000

[a] This data file contains stability array (STAR) data that show the frequencies of occurrence of the wind blowing from a particular direction (column 1), at a particular stability (classes A to F, column 2), at a particular speed. For each direction and each stability class, the probability of occurrence is listed for each of six wind speed bins (columns 3 to 8). The wind speed bins correspond to 1.5, 5.0, 8.5, 13.5, 19.0, and 23.0 knots (0.772, 2.572, 4.372, 6.945, 9.774, and 11.832 m/s), respectively.

TABLE 4 Radionuclide Source Terms for the Proposed Remedial Action Alternatives at the Weldon Spring Site[a]

Radionuclide	Source Terms for Chemical Stabilization/Solidification (Ci/yr)		Source Terms for Vitrification (Ci/yr)	
	Average Year	Maximum Year[b]	Average Year	Maximum Year[b]
Actinium-227	2.7×10^{-5}	4.7×10^{-5}	1.5×10^{-5}	2.7×10^{-5}
Lead-210	4.1×10^{-5}	8.2×10^{-5}	1.0×10^{-3}	1.5×10^{-3}
Protactinium-231	3.6×10^{-5}	6.1×10^{-5}	2.1×10^{-5}	3.5×10^{-5}
Radium-226	3.5×10^{-5}	6.3×10^{-5}	2.3×10^{-5}	4.0×10^{-5}
Radium-228	1.6×10^{-5}	3.0×10^{-5}	1.1×10^{-5}	2.1×10^{-5}
Radon-222	3.5×10^{1}	5.0×10^{1}	5.0×10^{1}	6.6×10^{1}
Thorium-230	1.2×10^{-3}	2.1×10^{-3}	6.7×10^{-4}	1.2×10^{-3}
Thorium-232	4.1×10^{-6}	6.5×10^{-6}	3.5×10^{-6}	5.3×10^{-6}
Uranium-235	3.8×10^{-6}	6.0×10^{-6}	2.8×10^{-6}	4.2×10^{-6}
Uranium-238	8.2×10^{-5}	1.3×10^{-4}	6.1×10^{-5}	8.9×10^{-5}

[a] The radiological doses associated with the other radionuclides in the uranium-238, thorium-232, and uranium-235 radioactive decay series were calculated on the basis of the results of the radiological source term analysis. See related discussion in Sections 2.3.2.1 and 4.1 of the BA (DOE 1992a).

[b] The maximum year is 1998 for all radionuclides except radon-222. For radon-222, the maximum year is 1994 under chemical stabilization/solidification and 1995 under vitrification.

TABLE 5 Default CAP88-PC Input Parameters for Releases from the Weldon Spring Site

Input Parameter	Value
Agricultural productivity by unit area	
Grass-cow-milk-humans pathway	0.280 kg/m^2
Produce or leafy vegetables ingested by humans	0.716 kg/m^2
Fraction of year animals graze on pasture	0.40
Fraction of daily feed that is pasture grass when animal grazes on pasture	0.43
Period of exposure during growing season	
Pasture grass	720 hours
Crops or leafy vegetables	1,440 hours
Fallout interception fraction	
Vegetables	0.20
Pasture	0.57
Removal rate constant for physical loss by weathering	2.9×10^{-3} per hour
Buildup time for radionuclides deposited on ground and water	1.5×10^{4} days
Consumption rate of contaminated feed or forage by an animal (dry weight)	15.6 kg/d
Milk production of cow	11.0 L/d
Transport time from animal feed-milk-humans	2.0 days
Time delay	
Ingestion of pasture grass by animals	0 hours
Ingestion of stored feed by animals	2,160 hours
Ingestion of leafy vegetables by humans	336 hours
Ingestion of produce by humans	340 hours
Fraction of radioactivity retained on leafy vegetables and produce after washing	0.5
Average time from slaughter of animal to consumption of meat	20 days
Muscle mass of animal at slaughter	200 kg
Fraction of animal herd slaughtered per day	3.8×10^{-3}
Beef cattle density	3.43×10^{-1}/km^2
Milk cattle density	1.89×10^{-2}/km^2
Land fraction cultivated for vegetable crops	8.14×10^{-3}

4 RESULTS AND DISCUSSION

The estimated radiological impacts to the population within 80 km (50 mi) of the Weldon Spring site, assuming chemical stabilization/solidification of the waste, are presented in Table 6. The results are presented both excluding and including the impacts associated with radon-222 releases. The estimated doses and health effects associated with radon-222 are presented in Table 7; these estimates are based on the release of 1 Ci of radon-222 in 1 year. For the chemical stabilization/solidification treatment option, the average annual radon-222 release is estimated to be 35 Ci. The maximum amount of radon-222 released in any year is estimated to be 50 Ci. Table 6 also shows the estimated annual doses to the same population (about 3 million persons) from natural background radiation. The estimated dose from cleanup activities is less than 0.001% of the dose received from the natural background.

The contributions to the collective 50-year CEDE by exposure pathway, the doses associated with the two radionuclides contributing most of the dose (radon-222 and thorium-230), and the doses to two specific organs (the thyroid and the gonads) are given in Table 6. The health effects in terms of cancer induction and genetic effects among the exposed population were estimated with EPA risk factors (EPA 1989a), as described in Section 2.2.

The estimated radiological doses and health effects among the population within 80 km (50 mi) of the Weldon Spring site as a result of cleanup activities are given in Table 8 for the vitrification option. During vitrification, the average and maximum radon-222 releases are estimated to be 50 and 66 Ci/yr, respectively. The total collective CEDE estimated for that population is slightly less for the vitrification option than the chemical stabilization/solidification option. However, either option would produce impacts that are much less than those that would result from natural background radiation during the same time period.

TABLE 7 Estimated Population Doses and Health Effects for Atmospheric Releases of 1 Curie of Radon-222 from the Weldon Spring Site[a]

Parameter	1 Year	During 7-Year Cleanup Period
CEDE[b] (person-rem)	5.0×10^{-2}	3.5×10^{-1}
External exposure	4.5×10^{-6}	3.2×10^{-5}
Inhalation	5.0×10^{-2}	3.5×10^{-1}
Ingestion	0.0	0.0
Person-working level[c]	1.5×10^{-2}	1.1×10^{-1}
Thyroid CDE[d] (person-rem)	4.8×10^{-2}	3.4×10^{-1}
Gonads CDE (person-rem)	4.9×10^{-2}	3.4×10^{-1}
Cancer incidents[e]	3×10^{-5}	2×10^{-4}
Genetic effects[f]	1×10^{-5}	9×10^{-5}

[a] Estimated for the population of about 2,922,000 within an 80-km (50-mi) radius of the site.

[b] CEDE = committed effective dose equivalent. Also listed by pathway (external exposure, inhalation, ingestion).

[c] One working level is defined as any combination of short-lived decay products of radon-222 in 1 L of air that will release 1.3×10^5 MeV of alpha particle energy. Person-working level is the integrated sum of the radon decay product concentrations to which the population within the 80-km (50-mi) radius of the site is exposed.

[d] CDE = committed dose equivalent.

[e] Calculated by multiplying the CEDE by the risk factor of 6×10^{-4}/person-rem (EPA 1989a). Rounded to one significant figure.

[f] Genetic effects are defined as the calculated number of severe physical or mental defects in the offspring of exposed persons. Calculated by multiplying the sum of the gonads CDE and the external dose by the risk factor of 2.6×10^{-4}/person-rem (EPA 1989a). Rounded to one significant figure.

TABLE 8 Estimated Population Doses and Health Effects from Atmospheric Releases during Cleanup Activities at the Weldon Spring Site: Vitrification[a]

	Excluding Radon-222			Including Radon-222	
Parameter	Average Year	Maximum Year[b]	During 7-Year Cleanup Period	Average Year	During 7-Year Cleanup Period
CEDE[c] (person-rem)	2.0	3.5	1.4×10^{1}	4.5	3.2×10^{1}
External exposure	6.3×10^{-4}	9.9×10^{-4}	4.4×10^{-3}	8.6×10^{-4}	6.0×10^{-3}
Inhalation	1.8	3.2	1.3×10^{1}	4.3	3.0×10^{1}
Ingestion	1.8×10^{-1}	2.7×10^{-1}	1.3	1.8×10^{-1}	1.3
Thorium-230	1.5	2.6	1.1×10^{1}	1.5	1.1×10^{1}
Radon-222	NA[d]	NA	NA	2.5	1.8×10^{1}
Thyroid CDE[e] (person-rem)	3.0×10^{-2}	4.7×10^{-2}	2.1×10^{-1}	2.4	1.7×10^{1}
Gonads CDE (person-rem)	3.7×10^{-2}	5.9×10^{-2}	2.6×10^{-1}	2.5	1.7×10^{1}
Cancer incidents[f]	1×10^{-3}	2×10^{-3}	8×10^{-3}	3×10^{-3}	2×10^{-2}
Genetic effects[g]	1×10^{-5}	2×10^{-5}	7×10^{-5}	7×10^{-4}	5×10^{-3}
Natural background[h] (person-rem)	3×10^{5}	3×10^{5}	2×10^{6}	9×10^{5}	6×10^{6}

[a] Estimated for the population of about 2,922,000 within an 80-km (50-mi) radius of the site.

[b] Maximum year is 1998, according to current plans.

[c] CEDE = committed effective dose equivalent. Also listed by pathway (external exposure, inhalation, ingestion) and by radionuclide (only the major contributors).

[d] NA = not applicable.

[e] CDE = committed dose equivalent.

[f] Calculated by multiplying the CEDE by the risk factor of 6×10^{-4}/person-rem (EPA 1989a). Rounded to one significant figure.

[g] Genetic effects are defined as the calculated number of severe physical or mental defects in the offspring of exposed persons. Calculated by multiplying the sum of the gonads CDE and the external dose by the risk factor of 2.6×10^{-4}/person-rem (EPA 1989a). Rounded to one significant figure.

[h] Assumed to be 0.1 rem/yr per person excluding radon and 0.3 rem/yr per person including radon, which are the national averages (NCRP 1987a). The background dose is assumed to be the same for both the average year and the maximum year.

5 REASONABLE RADIUS OF IMPACT

One measure of the reasonable radius of impact around the Weldon Spring site could be the distance at which an individual would receive a relatively small fraction of the maximum individual dose from cleanup activities. The variation of an individual's dose equivalent rate (the weighted sum of organ doses from all pathways) with distance and direction under the chemical stabilization/solidification option is given in Table 9 for all radionuclides except radon-222 and in Table 10 for radon-222. The doses in Table 9 are for 1998, the year when all radionuclides except radon-222 are projected to be released in the largest amount for any year during operations, according to current plans. The doses in Table 10 were calculated for 1 Ci of radon-222 released in 1 year. To obtain the doses from the release of X curies of radon-222 in 1 year, the values in the table have to be multiplied by X. Note that an individual receives successively less dose in all directions as the individual moves farther away from the site.

The results presented in Tables 9 and 10 indicate that the highest dose would be about 1.3 mrem/yr for a hypothetical individual living at the site boundary to the north. The estimated dose to a hypothetical individual at the site boundary averaged over all directions is about 0.58 mrem/yr. An individual located 5 km (3 mi) from the site would receive about 5% of the dose received by an individual at the site boundary. This distance, 5 km (3 mi), is taken to be the reasonable radius of impact for the site. The value of 5 km (3 mi) is conservative because the NCRP (1987b) has recommended that population assessments be limited to those individuals receiving a dose in excess of 1 mrem/yr from site releases.

About 10,700 persons reside within 5 km (3 mi) of the Weldon Spring site. (This estimate is based on 1990 census data and the average population density of St. Charles and St. Louis counties. The number of people actually residing within this radius is significantly lower. Thus, the population doses calculated for the potentially impacted population are overestimated.) The estimated collective radiological impacts for these individuals from cleanup activities are listed in Table 11. The highest population dose associated with these activities in any 1 year is about 1.2 person-rem, which is about 0.04% of the dose these same individuals would receive from natural background radiation in an average year.

TABLE 9 Distribution of Individual Dose Equivalent Rate with Distance and Direction around the Weldon Spring Site in 1998 for the Chemical Stabilization/Solidification Option, Excluding Radon-222[a]

Direction	Individual Dose Equivalent Rate with Distance and Direction from the Site (mrem/yr)									
	0-1 mi	1-2 mi	2-3 mi	3-4 mi	4-5 mi	5-10 mi	10-20 mi	20-30 mi	30-40 mi	40-50 mi
N	1.0	1.7×10^{-1}	7.6×10^{-2}	4.5×10^{-2}	3.0×10^{-2}	1.3×10^{-2}	4.3×10^{-3}	1.9×10^{-3}	1.0×10^{-3}	5.6×10^{-3}
NNW	5.1×10^{-1}	8.7×10^{-2}	3.8×10^{-2}	2.2×10^{-2}	1.5×10^{-2}	6.6×10^{-3}	2.1×10^{-3}	9.1×10^{-4}	4.8×10^{-4}	2.7×10^{-4}
NW	5.3×10^{-1}	9.3×10^{-2}	4.0×10^{-2}	2.4×10^{-2}	1.6×10^{-2}	6.8×10^{-3}	2.1×10^{-3}	8.5×10^{-4}	4.2×10^{-4}	2.1×10^{-4}
WNW	3.1×10^{-1}	5.3×10^{-2}	2.3×10^{-2}	1.3×10^{-2}	8.8×10^{-2}	3.8×10^{-3}	1.1×10^{-3}	4.6×10^{-4}	2.3×10^{-4}	1.2×10^{-4}
W	4.0×10^{-1}	6.8×10^{-2}	2.9×10^{-2}	1.7×10^{-2}	1.1×10^{-2}	4.9×10^{-3}	1.5×10^{-3}	6.1×10^{-4}	3.0×10^{-4}	1.5×10^{-4}
WSW	2.3×10^{-1}	3.9×10^{-2}	1.7×10^{-2}	9.7×10^{-3}	6.3×10^{-3}	2.8×10^{-3}	8.2×10^{-3}	3.3×10^{-4}	1.7×10^{-4}	8.5×10^{-5}
SW	3.2×10^{-1}	5.4×10^{-2}	2.4×10^{-2}	1.4×10^{-2}	9.1×10^{-3}	4.0×10^{-3}	1.2×10^{-3}	5.1×10^{-4}	2.6×10^{-4}	1.4×10^{-4}
SSW	2.8×10^{-1}	4.8×10^{-2}	2.1×10^{-2}	1.2×10^{-2}	8.1×10^{-3}	3.6×10^{-3}	1.1×10^{-3}	4.8×10^{-4}	2.5×10^{-4}	1.4×10^{-4}
S	4.2×10^{-1}	7.1×10^{-2}	3.1×10^{-2}	1.8×10^{-2}	1.2×10^{-2}	5.4×10^{-3}	1.8×10^{-3}	7.7×10^{-4}	4.2×10^{-4}	2.4×10^{-4}
SSE	3.9×10^{-1}	6.6×10^{-2}	2.9×10^{-2}	1.7×10^{-2}	1.1×10^{-2}	5.0×10^{-3}	1.6×10^{-3}	6.7×10^{-4}	3.5×10^{-4}	2.0×10^{-4}
SE	5.1×10^{-1}	8.9×10^{-2}	3.9×10^{-2}	2.3×10^{-2}	1.5×10^{-2}	6.7×10^{-3}	2.1×10^{-3}	8.8×10^{-4}	4.6×10^{-4}	2.5×10^{-4}
ESE	4.8×10^{-1}	8.3×10^{-1}	3.6×10^{-2}	2.2×10^{-2}	1.4×10^{-2}	6.3×10^{-3}	2.0×10^{-3}	8.4×10^{-4}	4.4×10^{-4}	2.4×10^{-4}
E	6.3×10^{-1}	1.1×10^{-2}	4.8×10^{-2}	2.8×10^{-2}	1.8×10^{-2}	8.1×10^{-3}	2.4×10^{-3}	1.0×10^{-3}	5.1×10^{-4}	2.6×10^{-4}
ENE	3.2×10^{-1}	5.4×10^{-2}	2.4×10^{-2}	1.4×10^{-2}	9.0×10^{-3}	4.0×10^{-3}	1.2×10^{-3}	5.1×10^{-4}	2.6×10^{-4}	1.4×10^{-4}
NE	3.6×10^{-1}	6.2×10^{-2}	2.7×10^{-2}	1.6×10^{-2}	1.0×10^{-2}	4.6×10^{-3}	1.4×10^{-3}	6.1×10^{-4}	3.2×10^{-4}	1.7×10^{-4}
NNE	6.4×10^{-1}	1.1×10^{-1}	4.9×10^{-2}	2.9×10^{-2}	1.9×10^{-2}	8.7×10^{-3}	2.8×10^{-3}	1.2×10^{-3}	6.3×10^{-4}	3.4×10^{-4}

[a] Data for radon-222 are presented in Table 10. Doses given in this table are at the midpoint of the specified range.

TABLE 10 Distribution of Individual Dose Equivalent Rate with Distance and Direction around the Weldon Spring Site for 1 Curie of Radon-222 Released in 1 Year[a]

	Individual Dose Equivalent Rate with Distance and Direction from the Site (mrem/yr)									
Direction	0-1 mi	1-2 mi	2-3 mi	3-4 mi	4-5 mi	5-10 mi	10-20 mi	20-30 mi	30-40 mi	40-50 mi
N	5.0×10^{-3}	9.2×10^{-4}	4.3×10^{-4}	2.7×10^{-4}	1.9×10^{-4}	9.3×10^{-5}	3.9×10^{-5}	2.1×10^{-5}	1.3×10^{-5}	9.7×10^{-6}
NNW	2.6×10^{-3}	4.6×10^{-4}	2.1×10^{-4}	1.3×10^{-4}	9.2×10^{-5}	4.6×10^{-5}	1.9×10^{-5}	9.9×10^{-6}	6.4×10^{-6}	4.6×10^{-5}
NW	2.7×10^{-3}	5.1×10^{-4}	2.4×10^{-4}	1.5×10^{-4}	1.1×10^{-4}	5.4×10^{-5}	2.3×10^{-5}	1.2×10^{-5}	8.0×10^{-6}	5.8×10^{-6}
WNW	1.5×10^{-3}	2.9×10^{-4}	1.4×10^{-4}	8.6×10^{-5}	6.0×10^{-5}	3.0×10^{-5}	1.3×10^{-5}	6.7×10^{-6}	4.4×10^{-6}	3.2×10^{-6}
W	2.0×10^{-3}	3.7×10^{-4}	1.7×10^{-4}	1.1×10^{-4}	7.6×10^{-5}	3.8×10^{-5}	1.6×10^{-5}	8.4×10^{-6}	5.5×10^{-6}	3.9×10^{-6}
WSW	1.1×10^{-3}	2.1×10^{-4}	9.9×10^{-5}	6.2×10^{-5}	4.3×10^{-5}	2.2×10^{-5}	9.0×10^{-6}	4.8×10^{-6}	3.1×10^{-6}	2.2×10^{-6}
SW	1.6×10^{-3}	3.0×10^{-4}	1.4×10^{-4}	8.6×10^{-5}	6.0×10^{-5}	3.0×10^{-5}	1.3×10^{-5}	6.6×10^{-6}	4.3×10^{-6}	3.1×10^{-6}
SSW	1.4×10^{-3}	2.6×10^{-4}	1.2×10^{-4}	7.4×10^{-5}	5.2×10^{-5}	2.6×10^{-5}	1.1×10^{-5}	5.7×10^{-6}	3.7×10^{-6}	2.6×10^{-6}
S	2.1×10^{-3}	3.8×10^{-4}	1.7×10^{-4}	1.1×10^{-4}	7.5×10^{-5}	3.8×10^{-5}	1.6×10^{-5}	8.2×10^{-6}	5.4×10^{-6}	3.9×10^{-6}
SSE	1.9×10^{-3}	3.6×10^{-4}	1.7×10^{-4}	1.0×10^{-4}	7.2×10^{-5}	3.6×10^{-5}	1.5×10^{-5}	7.8×10^{-6}	5.1×10^{-6}	3.7×10^{-6}
SE	2.5×10^{-3}	4.8×10^{-4}	2.3×10^{-4}	1.4×10^{-4}	1.0×10^{-4}	5.0×10^{-5}	2.1×10^{-5}	1.1×10^{-5}	7.4×10^{-6}	5.4×10^{-6}
ESE	2.4×10^{-3}	4.5×10^{-4}	2.1×10^{-4}	1.3×10^{-4}	9.1×10^{-5}	4.6×10^{-5}	1.9×10^{-5}	1.0×10^{-5}	6.6×10^{-6}	4.8×10^{-6}
E	3.1×10^{-3}	6.1×10^{-4}	2.9×10^{-4}	1.8×10^{-4}	1.3×10^{-4}	6.4×10^{-5}	2.8×10^{-5}	1.5×10^{-5}	9.6×10^{-6}	7.0×10^{-6}
ENE	1.6×10^{-3}	3.0×10^{-4}	1.4×10^{-4}	8.7×10^{-5}	6.1×10^{-5}	3.0×10^{-5}	1.3×10^{-5}	6.9×10^{-6}	4.5×10^{-6}	3.2×10^{-6}
NE	1.8×10^{-3}	3.4×10^{-4}	1.6×10^{-4}	9.8×10^{-5}	6.9×10^{-5}	3.4×10^{-5}	1.5×10^{-5}	7.8×10^{-6}	5.1×10^{-6}	3.7×10^{-6}
NNE	3.2×10^{-3}	6.0×10^{-4}	2.8×10^{-4}	1.9×10^{-4}	1.2×10^{-4}	6.2×10^{-5}	2.6×10^{-5}	1.4×10^{-5}	9.0×10^{-6}	6.5×10^{-6}

a Doses given in this table are at the midpoint of the specified range.

TABLE 11 Estimated Radiological Impacts from Airborne Emissions for the Population within 3 Miles of the Weldon Spring Site[a]

Treatment Option/ Parameter	Average Year	Maximum Year[b]	During 7-Year Cleanup Period
Chemical stabilization/solidification			
CEDE[c] (person-rem)	7.8×10^{-1}	1.2	5.5
Cancer incidents[d]	5×10^{-4}	7×10^{-4}	3×10^{-3}
Vitrification			
CEDE[c] (person-rem)	6.6×10^{-1}	9.3×10^{-1}	4.6
Cancer incidents[d]	4×10^{-4}	6×10^{-4}	3×10^{-3}
Natural background[e] (person-rem)	3×10^{3}	3×10^{3}	2×10^{4}

[a] Estimated for the population of about 10,700 within 5 km (3 mi) of the site.

[b] Maximum year is 1998, according to current plans.

[c] CEDE = committed effective dose equivalent.

[d] Calculated by multiplying the CEDE by the risk factor of 6×10^{-4}/person-rem (EPA 1989a). Rounded to one significant figure.

[e] Assumed to be 0.3 rem/yr per person, which is the national average (NCRP 1987a). The background dose is assumed to be the same for both the average year and the maximum year.

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