MASTER

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue, Argonne, Illinois 60439

ANL/EES-TM-308

WELDON SPRING HISTORICAL DOSE ESTIMATE

ANL/EES-TM--308

DE86 014085

by

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Energy and Environmental Systems Division

July 1986

work sponsored by

U.S. DEPARTMENT OF ENERGY
Technical Services Division
Oak Ridge, Tennessee

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ACKNOWLEDGMENTS

The authors are grateful to many individuals for assistance in the preparation of this report. Special thanks are due to Mont Mason, the former Health and Safety Supervisor at the Weldon Spring plant, for providing valuable information on plant operations and a thorough review of the manuscript. Thanks are also due to Jerry Wing of Oak Ridge Operations Office for many useful comments. The authors are grateful to John Crellin of the Missouri Department of Health and Safety for providing the population data used in this report and to R.I. Orewiler for providing measurements of the emission stacks. The expert assistance with computer graphics and programming provided by Al Zielen and Paul Hess with the help of student assistants Leticia Arias, Mark R. Hopf, John J. Miklic, and John M. Pirc is greatly appreciated. The authors are also grateful to Pam Merry-Libby and Tom Gilbert for careful review of the manuscript and useful suggestions and to Dimis Wyman, Kerri Schroeder, and Lorenza Ceballos of the Editorial/Word Processing staff for expert assistance.

SUMMARY

This study was conducted to determine the estimated radiation doses that individuals in five nearby population groups and the general population in the surrounding area may have received as a consequence of activities at a uranium processing plant in Weldon Spring, Missouri. The study is retrospective and encompasses plant operations (1957-1966), cleanup (1967-1969), and maintenance (1969-1982).

The plant is located within the St. Louis, Missouri, metropolitan area in St. Charles County and was operated by the U.S. Atomic Energy Commission (AEC) as a uranium feed materials plant between 1957 and 1966. From 1958 through 1964, an average 14,500 metric tons (16,000 tons) of uranium materials were received per year for either processing or reshipping. In 1965 and 1966, thorium oxide was processed in addition to uranium, first in the pilot plant buildings and later in the main refinery buildings.

The Weldon Spring plant was closed in 1966 and transferred to the U.S. Department of the Army in 1967 to be converted for herbicide production. Between 1968 and 1969, some of the buildings used for uranium and thorium processing were partially decontaminated and dismantled. In 1969, prior to becoming operational, the herbicide production project was canceled. The site has remained essentially undisturbed since 1969.

There has been some concern expressed by area residents that radioactivity released during and after plant operations may have posed a health hazard to the surrounding population. This study provides estimates of radiation doses to "nearby population groups," i.e., individual members of the population most likely to have received the greatest exposure and the general population. The nearby population groups fall into two broad categories: those who spent a significant amount of time in the immediate vicinity of the site and those who were near the site for only short periods of time. The first category includes (1) staff and students at Francis Howell High School, (2) employees and users of the St. Charles County Extension Center, and (3) residents in the immediate vicinity of the plant. The second category consists of (1) visitors to the neighboring wildlife areas and (2) people

regularly driving through the neighborhood of the site. In addition, dose estimates are provided for the general population residing within 80 km (50 mi) of the plant.

The radiological monitoring data collected for the Weldon Spring area both during and after plant operations constitute the principal data base for this study. However, because these data are incomplete, it was necessary to deduce some information needed for the radiological calculations from the history of plant operations and activities after the plant was closed. Calculations were also performed using information in a DOE materials balance study (Harris 1986).

Based on the calculations in this report, the dose estimates for members of the nearby population groups are as follows. Of the three periods considered, the largest doses to the general population in the surrounding area would have occurred during the plant operations period (1957-1966). Dose estimates for the cleanup (1967-1969) and maintenance (1969-1982) periods are negligible in comparison. Based on the monitoring data, if there was a person residing continually in a dwelling 1.2 km (0.75 mi) north of the plant, this person is estimated to have received an average of about 96 mrem/yr (ranging from 50 to 160 mrem/yr) above background during plant operations, whereas the dose to a nearby resident during later years is estimated to have been about 0.4 mrem/yr during cleanup and about 0.2 mrem/yr during the maintenance period. These values may be compared with the background dose in Missouri of 120 mrem/yr.

Estimated total yearly dose commitments during plant operations (1957-1966), including estimates based on both the monitoring data and on the materials balance study, are summarized in Figure S.1. The background dose (120 mrem/yr) and the then-current regulatory limit (500 mrem/yr whole-body dose, above background) are also shown for comparison. Based on the monitoring data, a full-time employee at the County Extension Center is estimated to have received an average dose of 30 mrem/yr. At Francis Howell High School, a typical student or faculty member would have received a dose of about 20 mrem/yr. The dose for a parent attending monthly meetings would have

Figure S.1. Estimated Average Yearly Dose Commitments for Members of Nearby Population Groups During Plant Operations, 1957-1966. Dose commitments include background dose and are adjusted for occupancy factors. Background dose = 120 mrem/yr; regulatory limit = 500 mrem/yr whole-body dose, above background.

been about 1% of that of a full-time student, or 0.2 mrem/yr. For nearby residents who are assumed to have spent all their time at their residences, the estimated average doses range from about 83 to 96 mrem/yr. A frequent visitor to a wildlife area is estimated to have received a dose of about 2 mrem/yr. A person driving through the site regularly would have received an estimated dose of about 0.2 mrem/yr. For comparison, a person taking a 4-hour airplane trip at 10,000 m (33,000 ft) incurs a dose of 2 mrem.

Results obtained using estimates of airborne radioactive releases from the materials balance study are on the average about three times larger than those from the monitoring data. The stack losses given in the materials balance study are based on a search of old records regarding site operations. The records do not contain estimates of the uncertainties. Based on experience in estimating releases, the results based on the monitoring data and on the materials balance study are remarkably consistent and probably represent reasonable estimates of releases from the site.

The most important exposure pathway during plant operations was inhalation of airborne particulates. All other pathways together contributed less than 5% to the total dose and can be neglected because the uncertainty of dose estimates is expected to be considerably greater than 5%.

Based on the monitoring data, the annual collective dose to the general population of 2.5 million people within 80-km of the site ranged from 310 person-rem in 1957 to 1,100 person-rem in 1962. The collective dose over the entire 10-yr period is estimated to be 6,200 person-rem.

The projected number of excess fatal cancers over the remaining lifetime of the general population of 2.5 million persons after exposure to the radioactive materials released from the Weldon Spring plant is approximately one. This is based on a risk factor of 0.00017 per million person-rem. It is estimated that there is a 97% chance that this excess cancer would be lung cancer, 1.4% chance it would be leukemia, and 1.6% chance it would be another type of cancer. The number of fatal cancers that would normally be expected in the same population is 520,000, of which 21,000 are expected to be

leukemia. The one additional estimated cancer death represents an increase of 0.0002%.

The total dose commitment of 960 mrem over the 10-yr operating period to a resident located 1.2 km (0.75 mi) north of the site is estimated to result in an additional risk of fatal cancer of 1 in 5000. This can be compared with the normal risk of fatal cancer of about 1 in 5.

There are many uncertainties associated with the dose estimates presented in this report. These uncertainties result from uncertainties in the data and uncertainties in the models used to obtain dose estimates from the data. The report includes a qualitative discussion of these uncertainties.

1. INTRODUCTION

1.1 PURPOSE OF STUDY AND BACKGROUND

This study was conducted to obtain estimates of radiation doses to individuals in five nearby population groups and to the general population as a consequence of the activities at a uranium and thorium processing plant in Weldon Spring, Missouri. The study is retrospective and encompasses plant operations (1957-1966), cleanup, (1967-1969), and maintenance (1969-1982).

The Weldon Spring site is located within the St. Louis, Missouri, metropolitan area in St. Charles County. It consists of a 68-ha (169-acre) area containing buildings of a uranium feed materials plant, a 21-ha (52-acre) area with four raffinate pits, and a 3.2-ha (8-acre) quarry located about 7 km (4 mi) southwest of the plant and pits (Figure 1.1). The site is surrounded by three wildlife areas frequented by users from the St. Louis metropolitan area and other regions. A high school serving the whole southern portion of St. Charles County is located within 1.1 km (0.69 mi) of the site. The St. Charles County Extension Center, located within 0.9 km (0.6 mi) of the site, has a small full-time staff and is used regularly by various community groups. Three roads carrying a moderate amount of traffic pass through the area of the Weldon Spring site.

The plant was operated by the U.S. Atomic Energy Commission (AEC) as a uranium feed materials plant between 1957 and 1966. From 1958 through 1964, an average 14,500 metric tons (MT) (16,000 tons) of uranium materials were received per year for either processing or reshipping. In 1965 and 1966, thorium oxide was processed in addition to uranium, first in the pilot plant buildings and later in the main refinery buildings (Mason 1985).

The plant's main activity was to convert uranium concentrates to uranium trioxide, uranium tetrafluoride, and uranium metal. The plant was also a sampling station. Most domestic concentrates were sampled there. About 50% of the yellowcake (uranium concentrate) sampled at Weldon Spring was shipped

Figure 1.1. Map of the Weldon Spring Area. Contours are shown in feet above mean sea level. Source: Based on U.S. Geological Survey 7.5 minute maps of the Weldon Spring Quadrangle and Defiance Quadrangle.

out to other plants, the Fernald plant in Ohio and the Metropolis plant in Illinois (Mason 1985).

The Weldon Spring plant was closed in 1966 and transferred to the Army in 1967 to be converted for herbicide production. Between 1968 and 1969, some of the buildings used for uranium and thorium processing were partially decontaminated and some of the equipment was dismantled. In 1969, prior to becoming operational, the herbicide production project was canceled. The Weldon Spring site has remained essentially undisturbed since 1969.

During plant operations (1957-1966), radioactive sludge residues (raffinates) generated in uranium and thorium processing were deposited in on-site raffinate pits, and the buildings, equipment, and some small areas of immediate terrain of the plant became contaminated by radioactive materials. Also, from 1958 to 1969, radioactive wastes were deposited in a nearby quarry. Additional small areas of radioactive contamination exist along surface drainages from these sites as well as along the rail and highway rights-of-way between the plant and the quarry.

1.2 APPROACH USED

There has been some concern expressed by area residents that the radioactivity released during and after plant operations may pose a health hazard to the surrounding population. This study was undertaken to provide a documented basis for assessing whether any radiation-induced health effects could have been caused by the radioactivity released as a consequence of activities at the Weldon Spring site. The study identifies individual members of the general population most likely to have received the greatest exposure and provides dose estimates for these individuals. These individuals will be referred to as members of "nearby population groups" and are described in Section 2. In addition, dose estimates are provided for the general population residing within 80 km (50 mi) of the plant. Dose estimates for workers at the plant are beyond the scope of this study.

The radiological monitoring data collected in the Weldon Spring area both during and after plant operations constitute the principal data base for this

study. However, because these data are incomplete, it was necessary to deduce some information needed for the radiological calculations from the history of plant operations and activities after the plant was closed. The history of the site relevant to this study is summarized in Section 3. The radiological data are described in Section 4 and Appendix A.

To obtain dose estimates for the nearby population groups and the general population, one must estimate the source terms, i.e., quantities describing the source of radiological contamination, and identify the pathways by which the contaminants could reach individuals. The derivation of source terms, identification of pathways, and calculated dose estimates are presented in Section 5. A summary discussion of the dose estimates and the uncertainties in their calculation are presented in Section 6. Models are used to (1) describe the transport of radiation or radioactive materials from the point of release to the point of human exposure and (2) obtain dose estimates to individuals at the point of human exposure. The models used in this study and other calculational details are described in Appendix B. A list of abbreviations is provided in Appendix C.

2. NEARBY POPULATION GROUPS

Persons likely to have experienced the largest exposure to radiological contaminants released from the plant are those who lived or worked in the immediate vicinity of the Weldon Spring site from 1957 to 1982 (the period studied in this report). Five nearby population groups are identified and assessed for the radiological doses they may have received as a result of activities at the Weldon Spring site during the study period.

The nearby population groups fall into two broad categories: those who spent a significant amount of time in the immediate vicinity of the site and those who were near the site only for only short periods of time. The first category includes: (1) staff and students at Francis Howell High School, (2) employees and users of the St. Charles County Extension Center, and (3) residents in the immediate vicinity of the plant. The second category consists of: (1) visitors to the neighboring wildlife areas and (2) people regularly driving through the neighborhood of the site. In addition, the doses to individuals residing within an 80-km (50-mi) radius of the site are estimated. The locations (distance from site) of the population groups that were likely to be near the site for significant amounts of time are as follows: County Extension Center, 0.9 km (0.6 mi); Francis Howell High School, 1.1 km (0.69 mi); north resident, 1.2 km (0.75 mi); and northwest resident, 1.6 km (1.0 mi). A brief description of these population groups follows.

2.1 STAFF AND STUDENTS AT FRANCIS HOWELL HIGH SCHOOL

The Francis Howell School District encompasses the southern portion of St. Charles County from the city of St. Charles along State Route 94 to the west. Francis Howell High School is located 1.1 km (0.69 mi) from the plant site on State Route 94 (Figure 1.1). It is the only high school in the district.

Student enrollment has steadily increased from 500 in 1955 to more than 2,000 in the 1980s (see Figure 2.1). In addition to regular classes, a

Figure 2.1. Enrollment at Francis Howell High School, 1955-1985.

preschool program (150-200 students) and a parenting class (80 parents) use the school facilities. It is estimated that, during the school year, there are 2,300 people on campus on a daily basis (Rebore 1984). For the historical dose estimates, it is assumed that a full-time student or faculty member attended school 8 hours per day, 5 days per week, 48 weeks per year (including summer school).

School officials have been concerned about airborne radioactive releases from the Weldon Spring site. Some parents have refused to enroll their children in the preschool program because of their concern for potential health effects from the Weldon Spring site.

2.2 STAFF AND USERS OF THE ST. CHARLES COUNTY EXTENSION CENTER

The St. Charles County Extension Center (Figure 1.1) is operated jointly by the University of Missouri and Lincoln University. The buildings currently used by the Center were constructed in the 1940s; the buildings were

subsequently transferred to the University of Missouri for use as a research station. In 1975, the research station closed and the Center assumed occupancy. A record of employment history and activities for the Center are presented in a report of the Missouri Cooperative Extension Service (undated).

Currently, there are seven full-time and two part-time staff members working at the Center. For the past decade, a total of 37 persons served the Center with an average employment period of 3.3 years. For the historical dose estimate, it is assumed that a typical full-time employee worked 8 hours per day, 5 days per week, 50 weeks per year.

Since 1978, the Center has been used frequently by many local groups. There are approximately 150 meetings per year lasting two to three hours. The average attendance has been about 3,500 persons per year.

2.3 RESIDENTS IN THE IMMEDIATE VICINITY

Two nearby residences in the Busch Wildlife Area were occupied continuously during the period under study (Cassidy 1986). One was located 1.2 km (0.75 mi) north of the site and the other is located 1.6 km (1.0 mi) northwest.

2.4 VISITORS TO THE NEIGHBORING WILDLIFE AREAS

The Missouri Conservation Commission operates three wildlife areas in the vicinity of the Weldon Spring site: the August A. Busch Memorial Wildlife Area [2,833 ha (7,000 acres)], the Weldon Spring Wildlife Area [3,035 ha (7,500 acres)], and the Howell Island Wildlife Area [1,052 ha (2,600 acres)] (Figure 1.1). The Busch Wildlife Area and Weldon Spring Wildlife Area are immediately adjacent to the plant, raffinate pits, and quarry.

Attendance, calculated from axle counts of vehicle traffic, has been recorded from 1976 to date for the Busch Wildlife Area by the Conservation Commission; no such records are available for the other two wildlife areas. The average annual attendance at the Busch area is approximately 700,000 (no differentiation between repeat visitors and one-time visitors) (Cassidy

1984). The average time spent per visit in the wildlife area is only 4 hours. Use of the Busch area is most intense in the spring and summer months, ranging from 102,000 to 130,000 visitors per month.

The Weldon Spring Wildlife Area has a drainageway that is radioactively contaminated by discharges from the plant. The contamination necessitated the relocation of a hiking trail in the area. In addition, low levels of radioactivity have been detected in three fishing lakes and a spring in the wildlife areas adjacent to the Weldon Spring site. Signs have been posted warning hikers not to drink the water.

2.5 PEOPLE REGULARLY DRIVING NEAR THE SITE

Three roads pass through the area of the Weldon Spring site (see Figure 1.1): Route D (north of the raffinate pits and plant, and between the Busch and Weldon Spring wildlife areas), U.S. Route 40/61 (northeast of the Busch area), and State Route 94 (southeast of the Weldon Spring site). The closest road is Route 94, which passes within 0.5 km (0.3 mi) of the site. People driving on this road at 60 km/h (37 mph) would spend about 40 minutes within 20 km (12.5 mi) of the site. The average time spent on the other segments (Route D and U.S. 40/61) is expected to be less due to the much shorter distances involved.

The Missouri Highway and Transportation Department has some traffic data for highways near the Weldon Spring area, dating from 1962; these data show that the traffic flow has quadrupled in the past 23 yr (Figure 2.2). It seems reasonable to assume that the traffic flow through the Weldon Spring area has followed a similar pattern over the years.

2.6 GENERAL POPULATION WITHIN AN 80-km RADIUS OF THE SITE

The estimated doses to individuals residing within an 80-km radius of the site were calculated as a function of distance from the site at 16 radial intervals for each year of operation for which monitoring data are available. Collective population doses were calculated using population distribution data for 1960 and 1970 (Tables 2.1 and 2.2). Population values

for 1961-1966 were obtained by a linear interpolation between the 1960 and 1970 values. For the region within a 20-km radius of the source, the population data were at the census-tract level; outside the 20-km radius, the data were at the county level.

Figure 2.2. Average Daily Traffic Volume as a Function of Time in the Vicinity of the Weldon Spring Site (based on traffic flow on U.S. 40/61 east of State Route 94 and on State Route 94 north of U.S. 40/61). Source: Bechtel Natl. (undated).

Table 2.1. Population Distribution within an 80-km Radius of the Weldon Spring Site, 1960

Distance from Site (km)	Population at Direction from Site							
	N 0°	NNE 22.5°	NE 45.0°	ENE 67.5°	E 90.0°	ESE 112.5°	SE 135.0°	SSE 157.5°
1- 2	20	20	20	20	20	20	20	20
2- 3	30	30	30	30	30	30	29	25
3- 4	39	39	39	39	39	39	39	39
4- 5	57	57	57	57	57	57	57	57
5-10	560	560	560	440	424	479	479	479
10-20	1,503	1,809	1,573	1,603	2,446	7,907	5,260	2,077
20-30	1,590	910	3,589	33,523	53,442	53,442	53,442	38,539
30-40	1,268	2,121	3,966	53,904	277,004	421,422	47,001	5,273
40-50	1,903	3,089	8,437	42,239	319,077	356,624	32,001	6,379
50-60	2,189	3,338	7,063	26,799	26,955	32,528	6,299	6,816
60-70	2,618	3,428	4,632	25,152	32,268	38,442	12,611	7,766
70-80	3,078	3,657	5,294	23,185	37,232	44,356	12,598	7,607

Distance from Site (km)	Population at Direction from Site							
	S 180.0°	SSW 202.5°	SW 225.0°	WSW 247.5°	W 270.0°	WNW 292.5°	NW 315.0°	NNW 337.5°
1- 2	20	20	20	20	20	20	20	20
2- 3	29	30	30	30	30	30	30	30
3- 4	28	39	39	39	39	39	39	39
4- 5	41	40	56	45	57	57	57	57
5-10	301	120	124	140	210	243	385	560
10-20	1,138	187	457	490	490	520	1,347	1,396
20-30	35,762	1,809	2,400	2,211	1,638	2,211	2,402	1,858
30-40	4,725	2,532	2,460	1,811	1,090	1,131	1,255	1,255
40-50	6,075	3,256	3,256	2,977	1,587	1,455	1,614	1,614
50-60	6,969	3,739	3,979	3,979	2,531	1,761	1,967	1,983
60-70	6,620	2,549	4,458	3,509	2,165	2,046	2,272	2,392
70-80	5,933	2,070	3,638	2,727	2,502	2,363	2,838	2,781

Total 1-80 km population is 2,580,000

Source: U.S. Bureau of the Census (1960, 1973).

Table 2.2. Population Distribution within an 80-km Radius of the Weldon Spring Site, 1970

Distance from Site (km)	Population at Direction from Site							
	N 0°	NNE 22.5°	NE 45.0°	ENE 67.5°	E 90.0°	ESE 112.5°	SE 135.0°	SSE 157.5°
1- 2	45	45	45	45	45	45	45	45
2- 3	67	67	67	67	67	67	65	47
3- 4	86	86	86	86	86	86	86	86
4- 5	128	128	128	128	128	104	126	121
5-10	1,030	1,030	1,030	969	859	1,030	564	568
10-20	2,736	4,028	3,364	4,487	13,057	25,805	8,266	2,780
20-30	2,319	871	6,284	45,918	72,267	72,267	72,267	53,379
30-40	1,329	2,262	6,346	73,508	255,225	365,261	64,049	8,361
40-50	2,033	3,356	9,356	56,564	275,340	303,322	43,595	10,011
50-60	2,263	3,506	7,776	30,526	29,906	35,336	7,233	10,431
60-70	2,549	3,440	4,905	27,998	35,744	41,761	14,084	11,793
70-80	2,951	3,563	5,441	25,682	41,243	48,186	14,134	10,833

Distance from Site (km)	Population at Direction from Site							
	S 180.0°	SSW 202.5°	SW 225.0°	WSW 247.5°	W 270.0°	WNW 292.5°	NW 315.0°	NNW 337.5°
1- 2	45	45	45	45	45	45	45	45
2- 3	65	67	67	67	67	67	67	67
3- 4	57	86	86	86	86	86	86	86
4- 5	87	82	94	97	128	128	128	128
5-10	397	143	149	188	372	458	831	1,030
10-20	1,401	205	547	589	589	638	1,557	2,285
20-30	48,504	2,237	3,623	3,629	2,523	3,629	3,998	2,949
30-40	7,315	3,132	3,035	2,170	1,208	1,289	1,532	1,532
40-50	9,405	4,026	4,026	3,655	1,801	1,657	1,969	1,969
50-60	10,758	4,594	4,921	4,921	2,957	1,894	2,397	2,357
60-70	10,099	2,918	5,504	4,036	2,164	2,052	2,482	2,568
70-80	7,991	2,246	4,317	2,685	2,459	2,342	2,855	2,765

Total 1-80 km population is 2,750,000

Source: U.S. Bureau of the Census (1972, 1973).

3. HISTORY OF ACTIVITIES AT THE WELDON SPRING SITE

The activities associated with a possible radiological hazard at the Weldon Spring site are summarized in Table 3.1. Three distinct periods can be identified: plant operations (1957-1966), cleanup (1967-1969), and maintenance (1969-1982). It is expected that the largest exposure to radioactive contaminants occurred during plant operations. The dispersal of contaminants during the cleanup period is not expected to be significant. During the maintenance period, there were no major activities that would have caused significant exposure to radioactive materials. A more detailed description of the activities follows. Activities associated with airborne releases are emphasized in the following discussion because the largest contribution to doses is expected to be from airborne effluents.

3.1 PLANT OPERATIONS (1957-1966)

The plant's main activity was to convert uranium concentrate to uranium trioxide (UO_3), uranium tetrafluoride (UF_4), and uranium metal. The material received at the plant was yellowcake (uranium concentrate). A schematic diagram of a wet solvent extraction method used for UF_4 production is presented in Figure 3.1 (a detailed description of UF_4 production can be found in Harrington and Ruehle [1959]). Before entering the refinery, the ore concentrate underwent a sampling and preparation process in the sampling plant. The various buildings used for uranium processing are shown in Figure 3.2; the buildings that produced most of the discharges into the air are listed in Table 3.2. Activities that took place in these buildings are described below (Mallinckrodt Chemical Works 1962, undated-A, undated-B; Mason 1985).

Building 101 was the sampling building. Ore concentrate (about 60-70% uranium content) arrived there in drums. The drums were opened, the concentrate was sampled using one of the two sampling methods -- auger or mechanical sampling, and the drums were emptied into hoppers at the top of the building. From there, the material was transferred to portable hoppers for

Table 3.1. History of Radioactive Effluent Generating Activities at the Weldon Spring Site, 1957-1982

Date	Event ^a
1957-1966	<p>Operation of uranium feed materials plant.</p> <p>Uranium concentrate converted to uranium trioxide, uranium tetrafluoride, and uranium metal.</p> <p>Some thorium processing.</p> <p>Raffinate from the processing removed to raffinate pits.</p> <p>14,500 metric tons (MT) of uranium materials received for processing and sampling per year between 1958 and 1964.</p> <p>Some thorium processed between 1965 and 1966.</p>
December 1966	Plant closed; hopper and process lines emptied, dust collectors cleaned out.
January 1967-?	Site used as interim storage depot for yellowcake. ^b
March 1968-June 1969	<p>Decontamination and equipment removal for Buildings 103 and 105.</p> <p>About 1,000 MT rubble removed to the quarry.</p> <p>About 2,000 MT scrap moved to Tennessee.</p> <p>About 200 MT steel parts moved to Ohio.</p> <p>About 100 MT uranium oxide removed from the buildings.</p>
1969-1982	Site remained essentially undisturbed.

^a Source: Ryckman & Associates (1978).

^b Source: Mason (1985).

transfer to the refinery. Yellowcake dust was collected in three large dust collectors, each with its own stack. Some yellowcake was repackaged in drums and shipped out; the rest was put into hoppers and moved to Building 103 for digestion. The dust collection system was vacuum cleaned from time to time, and the collected dust was reprocessed. Uranium dust was also washed off the drums, equipment, and floors, and this dust was also reprocessed.

Figure 3.1. Typical UF_4 Production Wet Solvent Extraction-Fluorination Block Diagram. Source: U.S. Environmental Protection Agency (1973).

Figure 3.2. Major Process and Support Buildings of the Weldon Spring Plant. Only those buildings discussed in this report are labeled.
Source: Adapted from Niedermeyer (1976).

Table 3.2. Location and Height of Stacks^a

Building No.	Number of Stacks	Discharge	Height of Stack meters (feet)
101	2-3	Yellowcake dust ($\text{Na}_2\text{U}_2\text{O}_7$)	35 (115)
103	1 Several 1	Yellowcake dust UO_3	23 (74)
201	6	UO_2 , UF_4 , and U_3O_8	14-34 (47-110)
301	Several	UF_4 and MgF with 1% uranium	23 (74)
	1	U_3O_8	

^a Height of stacks from Orewiler (1986) and Nemec (1986).

Building 103 was the first building of the refinery plant. Concentrate was brought in hoppers to the top of the building where there was one dust collector with one stack to collect yellowcake dust. The concentrate was heated and digested with nitric acid to produce a solution of uranyl nitrate. The digested material was passed to Building 105 in liquid form.

Pure uranyl nitrate solution was extracted in Building 105. In this part of the plant, the material remained in liquid form. Impurities generated in the purification process were bled off in the raffinate, and the raffinate was pumped to the pits. This raffinate contained a conglomerate of radionuclides including thorium and radium in small concentrations.

Uranyl nitrate solution was pumped back to Building 103 for the denitration process, in which UO_3 was produced in powder form. This was the dustiest part of the whole operation. The denitration process was carried out in about 20 steel pots located at the south end of the building. The pots were inside big hoods with separate exhaust systems that vacuumed UO_3 from the pots and

sent it to separate dust collectors. There was also a backup collection system on the pneumatic conveying system.

Uranium trioxide was packaged into transfer hoppers and transferred from Building 103 to the top of Building 201, the green salt (UF_4) plant, where it was emptied into a reduction reactor. Hydrogen gas reduced UO_3 to uranium dioxide (UO_2). From the top of the building to completion, the operation was in a sealed system, and there was very little dusting inside the building. The reduction process offgas contained excess hydrogen gas, which was burned immediately inside the building. A hood exhausted the combustion products into a dust collector. To cool the exhaust, which was laden with UO_2 , ambient air was vented into the collectors. For this phase of the operation, there was one dust collector for the six banks of reduction furnaces.

The next step was hydrofluorination, which transformed UO_2 to UF_4 or green salt. The excess hydrogen fluoride (HF) gas from the hydrofluorination process was filtered through carbon filters to recover uranium, which was recycled to black oxide (U_3O_8). The discharge from the UF_4 reactor system went to a mechanical system where it was crushed and blended to obtain desired particle sizes. On the roof of Building 201, there were two additional dust collectors associated with the mechanical system to collect UF_4 dust. There was also a reverter in the building to convert UF_4 into U_3O_8 ; there may have been a small dust collector for this process.

Green salt was packaged in transfer hoppers and moved to the metals plant, Building 301. There, magnesium was used to convert UF_4 to solid uranium metal in a multistep process. Green salt and magnesium were mixed in a blender; the mixture was then placed in individual steel shells at the filling machine and sent to the furnaces for firing. The process generated green salt dust; UF_4 and magnesium fluoride (MgF), with 1-2% of residual uranium in various forms, were discharged from several dust collectors at the ground level on the south side of the building. A rotary kiln (calciner) in Building 301 was used to burn uranium metal chips and convert them to U_3O_8 . A dusty discharge that was produced in this operation, mostly U_3O_8 , was collected in one standard dust collector.

Two other buildings on-site, pilot plants 403 and 404, produced discharges into the air. There were two to four dust collectors for these two buildings, and the discharges were of the same type as at the main plant but in much smaller amounts.

The locations and heights of stacks are summarized in Table 3.2.

3.2 CLEANUP (1967-1969) AND MAINTENANCE (1969-1982)

The plant was closed at the end of 1966 and shutdown procedures were implemented. Under shutdown procedures, hoppers and process lines were emptied and dust collectors and other points of material accumulation were cleaned out. Only a few pounds of pure compounds were present in any single piece of equipment. The bulk of the radiological materials remaining on-site were located outside the primary production lines in building sumps and in secondary pieces of process equipment and piping without routine access ports.

For a short time after plant closure, some of the buildings were used for interim storage of drummed yellowcake from other mills. This yellowcake was later shipped to various plants for refining and processing.

In 1967, 68 ha (169 acres) of the plant, including Buildings 103 and 105, was transferred from the AEC to the Army for herbicide production. The Army started decontamination and equipment removal in Buildings 103 and 105 in March 1968. About $4,600 \text{ m}^3$ ($6,000 \text{ yd}^3$) of contaminated and unrecoverable material was hauled to the quarry 6.4 km (4 mi) south on State Route 94. About 2,200 MT of contaminated scrap was shipped via rail and truck to a Knoxville, Tennessee, contractor. Another AEC contractor, National Lead Company of Ohio, received 20 railcars and one truckload of stainless steel piping, valves, vessels, and spare parts. Approximately 135 barrels of uranium oxide were recovered from the buildings. A high-pressure hot water solution containing an acidic wetting agent was used to partially decontaminate Buildings 103 and 105. Portions of some concrete floors were removed and covered with tar and new concrete to mask radiological contamination.

Construction of the herbicide facility began in December 1968, but was terminated when the project was canceled in early 1969. Cleanup and shutdown work was conducted on the site until June 1969 when the Kansas City District of the Corps of Engineers obtained custody of the 68-ha (169-acre) tract containing the plant. The AEC maintained control of the 21 ha (52 acres) surrounding the raffinate pits (U.S. Dept. Army 1978). From 1969 until the present, no major activities have taken place at the site.

4. RADIOLOGICAL DATA

The available radiological data for the Weldon Spring site is generally spotty and variable in coverage. No data are available for the years 1966 to 1974 other than some 1967 measurements on the raffinate pits. The available monitoring data for off-site locations (at or outside perimeter fences) for the period 1957 to 1982 are summarized in Table 4.1 and discussed below. Soil data are not included because these data are not needed to make the dose estimates in this analysis. However, both air data and recent surface water and groundwater data for on-site locations have been included. Greater detail regarding the data and their sources is presented in Appendix A.

4.1 RADIONUCLIDES IN AIR

Air concentrations of uranium were measured from 1959 through 1965 along the plant site perimeter, around buildings on the site, at the south edge of the quarry, and at a water plant 3.2 km (2 mi) away (1965 only). Concentrations up to 2.2 pCi/m^3 were detected (Table A.3); the next highest value was 1.0 pCi/m^3 . The value of 2.2 pCi/m^3 is 100 times the value at the water plant (0.02 pCi/m^3), which is assumed here to be a background value. Except for data taken in the first quarter of 1961, most values are at most 0.2 pCi/m^3 . Because this covers a period during which the plant was in operation, even less would be expected to be present in the air for the year 1967 and for later years after the plant was closed.

Air concentrations of radon were measured from 1977 through 1982 around the pit and quarry perimeter fences and at four off-site areas in and around the Busch area (Table A.2). In the pit area, values ranged from background to 4.7 pCi/L or 16 times background (measured in Florissant, Missouri, as 0.3 pCi/L -- Bechtel Natl. 1984b). In the quarry area, values ranged from background to 2.03 pCi/L . Off-site peak values were lower, up to 0.66 pCi/L .

Table 4.1. Summary of Radiological Monitoring Data for the Weldon Spring Site

Radiological Species	Medium	Monitoring Period	Description of Sampling Locations	Background
Radon	Air	1977-1982	Raffinate pits and quarry perimeter fences; also four areas in and around the Busch area	0.3 pCi/L (measured in Florissant, MO) (Bechtel Natl. 1984b)
Uranium	Air	1959-1965	Along perimeter and around buildings of chemical plant, south edge of quarry, at water plant 3.2 km (2 miles) from the site	0.02 pCi/m ³ (measured at water plant, 3.2 km from site)
Surface gamma radiation	Air	1978, 1979, 1982	Same as for radon-222	10-15 μ R/h (Bechtel Natl. 1983)
Gamma radiation	Air	1975, 1976, 1980	Aerial radiological surveys over Weldon Spring site and quarry	-
Uranium	Surface water	1959-1965, 1974-1982	Process sewer easement, northwest stream from site, Femme Osage Slough and Creek, springs, water plant intake, lakes in Busch area, sites along Schote and Dardenne creeks, Missouri River	0.001-0.004 mg/L (0.3-1.3 mg/L) (lowest values measured away from plant site)
Radium-226	Surface water	1974-1982	Process sewer easement, northwest stream from site, Femme Osage Slough and Creek, springs, water plant intake, Busch area streams	0.1-0.2 pCi/L (measured in Busch drinking water and spring into Busch Lake 33) (deRoos 1984)
Radium-228	Surface water	1974-1981	Same as for radium-226	0.45 pCi/L (detection level)
Gross alpha and beta	Surface water	1977-1982	Two Busch area sites, lake and drinking water, two Missouri River sites above and below Weldon Spring discharge, Weldon Spring water supply	-
Various radioactive species	Fish	1980, 1983, 1984	Femme Osage Slough and Creek, lakes in Busch area	-
Uranium	Ground-water	1980-1983	Around raffinate pits, outside quarry fence	0.002-0.005 mg/L (0.7-1.7 pCi/L) (detection level)
Radium-226	Ground-water	1982-1984	Pits and quarry areas, Busch area springs, wells at nearby residences	0.1 pCi/L (detection level)
Gross alpha and beta	Ground-water	1984	Busch area springs, wells at nearby residences	-

Table 4.1. Continued

Radiological Species	Concentration Ranges	Locations of Contamination	Comments
Radon	Background to 4.7 pCi/L	None	
Uranium	Background to 2.21 pCi/m ³	Roof of maintenance building. High value of 2.21 pCi/m ³ occurred once in 1961. All other values are less than 1.0 pCi/m ³ .	
Surface gamma radiation	Background to 234 μ R/h	None	
Gamma radiation	Background to 810-1620 μ R/h	Raffinate pits, quarry	Sources of elevated radiation outside of fence may be scattered radiation from raffinate pits.
Uranium	Background to 1100 pCi/L	Process sewer outfall and easement, northwest streams from site, Femme Osage Slough (up to 1100 pCi/L) Busch area lakes, Schote and Dardenne creeks (up to 100 pCi/L)	High concentrations were found in 1959 and 1960.
Radium-226	Background to 150 pCi/L	Process sewer outfall and easement	Other areas have values up to 3.1 pCi/L. Values for 12/81 appear anomalously high
Radium-228	Background to 9.0 pCi/L	None	Values for 12/81 appear anomalously high.
Gross alpha and beta	-	Possibly Busch Lake 36	Values for gross alpha in Busch Lake 36 range from 3x to 70x values for drinking water. No difference in Missouri River values above and below plant discharge.
Various radioactive species	For edible parts, 0.0003 to 0.028 pCi/g U; 0.0002 to 0.021 pCi/g Ra-226	None	
Uranium	Background to 3100 pCi/L	Borehole water between Femme Osage Slough and MKT railroad	No contamination in alluvium south of slough. Insufficient data for raffinate pits. Only 2 of 6 boreholes could be sampled; these showed no contamination.
Radium-226	Background to 7.0 pCi/L	None	Values for residence wells range up to 0.5 pCi/L.
Gross alpha and beta	Background to 135 pCi/L(α), 36 pCi/L(β)	Burgermeister Spring	Residence wells have no contamination. Source of contamination for Burgermeister Spring is believed to be from Ash Pond effluent.

4.2 RADIONUCLIDES IN SURFACE WATER AND GROUNDWATER

Uranium concentrations in surface waters were measured from 1959 to 1965 and from 1974 to 1982. Samples were collected at many locations around the Weldon Spring site and quarry site, in the Missouri River, in water intakes to treatment plants, and at a few sites in the Busch Wildlife Area. High values indicating contamination, up to 1100 pCi/L, were found only at the exit streams from the Weldon Spring site (process sewer outfall stream and drainageway easement and northwest streams). Other off-site locations measured in 1982 or earlier had values ranging up to 170 pCi/L (Femme Osage Slough). Concentrations up to 12 pCi/L were measured in lakes in the Busch area, except for the years 1959 and 1960 when higher concentrations were detected (Appendix A, Tables A.4 and A.5).

Radium-226 and radium-228 concentrations in surface waters were measured from 1974 through 1982 in the same locations as the uranium measurements (Appendix A, Tables A.6 and A.7). No contamination was found except in the process sewer outfall stream and drainageway easement. Measurements made in December 1981 also indicate some radium-226 contamination in Femme Osage Creek and Femme Osage Slough. It is not clear whether this is real or an error of measurement; even so, the contamination levels are low. The maximum values measured -- exclusive of the process sewer outfall and the pools next to Pit 3 -- were 15 to 30 times background (background is assumed to be 0.1 to 0.2 pCi/L, the lowest values observed in drinking water in the Busch Wildlife Area and in the spring into Busch Lake 33 [deRoos 1984]). No radium-226 or radium-228 measurements in surface water were made prior to 1974 at vicinity properties.

Gross alpha and beta activity were also measured in surface water during the 1977-1982 time period at two sites in the Busch area and at two Missouri River sites (upstream and downstream from the outfall of the drainageway easement for the Weldon Spring site) (Table A.8). According to the Missouri river data, the river is not contaminated by discharges from the site. Measured concentrations in the Busch area indicate a slight contamination of the water of Lake 36.

Limited measurements of uranium concentrations in groundwater began in 1980 (Table A.11). They are confined to 2 boreholes in the raffinate pits area (4 others had insufficient water) and 23 boreholes in the quarry area. The data indicate no uranium contamination of groundwater in and around the pit area, although the measurements are so limited that this conclusion is quite tentative. The data do indicate some uranium contamination of the groundwater between the slough and the Missouri Kansas and Texas (MKT) railroad. The area of contamination, which may be due to uranium migration in water moving in rock fissures from the quarry, has been delineated by an extensive series of borehole measurements (Berkeley Geosci. Assoc. 1984). It is also possible that surface uranium contamination of the soil in this area (Boerner 1986) has influenced the measured data.

Concentrations of radium-226 were also measured in borehole water at many of the same sites where uranium levels were measured (Table A.11). The results indicate little or no contamination at any of the sites. Measurements made in 1984 in the wells of several residences near the site and in springs in the wildlife areas also detected no radium-226 contamination.

Gross alpha and beta concentrations were also measured in 1984 in the well water of nearby residences and in the water from springs in the nearby wildlife areas (Table A.12). No contamination was found except for Burgermeister Spring, which had a gross alpha concentration of about 135 pCi/L and a gross beta concentration of about 36 pCi/L. The source of this contamination is believed to be effluent from the plant ash pond (Dean 1985).

4.3 DIRECT RADIATION

The intensity of gamma radiation was measured in 1978, 1979, and 1982 at the same locations where radon concentrations were measured. The values (Table A.1) ranged from within the background range of 10 to 15 $\mu\text{R/h}$ (Rechtel Natl. 1983) to at most 16 to 23 times background (one value, 234 $\mu\text{R/h}$, measured at the fence southwest of Pits 1 and 2); all other values were 37 $\mu\text{R/h}$ or less. These results show little or no increase in gamma ray intensity contributed by radioactive contamination outside the quarry and

raffinate pits. The one exception is a small area of contamination near the gate in the perimeter fence around the raffinate pits.

Similar results were found by aerial radiological surveys of gamma ray intensities (Jobst 1976, 1977). The surveys made in 1975 and 1976 showed background values except at the raffinate pits, quarry, and plant. The data also suggested the possible existence of a source 500 m northwest of Pit 4, although the higher values close to the pit may represent scattered radiation or "shine" from the pits.

4.4 DISCUSSION

Some of the monitoring data presented here can be used to estimate concentrations of radiological species for time periods during which no measurements were taken. For example, one can conclude that concentrations of radon-222 in the air at the perimeter fences were lower before 1977 than in the period 1977-1982. This follows from the fact that radon-222 air concentrations are proportional to radium-226 concentrations on the site. Because of the presence of the long-lived radium-226 parent, thorium-230, in the raffinate pits and quarry (Bechtel Natl. 1984a, 1985), it can be shown that concentrations of radium-226 were lower in the past than they are at present and that they are increasing approximately linearly with time. If no remedial action is taken, concentrations will continue to increase to a maximum value at 9,000 years in the future. The maximum is 30 times higher than the current concentration. As a result, the recent radon-222 air measurements represent upper limits (to within statistical fluctuations) for concentrations of radon-222 measured earlier.

The low concentrations of uranium measured recently in boreholes drilled around the raffinate pits suggest that no uranium has leached from the pits into the groundwater in the bedrock under the pits. Based on modeling results of the movement of uranium in the clay under the pits toward the groundwater, essentially no uranium has migrated into the groundwater at present (Tsai et al. 1984). Consequently, one may conclude that during the period 1959-1982, uranium (or any other less mobile species such as radium-226) did not migrate from the pits into the bedrock groundwater. This conclusion is based on the

supposition that, by the above argument, current contributions represent upper limits for past contributions and current contributions are determined to be very small. However, this conclusion must be regarded as tentative because so few data on groundwater concentrations are available (only two of the six boreholes contained sufficient water to sample).

5. CALCULATION OF DOSE ESTIMATES

Radiation doses from the Weldon Spring site have been calculated for two groups: members of the nearby population groups described in Section 2 and the general population within an 80-km radius of the plant. The estimates presented in this section are based on detailed analyses of the sources and rates of radioactive releases and the pathways by which dispersed radioactive materials may reach human beings and irradiate their tissues. The methods used for dose calculations are described qualitatively in this section and in detail in Appendix B.

The analyses are performed separately for each of the three periods identified in Section 3: plant operations (1957-1966), cleanup (1967-1969), and maintenance (1969-1982). The plant operations period is considered in much greater detail than the remaining periods because it is associated with the largest potential exposure to radioactive materials.

5.1 PLANT OPERATIONS (1957-1966)

5.1.1 Pathway and Source Identification

Potential sources of radioactive releases from plant operations and the pathways and exposure modes by which these releases could reach humans are shown in Figure 5.1. They are (1) direct radiation from the plant, causing exposure from external radiation; (2) airborne releases containing uranium, thorium, and their decay products -- including radon gas and its daughters -- leading to exposure from inhalation, ingestion, and external radiation; and (3) waterborne releases contaminating nearby streams and lakes, as well as the groundwater, leading to exposure from drinking water and eating contaminated fish. During plant operations, radionuclides were discharged to the sewers and carried to the Missouri River. This effluent stream was diluted in the river to concentrations considerably below acceptable levels (Task Force 1967).

Figure 5.1. Major Exposure Pathways.

Although some hunting has occurred in the Busch Wildlife Area, the contribution to dose from consumption of game would be insignificant because (1) the total amount of game killed has been small (about 16 deer per year in the 1960s, 40 deer per year in the 1970s, and 80 deer per year in the 1980s [Garr 1986]) and (2) the estimated meat contamination would not be significant (Dickson et al. 1978). The contribution to dose from the groundwater pathway would be insignificant because there has not been enough time for transport of the radionuclides from contaminated areas to the wells used for domestic water supplies. (Radiation doses from recreational activities at one Busch Wildlife Area location have been estimated by Wang et al. [1986] to be 0.14 mrem/yr.)

Of the three pathways considered, atmospheric contamination by airborne releases is by far the most important (see Section 5.1.4). The pathways from waterborne releases and direct radiation from the plant are much less important and, for all practical purposes, can be neglected. They are estimated in this study for illustration and comparison.

The principal exposure modes by which radioactivity from airborne releases reaches human beings and irradiates their tissues include (1) direct external exposure from radionuclides in the air or on the ground; (2) inhalation of radioactivity into the lungs, possibly followed by redistribution to other organs of the body; and (3) ingestion of radioactivity in foodstuffs. Exposure by inhalation and ingestion results in the radioactive material being deposited inside the body and irradiating it from within. Accordingly, doses received via these pathways are referred to as internal doses so as to distinguish them from radiation received from sources external to the body.

5.1.2 Atmospheric Transport Model

Radioactive materials released from the plant are moved through the air and diluted in such a way that the air concentrations decrease as the distance from the plant increases. The dispersion of airborne radionuclides also depends on wind speed and direction and on other atmospheric conditions. The dispersion model used here to describe the transport of radioactive materials through the atmosphere and to estimate their air concentrations and amounts deposited on ground surfaces is based on the Gaussian plume model described in

more detail in Appendix B. The model is modified to account for plume depletion due to deposition of particulate materials on ground surfaces. Some of the particulates deposited on the ground become resuspended. A correction factor to account for resuspension is estimated using a model based on experimental data. Plume depletion can also occur by radioactive decay of airborne material, but this effect is important only for short-lived radionuclides. A correction for in-transit decay is applied to radon gas releases. The model also accounts for ingrowth and decay of radon daughters during atmospheric transport. Ground concentrations resulting from deposition over the lifetime of plant operations are calculated from the deposition rates.

Once the ground concentrations and total air concentrations have been established as a function of time, distance, and direction from the plant, radiation exposure rates and doses to an individual at a given location may be estimated by relatively straightforward calculations. The equations, assumptions, and dose conversion factors used to calculate doses in this analysis are presented in Appendix B.

5.1.3 Source Term Estimation

5.1.3.1 Source Terms for Airborne Particulate Releases

The source terms for uranium and its decay products were estimated from monitoring data for airborne uranium at several locations around the plant from 1959 to 1965 (the plant was in operation from 1957 through 1966, but no monitoring data are available for the years 1957, 1958, and 1966). The atmospheric dispersion model was used to estimate the source terms as follows. Several annual average air concentration measurements at different locations (Table A.3) were used for each year. For each of the measured values, the atmospheric dispersion model and the meteorological data collected at the St. Louis-Lambert Airport from 1960 through 1964 (Appendix B, Figure B.1 and Table B.3) were used to calculate the values of the source term, which in this case is the amount of uranium released into the air per year. In this way, several source term values were calculated for each year -- one for each of the concentration measurements. These calculated

source terms were averaged for each year, and this average value was used as the source term estimate.

The average values together with their standard deviations are listed in Table 5.1 for each year. Uranium releases for the years for which no monitoring data are available (1957, 1958, 1966) were estimated from the average value for the 1959-1965 period. The total uranium discharged to the atmosphere during plant operations (1957-1966) is estimated to be about 13 Ci. This amount corresponds to about 20 MT of uranium metal, or about 2 MT of uranium per year.

Table 5.1. Calculated Release of Uranium
Radioactivity to the Atmosphere,
1957-1966

Year	Uranium Released (Ci/yr)	
	Monitoring Data ^a	Materials Balance Study ^b
1957	0.67 ± 0.53 ^{c,d}	2.2 ^{d,e}
1958	1.3 ± 1.1 ^c	4.3 ^e
1959	1.3 ± 0.59	4.3 ^e
1960	1.2 ± 0.23	4.8
1961	1.6 ± 0.51	4.8
1962	2.1 ± 2.4	4.8
1963	0.84 ± 0.60	4.8
1964	1.5 ± 0.94	5.0
1965	0.80 ± 0.54	2.8
1966	1.3 ± 1.1 ^c	2.8

^a Based on the monitoring data in Table A.3.

^b Based on the data from the materials balance study (Harris 1986) in Table A.13.

^c Computed from the 1959-1965 average because no monitoring data are available for 1957, 1958, and 1966.

^d 1957 values are one-half the 1958 values because the plant was open for only one-half year in 1957.

^e Computed from 1960-1966 average because no values are available for 1957-1959 in the materials balance study (Harris 1986).

Airborne uranium releases for the plant were also estimated in the materials balance study (Table 5.1) (see also Table A.13). These estimates are about three times larger than the estimates from the monitoring data. Thus, based on the materials balance study, the total uranium discharged to the atmosphere during plant operations (1957-1966) was 41 Ci or 61 MT, corresponding to about 6 MT per year.

Release rates were also assumed for uranium decay products. Based on estimates for yellowcake composition (Sears et al. 1975), it was assumed that the activities for thorium-230, radium-226, and lead-210 were 5%, 1%, and 1%, respectively, of that of uranium-238.

5.1.3.2 Source Term for Radon Emission

Only a fraction of radon (about 20%) is readily released when tied to solid particles; however, all radon trapped in the concentrate would have been released during the digestion process in Building 103. The offgases containing radon and nitrogen oxides from the digestion process were conveyed to the acid recovery plant. This plant was located about 30 m west of Building 103 between Building 103 and the water tower (see Figure 3.2). The discharge from the acid recovery plant was the prime source of radon emission (Mason 1985).

To estimate the amount of radon released, information is needed on the amount of uranium materials processed in the refinery (Buildings 103 and 105). According to Mason (1985), about 5,000 MT/yr was processed; according to the U.S. Department of the Army (1978), the amount was about 14,500 MT/yr. The capacity of the refinery when it operated continuously was 20,000 MT/yr of UO_3 (U.S. At. Energy Comm. 1966). Because of the uncertainty regarding the amount of uranium materials processed, dose estimates are calculated for both 5,000 and 14,500 MT/yr. The following assumptions were made: (1) 5,000 to 14,500 MT of uranium materials was processed per year; (2) of this, 70% was uranium; (3) radium activity was 1% of uranium activity (this estimate is probably conservatively high; several different estimates of radium content in yellowcake are available, e.g., 0.06%, 0.2%, and 2% of uranium activity [Sears et al. 1975]); (4) radon was in equilibrium with

radium; and (5) all radon escaped during processing. Based on these assumptions, the radon release rate is estimated to be 12-34 Ci/yr.

5.1.3.3 Source Terms for Waterborne Ingestion Pathways

Ingestion of radionuclides from the plant's waterborne releases could occur in two ways: from drinking contaminated water and from eating fish caught in the surrounding waters. The contamination levels for the drinking water pathway were obtained directly from monitoring data. For water that could have been consumed by people in significant quantities, the only monitoring data available are the 1984 sampling data of several springs and wells at nearby residences (Table A.12). Because it takes a long time for the contaminants to reach the water supply, these values probably represent the upper limit of the contamination levels during plant operations. One exception to this is Burgermeister Spring in the Busch Wildlife Area, where above-background radioactive contamination has been detected. However, it is unlikely that water has been consumed from this spring on a regular basis. (Potential radiological impacts associated with contaminated water from Burgermeister Spring have been estimated to be insignificant [Wang et al. 1986].) For the fish ingestion pathway, an upper limit for the contamination level was obtained from recent measurements of radionuclide concentrations in fish caught in the Busch Wildlife Area and in Femme Osage Slough (Tables A.9 and A.10).

Radionuclides could also have been ingested due to airborne releases from the plant. The models, equations, data, and assumptions needed to calculate radioactivity concentrations in vegetables due to airborne releases, and the resulting individual doses, are described in Appendix B.

5.1.3.4 Source Term for External Radiation

Exposure of the general population to external radiation could have occurred due to direct radiation from radioactive material present at the plant and due to radiation from contaminants dispersed through the air and deposited on the ground. The source term for direct radiation from material present at the plant is estimated from the average amount of uranium present

at the plant. Based on data in various publications of Mallinckrodt Chemical Works (1962, undated-A, undated-B), it is estimated that, at any one time, the plant contained between 2,000 and 3,000 MT of uranium-238 -- which corresponds to 700 to 1,000 Ci. Based on data from the materials balance study, it is estimated that the average yearly inventory was about 6 MT -- which corresponds to 2,000 Ci. Most of the exposure of the general population to radiation from this material would have occurred when it was in drums on a storage pad just outside the sampling plant. Radiation emanating from the material while it was being processed inside various buildings would not have contributed significantly to the source term because it would have been shielded by the buildings and the processing equipment.

Calculations of external dose rates from airborne radioactive materials and from those deposited on the ground are included in the overall dose estimates. Calculational details are described in Appendix B.

5.1.4 Dose Estimation

The source terms estimated in Section 5.1.3 were used to estimate doses to members of the nearby population groups and to the general population. The meteorological data collected at the St. Louis-Lambert Airport from 1960 through 1964 (Figure B.1 and Table B.3) were used as input into the atmospheric dispersion calculations. Concentrations of radionuclides contained in the air and deposited on the ground were calculated at distances up to 80 km from the Weldon Spring plant site.

Exposures to radionuclides originating in the effluents released from the Weldon Spring site were converted to estimates of radiation dose to individuals using models and data recommended by the International Commission on Radiological Protection (1977, 1979-1980). The estimated radiation doses to the total body and to internal organs from external exposure to penetrating radiation are approximately equal, but the doses from internal exposure may vary considerably because some radionuclides concentrate in certain organs of the body. In this analysis, "dose" due to internal exposure represents the 50-yr effective dose equivalent commitment expressed in units of millirem (mrem). (The exception is the dose to the lung from inhalation of radon

daughters, which represents the 50-yr dose commitment to the bronchial epithelium.) Annual doses (mrem/yr) are 50-yr dose commitments resulting from a 1-yr exposure period. Effective dose equivalent commitments (i.e., whole-body equivalent doses) are calculated according to the ICRP recommendations and are based on the "reference man" (Int. Comm. Radiol. Prot. 1974, 1977). The collective population dose estimate in person-rem is the sum of the effective dose equivalent commitments for all exposed individuals within a given area. Population doses were calculated to within an 80-km radius of the Weldon Spring site.

5.1.4.1 Doses to Nearby Population Groups

Airborne Releases. The dose commitments to individuals if they continuously occupied a residence at the identified locations would have resulted primarily from inhalation of particulates. The dose estimates are based on outdoor concentrations of radioactive particulates. Indoor concentrations of particulates originating outdoors are usually smaller (Spengler et al. 1981; Dockery and Spengler 1981; Yocum 1982). The reduction in indoor concentrations depends on several factors such as whether the building is air-conditioned or the windows are open. To the extent that the residents spent a portion of their time indoors, the estimated doses would be less. For example, if the indoor concentrations were 75% of the outdoor concentrations (Dockery and Spengler 1981) and if the resident spent about half the time indoors, then the doses would be reduced by about 10%. The actual living conditions at the two residence locations during the period of study are not known nor are any measurements available for indoor vs. outdoor concentrations of uranium oxide particulates. Because the possible reduction in total dose is well within the uncertainty in the dose estimates, a correction factor for indoor concentrations is not applied. Therefore, with respect to this factor, the estimated doses are conservative.

The calculated individual effective dose commitments for the nearby population groups are given in Tables 5.2 and 5.3 for 1957 through 1966. For airborne releases, 98% of the dose would have resulted from inhalation of particulates, less than 1% from ingestion of vegetables, and less than 0.1%

Table 5.2. Estimated Annual Dose Commitments for Members of Nearby Population Groups from Airborne Particulate Releases, 1957-1966, Based on Monitoring Data

Location	Effective Dose Equivalent (mrem/yr)					
	1957 ^e	1958 ^e	1959	1960	1961	1962
County Extension Center ^a	14	27	27	25	34	46
Francis Howell High School ^b	10	21	20	18	24	33
North resident ^c	50	100	97	88	120	160
Northwest resident ^c	44	87	85	77	100	140
Background ^d	120	120	120	120	120	120

Location	Effective Dose Equivalent (mrem/yr)				Total Dose Equivalent ^f (mrem)
	1963	1964	1965	1966 ^e	
County Extension Center ^a	18	32	17	27	280
Francis Howell High School ^b	13	24	12	21	200
North resident ^c	64	120	61	100	960
Northwest resident ^c	56	100	53	87	830
Background ^d	120	120	120	120	1200

^a Computed for a full-time employee assumed to work 8 hours per day, 5 days per week, 50 weeks per year.

^b Computed for a full-time student or faculty member assumed to attend school 8 hours per day, 5 days per week, 48 weeks per year (including summer school).

^c Continuous exposure is assumed.

^d Source: U.S. Department of Energy (1980).

^e The values for 1958 and 1966 are assumed to be averages of the 1959-1965 values. The 1957 values are assumed to be one-half of the 1958 values because, in 1957, the plant was in operation for only one-half year.

^f Over the operating lifetime of the plant.

Table 5.3. Estimated Annual Dose Commitments for Members of Nearby Population Groups from Airborne Particulate Releases, 1957-1966, Based on Materials Balance Study Data

Location	Effective Dose Equivalent (mrem/yr)					
	1957 ^e	1958 ^e	1959 ^e	1960	1961	1962
County Extension Center ^a	44	89	89	100	100	100
Francis Howell High School ^b	33	66	64	75	75	75
North resident ^c	160	320	320	360	360	360
Northwest resident ^c	140	280	280	320	320	320
Background ^d	120	120	120	120	120	120

Location	Effective Dose Equivalent (mrem/yr)				Total Dose Equivalent ^f (mrem)	
	1963	1964	1965	1966 ^e		
County Extension Center ^a	100	110	60	60	850	
Francis Howell High School ^b	75	100	57	57	680	
North resident ^c	360	400	210	210	3,100	
Northwest resident ^c	320	330	180	180	2,700	
Background ^d	120	120	120	120	1200	

^a Computed for a full-time employee assumed to work 8 hours per day, 5 days per week, 50 weeks per year.

^b Computed for a full-time student or faculty member assumed to attend school 8 hours per day, 5 days per week, 48 weeks per year (including summer school).

^c Continuous exposure is assumed.

^d Source: U.S. Department of Energy (1980).

^e The values for 1958 and 1959 are assumed to be averages of the 1960-1966 values. The 1957 values are assumed to be one-half of the 1958 values because, in 1957, the plant was in operation for only one-half year.

^f Over the operating lifetime of the plant.

from ingestion of meat. The estimated effective dose commitments during plant operations based on monitoring data (Table 5.2) range from a low of about 44 mrem/yr in 1957 at the northwest residence to a high of 160 mrem/yr during 1962 at the north residence. Dose estimates based on the materials balance study (Table 5.3) are about three times higher, ranging from a low of about 140 mrem/yr during 1957 at the northwest residence to a high of about 400 mrem/yr during 1964 at the north residence.

The estimated annual dose commitments to the lung from radon emissions during the same period are presented in Table 5.4. The dose from radon is considerably smaller than that from airborne particulates.

Table 5.4. Estimated Average Annual Dose Commitments to Lung from Radon Emissions, 1957-1966

Location	Annual Dose Equivalent ^d (mrem/yr)	Total Dose Equivalent ^{d,e} (mrem)
County Extension Center ^a	0.38 - 4.8	3.6 - 10
Francis Howell High School ^b	0.23 - 0.67	2.2 - 6.4
North resident ^c	1.0 - 3.0	9.5 - 21
Northwest resident ^c	0.9 - 2.6	8.6 - 18

^a Computed for a full-time employee assumed to work 8 hours per day, 5 days per week, 50 weeks per year.

^b Computed for a full-time student or faculty member assumed to attend school 8 hours per day, 5 days per week, 48 weeks per year (including summer school).

^c Continuous exposure is assumed.

^d The two values correspond to the two source term estimates of 12 and 34 pCi/yr.

^e During 9.5 years of plant operations.

Waterborne Releases. Dose estimates for aquatic pathways were calculated directly from radionuclide concentrations in drinking water and fish (Section 5.1.3.3) and are presented in Table 5.5. The dose conversion factors

Table 5.5. Summary of Estimated Radiation Doses to Individuals at Locations of Potential Exposure via the Aquatic Pathway

Pathway	Location	Effective Dose Equivalent (mrem/yr)
Aquatic food chains to fish ^a	Busch Wildlife Area	0.03
	Femme Osage Slough	0.6
	Femme Osage Creek	0.03
Drinking water ^b	Well at Saladin residence	0.19
	Well at Cassidy residence	0.081
	Well at Busch Headquarters	0.22
	Well at Beffa residence	0.11
	Well at Shaw residence	0.12
	Spring at Busch Lake 33 ^c	0.12
	Burgermeister Spring ^c	11.0
	Spring #1, Lost Valley ^c	0.081
	Spring #2, Lost Valley ^c	0.16

^a Based on analysis of the edible part of fish samples and assuming a fish consumption rate of 6.9 kg/yr.

^b Assuming a water consumption rate of 370 L/yr.

^c Although the estimated dose is based on a water consumption rate of 370 L/yr, it is unlikely that this much water would have been consumed from this source.

Note: Average background dose in Missouri is about 120 mrem/yr (U.S. Dept. Energy 1980).

for ingestion used in this calculation are given in Appendix B (Table B.5). The calculated dose estimates are quite small. The only dose value larger than 1 mrem/yr is the effective dose equivalent from drinking water from Burgermeister Spring in the Busch Wildlife Area at the rate of 370 L/yr. It is very unlikely that anyone consumed water from this spring on a regular basis, although it is possible that an individual might have consumed about one liter of its water per year and thus received an effective dose equivalent of 0.03 mrem/yr.

Doses from Direct Radiation. During plant operations, the dose to the general population from direct radiation would have been primarily due to gamma radiation from short-lived products of uranium-238 contained in the concentrate while it was stored on the storage pad. The estimated annual doses to members of nearby population groups are given in Table 5.6. Calculational details are provided in Appendix B. These estimates are probably conservatively high, based on the source term of 700-2,000 Ci.

The self-shielding effect of the concentrate also had to be taken into account. To estimate this effect, it was assumed -- based on information in various publications of Mallinckrodt Chemical Works (1962, undated-A, undated-B) -- that the drums holding the concentrate were stacked in three layers, occupying a total area of between 1,000 and 2,000 m². Each drum had a volume of 0.2 m³ (55 gal) and contained 430 kg of yellowcake (70% uranium content). Based on these assumptions it is estimated that self-shielding

Table 5.6. Estimated Annual Dose to Members of Nearby Population Groups from Direct Radiation, 1957-1966^a

	Annual Dose ^{d,e} (mrem/yr)	Total Dose ^{d,e} (mrem)
County Extension Center ^a	0.02 - 1.0	0.2 - 10
Francis Howell High School ^b	0.002 - 0.04	0.02 - 0.4
North resident ^c	0.003 - 0.08	0.03 - 0.8
Northwest resident ^c	0.0001 - 0.004	0.001 - 0.04

^a Computed for a full-time employee assumed to work 8 hours per day, 5 days per week, 50 weeks per year.

^b Computed for a full-time student or faculty member assumed to attend school 8 hours per day, 5 days per week, 48 weeks per year (including summer school).

^c Continuous exposure is assumed.

^d During 9.5 years of plant operations.

^e The smaller value is calculated with a source term of 700 Ci and a self-shielding factor of 1000; the larger value is calculated with a source term of 2000 Ci and a self-shielding factor of 100 (see text). The values are reported to 1 significant figure.

effects would have reduced the direct radiation dose by a factor of about 100 to 1,000. Values corresponding to both estimates are presented in Table 5.6.

The estimated dose from direct radiation is quite small. It is about 2% of the dose due to airborne releases (Tables 5.2 and 5.3) at the County Extension Center (0.76 km [0.47 mi] from the plant), decreases rapidly with distance, and becomes negligible for distances from the source somewhat larger than 1 km (0.62 mi).

In summary, all exposure modes other than inhalation of particulates together contributed less than 5% of the total estimated dose. The uncertainty of the dose estimates is expected to be much larger than 5%. Therefore, it is consistent with the accuracy of calculations in this report to base all dose estimates on inhalation of particulates. For the individual dose estimates to the general population, only inhalation exposure modes are considered.

5.1.4.2 Doses to the General Population

The annual effective dose commitments to individuals residing within an 80-km radius of the Weldon Spring site were calculated based on the source releases estimated from monitoring data for each of 16 wind sectors at distances up to 80 km (50 mi). The results are given in Tables 5.7 through 5.13 for the years for which monitoring data are available (1959 through 1965). The same data are presented graphically as isopleths in Figures 5.2 through 5.15. Figures 5.2 through 5.8 show the radiation dose isopleths on a logarithmic scale for the 80-km (50-mi) radius; Figures 5.9 through 5.15 show the same data on a linear scale for the 16-km (20-mi) radius. The data represent the dose that an individual would have received if that individual remained in the specified location continually for one full year. Thus, a person spending 24 hours per day at a location 1.5 km (0.31 mi) north of the plant would have received a dose of 89 mrem above background (120 mrem/yr) for the full year in 1959.

The collective effective dose commitments to the general population within an 80-km radius of the Weldon Spring site resulting from 1957-1966

Table 5.7. Estimated Individual Effective Dose Equivalent for the Population Within an 80-km Radius of the Weldon Spring Site, 1959

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	89	43	24	15	6.0	1.7
NNE	45	21	12	7.6	3.0	0.83
NE	50	24	13	8.3	3.2	0.85
ENE	63	30	16	9.9	3.6	0.93
E	99	47	25	15	5.4	1.3
ESE	99	45	24	15	5.5	1.4
SE	73	32	17	10	3.8	1.0
SSE	51	22	11	7.0	2.6	0.71
S	46	20	11	6.5	2.4	0.62
SSW	55	24	12	7.4	2.6	0.62
SW	71	31	16	9.2	3.0	0.67
WSW	59	25	13	7.5	2.5	0.57
W	69	29	15	8.7	2.9	0.66
WNW	92	40	21	12	4.2	1.0
NW	110	52	27	16	5.7	1.3
NNW	90	42	22	14	5.1	1.3

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	0.64	0.34	0.21	0.15	0.11	0.081
NNE	0.31	0.17	0.10	0.071	0.051	0.039
NE	0.32	0.17	0.10	0.071	0.051	0.039
ENE	0.34	0.18	0.11	0.076	0.054	0.041
E	0.46	0.23	0.14	0.095	0.067	0.050
ESE	0.54	0.29	0.18	0.12	0.090	0.068
SE	0.40	0.22	0.14	0.095	0.069	0.053
SSE	0.27	0.15	0.091	0.063	0.046	0.035
S	0.23	0.12	0.078	0.054	0.039	0.030
SSW	0.22	0.11	0.070	0.048	0.034	0.026
SW	0.23	0.11	0.068	0.046	0.032	0.024
WSW	0.20	0.10	0.063	0.043	0.031	0.023
W	0.23	0.12	0.074	0.051	0.037	0.028
WNW	0.36	0.19	0.11	0.078	0.055	0.042
NW	0.46	0.23	0.14	0.095	0.067	0.050
NNW	0.48	0.25	0.16	0.11	0.077	0.058

^a The distances represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

Table 5.8. Estimated Individual Effective Dose Equivalent
for the Population Within an 80-km Radius of the
Weldon Spring Site, 1960

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	80	39	22	14	5.4	1.5
NNE	41	19	11	6.9	2.7	0.75
NE	45	21	12	7.5	2.9	0.78
ENE	58	27	15	9.0	3.3	0.84
E	89	43	23	14	4.9	1.2
ESE	90	41	22	13	5.0	1.3
SE	66	29	15	9.3	3.5	0.94
SSE	46	20	10	6.4	2.4	0.64
S	42	18	9.6	5.9	2.2	0.57
SSW	50	22	11	6.7	2.3	0.56
SW	64	28	14	8.3	2.7	0.61
WSW	53	23	11	6.8	2.2	0.52
W	62	27	13	7.9	2.6	0.60
WNW	83	36	19	11	3.9	0.92
NW	100	47	25	15	5.1	1.2
NNW	81	38	20	12	4.6	1.2

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	0.58	0.31	0.19	0.13	0.097	0.073
NNE	0.29	0.15	0.093	0.064	0.046	0.035
NE	0.29	0.15	0.093	0.064	0.046	0.035
ENE	0.31	0.16	0.10	0.069	0.049	0.037
E	0.42	0.21	0.13	0.086	0.061	0.045
ESE	0.49	0.26	0.16	0.11	0.081	0.062
SE	0.36	0.19	0.12	0.086	0.063	0.048
SSE	0.25	0.13	0.082	0.057	0.042	0.032
S	0.21	0.11	0.071	0.049	0.036	0.027
SSW	0.20	0.10	0.063	0.043	0.031	0.023
SW	0.21	0.10	0.062	0.041	0.029	0.022
WSW	0.18	0.094	0.057	0.039	0.028	0.021
W	0.21	0.11	0.067	0.046	0.033	0.025
WNW	0.33	0.17	0.10	0.070	0.050	0.038
NW	0.42	0.21	0.13	0.086	0.061	0.045
NNW	0.44	0.23	0.14	0.097	0.070	0.053

^a The values shown represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

Table 5.9. Estimated Individual Effective Dose Equivalent
for the Population Within an 80-km Radius of the
Weldon Spring Site, 1961

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	110	52	29	19	7.3	2.0
NNE	55	26	15	9.3	3.6	1.0
NE	61	29	16	10	3.9	1.0
ENE	77	36	20	12	4.4	1.1
E	120	57	31	19	6.6	1.6
ESE	120	55	30	18	6.7	1.7
SE	89	39	20	13	4.7	1.3
SSE	62	26	14	8.6	3.2	0.86
S	56	25	13	7.9	2.9	0.76
SSW	67	29	15	9.0	3.1	0.76
SW	87	38	19	11	3.7	0.82
WSW	72	31	15	9.1	3.0	0.70
W	84	36	18	11	3.5	0.81
WNW	110	49	25	15	5.2	1.2
NW	130	63	33	20	6.9	1.6
NNW	110	51	27	17	6.2	1.6

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	0.79	0.42	0.26	0.18	0.13	0.099
NNE	0.38	0.20	0.13	0.086	0.062	0.047
NE	0.39	0.20	0.13	0.086	0.062	0.047
ENE	0.42	0.22	0.13	0.092	0.066	0.050
E	0.56	0.29	0.17	0.12	0.082	0.061
ESE	0.66	0.35	0.22	0.15	0.11	0.083
SE	0.49	0.26	0.16	0.12	0.084	0.065
SSE	0.33	0.18	0.11	0.077	0.056	0.043
S	0.29	0.15	0.095	0.066	0.048	0.037
SSW	0.27	0.14	0.085	0.058	0.042	0.031
SW	0.28	0.14	0.083	0.056	0.039	0.029
WSW	0.24	0.13	0.077	0.053	0.038	0.029
W	0.29	0.15	0.091	0.062	0.045	0.034
WNW	0.44	0.23	0.14	0.095	0.068	0.051
NW	0.56	0.29	0.17	0.11	0.082	0.061
NNW	0.59	0.31	0.19	0.13	0.094	0.071

^a The values shown represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

Table 5.10. Estimated Individual Effective Dose Equivalent for the Population Within an 80-km Radius of the Weldon Spring Site, 1962

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	150	72	40	26	10	2.8
NNE	76	36	20	13	5.0	1.4
NE	84	40	22	14	5.3	1.4
ENE	110	50	27	17	6.1	1.6
E	160	79	42	26	9.1	2.2
ESE	170	76	41	25	9.1	2.4
SE	120	53	28	17	6.4	1.7
SSE	85	36	19	12	4.4	1.2
S	77	34	18	11	4.0	1.0
SSW	93	40	21	12	4.3	1.0
SW	120	52	26	15	5.0	1.1
WSW	99	42	21	12	4.2	0.96
W	110	49	25	15	4.8	1.1
WNW	150	67	34	21	7.1	1.7
NW	180	86	46	27	9.5	2.2
NNW	150	70	37	23	8.5	2.2

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	1.1	0.57	0.36	0.25	0.18	0.13
NNE	0.53	0.28	0.17	0.12	0.085	0.065
NE	0.53	0.28	0.17	0.12	0.085	0.064
ENE	0.57	0.30	0.18	0.13	0.091	0.069
E	0.77	0.39	0.23	0.16	0.11	0.084
ESE	0.90	0.48	0.30	0.21	0.15	0.11
SE	0.67	0.36	0.23	0.16	0.12	0.089
SSE	0.45	0.24	0.15	0.11	0.077	0.059
S	0.39	0.21	0.13	0.091	0.066	0.050
SSW	0.37	0.19	0.12	0.080	0.057	0.043
SW	0.38	0.19	0.11	0.077	0.054	0.040
WSW	0.34	0.17	0.11	0.073	0.052	0.039
W	0.39	0.20	0.12	0.085	0.061	0.046
WNW	0.61	0.31	0.19	0.13	0.093	0.070
NW	0.77	0.39	0.23	0.16	0.11	0.083
NNW	0.81	0.42	0.26	0.18	0.13	0.097

^a The values shown represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

Table 5.11. Estimated Individual Effective Dose Equivalent for the Population Within an 80-km Radius of the Weldon Spring Site, 1963

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	58	28	16	10	3.9	1.1
NNE	30	14	7.8	5.0	2.0	0.54
NE	33	16	8.6	5.4	2.1	0.56
ENE	42	20	11	6.5	2.4	0.61
E	65	31	16	10	3.6	0.86
ESE	65	30	16	9.8	3.6	0.93
SE	48	21	11	6.8	2.5	0.68
SSE	33	14	7.5	4.6	1.7	0.47
S	30	13	7.0	4.3	1.6	0.41
SSW	36	16	8.1	4.9	1.7	0.41
SW	47	20	10	6.0	2.0	0.44
WSW	39	17	8.4	4.9	1.6	0.38
W	45	19	9.6	5.7	1.9	0.44
WNW	61	26	14	8.1	2.8	0.67
NW	73	34	18	11	3.7	0.87
NNW	59	27	15	9.1	3.3	0.86

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	0.42	0.23	0.14	0.097	0.070	0.053
NNE	0.21	0.11	0.068	0.047	0.034	0.025
NE	0.21	0.11	0.068	0.047	0.033	0.025
ENE	0.22	0.12	0.072	0.050	0.036	0.027
E	0.30	0.15	0.092	0.062	0.044	0.033
ESE	0.35	0.19	0.12	0.081	0.059	0.045
SE	0.26	0.14	0.089	0.062	0.046	0.035
SSE	0.18	0.096	0.060	0.042	0.030	0.023
S	0.15	0.082	0.051	0.036	0.026	0.020
SSW	0.15	0.075	0.046	0.031	0.022	0.017
SW	0.15	0.075	0.045	0.030	0.021	0.016
WSW	0.13	0.068	0.042	0.028	0.020	0.015
W	0.15	0.080	0.049	0.033	0.024	0.018
WNW	0.24	0.12	0.075	0.051	0.036	0.027
NW	0.30	0.15	0.092	0.062	0.044	0.033
NNW	0.32	0.17	0.10	0.070	0.051	0.038

^a The values shown represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

Table 5.12. Estimated Individual Effective Dose Equivalent for the Population Within an 80-km Radius of the Weldon Spring Site, 1964

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	110	51	28	18	7.1	2.0
NNE	54	26	14	9.0	3.5	0.98
NE	59	28	15	9.8	3.8	1.0
ENE	75	35	19	12	4.3	1.1
E	120	56	30	18	6.5	1.5
ESE	120	54	29	18	6.5	1.7
SE	87	38	20	12	4.6	1.2
SSE	60	26	14	8.4	3.1	0.84
S	55	24	13	7.7	2.8	0.74
SSW	66	29	15	8.8	3.0	0.74
SW	84	37	19	11	3.6	0.80
WSW	70	30	15	8.9	3.0	0.68
W	82	35	18	10	3.4	0.79
WNW	110	48	24	15	5.0	1.2
NW	130	61	32	20	6.7	1.6
NNW	110	49	27	16	6.0	1.5

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	0.77	0.41	0.25	0.18	0.13	0.096
NNE	0.37	0.20	0.12	0.084	0.061	0.046
NE	0.38	0.20	0.12	0.084	0.061	0.046
ENE	0.41	0.21	0.13	0.090	0.065	0.049
E	0.55	0.28	0.17	0.11	0.080	0.059
ESE	0.64	0.34	0.21	0.15	0.11	0.081
SE	0.47	0.26	0.16	0.11	0.082	0.063
SSE	0.32	0.17	0.11	0.075	0.055	0.042
S	0.28	0.15	0.093	0.064	0.047	0.036
SSW	0.26	0.14	0.083	0.057	0.041	0.031
SW	0.27	0.13	0.081	0.054	0.038	0.029
WSW	0.24	0.12	0.075	0.052	0.037	0.028
W	0.28	0.14	0.088	0.061	0.044	0.033
WNW	0.43	0.22	0.14	0.092	0.066	0.049
NW	0.55	0.28	0.17	0.11	0.079	0.059
NNW	0.58	0.30	0.19	0.13	0.092	0.069

^a The values shown represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

Table 5.13. Estimated Individual Effective Dose Equivalent for the Population Within an 80-km Radius of the Weldon Spring Site, 1965

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	1.5 km ^a	2.5 km	3.5 km	4.5 km	7.5 km	15.0 km
N	56	27	15	9.6	3.8	1.0
NNE	28	13	7.5	4.8	1.9	0.52
NE	31	15	8.2	5.2	2.0	0.54
ENE	40	19	10	6.2	2.3	0.58
E	62	29	16	9.6	3.4	0.82
ESE	62	28	15	9.3	3.4	0.89
SE	46	20	10	6.5	2.4	0.65
SSE	32	14	7.2	4.4	1.6	0.44
S	29	13	6.6	4.1	1.5	0.39
SSW	35	15	7.8	4.6	1.6	0.39
SW	44	19	9.8	5.7	1.9	0.42
WSW	37	16	8.0	4.7	1.6	0.36
W	43	18	9.3	5.5	1.8	0.42
WNW	58	25	13	7.7	2.7	0.64
NW	69	32	17	10	3.5	0.83
NNW	56	26	14	8.7	3.2	0.82

Direction	Dose Equivalent (mrem/yr) at Distance from Site					
	25.0 km	35.0 km	45.0 km	55.0 km	65.0 km	75.0 km
N	0.40	0.21	0.13	0.093	0.067	0.051
NNE	0.20	0.10	0.064	0.044	0.032	0.024
NE	0.20	0.10	0.065	0.044	0.032	0.024
ENE	0.21	0.11	0.069	0.047	0.034	0.026
E	0.29	0.15	0.088	0.059	0.042	0.031
ESE	0.34	0.18	0.11	0.077	0.056	0.043
SE	0.25	0.13	0.085	0.059	0.043	0.033
SSE	0.17	0.091	0.057	0.040	0.029	0.022
S	0.15	0.078	0.049	0.034	0.025	0.019
SSW	0.14	0.072	0.044	0.030	0.021	0.016
SW	0.14	0.071	0.043	0.029	0.020	0.015
WSW	0.13	0.065	0.040	0.027	0.019	0.015
W	0.15	0.076	0.046	0.032	0.023	0.017
WNW	0.23	0.12	0.071	0.049	0.035	0.026
NW	0.29	0.15	0.088	0.059	0.042	0.031
NNW	0.30	0.16	0.098	0.067	0.048	0.036

^a The values shown represent the midway values of the range, e.g., 1.5 km is midway between 1 and 2 km.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.2. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [$\log (\text{mrem/yr})$], 1959, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.3. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [log (mrem/yr)], 1960, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.4. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [$\log (\text{mrem/yr})$], 1961, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.5. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [log (mrem/yr)], 1962, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.6. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [log (mrem/yr)], 1963, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.7. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [log (mrem/yr)], 1964, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr	log (mrem/yr)	mrem/yr
-2.5	0.0032	-0.75	0.178	1.0	10.0
-2.25	0.0056	-0.5	0.316	1.25	17.8
-2.0	0.01	-0.25	0.562	1.5	31.6
-1.75	0.0178	0	1.0	1.75	56.2
-1.5	0.0316	0.25	1.78	2.0	100.0
-1.25	0.0562	0.5	3.16	2.25	177.8
-1.0	0.1	0.75	5.62	2.5	316.2

Figure 5.8. Historical Dose Contours Within an 80-km (50-mi) Radius of the Weldon Spring Plant Site [log (mrem/yr)], 1965, Based on Monitoring Data. The right-hand figure is a three-dimensional representation of the left-hand figure. The values on the contours are logarithms of the dose rates; the table provides conversions to dose rates in mrem/yr, e.g., contour "-0.25" represents a dose rate of 0.562 mrem/yr.

Figure 5.9. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1959.

Figure 5.10. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1960.

Figure 5.11. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1961.

Figure 5.12. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1962.

Figure 5.13. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1963.

Figure 5.14. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1964.

Figure 5.15. Weldon Spring Historical Dose Contours at a 16-km (10-mi) Radius (mrem/yr), 1965.

plant releases, based on monitoring data, are presented in Table 5.14. These collective dose commitments were calculated using population distributions for 1960 and 1970 (Tables 2.1 and 2.2). Population values for the years 1961-1966 were obtained by a linear interpolation between the 1960 and 1970 values. For the region within a 20-km radius from the source, the population data used were at the census tract level; outside the 20-km radius, the data used were at the county level. Values outside the 20-km radius of the site correspond to individual doses of less than 1 mrem/yr per person. According to proposed U.S. Nuclear Regulatory Commission (1986) regulations, the collective population dose would not have to be considered for dose values smaller than 1 mrem/yr per person.

Based on the monitoring data, the annual collective dose to the general population of 2.5 million people within 80-km of the site ranged from 310 person-rem in 1957 to 1,100 person-rem in 1962. The collective dose over the entire 10-yr period is estimated to be 6,200 person-rem.

The projected number of excess fatal cancers over the remaining lifetime of the general population of 2.5 million persons after exposure to the radioactive materials released from the Weldon Spring plant is approximately one. This is based on a risk factor of 0.00017 per million person-rem (Int. Comm. Radiol. Prot. 1977). It is estimated that there is a 97% chance that this excess cancer would be lung cancer, 1.4% chance it would be leukemia, and 1.6% chance it would be another type of cancer. The number of fatal cancers that would normally be expected in the same population is 520,000, of which 21,000 are expected to be leukemia (based on a cancer death rate of 20.9%, of which 4% are leukemia [U.S. Dept. Health Human Serv. 1980]). The one additional cancer death represents an increase of 0.0002%.

The total dose commitment of 960 mrem over the 10-yr operating period to a resident located 1.2 km (0.75 mi) north of the site is estimated to result in an additional risk of fatal cancer of 1 in 5000. This can be compared with the normal risk of fatal cancer of about 1 in 5.

Table 5.14. Estimated Collective Dose Commitments to the Population Within an 80-km Radius of the Weldon Spring Site, 1957-1966, Based on Monitoring Data

Distance from Site (km)	Dose Commitment (person-rem)					
	1957 ^a	1958 ^a	1959	1960	1961	1962
1- 2	12	24	23	21	32	49
2- 3	8	16	16	14	21	33
3- 4	6.5	11	11	10	15	22
4- 5	4.8	9.5	9	9	13	19
5-10	13	26	25	23	33	48
10-20	18	36	34	31	48	75
Subtotal 1-20	62	120	120	110	160	250
20-80	250	490	470	430	580	800
Total	310	610	590	540	740	1,100

Distance from site (km)	Dose Commitment (person-rem)				Background (person-rem)	
	1963	1964	1965	1966 ^a	1958	1966
1- 2	21	41	24	42	37	65
2- 3	14	28	16	28	55	95
3- 4	10	19	11	20	71	130
4- 5	8	16	9	16	100	170
5-10	20	39	22	37	700	1,000
10-20	33	66	38	66	3,500	6,400
Subtotal 1-20	110	210	120	210	4,500	7,900
20-80	320	570	300	500	290,000	300,000
Total	420	780	420	710	290,000	300,000

^a The doses for 1957, 1958, and 1966 are based on the average values of individual doses for the 1959-1965 period. The 1957 values are one-half of the 1958 values because the plant was in operation for only one-half year.

5.2 CLEANUP PERIOD (1967-1969)

Activities contributing to radioactive releases during the shutdown and cleanup period (Table 3.1) consisted of removal of scrap, rubble, and some uranium oxide from plant buildings. In addition, effluents were released from radioactive wastes in various locations around the site.

Radiological monitoring data are not available for the cleanup period. Therefore, the dose to the general population can be estimated only very roughly based on the activities during this period (summarized in Table 3.1). The main contribution to the dose would have been from airborne releases of uranium that occurred during cleanup operations and from the radioactive wastes at the site. The airborne releases during cleanup would have been due mostly to the removal of uranium oxide; airborne releases caused by the removal of scrap and rubble would have been negligible. It is estimated that about 100 MT of uranium oxide was removed from the buildings during this period. This is less than 1% of the amount of uranium materials processed yearly during plant operations (see Table 3.1). Moreover, transferring uranium oxide into barrels for shipment was a simple operation that did not involve the chemical processes of converting concentrates to uranium metal. Therefore, major uranium releases from processing stacks for the plant operations period were eliminated during this cleanup period. Based on these considerations, it is estimated that airborne releases during the cleanup period were about 0.1% of those during plant operations. This release would have resulted in an estimated maximum effective dose equivalent of about 0.2 mrem to a nearby resident.

In addition to releases from cleanup operations, releases could also have been generated from wind erosion of, and radon emanation from, residues in the pits and quarry, in and around plant buildings, along the roads, and along the railroad tracks -- the latter two known as "vicinity properties". The radioactive releases during this maintenance period and the resulting doses were estimated to be, at most, at current levels. Based on the current levels and conditions of contamination at the pits, quarry, and vicinity properties, the annual radioactive releases are estimated to be about 0.001 of those estimated for the operations period. The estimated current dose commitments

for individuals of the nearby population groups are less than 0.2 mrem/yr. Adding the 0.2 mrem/yr dose estimate to the 0.2 mrem/yr dose calculated in this analysis for cleanup operations, the total individual dose during this period is estimated to have been less than 0.4 mrem/yr. For comparison, the background dose in Missouri is 120 mrem/yr (U.S. Dept. Energy 1980), and a person taking a 4-hour airplane trip at 10,000 m (33,000 ft) incurs a dose of 2 mrem.

5.3 MAINTENANCE PERIOD (1969-1982)

During the maintenance period, the plant site remained mostly undisturbed. There were no activities at the plant that resulted in substantial amounts of radioactive releases, such as those that occurred during plant operations and cleanup. Radioactive releases were primarily from radioactive wastes at the site. The dose estimate in this analysis for a maximally exposed individual is 0.2 mrem/yr (see Section 5.2). For comparison, the background dose in Missouri is 120 mrem/yr (U.S. Dept. Energy 1980), and a person taking a 4-hour airplane trip at 10,000 m (33,000 ft) incurs a dose of 2 mrem.

6. DISCUSSION OF RESULTS

6.1 SUMMARY OF DOSE ESTIMATES

The dose estimates calculated in this report and presented in Section 5 indicate that, of the three periods considered, the plant operations period (1957-1966) was associated with the largest potential doses to the population in the surrounding area. The dose estimates for the cleanup (1967-1969) and maintenance (1969-1982) periods are small enough to be negligible. Thus, based on monitoring data, a person residing 1.2 km (0.75 mi) north of the plant is estimated to have received an average dose of about 96 mrem/yr during plant operations (Table 6.1) whereas a nearby resident during later years is estimated to have received an average dose of about 0.4 mrem/yr during cleanup and about 0.2 mrem/yr during the maintenance period. These values may be compared with the background dose of 120 mrem/yr in Missouri (U.S. Dept. Energy 1980).

The most important exposure pathway during plant operations was inhalation of airborne particulates. All other pathways together contributed less than 5% to the total dose and can be neglected because the uncertainty of dose estimates is expected to be considerably greater than 5%.

Average yearly dose estimates for 1957-1966 for members of nearby population groups (see Section 2), corrected to account for occupancy times, are presented in Table 6.1. Estimates based on both the monitoring data and on the materials balance study are included. At the County Extension Center, it is assumed that a full-time employee worked there 8 hours per day, 5 days per week, for 50 weeks of the year; such an employee is estimated to have received an average dose of 28 mrem/yr (based on monitoring data) or 85 mrem/yr (based on the materials balance study). At Francis Howell High School, a student or faculty member is assumed to have been there 8 hours per day, 5 days per week, for 48 weeks of the year; such persons are estimated to have received an average dose of about 20 mrem/yr (based on monitoring data) or 68 mrem/yr (based on the materials balance study). The dose for a parent attending monthly meetings would have been about 1% of that of a full-time

Table 6.1. Occupancy-Adjusted Average Yearly Dose Estimates for Members of Nearby Population Groups During Plant Operations, 1957-1966

Nearby Population Group	Effective Dose Equivalent (mrem/yr)	
	Monitoring Data	Materials Balance Study
County Extension Center Full-time employee ^a	28	85
Francis Howell High School Full-time student or faculty member ^b	20	68
Parent attending monthly meetings ^c	0.2	0.64
North resident	96	310
Northwest resident	83	270
Visitor to a wildlife area ^d	2	7
Person driving through the site regularly ^e	0.2	0.7
Background	120	120

^a Full-time employee is assumed to work 8 hours per day, 5 days per week, for 50 weeks of the year.

^b Full-time student or faculty is assumed to attend school (including summer school) 8 hours per day, 5 days per week, for 48 weeks of the year.

^c A parent is assumed to attend one meeting per month, lasting 3 hours, for 6 months of the year.

^d A visitor to a wildlife area is assumed to spend 4 hours per visit in an area about 1.5 km from the plant, once per week for 6 months of the year.

^e A person driving through the site regularly is assumed to spend 40 minutes per day within 20 km of the site.

student, or 0.2 to 0.7 mrem/yr. Nearby residents are assumed to have spent all their time at their residences; their estimated average doses range from about 83 to 96 mrem/yr (based on monitoring data) or 270 to 431 mrem/yr (based on the materials balance study).

Dose estimates for persons who were near the plant for a short time only are also presented in Table 6.1. One such person would be a visitor to a wildlife area. Assuming 26 visits per year (once per week for 6 months of the year) and 4 hours per visit in an area about 1.5 km from the plant, the dose

to such an individual is estimated to have been about 2 to 7 mrem/yr. Another such person would be someone driving through the site regularly; assuming that this person spent 40 minutes per day within 20 km of the site on a road passing through the area, the estimated dose is about 0.2 to 0.7 mrem/yr.

For all members of the nearby population groups, dose estimates based on the estimated airborne releases given in the materials balance study are, on the average, about three times larger than those based on the monitoring data. These dose estimates may be compared to radiation doses from various common sources as presented in Table 6.2.

Table 6.2. Comparison of Radiation Doses
from Various Common Sources

Source	Dose
Four-hour airplane trip at 10,000 m (33,000 ft)	2 mrem
Living in Colorado instead of Missouri	50 mrem/yr
Living in a house made of brick instead of wood	20-50 mrem/yr
Diagnostic X-ray	20 mrem
Background in Missouri	120 mrem/yr

Sources: International Atomic Energy Agency (1979); U.S. Department of Energy (1980).

Based on monitoring data, the collective dose commitment to the general population of 2.5 million persons within an 80-km radius of the site is estimated to be 6,200 person-rem for the entire period of plant operations (1957 to 1966); this corresponds to one additional fatal cancer. Based on data from the materials balance study, the 10-yr collective dose is estimated to be about three times as large, or 19,000 person-rem, which corresponds to three additional fatal cancers. This may be compared to 520,000 fatal cancers that would normally be expected in the same population over its remaining lifetime (after exposure).

6.2 DISCUSSION OF UNCERTAINTIES

There are many uncertainties associated with the dose estimates presented in this report. These uncertainties are caused by several factors that could generally be grouped into two categories: uncertainties in the data and uncertainties in the models used to obtain dose estimates from the data. Not enough is known about these uncertainties to discuss them quantitatively; therefore, only a qualitative discussion will be presented.

Data that are very important for the estimates in this report are the monitoring data for uranium air concentrations presented in Table A.3 because the source terms for airborne emissions are calculated from these data. The uncertainties associated with both the concentration values and the exact locations of the monitoring points are not known. However, they are partly reflected in the standard deviation values of the estimated source terms -- uranium release rates -- in Table 5.1.

The average yearly release of uranium to the atmosphere from 1957 to 1966, estimated from the monitoring data, is 2.0 ± 1.2 MT/yr (1.3 ± 0.83 Ci/yr). The average yearly uranium stack loss based on the materials balance study (Harris 1986) is 6.2 MT per year, which is about three times larger. Consequently, the dose estimates based on the materials balance study are also about three times larger. The stack losses reported in the materials balance study are based on a search of old records of site operations. The records do not contain estimates of the uncertainties. Based on experience in estimating releases, the results based on the monitoring data and on the materials balance study are remarkably consistent and probably represent reasonable estimates of releases from the site.

The uncertainties in the model can affect the results of this study in different ways. A thorough sensitivity analysis would be required to determine these effects quantitatively. Such an analysis would involve varying different parameters of the model to see how such variations affected the results. This kind of analysis is beyond the scope of this report, and the discussion here is limited to identifying possible sources of uncertainties.

Some of the parameters that enter into the model used to calculate air concentrations from stack emissions pertain to stack specifications and operating conditions. Stack heights, locations, and dimensions were obtained from recent measurements and are judged to be reliable. However, airborne emissions were released from several stacks, and it is not known how much each stack contributed. In addition, some stacks were located close to other buildings, and wake effects could have affected the effective release height. To account for these effects, a uniform area emission source was assumed. Values of other parameters -- such as emission rates, release temperatures, and filter types and sizes -- were not available and are assumed based on typical operating conditions for such plants. Also, the dispersion model can be sensitive to meteorological data. The data used here are averages of wind speed and stability class values over a 5-yr period (1960-1964) at the St. Louis-Lambert Airport because such data are not available for the Weldon Spring site. It is possible that local variations in these values as well as variations that occur over shorter time periods could affect the results.

In addition, the dose conversion factors are uncertain. For example, dose conversion factors for different uranium compounds can vary by two orders of magnitude, depending on the solubility of the uranium compounds in body fluids (Int. Comm. Radiol. Prot. 1979-1980; Dunning et al. 1981). Because the proportion of different compounds in the airborne emissions is not known, the dose conversion factors used in this study are those that yield the highest effective dose equivalents and are based on the solubility classes recommended by the International Commission on Radiological Protection (1979-1980). On the other hand, the dose conversion factors also depend on particle size. An average aerodynamic diameter size of $1\text{ }\mu\text{m}$ was assumed for all radionuclides except radon decay products. Smaller particle dimensions would lead to larger dose conversion factors.

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APPENDIX A. DESCRIPTION OF RADIOLOGICAL MONITORING DATA

The radiological monitoring data available for the Weldon Spring area for the years 1959-1982 are presented in this appendix. The concentrations of specific radiological parameters measured in air, surface water, groundwater, or soil for different sample collection dates are presented in separate tables. Associated with each table are one or more figures showing the locations of the sampling points. (Note: the tables and figures are presented at the end of the text of this appendix.) Air monitoring data for locations within the Weldon Spring plant site are also presented here because these data are needed to estimate doses to people in off-site areas.

The results of gamma radiation intensity measurements along or near the pit and quarry perimeter fences and at a few off-site locations are presented in Table A.1. Figures A.1 and A.2 show the sampling locations. All external radiation data except the November 1982 data were obtained by use of thermoluminescent detectors (Bechtel Natl. 1983b; NLO 1974-1981); the November 1982 data were obtained using a sodium iodide crystal detector calibrated by use of an ion chamber (Bechtel Natl. 1984b).

The data show the presence of a small area of contamination at the fence southwest of Pits 1 and 2. All other values are within or close to the background range of 10 to 15 $\mu\text{R/h}$ (Bechtel Natl. 1983b). It is not known why the values for gamma intensities during April 1982 through September 1982 are about half the values for 1978 and 1979. Most of the 1982 values are less than or within the background range whereas the earlier values range up to more than twice the background levels.

Aerial radiological surveys were carried out for the Weldon Spring site in November 1975 (Jobst 1976) and May 1976 (Jobst 1977), and for the quarry area in July 1980 (Feimster 1982). The data were obtained by use of a sodium iodide crystal detector in repeated flights over the area. For the 1975 results, contributions from cosmic rays and radon as well as aircraft and detector background were assumed to be equivalent to the measured intensity over the Missouri River. This value was subtracted from the raw data to give the measured intensities contributed by radiation from the ground. The

resultant data, in microRoentgens per hour ($\mu\text{R/h}$), were converted to equivalent intensities over the site at 1 meter above ground. The results show essentially background values everywhere except at the quarry and raffinate pits, which appear as two discrete sources (Jobst 1976). Gamma ray intensities measured at the raffinate pits were as high as 1,200 to 1,600 $\mu\text{R/h}$. The peak value at the quarry was lower, 120 to 160 $\mu\text{R/h}$.

The 1976 survey was carried out at a finer resolution than the 1975 survey (the flight elevation was lower, 30 m, and more flight transects were flown). Raffinate Pits 3 and 4, and 1 and 2, are resolved as discrete sources and there is indication of a source 500 m north of Pit 4 which may be partly outside the fence (this may be contaminated location #3 as described in the report of Boerner [1986]). However, further detailed studies are needed (Jobst 1977). The results of the 1980 survey of the quarry area show that all areas are at background levels except for the quarry, which appears as a single source with a peak gamma intensity of 25 to 60 $\mu\text{R/h}$ (Feimster 1982).

The results of measurements of air concentrations of radon-222 at various locations and at various times from May 1977 to October 1982 are given in Table A.2. The locations are the same as those used for measurements of gamma radiation intensities and are shown in Figures A.1 and A.2. The data for the period from June 1980 through October 1982 were obtained by use of track etch (Terradex) detectors mounted at various site locations for 3 months or more. The data for 1977 and 1979 were obtained by measurement of the amount of radon in grab samples of air.

The data for the quarry and pit perimeter fences show much variability, ranging from a low of 0.10 pCi/L to a high of 4.7 pCi/L. There is also much variation with time in the data for each perimeter location. In particular, for most locations, concentrations measured in 1980 and early 1981 (up to May) are higher than concentrations measured in late 1981 and 1982. It is not clear whether this variation is real or is due to uncertainties introduced by the measurement procedure. There is less variation in the data for off-site locations, both for different locations at the same time and at the same location for different times. In addition, radon concentrations vary with seasonal and weather changes as well as day and night.

The radon concentrations for perimeter fence locations range from values close to a background value of 0.29 pCi/L measured at Florissant, Missouri (Bechtel Natl. 1984a), to concentrations that are well above background. All of the concentrations for off-site locations lie within a range of values from 0.10 to 0.66 pCi/L, which includes the background value (Table A.2).

The measured values of air concentrations of uranium (in pCi/m³) for several locations around the plant as well as for two off-site locations for the years 1959 to 1965 are presented in Table A.3. The perimeter locations for the measurements made from the fourth quarter of 1962 through 1965 are shown in Figure A.3. The locations for some of the earlier measurements are shown in Figure A.4. The on-site data are presented here because they can be useful in estimating source terms for calculation of doses to off-site populations.

Air concentrations of uranium on the plant perimeter from October 1962 through 1965 were found to be quite variable, ranging from a low value of 0.02 pCi/m³ to a high value of 0.47 pCi/m³. Concentrations measured at different locations (Figure A.4) from 1959 through September 1962 ranged from 0.007 pCi/m³ to 2.2 pCi/m³. The latter high value was measured in the first quarter of 1961 on the roof of the maintenance building. Most of the measured concentrations are higher than the single value of 0.02 pCi/m³ measured in 1965 at an off-site location, the water plant 3.2 km (2 mi) from the site.

Measurements of concentrations of radioactive species in surface water at vicinity properties locations are much more extensive than are measurements of air concentrations. This is especially true for uranium for which measurements are available for much of the 25-yr period of concern (1957-1982). The results of uranium concentration measurements for surface water at several locations from June 1974 to October 1982 are given in Table A.4. Measured uranium concentrations for the years 1959 through 1965 are given in Table A.5. No data are available for the 1966-1973 period. The locations of the sampling sites are shown in Figures A.5 through A.8. A few samples with entries in the tables are not located on the figures because their locations are not known exactly (their approximate locations are described in the tables).

At many of the sample locations -- such as 7, 8, 9, 13, 18, 20-25, and 29 -- there are low, fairly constant concentrations of uranium, especially for the later time period. These are probably background values. In general, measurements taken in the earlier time period show higher values than those taken in the 1974-1982 period. Uranium concentrations measured at other sample locations (e.g., 1-6, 10, 11, 14, 19, 30, 33, 35, 37) are higher and somewhat more erratic. This indicates the possible presence of uranium contamination at these locations.

The concentrations (in pCi/L) of radium-226 and radium-228 in surface water at different times for several locations in the Weldon Spring area are presented in Tables A.6 and A.7. The sample number locations are shown in Figures A.5, A.6, and A.7. The value of 0.45, which appears often, results from conversion of the literature value of 0.001 disintegrations/minute/mL to pCi/L; it is the lowest definite value reported.

In general, the data in the tables indicate the presence of very little or no radium for most locations over the time period of sampling. The exceptions are various locations along the process sewer drainage streams and pools east of Pit 3 (sample numbers 1-4, 14). Except for sample locations 1 and 4, the results show that the concentrations of radium-226 and radium-228 are fairly constant over the time period of sampling. The exceptions are the data for samples collected in December 1981, which show higher concentrations for most locations than do the results for samples collected at other times. It is not known whether these high concentrations are real or are an experimental artifact. One notes that the December 1981 data are the only data for which the results are presented separately as soluble radium and insoluble radium concentrations, which must be added together to get the total concentrations. This is the case for both radium-226 and radium-228 (Bechtel Natl. 1983a).

A general measure of radioactivity levels in water can be obtained by measurement of gross alpha and beta activity. The results of some measurements of these parameters for a few Weldon Spring locations and times are presented in Table A.8. The data show that, for all the sites, both alpha and beta activity concentrations fluctuate appreciably with time. In measurements taken in the Missouri River upstream and downstream from the plant on 14

sampling dates, the upstream values exceeded the downstream values -- even with the uncertainties included -- on three sampling dates for beta activity and two sampling dates for alpha activity. This is the opposite of what is expected (because downstream activity should be at least as great as upstream activity), and indicates possible experimental uncertainties other than those shown in the table.

The data in Table A.8 also indicate the presence of radioactive contamination of Busch Lake 36, based on the fact that alpha and beta activity levels in the lake are higher than in the drinking water. It is not known whether the high alpha and beta activity levels observed for both the lake and drinking water in April 1979 are real or are due to experimental error.

A small amount of monitoring data are available on concentrations of uranium-238, thorium-232, radium-226, and radium-228 in surface soils and sediments in vicinity areas of the Weldon Spring site. However, these data are not included here because they are not useful in determining dose effects to the nearby population groups that are of concern in this study.

Analyses of the radioactive contamination of fish taken from Femme Osage Slough, Femme Osage Creek, and some lakes in the Busch Wildlife Area have been carried out. The results are given in Tables A.9 and A.10. The locations of the lakes described in Table A.10 are shown in Figure A.7. Data for samples taken in 1983 and 1984 are included because they can be useful for estimating concentrations of radioactive parameters in fish for the time period of interest, 1957-1982.

Data on fish taken from Femme Osage Slough and Femme Osage Creek are included here because the area was opened to the public for recreational use, including fishing, in 1980. Prior to that, access to the area along State Route 94 was restricted because the land was used by the University of Missouri (Weidner and Boback 1982).

The data presented so far for concentrations of radioactive materials in water have been limited to surface water concentrations only. It is also of interest to determine if radioactive contamination has migrated from the site

in the groundwater and contaminated any nearby drinking water supplies. However, very few data were taken on groundwater contamination prior to the end of 1982, which is the end of the period of interest for this study. Because of this, groundwater data -- including that available for 1984 -- are presented here (Tables A.11 and A.12).

It is expected that measured values of radioactive species in groundwater near the raffinate pits represent background levels only. The reason is that, because of the thick layer of clay underlying the raffinate pits, the time required for contaminants to move from the pits to the groundwater would be expected to be appreciable. As a consequence, contaminants from the raffinate pits have not yet moved through the clay into the groundwater outside the Weldon Spring site.

The available data on uranium, radium-226, and gross alpha and beta concentrations in water in boreholes drilled around the pits and quarry for some recent collection dates are presented in Tables A.11 and A.12. The radium-226 and gross alpha and beta data also include samples from wells at nearby residences and springs in the Busch and Weldon Spring wildlife areas. The locations of some of the sampling sites are shown in Figures A.9 and A.10. Holes W1 through W7 were constructed so that water is collected from a 0.3-m (1-ft) thick layer immediately above bedrock. Depths to bedrock ranged from 6.1 m (20 ft) to more than 15 m (50 ft) (Berkeley Geosci. Assoc. 1984).

The data on concentrations of radioactive species in water in the boreholes around the raffinate pits are available for only two of the six boreholes. The remaining four had either no water or too little to yield an adequate sample. The radium concentrations for the two boreholes range from 0.1 to 3.4 pCi/L. The high value is only 4 times the value of 0.9 pCi/L, which has often been measured in incoming water to the St. Charles County Water Treatment Plant (Table A.6). The uranium concentrations range from less than 0.005 mg/L to 0.027 mg/L. The high value is only about 7 times the value 0.004 mg/L, which has often been measured for the same water source noted above for radium (Table A.4). These values suggest that little or no uranium or radium has migrated from the raffinate pits through the underlying clay to the groundwater in the bedrock. However, as noted, the data are quite sparse.

Comparison of the background values with the uranium and radium-226 concentrations in the boreholes around the quarry show little or no radium contamination. The largest value (OBS-12 in 4/82) is about 7pCi/L (15 times background). However, the uranium data show definite evidence of contamination, with values as high as 3700 pCi/L (1800 times background) in the groundwater between Femme Osage Slough and the Missouri Kansas and Texas (MKT) railroad. A more extensive sampling program also shows a zone of uranium contamination of groundwater in this area (Berkeley Geosci. Assoc. 1984). At present, it is not clear whether this is due to migration of uranium in groundwater through rock fissures from the quarry or downward migration from surface uranium contamination. The data suggest that little or no uranium contamination has migrated across or under Femme Osage Slough into the alluvium between the slough and the Missouri River. This is shown by the fact that uranium concentrations in boreholes O-3 and OBS-12 between the slough and the Missouri River are, at most, 5 pCi/L (3 times background).

According to the data in Table A.12, there is no radium-226 contamination of water in wells of nearby residences or in springs of the surrounding wildlife areas. However, there is evidence of radioactive contamination in Burgermeister Spring in that the gross alpha and beta concentrations are high. The source of this contamination is believed to be effluent from Ash Pond on the plant site (Dean 1985; Wang et al. 1986).

Estimates of discards from the plant were obtained from the materials balance study (Harris 1986). The recorded annual discards to the various plant stacks, sewers, and raffinate pits are shown in Table A.13. The annual stack discard (atmospheric release) values are engineering estimates derived from airflows and other process factors along with stack monitoring data. Because of the large volume of natural uranium processed in all plant facilities, natural uranium accounted for about 94% of the total stack discards of 45,041 kg (all uranium), or approximately 12 kg (28 lb) per day during the operating life of the plant. The chemical and physical forms of such releases varied but were essentially oxides of uranium (or their equivalent).

Table A.1. Gamma Radiation Intensities Measured at the Weldon Spring Site

Gamma Radiation Intensities (μR/h)				
Sample Number and Location	Nov 82	Apr 82– Sep 82 ^a	Nov 79	May 78– Nov 78
<u>Pit Area</u>				
1 Fence, north of Pit 3		14.5 ± 1.7	27	
2 Fence, northeast of Pit 3	25			
3 Fence, east of Pit 3		10.5 ± 1.5	25	
4 Fence, east of Pits 1 & 2		12.4 ± 1.2	37	9 sites along fence had values from 14 to 34, averaging 23
5 Fence, north of Gate	10			
6 Fence, southwest of Pits 1 & 2	234			
7 Fence, south of Pit 4		8.4 ± 20	13	
8 Fence, west of Pit 4		9.6 ± 1.6	14	
<u>Quarry Area</u>				
9 Fence along St. Rt. 94, at west end near entrance to lower gate		8.9 ± 1.5	16	
10 Fence along St. Rt. 94, at east end near upper gate		12.0 ± 1.3	37	
11 Fence, near upper gate		10.8 ± 1.0	–	
12 Fence, southeast corner along top of quarry		8.3 ± 1.5	17	
13 Fence at top of southern edge of quarry		10.2 ± 25	–	8 sites along fence had values from 16 to 41, averaging 22
14 Fence at lower quarry gate		8.2 ± 2.3	13	
<u>Offsite</u>				
15 Army Reserve site, fence behind guard office		6.9 ± 1.1		
16 University of Missouri Research Center, post near garden area		8.1 ± 2.1		
17 Busch Wildlife Area, fence at weather station		7.4 ± 1.9		
18 Busch Wildlife Area		8.2 ± 1.8		

^a Uncertainties give 95% confidence level. Background is 10 to 15 $\mu\text{R/h}$.

Sources: Nov 82, Bechtel National (1984b); Apr 82–Sep 82, Bechtel National (1983b); Nov 79 and May 78–Nov 78, NLO (1974–1981).

Table A.2. Air Radon Concentrations at the Weldon Spring Site

Sample Number and Location	Radon Concentration (pCi/L)									
	Source A ^a		Source B ^b			Source C ^c		Source D ^d		
	4/82- 9/82	12/81- 3/82	9/81- 12/81	5/81- 9/81	3/81- 5/81	11/80- 3/81	6/80- 11/80	11/79	5/79	5/77
<u>Pit Area</u>										
1 Fence, north of Pit 3	0.53	0.58	0.26	0.53	2.78	1.29	0.74 ^e	-	-	0.44
3 Fence, east of Pit 3	0.55	0.35	0.26	0.80	1.71	1.26	1.11 ^e	-	-	0.11
4 Fence, east of Pits 1 & 2	0.26	0.27	0.22	0.66	3.34	4.70	3.4 ^e	0.6	<0.5	3.0
7 Fence, south of Pit 4	0.16	0.30	0.45	1.21	0.53	0.35	0.59	-	-	0.23
8 Fence, west of Pit 4	0.24	0.84	1.52	1.07	0.87	0.50	0.56	<0.5	<0.5	0.10
<u>Quarry</u>										
9 Fence along St. Rt. 94, at west end near entrance to lower gate	0.32	0.40	0.31	0.66	0.59	0.40	0.23	-	<0.5	0.21
10 Fence along St. Rt. 94, at east end near upper gate	1.03	0.48	0.13	1.07	0.36	0.39	0.90	<0.5	0.6	0.18
11 Fence, near upper gate	0.92	0.86	0.36	1.89	0.59	1.15	0.87	<0.5	<0.5	0.40
12 Fence, southeast corner along top of quarry	1.55	1.07	1.01	2.03	1.04	0.53	0.81 ^e	-	-	1.0
13 Fence at top of southern edge of quarry	0.52	0.30	0.82	0.94	0.19	0.28	0.78 ^e	-	-	
14 Fence at lower quarry gate	0.47	0.51	0.54	0.53	- ^f	- ^f	0.50	-	<0.5	0.10

Table A.2. Continued

Sample Number and Location	Radon Concentration (pCi/L)									
	Source A ^a		Source B ^b			Source C ^c		Source D ^d		
	4/82- 9/82	12/81- 3/82	9/81- 12/81	5/81- 9/81	3/81- 5/81	11/80- 3/81	6/80- 11/80	11/79	5/79	5/77
<u>Offsite</u>										
15 Army Reserve site, fence behind guard office	0.13	0.12	0.17	0.53	0.53	0.13	0.20	-	-	-
16 University of Missouri Research Center, post near garden area	0.30	0.25	0.40	0.66	0.36	0.10	0.08	-	-	-
17 Busch Wildlife Area, fence at weather station	0.18	0.23	0.26	0.39	0.25	0.24	0.23	-	-	-
18 Busch Wildlife Area	0.41	0.15	0.22	0.53	- ^g	- ^g	- ^g	-	-	-

^a Source: Bechtel National (1983b). Values include background.

^b Source: Bechtel National (1983a).

^c Source: Weidner and Boback (1982).

^d Source: NLO (1974-1981). Measurements made on grab samples of air.

^e Filters were damaged.

^f Detectors destroyed by vandalism.

^g Sampling location installed in May 1981.

Table A.3. Air Concentrations of Uranium at the Weldon Spring Site^a

Sample Number and Location ^a	Uranium Concentration (pCi/m ³)				
	1965	1964		1963	1962
	Annual	Jul-Dec	Jan-Jun	Jan-Jun	Oct-Dec
Plant perimeter sites:					
1 North of water tower	0.15	0.27	0.22	0.12	0.17
2 North-northeast of water tower	0.06	0.23	0.30	0.02	0.048
3 Northeast of water tower	-	0.015	0.20	0.022	0.064
4 East of water tower	-	0.05	0.12	0.085	0.062
5 Southeast of water tower	0.13	0.02	0.13	0.26	0.038
6 South of water tower	0.04	0.02	0.03	0.057	0.11
7 Southwest of water tower	-	0.47	0.08	0.18	0.057
8 West of water tower	-	0.12	0.10	0.074	0.12
9 Northwest of water tower	-	0.15	0.32	0.053	0.12
Water plant 3.2 km from site	0.02	-	-	-	-
South edge of quarry	0.4	0.04	0.08	0.027	0.013

Sample Number and Location ^b	Uranium Concentration (pCi/m ³)				
	1962		1961		
	Jul-Sep	Jan-Jun	Jul-Sep	Apr-Jun	Jan-Mar
Plant perimeter sites:					
1 Northeast of plant	0.004	0.067	0.17	0.011	0.24
2 East of plant	0.10	0.11	0.015	0.083	0.54
3 North of plant	0.017	0.13	0.044	0.13	0.67
4 Northwest of plant	0.054	0.092	0.082	0.012	0.57
5 Southwest of plant	0.008	0.012	0.01	0.007	0.43
6 Southeast of plant	0.14	0.27	0.11	0.11	2.2
7 South-southwest of plant ^c	0.38	0.039	0.04	0.003	0.23
8 West of plant ^c	0.014	0.035	0.089	0.11	0.18
9 North-northwest of plant ^c	0.025	0.089	0.055	0.069	0.28
South edge of quarry	-	-	0.019	0.034	0.053

Table A.3. Continued

Sample Number and Location ^b	Uranium Concentration (pCi/m ³)				
	1960				1959
	Oct- Dec	Jul- Sep	Apr- Jun ^{c,d}	Jan- Mar ^{c,d}	Jan- Dec ^{c,d}
Plant perimeter sites:					
1 Northeast of plant	0.20	0.027	0.045	0.24	0.20
2 East of plant	0.13	0.090	0.11	0.42	0.17
3 North of plant	0.16	0.020	0.14	0.33	0.23
4 Northwest of plant	0.0093	0.029	0.065	0.24	0.05
5 Southwest of plant	0.0063	0.057	0.065	0.41	0.07
6 Southeast of plant	0.26	0.44	0.18	1.0	0.20
7 South-southwest of plant ^c	-	-	-	-	-
8 West of plant ^c	-	-	-	-	0.04
9 North-northwest of plant ^c	-	-	-	-	-
South edge of quarry	-	-	-	-	-

^a Locations are given in Figure A.3.

^b Locations are given in Figure A.4.

^c No maps showing locations are given in data source.

^d Locations are assumed to be the same as those given in Figure A.4.

Source: Mallinckrodt Chemical Works (1959-1965).

Table A.4. Concentrations of Uranium in Surface Water at Several Off-site Locations, 1974-1982^a

Sample Number and Location	Uranium Concentration (mg/L)					
	Oct 82	Apr 82	Dec 81	May 81	Nov 80	May 80
1 Process sewer outfall	1.7	2.0	1.2	1.4	1.7	2.5
2 Process sewer stream at St. Rt. 94	— ^b	— ^b	—	—	2.4	—
3 Process sewer stream near power line crossing	—	—	—	—	—	—
4 Process sewer stream near MKT railroad	—	—	—	—	—	—
5 Northwest stream, onsite	— ^b	3.0	2.9	—	0.04	0.08
6 Northwest stream, offsite at County Road D	— ^b	1.3	0.81	0.68	0.06	0.12
7 St. Charles County water treatment plant, incoming flow	<0.005	<0.005	<0.005	<0.003	<0.003	<0.003
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	0.021	<0.005	0.023	<0.003	<0.003	0.005
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	<0.005	<0.005	0.19	<0.003	0.004	<0.003
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.11	0.15	0.21	0.04	—	0.10
11 Femme Osage Slough, 280 m (920 ft) south-east of quarry pool	0.081	0.19	0.035	0.03	0.06	0.07
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.079	0.14	0.030	0.01	0.02	0.02
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	—	—	0.006	<0.003	<0.003	0.009
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base at pit wall	—	—	—	0.15	—	1.0
15 Outlet, Busch Lake 35	—	—	—	—	—	—
16 Inlet, Busch Lake 35	—	—	—	—	—	—
17 Busch Wildlife Area, stream between Lake 35 and County Road D	—	—	—	—	—	—

Table A.4. Continued

Sample Number and Location	Uranium Concentration (mg/L)					
	Nov 79	May 79	Nov 78	May 78	Nov 77	Jun 77
1 Process sewer outfall	1.4	1.4	1.9	2.0	1.4	1.4
2 Process sewer stream at St. Rt. 94	2.2	1.3	-	-	-	-
3 Process sewer stream near power line crossing	-	1.2	-	-	-	-
4 Process sewer stream near MKT railroad	-	0.40	-	-	-	-
5 Northwest stream, onsite	0.10	0.13	1.5	0.76	1.5	0.04
6 Northwest stream, offsite at County Road D	0.027	2.2	1.4	0.32	1.3	0.05
7 St. Charles County water treatment plant, incoming flow	0.004	0.003	0.002	0.004	0.002	0.004
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	0.003	0.002	0.003	0.003	0.003	0.003
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	0.003	0.004	0.003	0.001	0.004	0.004
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.30	0.13	0.12	0.10	0.14	0.28
11 Femme Osage Slough, 280 m (920 ft) south-east of quarry pool	0.16	0.15	0.14	0.26	0.02	0.01
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.03	0.05	0.12	0.06	0.008	0.009
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	0.005	0.003	0.003	0.001	0.003	0.001
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base at pit wall	0.70	0.06	0.04	-	-	-
15 Outlet, Busch Lake 35	-	-	-	-	-	-
16 Inlet, Busch Lake 35	-	-	-	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	-	-	-	-

Table A.4. Continued

Sample Number and Location	Uranium Concentration (mg/L) ^a					
	Oct 76	May 76	Oct 75 ^c	May 75	Nov 74	Jun 74
1 Process sewer outfall	2.8	0.78	0.90	1.8	3.0	1.4
2 Process sewer stream at St. Rt. 94	-	-	-	-	-	-
3 Process sewer stream near power line crossing	-	-	-	-	-	-
4 Process sewer stream near MKT railroad	-	-	-	-	-	-
5 Northwest stream, onsite	0.03	0.14	0.04	0.20	1.8	0.22
6 Northwest stream, offsite at County Road D	0.05	0.24	0.054	0.26	1.4	-
7 St. Charles County water treatment plant, incoming flow	0.001	0.003	0.003	0.003	0.003	0.002
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	0.001	0.004	0.008	0.001	-	-
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	0.002	0.002	0.004	0.002	-	-
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.14	0.50	0.40	-	-	-
11 Femme Osage Slough, 280 m (920 ft) south-east of quarry pool	-	0.16	0.074	0.19	-	-
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.04	-	0.058	0.067	-	0.06
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	0.004	0.004	-	-	0.004	-
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base at pit wall	-	-	-	-	-	-
15 Outlet, Busch Lake 35	-	-	0.036	-	-	-
16 Inlet, Busch Lake 35	-	-	0.035	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	0.044	-	-	-

^a 1 pCi/L of natural uranium is equivalent to 0.0015 mg/L.

^b No water in stream.

^c Drain weir from pits to process sewer closed in August 1975.

Sources: 1982 and December 1981, Bechtel National (1983a, 1983b); all other data, NLO (1974-1981).

Table A.5. Concentrations of Uranium in Surface Water at Several Off-site Locations, 1959-1965

Sample Number and Location	Uranium Concentration (mg/L) ^a										
	1965	1964		1963	1962		1961		1960		1959
	Annual	Dec	Jul-Jun	Jan-Jun	Jan-Dec	Jul-Jun	Jan-Sep	Jul-Jun	Jan-Dec	Jul-Jun	Jan-Annual
18 Dardenne Creek, upstream	<0.03	0.009	0.009	0.012	0.003	0.003	<0.003	0.009	0.009	0.21	0.09
19 Schote Creek County Rd, K Bridge	0.06	0.015	0.033	0.054	0.024	0.10	0.06	0.075	0.042	0.15	0.09
20 Cottleville Bridge	<0.03	0.012	0.012	0.021	0.009	0.009	0.021	0.012	0.021	0.09	0.09
21 St. Peters Bridge	<0.03	0.012	0.006	0.012	0.006	0.009	0.009	0.015	0.038	0.32	0.09
22 Kampville Bridge	<0.03	0.009	0.006	0.021	0.006	0.012	0.012	0.012	0.021	0.12	0.09
23 U.S. 40/61, Missouri Bridge, south side	<0.03	0.012	0.006	0.024	0.006	0.003	0.003	0.009	0.006	0.09	0.12
24 St. Louis Water Plant, Missouri River	<0.03	0.012	0.006	0.006	0.006	0.006	0.003	0.006	0.006	0.12	0.21
25 St. Charles Water Plant, Missouri River	<0.03	0.009	0.009	0.024	0.003	0.006	0.003	0.006	0.006	0.10	0.12
26 Busch Lake No. 9	<0.03	0.009	0.012	0.012	0.003	0.006	0.003	0.007	0.003	0.11	0.09
27 Busch Lake No. 10	0.03	0.015	0.006	0.003	0.006	0.006	0.006	0.009	0.007	0.14	0.06
28 Busch Lake No. 16	<0.03	0.006	0.006	0.006	0.003	-	-	-	-	-	-
29 Schote Creek, upstream	<0.03	0.02	0.009	0.006	0.003	0.003	0.006	0.006	0.018	0.15	0.09
30 West plant surface drainage	1.5	0.6	2.0	0.42	0.39	1.2	2.3	1.2	0.24	0.27	0.15
6 North plant surface drainage	0.9	0.6	0.5	0.48	0.51	1.4	0.51	1.3	1.2	0.72	0.51
31 Femme Osage outfall to Missouri River	<0.03	0.015	0.033	0.003	<0.003	0.003	0.009	0.015	0.009	-	-
4 Plant process sewer inlet to Missouri River	0.21	0.012	0.06	0.63	0.6	0.84	0.33	1.2	1.5	-	-
32 Defiance, upstream, Missouri River	<0.03	-	0.006	0.006	0.012	0.003	0.03	0.012	0.03	-	-
33 Lake across plant entrance (Busch Area)	0.045	0.012	0.018	0.03	0.024	0.009	0.003	0.022	-	-	-
34 Tributary, Little Femme Osage Creek	<0.03	0.018	0.018	<0.003	0.003	0.003	0.003	0.002	0.002	-	-
8 Little Femme Osage Creek, upstream	<0.03	0.009	0.006	<0.003	<0.003	0.012	0.0075	0.012	0.004	-	-
35 Little Femme Osage Creek, discharge culvert	<0.03	0.012	0.006	0.15	<0.003	0.11	0.014	0.011	0.005	-	-
9 Little Femme Osage Creek, MKT bridge	<0.03	0.02	0.006	<0.003	<0.003	0.006	0.003	0.014	0.003	-	-
36 Little Femme Osage Creek, downstream	<0.03	0.2	0.018	<0.003	<0.003	0.003	0.004	0.007	0.002	-	-
37 Process sewer	1.3	3.1	1.3	2.6	1.4	0.78	0.69	0.84	3.3	2.0	0.9
38 Gerald Wright's well	-	-	0.003	-	-	-	-	-	-	-	-
39 Busch Lake No. 11	-	-	-	-	-	0.003	0.003	0.0048	0.0045	0.13	0.06

^a 1 pCi/L of natural uranium is equivalent to 0.0015 mg/L.

Source: Mallinckrodt Chemical Works (1959-1965).

Table A.6. Concentrations of Radium-226 in Surface Water at Several Weldon Spring Locations, 1974-1982^a

Sample Number and Location	Radium-226 Concentration (pCi/L)					
	Oct 82 ^a	Apr 82 ^a	Dec 81 ^a	May 81 ^a	Nov 80	May 80
1 Process sewer outfall	3.0	3.3	5.9	1.8	5.4	9.0
2 Process sewer stream at St. Rt. 94	- ^b	- ^b	-		3.6	<0.45
3 Process sewer stream near power line crossing	-	-	-		-	-
4 Process sewer stream near MKT railroad	-	-	-		-	-
5 Northwest stream, onsite	- ^b	<0.12	2.7		<0.45	<0.45
6 Northwest stream, offsite at County Road D	- ^b	<0.10	2.4	<0.45	<0.45	<0.45
7 St. Charles Co. water treatment plant, incoming flow	0.72	0.6	<1.1	0.90	0.45	0.90
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	0.2	0.3	3.1	<0.45	<0.45	<0.45
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	0.2	0.1	3.0	<0.45	<0.45	<0.45
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.2	0.5	3.0	<0.45	-	0.45
11 Femme Osage Slough, 280 m (920 ft) southeast of quarry pool	0.2	0.2	0.86	0.45	0.45	<0.45
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.5	0.1	0.90	0.45	0.45	<0.45
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	-	-	<0.77	<0.45	<0.45	<0.45
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base at pit wall	-	-	-	31	-	0.45
15 Outlet, Busch Lake 35	-	-	-	-	-	-
16 Inlet, Busch Lake 35	-	-	-	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	-	-	-	-

Table A.6. Continued

Sample Number and Location	Radium-226 Concentration (pCi/L)					
	Nov 79	May 79	Nov 78	May 78	Nov 77	Jun 77
1 Process sewer outfall	22	12	4.0	6.3	4.0	2.7
2 Process sewer stream at St. Rt. 94	7.2	4.9	-	-	-	-
3 Process sewer stream near power line crossing	-	-	3.1	-	-	-
4 Process sewer stream near MKT railroad	-	2.7	-	-	-	-
5 Northwest stream, onsite	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
6 Northwest stream, offsite at County Road D	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
7 St. Charles Co. water treatment plant, incoming flow	0.45	0.45	0.90	0.90	0.90	0.90
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
11 Femme Osage Slough, 280 m (920 ft) southeast of quarry pool	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.90	<0.45	<0.45	<0.45	<0.45	<0.45
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	<0.45	<0.45	<0.45	<0.45	<0.45	<0.45
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base at pit wall	0.45	15	<0.45	-	-	-
15 Outlet, Busch Lake 35	-	-	-	-	-	-
16 Inlet, Busch Lake 35	-	-	-	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	-	-	-	-

Table A.6. Continued

Sample Number and Location	Radium-226 Concentration (pCi/L)					
	Oct 76	May 76	Oct 75 ^c	May 75	Nov 74	Jun 74
1 Process sewer outfall	45	36	7.9	63	77	150
2 Process sewer stream at St. Rt. 94	-	-	-	- -	-	-
3 Process sewer stream near power line crossing	-	-	-	-	-	-
4 Process sewer stream near MKT railroad	-	-	-	-	-	-
5 Northwest stream, onsite	<0.45	<0.45	<0.45	<0.45	0.45	<0.45
6 Northwest stream, offsite at County Road D	<0.45	<0.45	<0.45	<0.45	<0.45	-
7 St. Charles Co. water treatment plant, incoming flow	0.90	0.90	0.90	0.90	0.90	0.90
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	<0.45	0.45	<0.45	<0.45	-	-
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	<0.45	<0.45	0.45	<0.45	-	-
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.45	<0.45	<0.45	-	-	-
11 Femme Osage Slough, 280 m (920 ft) southeast of quarry pool	-	0.45	<0.45	<0.45	-	-
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.45	0.45	<0.45	<0.45	-	-
13 Background sample from spring at junction of St. Rt 94 and U.S. 40/61	<0.45	<0.45	-	-	<0.45	<0.45
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base at pit wall	-	-	-	-	-	-
15 Outlet, Busch Lake 35	-	-	<0.45	-	-	-
16 Inlet, Busch Lake 35	-	-	<0.45	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	<0.45	-	-	-

^a Source: Bechtel National (1983a, 1983b).

^b No water present.

^c Drain weir to sewer from pits closed in August 1975.

Source: NLO (1974-1981) unless otherwise noted.

Table A.7. Concentrations of Radium-228 in Surface Water at Several Weldon Spring Locations, 1974-1981^a

Sample Number and Location	Radium-228 Concentration (pCi/L)					
	Dec 81 ^a	May 81 ^a	Nov 80	May 80	Nov 79	May 79
1 Process sewer outfall	<7.2	1.35	1.8	<0.45	<4.5	1.35
2 Process sewer stream at St. Rt. 94	-	-	<0.45	<0.45	<4.5	0.45
3 Process sewer stream near power line crossing	-	-	-	-	-	<0.45
4 Process sewer stream near MKT railroad	-	-	-	-	-	<0.45
5 Northwest stream, onsite	<6.9	-	0.45	<0.45	<0.45	<0.45
6 Northwest stream, offsite at County Road D	<7.0	0.45	<0.45	<0.45	<0.45	<0.45
7 St. Charles County water treatment plant, incoming flow	<7.1	0.45	1.35	0.45	0.45	1.35
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	<6.7	0.90	0.45	0.90	<0.45	<0.45
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	<7.0	0.45	0.45	0.90	<0.45	0.45
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	<7.3	0.90	-	0.45	0.45	0.45
11 Femme Osage Slough, 280 m (920 ft) south-east of quarry pool	<8.1	1.35	0.45	0.45	-	0.45
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	<6.7	0.90	<0.45	0.90	-	0.45
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	<7.0	<0.45	<0.45	0.45	<0.45	<0.45
14 Pools about 15 m (50) ft east of Pit 3 discharge point near base of pit wall	-	9.0	-	6.3	4.5	<4.5
15 Outlet, Busch Lake 35	-	-	-	-	-	-
16 Inlet, Busch Lake 35	-	-	-	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	-	-	-	-

Table A.7. Continued

Sample Number and Location	Radium-228 Concentration (pCi/L)				
	Nov 78	May 78	Nov 77	Jun 77	Oct 76
1 Process sewer outfall	0.45	<0.45	0.45	4.5	<4.5
2 Process sewer stream at St. Rt. 94	-	-	-	-	-
3 Process sewer stream near power line crossing	-	-	-	-	-
4 Process sewer stream near MKT railroad	-	-	-	-	-
5 Northwest stream, onsite	0.45	<0.45	<0.45	1.35	<0.45
6 Northwest stream, offsite at County Road D	1.35	0.90	<0.45	0.45	0.45
7 St. Charles County water treatment plant, incoming flow	<0.45	0.45	0.90	1.8	0.90
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	0.90	0.90	0.45	0.45	<0.45
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	0.45	0.45	0.45	0.90	0.45
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.90	1.35	0.45	0.90	0.45
11 Femme Osage Slough, 280 m (920 ft) south-east of quarry pool	0.90	0.90	0.45	0.45	-
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.45	0.45	<0.45	<0.45	1.35
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	0.45	<0.45	<0.45	0.45	<0.45
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base of pit wall	0.90	-	-	-	-
15 Outlet, Busch Lake 35	-	-	-	-	-
16 Inlet, Busch Lake 35	-	-	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	-	-	-	-

Table A.7. Continued

Sample Number and Location	Radium-228 Concentration (pCi/L)				
	May 76	Oct 75 ^b	May 75	Nov 74	Jun 74
1 Process sewer outfall	<4.5	<0.45	1.8	9.0	4.5
2 Process sewer stream at St. Rt. 94	-	-	-	-	-
3 Process sewer stream near power line crossing	-	-	-	-	-
4 Process sewer stream near MKT railroad	-	-	-	-	-
5 Northwest stream, onsite	<0.45	<0.45	0.45	0.45	0.90
6 Northwest stream, offsite at County Road D	<0.45	<0.45	0.45	0.45	-
7 St. Charles County water treatment plant, incoming flow	0.90	2.2	1.35	1.35	1.8
8 Little Femme Osage Creek at St. Rt. 94, upstream from quarry	<0.45	<0.45	0.45	-	-
9 Little Femme Osage Creek at MKT railroad bridge, downstream from quarry	<0.45	<0.45	0.45	-	-
10 Little Femme Osage Slough, 200 m (670 ft) southwest of quarry pool	0.45	<0.45	-	-	-
11 Femme Osage Slough, 280 m (920 ft) south-east of quarry pool	<0.45	0.90	0.45	-	-
12 Femme Osage Slough, 820 m (2680 ft) east of quarry pool	0.45	0.45	0.45	-	1.35
13 Background sample from spring at junction of St. Rt. 94 and U.S. 40/61	0.90	-	-	0.90	-
14 Pools about 15 m (50 ft) east of Pit 3 discharge point near base of pit wall	-	-	-	-	-
15 Outlet, Busch Lake 35	-	0.45	-	-	-
16 Inlet, Busch Lake 35	-	1.35	-	-	-
17 Busch Wildlife Area, stream between Lake 35 and County Road D	-	<0.45	-	-	-

^a Source: Bechtel National (1983a).

^b Drain weir to sewer from pits closed in August 1975.

Source: NLO (1974-1981) unless otherwise indicated.

Table A.8. Gross Alpha and Beta Activity in Surface Water at Different Weldon Spring Locations, 1977-1982^a

Sample Date	Busch Wildlife Area				Missouri River				Weldon Spring Water Supply Treatment Plant	
	Busch Lake 36		Drinking Water		Upstream ^b		Downstream ^b		Alpha (pCi/L)	Beta (pCi/L)
	Alpha (pCi/L)	Beta (pCi/L)	Alpha (pCi/L)	Beta (pCi/L)	Alpha (pCi/L)	Beta (pCi/L)	Alpha (pCi/L)	Beta (pCi/L)	Alpha (pCi/L)	Beta (pCi/L)
Dec 82	32 ± 4	24 ± 2	1.2 ± 1.1	5.2 ± 1.1	6.5 ± 2.5	11 ± 1.4	8.2 ± 2.7	12 ± 1.5	<2.3	5.3 ± 1.3
Sep 82	16 ± 3	14 ± 2	<0.7	5.4 ± 1.1	11 ± 4	20 ± 4	13 ± 5	26 ± 4	2.8 ± 1.8	4.7 ± 1.5
May 82	28 ± 4.1	25 ± 2.7	9.4 ± 1.4	<10	31 ± 8	84 ± 4	31 ± 8	8.1 ± 4	<17	<14
Dec 81	35 ± 4	29 ± 2	1.8 ± 1.0	4.9 ± 1.2	4.0 ± 2.3	9.0 ± 2.1	3.8 ± 2.3	10 ± 2	<3.1	7.1 ± 2.1
Sep 81	22 ± 3	18 ± 2	<1.1	2.9 ± 1.1	4.4 ± 2.6	9.8 ± 2.4	5.8 ± 2.6	13 ± 3	<1.1	5.0 ± 1.3
Jul 81	45 ± 4	53 ± 2	11 ± 1.5	19 ± 2	8.2 ± 2.5	26 ± 2	<10	20 ± 2	<3.6	7.4 ± 1.6
Mar 81	86 ± 10	59 ± 5	1.3 ± 0.8	4.9 ± 1.1	2.6 ± 1.9	13 ± 2	4.6 ± 2.4	12 ± 2	<2.2	6.4 ± 1.6
Sep 80	30 ± 5	25 ± 2.5	<4	<5	<6.2	17 ± 2	-	-	<4.9	<7.1
Apr 80	33 ± 7	23 ± 3	<3.6	<5.1	<7.9	19 ± 2	<7.9	23 ± 2	<7.0	6.4 ± 2.0
Sep 79	82 ± 11	65 ± 5	-	-	51 ± 8	53 ± 5	<13	<14	<13	<14
Apr 79	320 ± 14	124 ± 4	<110	<100	<17	32 ± 6	<14	34 ± 6	<9.4	<7.7
Oct 78	2.3 ± 1.1	6.7 ± 1.3	<0.7	4.8 ± 1.1	30 ± 12	34 ± 4	31 ± 11	29 ± 3	<0.7	5.1 ± 1.3
May 78	-	-	-	-	6.0 ± 2.6	9.7 ± 1.4	7.3 ± 3.4	11 ± 2	<1.1	4.5 ± 1.1
Sep 77	-	-	-	-	22 ± 5	38 ± 2	<6.3	28 ± 2	-	-

^a Data given to two significant figures. Uncertainties represent two standard deviations and refer to counting statistics only. For several dates for which concentrations in dissolved and suspended components are given separately, values are sums of concentrations in dissolved and suspended components of water samples.

^b From chemical plant outfall.

Source: Peterson (1985).

Table A.9. Analysis of Fish from Femme Osage Slough and Femme Osage Creek

Sample Date and Description		Wet Weight (g)	Concentrations ^{a,b}					
			Total U	Th-232	Ra-226	Pb-210		
<u>Femme Osage Slough</u>								
6/80 - 4 Bullhead, 4 Big Mouth Buffalo								
	Edible part	534	<0.002	0.005±0.001	0.0008±0.0002	0.006±0.001		
	Bone part	102	0.084±0.015	<0.011	0.008±0.001	0.029±0.005		
6/80 - 4 Carp								
	Edible part	834	<0.001	0.006±0.002	0.076±0.0004	0.002±0.001		
	Bone part	158	0.108±0.015	0.017±0.012	0.0077±0.0007	0.026±0.006		
6/80 - 1 Largemouth Bass, 3 Bluegill, 6 Sunfish, 5 White Crappie								
	Edible part	434	0.003±0.002	<0.002	0.0088±0.0007	0.004±0.002		
	Bone part	91	<0.020	<0.011	0.017±0.002	<0.020		
6/80 - 1 Carp								
	Edible part	1178	0.039±0.004	0.008±0.002	0.011±0.006	0.080±0.008		
	Bone part	166	0.29±0.020	<0.011	0.023±0.002	0.026±0.006		

			Concentrations ^{a,b}					
Sampling Date	Sample Description	Total U	Th-232	Th-230	Th-228	Ra-228	Gross Alpha	Gross Beta
<u>Femme Osage Slough</u>								
2/84	Bluegill	0.036	0 ^c	0.009	0.007	0.006	0.001	3
3/83	Carp	0.018	0.004	0.005	0.009	0.004	0 ^c	4
3/83	Buffalo	0.014	0 ^c	0.024	0 ^c	0.003	0.08	3.3
<u>Femme Osage Creek</u>								
3/83	Carp	0.0095	0.002	0.004	0.003	0 ^c	0.014	2.9
3/83	Buffalo	0.005	0 ^c	0 ^c	0 ^c	0.001	0 ^c	2.6

^a Total uranium concentrations are given in µg/g wet weight. Concentrations of all other parameters are given in pCi/g wet weight. Where given, error limits are two standard deviations.

^b 1 µg/g total uranium is equivalent to 0.67 pCi/g.

^c The source reference (deRoos 1984) lists these entries as negative values. They have been replaced by zeros because negative values are not possible. A possible explanation for the negative concentrations is subtraction of a background count rate that is larger than the sample count rate.

Sources: 1980 data from Weidner and Boback (1982); 1983-1984 data from deRoos (1984).

Table A.10. Analysis of Fish from the August A. Busch Memorial Wildlife Area^a

Location, Fish type	Date of Sample Collection	Radionuclide Concentrations ^a (pCi/g wet weight edible part (fillet))						
		Gross Alpha	Gross Beta	Ra-226	Th-230	Th-232	Th-228	U ^a
<u>Lake 9</u>								
Largemouth bass	2/28/83	0.009	3.1	0.007	0.002	0.001	0.00009	0.006
Carp	2/28/83	0	3.3	0.001	0.002	0.0004	0	0.011
<u>Lake 10</u>								
Largemouth bass	2/28/83	0	3.0	0.001	0.003	0 ^b	0.006	0.008
Channel catfish	4/20/83	0.02	3.3	0.004	0.003	0	0.002	0.026
<u>Lake 34</u>								
Bluegill ^c	2/23/84	0 ^b	3.4	0.021	-	-	-	0.085
Tiger musky	2/3/84	0	3.4	0.0006	0.004	0.0001	0.002	0.012
Channel catfish	2/3/84	0 ^b	3.0	0.0008	-	-	-	0.008
Grass carp	2/3/84	0	4.9	0.003	0.003	0.001	0.006	0.007
<u>Lake 35</u>								
Largemouth bass	3/1/83	0	3.7	0.0004	0.0002	0.0006	0.003	0.007
Channel catfish	3/1/83	0.009	3.0	0.002	-	-	-	0.003
<u>Lake 36</u>								
Largemouth bass	3/1/83	0.02	3.2	0.0002	-	-	-	0.006
Channel catfish	5/19/83	0.016	3.0	0.002	0.011	0.002	0 ^b	0.011

^a A hyphen means that no values were measured. Uranium concentrations are given in µg/g. 1 µg/g of total uranium is equivalent to 0.67 pCi/g.

^b These values represent negative measured values. See footnote c of Table A.9.

^c Bluegills were not filleted. They were decapitated, eviscerated, and scaled.

Source: Adapted from deRoos (1984).

Table A.11. Concentrations of Uranium in Water in Boreholes at Several Locations, 1980-1983

Sample Number and Location		Uranium Concentrations (mg/L) ^a				
		1983	Oct 82	Apr 82	1981	1980
W1	South of Pit 4	- ^b	-	-	-	-
W2	West of Pit 4	0.027	<0.005	0.017	-	-
W3	Northeast of Pit 4	-	-	-	-	-
W4	Northeast of Pit 3	-	-	-	-	-
W5	Between Pits 3 and 4	-	0.010	0.024	-	-
W7	East of Pit 3	-	-	-	-	-
TWIN	North of quarry	-	-	-	-	0.12
OB-6	Between Femme Osage Slough and MKT railroad	6.1	6.8	6.6	-	4.4
OB-10	Between Femme Osage Slough and MKT railroad	6.8	6.5	7.6	9.2	7.2
O-3	South of Femme Osage Slough	0.007	<0.005	<0.005	<0.002	-
OBS-12	South of Femme Osage Slough	0.005	0.017	<0.005	>0.002	-
OB-1	West of quarry fence	0.013	0.026	0.007	N.D. ^b	0.16

^a 1 mg/L total uranium is equivalent to 670 pCi/L.

^b A hyphen indicates either that the hole was dry or insufficient water was present to obtain a sample. N.D. means not detectable.

Sources: 1983, Bechtel National (1984a); Oct 82 and Apr 82, Bechtel National (1983b); 1981 and 1980, Berkeley Geoscience Associates (1984).

Table A.12. Concentrations of Radium-226, Gross Alpha, and Gross Beta in Borehole Water at Several Locations, 1982-1984

Sample Number and Location		Radium-226 Concentrations (pCi/L)				Gross Alpha	Gross Beta
		Jan 84	1983	Oct 82	Apr 82	Jan 84 (pCi/L)	Jan 84 (pCi/L)
W1	South of Pit 4	-	- ^a	-	-	-	-
W2	West of Pit 4	-	0.1 ± 0.1	1.0 ± 0.3	0.6	-	-
W3	Northeast of Pit 4	-	-	-	-	-	-
W4	Northeast of 3	-	-	-	-	-	-
W5	Between Pits 3 and 4	-	-	3.4 ± 1.0	3.0 ± 1.0	-	-
W7	East of Pit 3	-	-	-	-	-	-
OB-1	West of quarry fence	-	2.0 ± 1.0	0.4 ± 0.1	6.0 ± 1.0	-	-
OB-6	Between Femme Osage Slough and MKT railroad	-	3.0 ± 1.0	0.3 ± 0.1	4.0 ± 1.0	-	-
OB-10	Between Femme Osage Slough and MKT railroad	-	1.4 ± 0.4	<0.1	0.8 ± 0.5	-	-
O-3	South of Femme Osage Slough	-	0.1	0.3 ± 0.1	4.0 ± 1.0	-	-
OBS-12	South of Femme Osage Slough	-	0.4 ± 0.1	0.9 ± 0.3	7.0 ± 1.0	-	-
	Spring at Busch Lake 33	0.2	-	-	-	1.5	2.5
	Well at Shaw residence	0.5	-	-	-	1.5	1.1
	Burgermeister Spring	0.3	-	-	-	135 ^b	36 ^b
	Well at Saladin residence	0.3	-	-	-	2.3	2.9
	Well at Cassidy residence	0.3	-	-	-	1.0	1.5
	Well at Busch Headquarters	0.5	-	-	-	2.7	1.1
	Well at Beffa residence	0.3	-	-	-	1.3	<1.0
	Spring #1 Lost Valley	-	-	-	-	1.0	2.1
	Spring #2 Lost Valley	-	-	-	-	1.9	<1.0

^a A dash indicates insufficient water for analysis.

^b Values for samples collected in March 1984 were 76 pCi/L (gross alpha) and 22 pCi/L (gross beta).

^c The residences are located within the Busch Wildlife Area (Figure A.7).

Sources: Jan 84, deRoos (1984); 1983, Bechtel National (1984a); Oct 82 and Apr 82, Bechtel National (1983b).

Table A.13. Annual Discards to Stacks, Sewers, and Raffinate Pits from Weldon Spring Plant Operations^a

Fiscal Year	Discards (kg/yr)					
	Natural Uranium			Depleted Uranium		
	Stacks	Sewers	Raffinate Pits	Stacks	Sewers	Raffinate Pits
1958	-	-	-	-	-	-
1959	-	-	-	-	-	-
1960	7,200	3,472	46,193	-	-	-
1961	7,200	6,461	12,502	0	0	0
1962	7,200	4,304	8,831	0	0	46
1963	7,200	6,374	18,448	0	0	0
1964	7,483	3,239	35,243	0	0	0
1965	4,200	1,254	13,069	0	0	0
1966	4,158	1,411	18,067	0	0	0
1967	<u>100</u>	<u>205</u>	<u>29</u>	<u>0</u>	<u>0</u>	<u>0</u>
TOTAL	44,741	26,720	152,382	0	0	46

Fiscal Year	Discards (kg/yr)					
	Slightly Enriched Uranium			Natural Thorium		
	Stacks	Sewers	Raffinate Pits	Stacks	Sewers	Raffinate Pits
1958	-	-	-	-	-	-
1959	-	-	-	-	-	-
1960	-	-	-	-	-	-
1961	0	0	0	0	0	0
1962	0	0	0	0	0	0
1963	0	0	0	0	0	0
1964	0	0	0	0	0	2,469
1965	300	979	2,828	0	0	16,170
1966	0	0	(20)	0	0	26,809
1967	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>30,750</u>
TOTAL	300	979	2,808	0	0	76,198

^a Discards were measured or estimated during plant operations and were added to offsite shipments for the respective year to determine total removals. Discards to raffinate pits in AEC Fiscal Years 1958 and 1959 (July 1, 1957, to June 30, 1959) were held in inventory as "potentially recoverable." Beginning in AEC Fiscal Year 1960 (July 1, 1959, to June 30, 1960), all previous and then current releases to the raffinate pits were treated as discards and removed from the operating inventory as the discards occurred.

Source: Harris (1986).

Figure A.1. Radon Monitoring (Terradex Detectors) and External Gamma Radiation Monitoring (TLD) Locations at the Weldon Spring Raffinate Pits and Nearby Off-site Areas. In this figure and in following figures, the numbers by the black triangles or dots refer to the sample numbers in the tables. Source: Adapted from Bechtel National (1984a).

Figure A.2. Radon Monitoring (Terradex Detectors) and External Gamma Radiation Monitoring (TLD) Locations at the Weldon Spring Quarry Site. Source: Adapted from Bechtel National (1983b).

Figure A.3. Sampling Locations on Perimeter of Weldon Spring Chemical Plant for Air Concentrations of Uranium. Source: Adapted from Mallinckrodt Chemical Works (1959-1965).

Figure A.4. Sampling Locations at Weldon Spring Chemical Plant for Air Concentrations of Uranium.
 Source: Adapted from Mallinckrodt Chemical Works (1959-1965).

Figure A.5. Water Sampling Locations at Waste Pit Area and Plant Site. The numbers denote the sample numbers given in Tables A.4 and A.5. Source: Adapted from Weidner and Boback (1982).

Figure A.6. Water Sample Locations at Quarry Area. The numbers denote the sample numbers as given in Tables A.4 and A.5. Source: Adapted from Weidner and Boback (1982).

Figure A.7. Water Sampling Locations in Busch Wildlife Area. The numbers enclosed in boxes denote the sample numbers given in Tables A.4 and A.5. Source: Adapted from deRoos (1984).

Figure A.8. Water Sampling Locations in the Vicinity of the Weldon Spring Site. The numbers denote the sample numbers as given in Tables A.4 and A.5. Source: Adapted from Mallinckrodt Chemical Works (1959-1965).

Figure A.9. Groundwater Sampling Locations at the Raffinate Pits.
Source: Adapted from Bechtel National (1984a).

Figure A.10. Groundwater Sampling Locations in the Vicinity of the Quarry. Source: Adapted from Bechtel National (1983b, 1984a).

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APPENDIX B. CALCULATIONAL DETAILS

B.1 CALCULATION OF AIR DISPERSION

The model used to estimate the ground-level concentration $C(r,\theta)$ downwind from a continuous source of emission is a gaussian plume model averaged over the cross-wind direction. The model, modified to correct for plume reflections, gives the following expressions for the ground-level concentration $C(r,\theta)$ at a location (r,θ) due to a point source Q at $(0,0)$

$$C(r,\theta) = \frac{nQ}{\pi\sqrt{2\pi}r\sigma\bar{u}(\theta)} \exp\left(-\frac{1}{2}\left(\frac{h}{\sigma}\right)^2\right) \quad (\text{B.1})$$

or

$$C(r,\theta) = \frac{Q}{2\pi r L} \quad (\text{B.2})$$

The particular atmospheric stability conditions that determine whether Equation B.1 or B.2 is used are given in Giardini and Yuan (1983). In the above equations,

n is the number of sectors used (16 in this case)

$\bar{u}(\theta)$ is the average wind speed in the direction θ

h is the source height

σ is vertical dispersion coefficient

L is the mixing height

The vertical dispersion coefficient σ is a parametric function of the distance from the source, with the parameters assuming different values for different atmospheric stability conditions (Gifford 1976; Martin and Tickvart 1968). It can be represented by the following formula

$$\sigma = ar^b + c \quad (\text{B.3})$$

where a , b , and c are constants that depend on the stability class, as shown in Table B.1.

Table B.1. Values of Constants Used to Estimate Martin-Tickvart Vertical-Dispersion Coefficients^a

Downwind Distance	Stability Class ^b	Constant		
		a	b	c
>1000 m	A	0.00024	2.094	-9.6
	B	0.55	1.098	2.0
	C	0.113	0.911	0.0
	D	1.26	0.516	-13
	E	6.73	0.305	-34
	F	18.05	0.18	-48.6
100-1000 m	A	0.00066 ^c	1.941	9.27
	B	0.0382 ^c	1.149	3.3
	C	0.113	0.911	0.0
	D	0.222	0.725	-1.7
	E	0.211	0.678	-1.3
	F	0.086	0.74	-0.35
<100 m	A	0.192	0.936	0.0
	B	0.156	0.922	0.0
	C	0.116	0.905	0.0
	D	0.079	0.881	0.0
	E	0.063	0.871	0.0
	F	0.053	0.814	0.0

^a Modified from Eimutis and Konicek (1972).

^b A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = moderately stable, F = very stable.

^c The values 0.0015 and 0.028 given by Eimutis and Konicek (1972) were typographical errors in the original work.

The atmospheric stability conditions are grouped into six classes ranging from extremely unstable (A) to very stable (F) (based on criteria by Pasquill 1974). The mixing height L , appearing in Equation B.2, is expressed in terms of the mean annual morning and afternoon mixing heights, L_{am} and L_{pm} , and it also depends on the atmospheric stability class (Powell et al. 1979). This dependence as well as the numerical values for the St. Louis region are shown in Table B.2. The discontinuities at sector boundaries, due to the sector-average approximation, are corrected by a linear interpolation of concentration between sector centerlines. For each radionuclide i , Equations B.1 and B.2 are used to compute the concentration $C_i(r, \theta, \bar{u}, Q, S)$ at the location (r, θ) at the wind speed $\bar{u}$, due to the source Q for a stability class S . The average annual concentration $\bar{C}_i$ is calculated by summing all concentrations $C_i(r, \theta, \bar{u}, Q, S)$ weighted by frequencies of $F(\bar{u}, \theta, S)$ over wind speed, direction, and stability class.

Table B.2. Mean Annual Mixing Height, L , in Terms of Morning and Afternoon Mixing Heights, L_{am} and L_{pm}

Stability Class ^a	Mixing Height L	
	Algebraic Expression	Numerical Value ^b
A, Extremely unstable	$L = 1.5 L_{pm}$	2,100 m
B, Moderately unstable	$L = L_{pm}$	1,400 m
C, Slightly unstable	$L = L_{pm}$	1,400 m
D, Neutral	$L = \frac{1}{2}(L_{am} + L_{pm})$	900 m

^a The mixing height does not apply to stable atmosphere (stability classes E and F).

^b Based on $L_{am} = 400$ m, and $L_{pm} = 1,400$ m.

Wind speeds in each of 16 directions or sectors are grouped in six classes (0-3, 4-6, 7-10, 11-16, 17-21, and >21 knots). The joint frequency distributions of wind speed, direction, and stability class employed to characterize the Weldon Spring site are presented in Table B.3 and illustrated in Figure B.1.

There were several release points of radionuclides ranging in height from about 14 to 35 m (Table 3.2), but it is not known how much each of the release

Table B.3. Meteorological Data at St. Louis-Lambert Airport (1960-1964):
Percent Wind Frequencies, $F(\bar{u}, \theta, s)$, by Direction and Stability Class

Wind Direc- tion	Percent Wind Frequency at Various Wind Speeds						
	0.9 km/h (1.5 mph)	3.4 km/h (5.5 mph)	6.2 km/h (10.0 mph)	9.7 km/h (15.5 mph)	13.4 km/h (21.5 mph)	17.5 km/h (28.0 mph)	All
<u>Stability Class 1</u>							
N	0.022	0.032	0.0	0.0	0.0	0.0	0.054
NNE	0.014	0.016	0.0	0.0	0.0	0.0	0.030
NE	0.008	0.016	0.0	0.0	0.0	0.0	0.024
ENE	0.012	0.018	0.0	0.0	0.0	0.0	0.030
E	0.016	0.025	0.0	0.0	0.0	0.0	0.041
ESE	0.009	0.018	0.0	0.0	0.0	0.0	0.027
SE	0.018	0.025	0.0	0.0	0.0	0.0	0.043
SSE	0.005	0.025	0.0	0.0	0.0	0.0	0.030
S	0.013	0.039	0.0	0.0	0.0	0.0	0.052
SSW	0.007	0.023	0.0	0.0	0.0	0.0	0.030
SW	0.015	0.034	0.0	0.0	0.0	0.0	0.049
WSW	0.010	0.025	0.0	0.0	0.0	0.0	0.035
W	0.020	0.034	0.0	0.0	0.0	0.0	0.054
WNW	0.017	0.034	0.0	0.0	0.0	0.0	0.051
NW	0.008	0.025	0.0	0.0	0.0	0.0	0.033
NNW	0.011	0.030	0.0	0.0	0.0	0.0	0.041
Totals	0.205	0.419	0.0	0.0	0.0	0.0	0.624
<u>Stability Class 2</u>							
N	0.054	0.126	0.073	0.0	0.0	0.0	0.253
NNE	0.067	0.137	0.089	0.0	0.0	0.0	0.293
NE	0.059	0.176	0.066	0.0	0.0	0.0	0.301
ENE	0.074	0.174	0.078	0.0	0.0	0.0	0.326
E	0.061	0.126	0.087	0.0	0.0	0.0	0.274
ESE	0.114	0.158	0.110	0.0	0.0	0.0	0.382
SE	0.070	0.155	0.084	0.0	0.0	0.0	0.309
SSE	0.033	0.135	0.107	0.0	0.0	0.0	0.275
S	0.080	0.187	0.107	0.0	0.0	0.0	0.374
SSW	0.053	0.151	0.089	0.0	0.0	0.0	0.293
SW	0.056	0.196	0.171	0.0	0.0	0.0	0.423
WSW	0.067	0.219	0.128	0.0	0.0	0.0	0.414
W	0.115	0.164	0.107	0.0	0.0	0.0	0.386
WNW	0.061	0.196	0.096	0.0	0.0	0.0	0.353
NW	0.074	0.137	0.110	0.0	0.0	0.0	0.321
NNW	0.061	0.116	0.082	0.0	0.0	0.0	0.259
Totals	1.099	2.553	1.584	0.0	0.0	0.0	5.236

Table B.3. Continued

Wind	Percent Wind Frequency at Various Wind Speeds						
Direc- tion	0.9 km/h (1.5 mph)	3.4 km/h (5.5 mph)	6.2 km/h (10.0 mph)	9.7 km/h (15.5 mph)	13.4 km/h (21.5 mph)	17.5 km/h (28.0 mph)	All
<u>Stability Class 3</u>							
N	0.025	0.130	0.242	0.055	0.0	0.0	0.452
NNE	0.019	0.139	0.221	0.032	0.0	0.0	0.411
NE	0.038	0.137	0.187	0.055	0.002	0.0	0.419
ENE	0.039	0.119	0.265	0.032	0.0	0.0	0.455
E	0.024	0.146	0.322	0.030	0.0	0.0	0.522
ESE	0.057	0.221	0.379	0.053	0.0	0.0	0.710
SE	0.053	0.201	0.386	0.062	0.002	0.0	0.704
SSE	0.035	0.162	0.509	0.103	0.009	0.0	0.818
S	0.043	0.199	0.710	0.167	0.021	0.0	1.140
SSW	0.017	0.082	0.486	0.087	0.007	0.0	0.679
SW	0.035	0.215	0.500	0.114	0.007	0.0	0.871
WSW	0.042	0.217	0.616	0.135	0.0	0.0	1.010
W	0.072	0.224	0.482	0.091	0.007	0.0	0.876
WNW	0.052	0.192	0.491	0.098	0.014	0.002	0.849
NW	0.028	0.137	0.374	0.096	0.002	0.002	0.639
NNW	0.026	0.122	0.301	0.057	0.002	0.002	0.500
Totals	0.605	2.633	6.471	1.267	0.073	0.006	11.055

<u>Stability Class 4</u>							
N	0.064	0.308	0.916	1.053	0.107	0.002	2.450
NNE	0.071	0.347	0.751	0.671	0.046	0.007	1.893
NE	0.106	0.388	0.638	0.390	0.023	0.005	1.595
ENE	0.090	0.397	0.667	0.370	0.021	0.0	1.545
E	0.095	0.372	0.968	0.527	0.046	0.005	2.013
ESE	0.102	0.429	1.256	0.941	0.087	0.007	2.822
SE	0.085	0.363	1.475	1.423	0.174	0.011	3.531
SSE	0.058	0.324	1.521	2.313	0.372	0.034	4.622
S	0.083	0.370	2.089	3.215	0.434	0.039	6.230
SSW	0.036	0.233	1.046	1.162	0.158	0.009	2.644
SW	0.048	0.290	0.964	0.881	0.087	0.014	2.284
WSW	0.060	0.322	0.801	1.167	0.144	0.041	2.535
W	0.083	0.404	0.936	1.295	0.329	0.119	3.166
WNW	0.088	0.377	1.206	3.003	1.286	0.244	6.204
NW	0.078	0.411	1.281	2.649	0.621	0.112	5.152
NNW	0.046	0.263	1.064	1.297	0.194	0.023	2.887
Totals	1.193	5.598	17.624	22.357	4.129	0.672	51.573

Table B.3. Continued

Wind Direction	Percent Wind Frequency at Various Wind Speeds						
	0.9 km/h (1.5 mph)	3.4 km/h (5.5 mph)	6.2 km/h (10.0 mph)	9.7 km/h (15.5 mph)	13.4 km/h (21.5 mph)	17.5 km/h (28.0 mph)	All
<u>Stability Class 5</u>							
N	0.0	0.144	0.281	0.0	0.0	0.0	0.425
NNE	0.0	0.219	0.194	0.0	0.0	0.0	0.413
NE	0.0	0.324	0.137	0.0	0.0	0.0	0.461
ENE	0.0	0.251	0.162	0.0	0.0	0.0	0.413
E	0.0	0.258	0.203	0.0	0.0	0.0	0.461
ESE	0.0	0.411	0.466	0.0	0.0	0.0	0.877
SE	0.0	0.518	0.580	0.0	0.0	0.0	1.098
SSE	0.0	0.340	0.893	0.0	0.0	0.0	1.233
S	0.0	0.388	1.514	0.0	0.0	0.0	1.902
SSW	0.0	0.247	0.690	0.0	0.0	0.0	0.937
SW	0.0	0.301	0.635	0.0	0.0	0.0	0.936
WSW	0.0	0.295	0.674	0.0	0.0	0.0	0.969
W	0.0	0.406	0.822	0.0	0.0	0.0	1.228
WNW	0.0	0.324	0.906	0.0	0.0	0.0	1.230
NW	0.0	0.199	0.461	0.0	0.0	0.0	0.660
NNW	0.0	0.196	0.397	0.0	0.0	0.0	0.593
Totals	0.0	4.821	9.015	0.0	0.0	0.0	13.836
<u>Stability Class 6</u>							
N	0.230	0.272	0.0	0.0	0.0	0.0	0.502
NNE	0.388	0.377	0.0	0.0	0.0	0.0	0.765
NE	0.620	0.461	0.0	0.0	0.0	0.0	1.081
ENE	0.463	0.301	0.0	0.0	0.0	0.0	0.764
E	0.561	0.324	0.0	0.0	0.0	0.0	0.885
ESE	0.681	0.628	0.0	0.0	0.0	0.0	1.309
SE	1.154	1.025	0.0	0.0	0.0	0.0	2.179
SSE	0.691	0.767	0.0	0.0	0.0	0.0	1.458
S	0.504	0.822	0.0	0.0	0.0	0.0	1.326
SSW	0.219	0.475	0.0	0.0	0.0	0.0	0.694
SW	0.285	0.564	0.0	0.0	0.0	0.0	0.849
WSW	0.522	0.612	0.0	0.0	0.0	0.0	1.134
W	1.029	1.119	0.0	0.0	0.0	0.0	2.148
WNW	0.713	0.710	0.0	0.0	0.0	0.0	1.423
NW	0.340	0.349	0.0	0.0	0.0	0.0	0.689
NNW	0.205	0.265	0.0	0.0	0.0	0.0	0.470
Totals	8.605	9.071	0.0	0.0	0.0	0.0	17.676

Figure B.1. Annual Wind Rose for St. Louis-Lambert Airport, 1960-1964. The concentric circles represent percent lapse.

points contributed to the total amount of airborne releases. To simplify the calculations, a uniform area source is assumed to be bounded by three principal release points -- Buildings 103, 201, and 301. A uniform release height of 20 m is assumed. Accordingly, point source Equations B.1 and B.2 had to be modified as described in Giardini and Yuan (1983).

B.2 PLUME DEPLETION

The concentration of radioactive materials in the atmosphere is depleted by the mechanisms of dry deposition, wet deposition, and radioactive decay. These depletion processes can be described by replacing the source strength Q by an effective source strength Q' in Equations B.1 and B.2. This effective source strength would decrease as the distance from the emission point increases.

B.2.1 Plume Depletion by Deposition

Deposition, as used in this context, includes the processes of gravitational settling, adsorption, particle interception, diffusion, chemical electrostatic effects, and rain wash. Total ground deposition is calculated from the deposition velocity, V_d , defined by Chamberlain (1953) as the ratio of the deposition rate $D(\text{Ci}/\text{m}^2\text{-s})$ to the ground-level air concentration $C(\text{Ci}/\text{m}^3)$. Thus, $V_d = D/C$.

For particulates, the deposition velocity, V_d , depends on a settling or fall velocity, V_s , given by Stoke's Law:

$$V_s = \frac{2}{9} \frac{R^2 g \rho}{\mu} \quad (\text{B.4})$$

where: V_s is settling or fall velocity,

R is radius of the particle,

g is acceleration due to gravity,

ρ is density of the particle, and

μ is atmospheric dynamic viscosity.

At fall velocities less than about 0.01 m/s, the vertical movement of the particle is dependent on larger vertical turbulent and mean air motion, and the effect of sedimentation is negligible. Where the sedimentation rate is significant ($V_s = 0.01$ to 1 m/s), the effect due to the resulting downward tilt of the plume centerline can be expressed by replacing its constant height, h , with a variable expression such that:

$$h(r) = h(0) - \frac{rV_s}{\bar{u}}; h(r) \geq 0 \quad (\text{B.8})$$

where r is the distance from the source and $\bar{u}$ is the mean wind speed. The model uses a deposition velocity $V_d = 0.01$ m/s for particulates with fall velocities, V_s , less than 0.01 m/s (Slade 1968). The products of radon decay in air (Pb-210 and Po-210) are exceptions. They are assumed to have an aerodynamic diameter of $0.3 \mu\text{m}$ and to deposit with a $V_d = 0.003$ m/s. For larger particles with fall velocities greater than 0.01 m/s, the calculated fall velocity is assumed to be the deposition velocity.

A variable effective source strength, Q' , which replaces the constant source strength Q_0 to correct for plume depletion due to deposition is a function of V_d and appropriate meteorological parameters. The integral expressions in the resulting equations are evaluated numerically.

B.2.2 Plume Depletion by Radon Daughter Ingrowth

Radioactive decay during transport through the atmosphere is considered for short-lived radon ($T_{1/2} = 3.8$ days). The transit time during which radioactive decay occurs can be approximated as the ratio of the distance traveled, r , to the wind speed, $\bar{u}$, or $t = r/\bar{u}$. The source strength as corrected for radioactive decay is:

$$Q(r) = Q_0 \exp \left(- \frac{\lambda_{Rn} r}{\bar{u}} \right) \quad (\text{B.5})$$

The ingrowth of radon daughter products is represented as follows:

The activities of radon daughter products are found by solving the appropriate set of differential equations using standard methods. The very short-lived daughter of Bi-214, Po-214, is omitted above because it is not explicitly treated in the kinetic transport equations; it is assumed to be in equilibrium with Bi-214 for purposes of dose evaluation.

B.3 CONCENTRATIONS IN ENVIRONMENTAL MEDIA

Environmental media concentrations are computed as functions of the calculated annual average air concentrations resulting directly from plant releases (not including resuspended air concentrations) and the time duration that those direct air concentrations have existed. The direct air concentrations are computed as described in Sections B.1 and B.2 and include the effects of depletion by deposition (for particulates) and ingrowth and decay during transit (for radon and daughters).

B.3.1 Ground Concentrations

Ground radionuclide concentrations are computed from the calculated airborne particulate concentrations arising directly from plant emissions. The ground concentration of radionuclide i depends directly on the direct deposition rate, which is given by the following relationship

$$D_{di} = C_{adi} V_d \quad (\text{B.6})$$

where: C_{adi} is the direct air concentration of isotope i (pCi/m^3), and

D_{di} is the resulting direct deposition rate of isotope i ($\text{pCi}/\text{m}^2\text{-s}$).

The concentration of isotope i on a ground surface from constant deposition at the rate D_{di} over time interval t is obtained from

$$C_{gi}(t) = D_{di} \frac{1 - \exp [-(\lambda_i + \lambda_e)t]}{\lambda_i + \lambda_e} \quad (B.7)$$

where: $C_{gi}(t)$ is the surface ground concentration of isotope i at time t (pCi/m²),

λ_e is the assumed rate constant for environmental loss (s⁻¹),

λ_i is the radioactive decay constant for isotope i (s⁻¹), and

t is the time interval over which deposition has occurred (s).

The environmental loss constant, λ_e , is designed to account for downward migration in soil and loss through chemical binding. It is assumed to apply to all isotopes subject to ground deposition. The value of λ_e is assumed to be 0.0139 yr⁻¹, which corresponds to an assumed 50-yr half-life of radionuclides in soil.

Ground concentrations are computed explicitly only for U-238, Th-230, Ra-226, and Pb-210. For all other isotopes, the ground concentration is assumed to be equal to that of the next higher-up parent for which the ground concentration is calculated explicitly. For Pb-210, ingrowth from deposited Ra-226 can be significant.

B.3.2 Total Air Concentrations

Total air concentrations are required in order to compute total deposition rates onto vegetation, inhalation doses, and external doses from irradiation by airborne activity. The total air concentration of each isotope at each location is computed as the sum of the direct air concentration and the resuspended air concentration as follows

$$C_{ai}(t) = C_{adi} + C_{ari}(t) \quad (B.8)$$

where: $C_{ai}(t)$ is the total air concentration of isotope i particle size p , at time t (pCi/m^3),

C_{adi} is the direct air concentration of isotope i (pCi/m^3), and

$C_{ari}(t)$ is the resuspended air concentration of isotope i at time t (pCi/m^3).

The resuspended air concentration is computed using a time dependent resuspension factor $R(t)$, which is defined as the ratio of the resuspended air concentration of the isotope to its surface concentration on the ground.

For small particles (less than $10 \mu m$ in diameter), the concentration factor, $R(t)$, has been determined empirically as

$$R(t) = (10^{-7}/V_d) e^{-\lambda_R t} \quad (\text{for } t \leq 1.82 \text{ years}) \quad (B.9a)$$

and

$$R(t) = (10^{-11}/V_d) \quad (\text{for } t > 1.82 \text{ years}) \quad (B.9b)$$

where: λ_R is the assumed decay constant of the resuspension factor -- equivalent to a 50-day half-life (5.06 yr^{-1}), V_d is the deposition velocity (m/s) defined previously, and $R(t)$ is in units of m^{-1} . The time is measured from the instant of deposition.

Total air concentrations are computed using Equations B.6 through B.9.

B.3.3 Concentrations in Vegetation

Vegetation concentrations are derived from ground concentrations and total deposition rates. Ground concentrations are used to determine vegetation concentrations resulting from root uptake of soil activity; total deposition rates are used to determine vegetation concentrations resulting from foliar retention of deposited activity. Total deposition rates are obtained by the following summation

$$D_i = C_{ai} V_d \quad (B.10)$$

where D_i is the total deposition rate including deposition of resuspended air concentrations ($\text{pCi}/\text{m}^2\text{-s}$).

Concentrations of released particulate materials can be environmentally transferred to the edible portions of vegetables, or to hay or pasture grass consumed by animals. Five categories of vegetation are treated in this analysis: edible aboveground vegetables, potatoes, other edible belowground vegetables. The model used to estimate concentrations in vegetation from that in air and soil takes into account the fraction of total deposition initially retained on plant surfaces, losses due to weathering processes such as wind turbulence and washoff, and, for belowground vegetables, the fraction of retained activity reaching the edible portions. Vegetation concentrations are computed using the following equation

$$C_{vi} = D_i F_r E_v \frac{1 - \exp(-\lambda_w t_v)}{Y_v \lambda_w} + C_{gi} \frac{B_{vi}}{P} \quad (B.11)$$

where: B_{vi} (Table B.4) is the soil to plant (environmental concentration) transfer factor for isotope i , vegetation type v (dimensionless),

C_{vi} is the resulting concentration of isotope i in vegetation v (pCi/kg),

E_v is the fraction of the foliar deposition reaching edible portions of vegetation v (dimensionless -- 1.0 for all aboveground vegetables and 0.1 for all belowground vegetables)

F_r is the fraction of total deposition retained on plant surfaces, 0.2 (dimensionless),

P is the assumed areal soil density for surface mixing ($40 \text{ kg}/\text{m}^2$),

t_v is the assumed duration (5.184×10^6 seconds or 60 days) of exposure while growing for vegetation v (s),

Y_v is the assumed yield density of vegetation v ($2 \text{ kg}/\text{m}^2$), and

λ_w is the decay constant accounting for weathering losses (assumed to have a 14-day half-life).

Table B.4. Environmental Concentration Transfer Factors
Used in This Analysis

Food Type	Soil to Plant Transfer Factors, B_{vj}			
	U-238	Th-230	Ra-226	Pb-210
Aboveground edible vegetables	0.0025	0.0042	0.014	0.004
Potatoes	0.0025	0.0042	0.003	0.004
Belowground edible vegetables	0.0025	0.0042	0.014	0.004

Source: U.S. Nuclear Regulatory Commission (1980).

B.4 DOSE CALCULATIONS FOR INDIVIDUALS

Doses to individuals have been calculated for all major exposure modes. These exposure modes include inhalation, external exposure to air and ground concentrations, and ingestion of vegetables. (Ingestion of meat contributes less than 0.1% to the individual dose.)

Because the radionuclides of concern in this study generally have relatively long residence times once they have been deposited in body organs, the total dose from a given intake will be delivered over an extended time period. Internal doses (from inhalation or ingestion pathways) have been calculated using dose conversion factors that yield the 50-yr internal dose commitment, i.e., the entire dose insult received over a period of 50 yr following intake into the body. Annual doses for individuals are the 50-yr dose commitments resulting from a 1-yr exposure period. In this study, dose represents the 50-yr effective dose equivalent commitments, which are calculated according to ICRP recommendations (Int. Comm. Radiol. Prot. 1974, 1977).

The effective dose equivalent is calculated by considering the total individual risk or health detriment from stochastic radiation effects (cancer, genetic effects), taking into account the dose in all risk-relevant tissues of the human body. This concept is based on the principle that, at a given level

of safety, the stochastic risk should be equal whether there is uniform irradiation of the whole body or nonuniform or partial irradiation of the body. The quantity "effective dose equivalent", D_E , is defined as

$$D_E = \sum_T W_T D_T \text{ (with } \sum_T W_T = 1)$$

by summing over all exposed relevant tissue T -- where D_T is the mean dose equivalent in tissue T and W_T is a weighting factor that represents the ratio of the stochastic risk resulting from tissue T to the total risk when the whole body is irradiated uniformly. The recommended values of the weighting factor W_T are gonads, 0.25; breasts, 0.15; red bone marrow, 0.12; the lung, 0.12; thyroid, 0.03; bone surfaces, 0.03; and remainder (total), 0.30. For the remainder tissues, a W_T value of 0.06 is applied to each of those five tissues receiving the highest dose equivalent.

B.4.1 Internal Doses

B.4.1.1 Inhalation Dose for Particulates

The uptake of radioactive material into the lungs via inhalation, and subsequent translocation to other body organs, is estimated from the airborne concentration of each radioisotope using the model developed by the Task Group on Lung Dynamics of Committee II of the International Commission on Radiological Protection (1966). The fraction of inhaled activity that is deposited and the region of the lung where deposition occurs are determined by the aerodynamic properties of the particles. The rate of removal of deposited material (or rate of clearance) and the site of its subsequent deposition, if it is not eliminated from the body, are determined by many factors -- including the physical and chemical form of the material, solubility characteristics, and point of initial deposition. The radioactive material irradiates lung tissue until cleared from the lungs and then, if not removed from the body, continues to irradiate tissue at the new site of deposition.

Inhalation doses to individuals are based on an inhalation rate of 20,000 L/day and are calculated using total air concentrations and the inhalation dose conversion factors given in Table B.5. The dose conversion

factors used to calculate the inhalation dose are those based on the solubility class that yields the highest effective dose equivalent for each radionuclide species as determined by ICRP recommendation (Dunning et al. 1981).

Table B.5. Dose Conversion Factors
Used in This Analysis

Radionuclide	Inhalation (mrem/yr)/(pCi/m ³) by Particle Size		Ingestion (mrem/pCi)
	1 μ m	0.3 μ m ^a	
U-238	1000	-	0.00022
U-234	1200	-	0.00026
Th-230	2700	-	0.00063
Ra-226	90	-	0.0014
Pb-210	27	95	0.00077
Po-210	92	120	0.002

^a Aerodynamic diameter size of 0.3 μ m is assumed for radon decay products.

Based on these dose conversion factors, particulate inhalation doses to individuals are calculated using the following equation:

$$d(\text{inh}) = \sum_i C_{ai} \text{DCF}_i(\text{inh}) \quad (\text{B.12})$$

where: C_{ai} is the total air concentration of isotope i (pCi/m³),

$d(\text{inh})$ is the resulting inhalation dose (mrem/yr), and

$\text{DCF}_i(\text{inh})$ is the inhalation dose conversion factor for isotope i (mrem/yr per pCi/m³).

B.4.1.2 Inhalation Dose for Radon Daughters

The only pathway of radon gas into the body is by inhalation, but it is not readily absorbed or deposited in the lung; thus, the dose from radon to the lung or other body tissue is not of great significance. However, radon

decays with a 3.82-day half-life through a series of short-lived daughter products (longest half-life in this chain is 27 minutes) to Pb-210 with a 22-yr half-life. The short-lived daughters, rather than radon itself, are of primary concern relative to the inhalation pathway.

Radon daughters formed in air are rapidly attached to aerosol particles as a result of their rapid diffusion. Rates of attachment are dependent on the concentration of particles in the atmosphere, the ambient humidity, and the surface-to-volume ratio of the particles. The observed mean half-life before attachment of a positive ion to atmospheric particles is less than 20 minutes. Since the first daughter product, Po-218, has a radioactive half-life of about three minutes, it is likely to decay to Pb-214 before becoming attached to an aerosol particle. Because of their longer radioactive half-lives, the other radon daughters are more likely to attach to atmospheric aerosols than is Po-218.

Unattached radon daughters are very readily deposited and retained on respiratory surfaces. The dose rate from radon daughters associated with aerosols, as for other particulates, is dependent on the particle's physical characteristics such as diameter, shape, and density. Also, the ratio of concentrations of radon daughters in the atmosphere to the concentration of radon is related to the mixing and dilution volume. Under equilibrium conditions, the activity of each daughter is equal to the activity of radon. A condition of equilibrium can be approached in a tightly enclosed volume, such as a poorly ventilated room.

In this analysis, doses to the critical lung tissue -- the bronchial epithelium -- from inhalation of short-lived radon daughters are computed on the basis of 100% indoor exposure in an adequately ventilated room using a dose conversion factor of 1.3 mrem/yr indoors per pCi/m³ of Rn-222 in outdoor air. The basis for this dose conversion factor consists of three major component parts as follows:

- (1) the average indoor working level* (WL) concentration resulting from an outdoor Rn-222 concentration of 1 pCi/m³ is approximately 5.0×10^{-6} WL;

- (2) the number of cumulative working-level months (WLM) of radon daughter exposure for an average individual surrounded by air at a constant concentration of one WL is about 25 WLM/yr; and
- (3) the committed dose equivalent to the bronchial epithelium (basal cell nuclei of segmented bronchi) per unit WLM exposure is about 10 rem (10,000 mrem) (Int. Comm. Radiol. Prot. 1981).

These factors all enter into Equation B.13, which yields the Rn-222 short-lived daughter inhalation dose conversion factor used in this study

$$\frac{1.3 \text{ mrem}}{\text{pCi/m}^3} = \frac{5.0 \times 10^{-6} \text{ WL}}{\text{pCi/m}^3} \times \frac{25 \text{ WLM/yr}}{\text{WL}} \times \frac{1 \times 10^4 \text{ mrem}}{\text{WLM}} \quad (\text{B.13})$$

In a normally ventilated dwelling or other structure, the indoor Rn-222 concentration will be approximately the same as that in the air immediately outside. However, the concentrations of short-lived daughters (Po-218, Pb-214, and Bi-214) may be higher than they are outdoors due to equilibration. Under adequate ventilation conditions, the concentration ratios of the short-lived daughters to that of the parent Rn-222 may be expressed as 1.0/0.9/0.51/0.35 (U.N. Sci. Comm. Effect At. Radiat. 1972). Based on these concentration ratios and an outdoor Rn-222 concentration of 1 pCi/m³, the indoor air will be at a concentration of approximately 5×10^{-6} WL (U.S. Environ. Prot. Agency 1973).

The working-level-month (WLM) is a unit used to express occupational exposure of uranium miners to short-lived radon daughter air concentrations. For an average individual, the number of WLMs per year of constant exposure to a one-WL concentration is given by:

$$\frac{25 \text{ WLM/yr}}{\text{WL}} = 0.5 \frac{12 \text{ WLM/WL-yr}}{40 \text{ h/wk} \times 52 \text{ wk/yr}} (8760 \text{ h/yr}) \quad (\text{B.14})$$

*Short-lived radon daughter concentrations are expressed in units called working levels (WL). One WL is defined as any combination of short-lived radon daughter concentrations in one liter of air that will produce 1.3×10^5 MeV of alpha energy in their complete decay to Pb-210. One working-level-month (WLM) represents occupational exposure to a one-WL concentration for one working month (about 170 hours).

The BEIR Report (Natl. Acad. Sci. 1972) presents a detailed discussion of radon daughter dosimetry and states that "1 rad/WLM is probably close to the upper limit for a reasonably uniform dose to the basal cell layer of the epithelium of the larger bronchi on a probabilities basis." Based on the figure of 0.5 rad/WLM adopted for use in the BEIR Report and a quality factor of 20 for alpha radiation, a value of 10 rem/WLM is derived. The ICRP report recommends a dose conversion factor of 6.4 to 17 rem per WLM (Int. Comm. Radiol. Prot. 1981). For this study, 10 rem/WLM is assumed.

B.4.1.3 Ingestion Doses

Upon ingestion of radioactivity in food, some fraction of each radionuclide is absorbed into the bloodstream and may be transported to various internal body organs. The only ingestion pathway of importance for the Weldon Spring site is the vegetation pathway.

Ingestion doses are calculated for ingestion of vegetables. Ingestion doses are based on vegetation concentrations established using Equation B.11, ingestion rates presented in Table B.6, and dose conversion factors given in Table B.5. Vegetable ingestion doses are computed under the assumption that an average of 50% of the initial activity will be lost in food preparation (Fletcher and Dotson 1971), usually involving processes such as washing, peeling, and boiling. Vegetable ingestion doses are computed as follows:

$$d(\text{veg}) = 0.5 \sum_{iv} U_v C_{vi} \text{DCF}_i(\text{ing}) \quad (\text{B.15})$$

where: C_{vi} is the concentration of isotope i in vegetation v (pCi/kg),

$d(\text{ing})$ is the resulting vegetable ingestion dose (mrem/yr),

$\text{DCF}_i(\text{ing})$ is the ingestion dose conversion factor for isotope i (mrem/pCi ingested) (see Table B.5),

U_v is the ingestion rate of vegetation type v by an individual (kg/yr) (see Table B.6), and

0.5 is the fraction of initial vegetable activity remaining after preparation for human consumption (dimensionless) (Fletcher and Dotson 1971).

Table B.6. Food Ingestion Rates

Foodstuff	Ingestion Rate (kg/yr)
Vegetables (Total):	105
Aboveground edible	40
Potatoes	60
Other belowground edible	5.0

^a All data from Fletcher and Dotson (1971). Ingestion rates are averages for typical rural farm households. No allowance is credited for portions of the year when locally or home grown food may not be available.

B.4.2 External Doses

B.4.2.1 External Doses from Air Concentrations and Ground Deposition

External doses resulting from exposure to air and ground deposition are computed using the dose conversion factors presented in Table B.7 and assuming 100% occupancy at a given location. Indoor exposure is assumed to occur 14 hours per day at a dose rate of 70% of the outdoor dose rate. This provides an effective dose reduction factor of 0.825. The following equation is used to calculate external doses:

$$d(\text{ext}) = 0.825 \sum_i C_{ai} \text{DCF}_i(\text{cld}) + C_{gi} \text{DCF}_i(\text{gnd}) \quad (\text{B.16})$$

where: C_{ai} is the total air concentration of isotope i (pCi/m^3),
 C_{gi} is the total ground concentration of isotope i (pCi/m^2),
 $\text{DCF}_i(\text{cld})$ is the dose factor for cloud exposure for isotope i (mrem/yr per pCi/m^3),
 $\text{DCF}_i(\text{gnd})$ is the dose factor for ground exposure for isotope i (mrem/yr per pCi/m^2), and
0.825 is the effective reduction factor due to structural shielding provided during part-time indoor exposure.

Table B.7. Dose Conversion Factors for External Exposure

Isotope	Dose Conversion Factors for External Doses to Whole Body	
	From Air Concentrations (mrem/yr per pCi/m ³)	From Ground Concentrations (mrem/yr per pCi/m ²)
U-238	1.57×10^{-6}	3.17×10^{-7}
Th-234	5.24×10^{-5}	1.66×10^{-6}
Pa-234m	6.64×10^{-5}	1.24×10^{-6}
U-234	2.49×10^{-6}	4.78×10^{-7}
Th-230	3.59×10^{-6}	6.12×10^{-7}
Ra-226	4.90×10^{-5}	9.47×10^{-7}
Rn-222	2.83×10^{-6}	5.03×10^{-8}
Po-218	6.34×10^{-7}	1.10×10^{-8}
Pb-214	1.67×10^{-3}	3.16×10^{-5}
Bi-214	1.16×10^{-2}	1.85×10^{-4}
Po-214	7.66×10^{-7}	1.33×10^{-8}
Pb-210	1.43×10^{-5}	2.27×10^{-6}

B.4.2.2 External Dose Due to Direct Radiation from the Plant

The direct radiation dose from the concentrate stored at the site during plant operations was primarily due to gamma radiation from Pa-234, the short-lived (1.2 min half-life) transformation product of U-238. Dose rate calculations are based on the following equation (see, for example, Chen et al. 1981) for the dose rate at a distance r from a point source:

$$\dot{D}(r) = \frac{S_0 k}{r^2} \sum_i f_i r_i B(\mu_i, r) e^{-\mu_i r} \quad (\text{rem/h}) \quad (\text{B.17})$$

where the summation index i identifies gamma energy, and

S_0 is the radioactivity of the source (Ci),

k is the conversion factor from roentgen to equivalent dose (0.95 rem/R),

f_i is the fraction of photons emitted per disintegration,

Γ_i is the specific gamma-ray constant ($R\text{-m}^2/\text{h-Ci}$),

μ_i is the air attenuation coefficient for photons (m^{-1}), and

B is the buildup factor.

For photon energies greater than 0.5 MeV, the buildup factor can be expressed as

$$B(\mu_i, r) = 1 + a_i \mu_i r e^{-b_i \mu_i r}. \quad (\text{B.18})$$

The parameter values for the gamma energies used in this estimate are listed in Table B.8.

Table B.8. Parameter Values Used to Estimate Gamma Radiation Dose from Uranium-238

Parameter ^a	Parameter Values for Different Gamma Energies			
	0.63 MeV	1.1 MeV	1.55 MeV	2.0 MeV
f_i	0.910	0.409	0.0859	0.0093
Γ_i	0.32	0.53	0.72	0.92
μ_i	0.0102	0.0078	0.0065	0.0057
a_i	1.43	1.09	0.91	0.8257
b_i	0.088	0.052	0.035	0.02407

^a Sources: f_i , Bell (1973); Γ_i , a_i , and b_i , Chen et al. (1981); μ_i , U.S. Public Health Service (1970).

It is estimated that between 700 and 1,000 Ci of uranium concentrate was stored in the drums at any one time. However, the concentrate itself will shield most of the radiation. It is conservatively estimated that self-shielding will reduce gamma radiation by a factor of 100 to 1,000. Because the area occupied by the drums is small compared to the distance to the nearest member of a nearby population group, it is reasonable to approximate the source by a point source.

B.4.3. Individual Total Doses

Total doses to individuals from all exposure pathways are obtained by adding the inhalation, ingestion, and external doses:

$$d(\text{tot}) = d(\text{inh}) + d(\text{ing}) + d(\text{ext}) . \quad (\text{B.19})$$

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APPENDIX C. LIST OF ABBREVIATIONS

$\mu\text{R/h}$	microRoentgens per hour	kg/yr	kilograms per year
$\mu\text{g/g}$	micrograms per gram	km	kilometers
μm	microns	km/h	kilometer per hour
<	less than	m	meters
>	greater than	m^{-1}	per meter
$\leq$	less than or equal to	m/s	meters per second
Bi	bismuth	m^2	square meters
Ci	curies	m^3	cubic meters
Ci/m^2	curies per square meter	mg/L	milligrams per liter
$\text{Ci/m}^2\text{-s}$	curies per square meter per second	mph	miles per hour
Ci/yr	curies per year	mrem	millirems
E	east	mrem/pCi	millirems per picocurie
H_2	hydrogen	mrem/yr	millirems per year
H_2O	hydrogen oxide (water)	Pa	protactinium
HF	hydrogen fluoride	Pb	lead
HNO_3	nitric acid	Po	polonium
L/yr	liters per year	pCi	picocuries
MT	metric ton	pCi/L	picocuries per liter
MgF	magnesium fluoride	pCi/g	picocuries per gram
N	north	pCi/kg	picocuries per kilogram
N_2	nitrogen	$\text{pCi/m}^2\text{-s}$	picocuries per square meter per second
$\text{Na}_2\text{U}_2\text{O}_7$	sodium diuranate	pCi/m^3	picocuries per cubic meter
S	south	R	radon
TBP	tributyl phosphate	Ra	radium
UF_4	uranium tetrafluoride	rem/R	rem per Roentgen
UO_2	uranium dioxide	rem/h	rem per hour
UO_3	uranium trioxide	s	second
W	west	s^{-1}	per second
WL	working level	Th	thorium
WLM	working level months	U	uranium
WLM/yr	working level months per year	wk	week
ft	foot, feet	yr	year
ha	hectare	yr^{-1}	per year
kg/m^2	kilograms per square meter		