Paper

DOSES TO WORKERS IN THE UNITED STATES NUCLEAR WEAPONS PROGRAM DUE TO EXTERNAL IRRADIATION AT THE DAWN OF THE ATOMIC ERA (1940–1960)

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Abstract—**Radiation doses to workers at the Manhattan Engineer District (MED) and Atomic Energy Commission (AEC) sites due to external irradiation during 1940–1960 are reviewed. Categorized radiation dose data were available from AEC annual reports for some years. Annual individual radiation dose data for nine MED/AEC sites for all years were available from the U.S. Department of Energy's Comprehensive Epidemiologic Data Resource. These data are combined to produce an estimate of external collective dose equivalent to 1,720 person-Sv for 1940–1960. During this period there were 19 criticality incidents; 41 persons in a workforce of several hundred thousand were accidentally overexposed in these and other incidents, including three men who died due to acute radiation syndrome.**

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Key words: dose; weapons; nuclear workers; exposure, occupational

INTRODUCTION

THE ATOMIC era in the United States began with a letter from Albert Einstein to President Franklin D. Roosevelt in October 1939, urging the development of nuclear weapons. Government sponsored experiments with nuclear reactors (known at the time as "atomic piles") and natural uranium began shortly thereafter. Nuclear efforts in the United States from 1939 through 1946 were developed and operated by the Manhattan Engineer District (MED) of the U.S. Army Corps of Engineers under the name "Manhattan Project." In 1947, the U.S. Atomic Energy Commission (AEC) took over control of nuclear programs and was the responsible government entity for the United States's nuclear weapons program through 1974. The AEC was succeeded by the U.S. Energy Research and Development Administration (ERDA) in 1974, which was succeeded by the U.S. Department of Energy (DOE) in 1977.

The period from 1940 to 1960 was marked by changes in radiation protection standards, practices, and capabilities. In some instances at research and uranium facilities, personal dose measurement devices were not issued and data are not available because potential for the chemical injury from inhaled or ingested uranium was believed to be greater than any of the external radiation exposures that might be associated with such operations. The periods for which dosimetry was not available are short and later data indicated the associated dose rates were under control. In this paper, data are limited to external radiation exposures. Neither the doses from inhalation nor from ingestion of radioactive materials by workers are included. There were accidental criticalities and other accidents that resulted in several workers receiving high radiation doses that were fatal in three cases.

Because this is a historical document, the non-Système Internationale d'Unités (SI) units in use at the time affect the expression of quantities in SI units. This may lead to an appearance of high precision when quantities are expressed in SI units. No attempt is made to *round* quantities expressed in SI units, and the reader should make no judgment concerning the precision of numbers such as "258 nC kg^{-1} (1 mR)."

OVERVIEW OF OPERATIONS

To gain a perspective of the dawn of the atomic age in the United States, an overview of operations is presented here, including a discussion of major sites, early dose limits, and early dosimetry.

Major sites

Most work involving nuclear material during the early World War II years (1940–1943) took place at major universities such as the University of Chicago, Columbia University, and the University of California, which had developed nuclear research capabilities during the 1930's. Activities of the MED during the remainder of the war (1942–1945) were concentrated at three primary sites: Hanford, Washington; Oak Ridge, Tennessee; and Los Alamos, New Mexico. In 1947, responsibility for special nuclear material production was transferred from MED to civilian control under the AEC.

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Table 1 lists the major MED and AEC sites, their dates of initial operation, and the type of activities performed.

Early dose limits

The radiation dose limits in effect at MED and AEC facilities from 1940 to 1960 were based on preventing non-stochastic effects. Thus, the "tolerance dose" (Henshaw 1941; Stone 1951) was used as the basis for the majority of limits discussed in this paper. During the war years, the limit was 25.8 μC kg^{-1} (0.1 R) per day based on a 6-d work week. Table 2 details the limits recommended for the 1947–1960 period by the National Council on Radiation Protection and Measurements (NCRP). In 1960, the Federal Radiation Council (FRC) also made recommendations (FRC 1960). In most cases AEC facilities followed the guidelines given by the NCRP. Although there was no "as low as reasonably achievable" (ALARA) concept (ICRP 1977) during the period 1940–1960, the NCRP and others at the Tri-Partite Conference in 1949 introduced the concept of "as low as practicable" (National Bureau of Standards 1954; NCRP 1971). Some sites, such as Hanford, used administrative limits that were lower than recommended limits. Such limits allowed a safety margin to account for the poor ability to measure neutron exposure (Wilson 1987).

Table 1. Historical names of major MED and AEC sites, 1940–1960.

Site	Date of initial operation	Primary activities
University of California Radiation Laboratory[a]	1930s[b]	Research
Columbia University	1930s[b]	Research
University of Chicago Metallurgical Laboratory	1940	Reactor Design Chemical Separations
Argonne National Laboratory	1947	Reactor Design Chemical Separations
Oak Ridge National Laboratory (X-10)	1942	Research
Mallinckrodt Chemical Works	1942	Uranium Processing
Oak Ridge Y-12 Plant	1943	Uranium Enrichment and Fabrication
Oak Ridge Gaseous Diffusion Plant (K-25)	1943	Uranium Enrichment
Hanford Engineer Works	1943	Plutonium Production
Los Alamos Scientific Laboratory/Zia Corp.	1943	Weapons Development
Mound Laboratory	1943	Isotope Separation
Linde Corporation Ceramics Plant	1943	Uranium Processing
Sandia Laboratory	1945	Weapons Development
Brookhaven National Laboratory	1947	Research
Knolls Atomic Power Laboratory	1947	Reactor Development
Idaho Engineering Laboratory	1949	Reactor Development
Pantex Plant	1950	Weapons Assembly/Disassembly
Savannah River Plant	1950	Nuclear Materials Production
Nevada Test Site	1951	Weapons Testing
Feed Materials Production Center (Fernald)	1951	Uranium Processing
Rocky Flats Plant	1951	Plutonium Fabrication
Lawrence Livermore Laboratory	1952	Weapons Development
Paducah Gaseous Diffusion Plant	1954	Uranium Enrichment
Portsmouth Gaseous Diffusion Plant	1956	Uranium Enrichment

[a] Now Lawrence Berkeley Laboratory.
[b] Prior to MED or AEC operations.

Early dosimetry

Film packets complemented by pocket ion chambers were used for personnel dosimetry in the early years of dosimetry development. While many pocket ion chambers could be read to the nearest 258 nC kg^{-1} [1 milliroentgen (mR)], film badges in use during the 1940's had detection thresholds of 7.74–10.32 μC kg^{-1} (30–40 mR); those used in the late 1950's had detection thresholds as low as 2.58 μC kg^{-1} (10 mR) (Wilson 1987). Film badge exchange occurred weekly, bi-weekly, monthly, or quarterly, depending on the site, time period, and nature of the exposure. Research is continuing on methods to deal with doses that were not recorded because they were below detection thresholds (NIOSH 1995; Watkins et al. 1994).

OCCUPATIONAL EXPOSURES

Occupational exposure data are not available for all sites for all periods of time in the early years. Annual external dose data for individual workers at some specific sites are available from the DOE's Comprehensive Epidemiologic Data Resource (CEDR) (U.S. DOE 1993). With the exception of 1956 and 1957, summary data for all AEC facilities were reported in the AEC Annual Reports and other summaries (U.S. AEC 1957, 1960, 1961; FRC 1960; Parker 1962). Data in annual increments were available only for 1955, 1958, 1959, and 1960. There are no records of committed effective dose equivalent from intakes of radioactive materials in MED, AEC, ERDA, and DOE facilities prior to 1989, although there are some records of air monitoring results and *in vivo* and *in vitro* bioassay data. The DOE and its contractors are reconstructing doses for those workers who had significant intakes prior to 1989. Generally, there are no records of individual exposures to radon and thoron progeny for MED/AEC workers during the period 1940–1960, although these were doubtless present in some workplaces.

Exposures at Atomic Energy Commission facilities

Table 3 provides a summary of the external dose equivalent data as published at the time by the AEC for its facilities between 1947 and 1960. The number of workers in five dose ranges is given for the time period 1947–1955, inclusive, and for the single years 1955, 1958, 1959, and 1960 (U.S. AEC 1957, 1960, 1961; Parker 1962). Information on collective dose and average (mean) dose is given for these time periods in the lower portion of the table. The best estimates of collective and average doses were made by least-squares fits of lognormal distributions to categorized data as described in Appendix A.

Fig. 1 illustrates a lognormal fit to AEC summary data for the 1958 reporting year. Lognormal fits are used

Table 2. Radiation protection recommendations and limits, 1947–1960 (National Bureau of Standards 1934, 1938, 1949, 1954, 1957, 1958). Table entries are in rems unless otherwise noted (R = roentgen). Age in years is denoted by N; 5(N − 18) was intended to limit the cumulative dose limit in rems to a worker at any period in his/her life.

Year	per day	per week	per qtr	per year	accumulated
1947	25.8 μC kg^{-1} (0.1 R)	129 μC kg^{-1} (0.5 R)			
1949		77.4 μC kg^{-1} (0.3 R)			
1950		77.4 μC kg^{-1} (0.3 R)			
1954		30 mSv (0.3 rem)		150 mSv (15 rem)	
1957		30 mSv (0.3 rem)	30 mSv (3 rem)	50 mSv average, 150 mSv maximum (5 rem average, 15 rem maximum)	50(N − 18) mSv (5(N − 18) rem)

Table 3. Summary of AEC Worker Radiation Exposures, 1947–1960 (AEC 1957, 1960, 1961; FRC 1960; Parker 1962). Table entries are numbers of person-years, except as noted.

Dose interval (mSv)	1947–55	1955	1958	1959	1960
0–10	186,836	56,708	59,455	71,630	77,522
10–50	8,468	3,157	6,271	3,912	4,629
50–100	569	285	159	66	41
100–150	73	41	11	2	2
>150	19	3	11	1	3
Total	195,965	60,194	65,907	75,611	82,197
Collective dose (person-Sv)	490	177	300	237	278
Average dose (mSv)	2.50	2.94	4.55	3.14	3.38

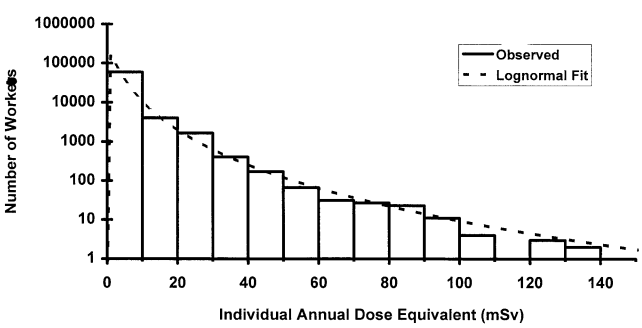

Fig. 1. Distribution of individual annual dose equivalent values for 65,907 AEC workers monitored during 1958. These values do not include doses from intakes of radioactive material. The average was 4.55 mSv and the collective dose was approximately 300 person-Sv, including 11 individuals exposed over 150 mSv (eight were involved in the 1958 criticality incident at Y-12; one worker at Los Alamos received 44 Sv during a criticality incident).

to calculate the collective dose and average dose values shown in Table 3. No attempt was made to correct for doses missed due to detection threshold problems.

Exposures at ten sites for which annual data are available

Table 4 shows collective doses due to external exposures for ten MED/AEC facilities. Data for nine of these are available in the CEDR databases. These are the Hanford Engineer Works (now the Hanford Site), the Los Alamos Scientific Laboratory (now Los Alamos National Laboratory, LANL), the Zia Corporation, the Linde Corporation Ceramics Plant, the Mound Laboratory, the Rocky Flats Plant (RF), the Savannah River Plant (now Savannah River Site, SRS), the Oak Ridge National Laboratory (ORNL, X-10), the Oak Ridge Gaseous Diffusion Plant (ORGDP, K-25) during 1944–1960. Data for the Oak Ridge Y-12 Plant were not available from CEDR, but were obtained from Strom (1983). For the first nine facilities, data are extracted from the CEDR database and are summed over all individuals. Neutron doses are probably underestimated. Working files and variables from CEDR used in this table are listed in Appendix B. Despite the fact that all data were presented in rems, all data are, as far as can be discerned, "badge dose" data, that is, uncorrected from raw measurements to effective dose or effective dose equivalent.

As of June 1994, the CEDR did not contain data for the Argonne National Laboratory, Brookhaven National Laboratory, Idaho National Engineering Laboratory, Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory, Mallinckrodt Chemical Works, Nevada Test Site, Paducah Gaseous Diffusion Plant, Pantex Plant, Pinellas Plant, Portsmouth Gaseous Diffusion Plant, Sandia National Laboratory, and the Oak Ridge Y-12 Plant. Data were also not accessible for U.S. Naval Operations that may have performed nuclear work (Bettis, Knolls Atomic Power Laboratory, Naval Research Laboratory, Charleston Naval Shipyard, General Dynamics Groton, Mare Island Naval Shipyard, Norfolk Naval Shipyard, Pearl Harbor Naval Shipyard, and Portsmouth Naval Shipyard).

Extrapolation of collective dose for 1940–1960

The AEC summaries include all facilities, but not all years; the CEDR and Y-12 data include all years for which facilities operated, but are not available for all facilities. The two incomplete data sets described above were used to estimate the collective dose for all AEC/MED sites for the entire period 1940–1960. The ten facilities listed in Table 4 had external collective doses of

Table 4. Collective penetrating dose equivalent at ten MED or AEC sites in the CEDR, by the sites' current names. All entries are in person-Sv. Blanks indicate zeroes or no monitoring or facility not in operation. K-25 = Oak Ridge Gaseous Diffusion Plant; LANL = Los Alamos National Laboratory; Linde = Linde Plant; RF = Rocky Flats Plant; SRS = Savannah River Site; ORNL = Oak Ridge National Laboratory; Y-12 = Y-12 Plant, Oak Ridge; Zia = Zia Corporation; CD = Collective Dose; CCD = Cumulative Collective Dose. Hanford data from Buschbom and Gilbert (1993), Table 3, and include only onsite doses. Y-12 data from Strom (1983) and Hudgins and Strom.[§] Row and column totals may not be exact due to rounding.

Year	Hanford	K-25	LANL	Linde	Mound	RF	SRS	ORNL	Y-12	Zia	CD	CCD
1940												
1941												
1942												
1943								1.08			1.08	1.08
1944	2.07		0.06					12.28			14.41	15.50
1945	13.10	0.01	3.99					2.86		0.02	19.97	35.47
1946	5.84	0.09	9.42					2.60		0.14	18.09	53.55
1947	4.20	0.03	4.01		0.43			2.41		0.61	11.69	65.24
1948	3.29	0.24	2.78.	0.21	0.43			3.15	0.13	0.35	10.58	75.83
1949	4.36	0.41	3.47	0.06	1.57			3.85	0.44	0.82	14.99	90.82
1950	5.84	0.22	4.37		1.50			4.14		0.74	16.81	107.63
1951	7.70	0.33	11.33		1.36			5.69		0.81	27.21	134.84
1952	11.93	0.51	6.86		1.80		0.21	9.97	3.11	0.97	35.36	170.20
1953	17.73	0.91	6.89		1.09	0.86	0.42	8.70	2.99	0.89	40.47	210.67
1954	15.66	0.32	9.11		0.75	0.44	0.57	8.85	2.16	1.47	39.34	250.01
1955	19.18	0.13	6.79		0.66	1.25	3.09	11.18	1.69	1.50	45.47	295.48
1956	19.44	0.12	11.24		0.48	1.45	6.29	11.47	1.87	1.84	54.20	349.67
1957	19.51	0.48	5.38		0.82	3.05	10.94	17.52	1.83	1.34	60.88	410.55
1958	26.13	0.52	55.99		1.46	5.46	8.71	19.21	24.68	2.22	144.39	554.94
1959	22.11	0.89	3.84		1.02	8.05	10.10	18.82	3.80	0.85	69.49	624.43
1960	26.30	1.00	4.24		1.58	5.79	18.69	10.12	4.10	1.62	73.44	697.87
Total	224.41	6.22	149.76	0.27	14.94	26.36	59.02	153.90	46.81	16.19	697.87	

528.29 person-Sv during 1947–1955 and 1958–1960, during which time our analysis indicates the entirety of the AEC facilities would have recorded 1,305 person-Sv. Assuming that the ratio of the collective dose for all of the AEC facilities to that from these ten sites remained constant (2.47) for the period 1940–1960, the occupational collective dose from external irradiation for the AEC for that period is estimated to be 1,720 person-Sv as shown in Table 5.

Uncertainties

Uncertainties in the doses discussed here come from five sources: uncertainties in the measurements themselves, inference of effective dose from measured quantities, measurements not made, censored data, and extrapolation uncertainties. It is not the purpose of this paper to review measurement uncertainties, which have been addressed in many publications (see, for example, Strom 1983; Fix et al. 1994; Gilbert and Fix 1995). Inference of effective dose from measured quantities (such as "film badge dose") has also been discussed elsewhere (Strom 1983; Crawford-Brown et al. 1989; National Research Council 1990; Watkins et al. 1994). Failure to change "badge dose" to effective dose results in a systematically high bias. Measurements were simply not made for some facilities and at some facilities for certain periods of time; a review of 40 DOE and predecessor agencies has been presented by Strom (1983, pages 182–228 and Appendixes C and D) showing gaps in monitoring. Also in Strom (1983, Appendix F) is a discussion of anecdotes about "large, unrecorded radiation exposures." Such stories, which include tales of lowered blood counts and radiation cataracts, lead one to believe that there were relatively high, by current occupational standards, unrecorded doses among nuclear physicists who began work prior to about 1943, when monitoring began in earnest. Regarding censored data, that is, potentially nonzero data that are reported as "less than detectable" or as zero, work continues on this problem (NIOSH 1995; Watkins et al. 1994). The kind of data censoring that occurs with occupational monitoring programs results in a systematic negative bias to doses recorded for individuals with low doses (Strom 1986). Also, it is believed that, due to fading, neutron doses

Table 5. Occupational collective dose from external irradiation for ten MED/AEC sites for years for which data are available. The calculated collective dose for 1940–1960 is an estimated 1,720 person-Sv (in italics). The year 1955 is only included once in the totals.

Year	AEC	10 sites	Ratio
1947–55	490	241.00	2.03
(1955)	(177)	(45.47)	(3.89)
1958	300	144.39	2.08
1959	237	69.46	3.41
1960	278	73.44	3.79
1947–55, 58, 59, 60	1305	528.29	2.47
1940–1960	1724 (calculated)	697.87	2.47

recorded on NTA film are upper bounds on true neutron doses (Parrish 1982); this produces a negative bias in doses.

The first four sources of uncertainty put together do not, in the opinion of the authors, result in an uncertainty greater than a factor of 2 in the collective dose inferred here. However, the extrapolation from sites and years for which we have data to sites and years for which we do not have data probably is not better than a factor of 2.

Criticality accidents and overexposures

Table 6 shows the history of criticality accidents in the United States. A total of three deaths due to acute radiation syndrome was recorded during 1940–1960. Overexposures are defined here by dose criteria developed jointly by DOE and NRC for designation of a medically significant exposure, that is, as exposures exceeding 250 mSv whole body, 6 Sv to skin/extremity, 750 mSv to other tissues, or 0.5 times the NCRP maximum organ burden (Fry 1980). There were 41 overexposures during 1940–1960: criticality incidents accounted for 24 overexposures including the three that were fatal; eight overexposures were due to total body irradiation; one overexposure was due to radionuclide intake; and eight overexposures were due to local (extremity) exposure (Lushbaugh et al. 1980).

Criticality accidents occurred in 1958 at the Los Alamos Scientific Laboratory and the Oak Ridge National Laboratory resulting in significant external whole body doses; these account for the high collective and average doses shown in Tables 3 and 4 for that year.

Doses from internal irradiation

For the few DOE and predecessor agency sites where they have been carefully assessed, occupational doses due to intakes of radioactive materials have generally been shown to be much less than doses from external sources (see, for example, Gilbert et al. 1989). However, at the Mound Laboratory, the collective internal doses may be much larger than the collective external doses (Wiggs et al. 1991). It is beyond the scope of this paper to address doses from intakes of radionuclides in any detail.

Table 6. U.S. criticality accidents and acute radiation syndrome fatalities, 1940–1960.

Year	Number of criticality accidents	Number of fatalities
1940–1944	0	0
1945	3	1
1946	1	1
1947	0	0
1948	0	0
1949	1	0
1950	0	0
1951	2	0
1952	2	0
1953	0	0
1954	3	0
1955	1	0
1956	1	0
1957	1	0
1958	2	1
1959	1	0
1960	1	0
Total	19	3

DISCUSSION

The estimated occupational collective dose equivalent due to external irradiation for all MED and AEC activities for 1940–1960 is 1,720 $\times\!\div$ 2 person-Sv. To put this figure into perspective, other events, sources, practices, or conditions involving radiation exposure (to external or internal irradiation or both) of various populations are shown in Table 7. Four one-time events are listed first. The accident at the Three Mile Island nuclear power plant resulted in an estimated 33 person-Sv to 2,000,000 people within 50 miles (Battist et al. 1979). The accident at Chernobyl resulted in an estimated 600,000 person-Sv to people in the northern hemisphere (UNSCEAR 1988). The 285,000 survivors of the nuclear bombings in Japan who were registered in 1950 received an estimated 47,000 person-Sv (Beebe et al. 1977). The people of earth will receive an estimated 5,000,000 person-Sv from all atmospheric nuclear weapons testing to date, most of which has already been received (UNSCEAR 1988).

Listed next are three sources of radiation exposure to earth's entire population. Each year, natural background exposure (including indoor radon) results in an estimated 11,000,000 person-Sv; medical practices result in an estimated 4,000,000 person-Sv; and nuclear power generation (normal operations) results in an estimated 30,000 person-Sv to both workers and the public.

Table 7. Comparison of the magnitudes of the collective effective dose equivalent associated with several events, sources, practices, and interventions.

Event	Collective dose (person-Sv)	How often?
Accident at Three Mile Island[a]	33	one time
Accident at Chernobyl[b]	600,000	one time
Survivors of nuclear bombings in Japan[c]	47,000	one time
Atmospheric nuclear weapons testing[b]	5,000,000	one time
Natural background exposure to Earth's population[b]	11,000,000	annually
Medical exposure to Earth's population[b]	4,000,000	annually
Nuclear power generation (normal operations)[b]	30,000	annually
Remediation of 104 houses in Pennsylvania for radon[d]	1,700 (averted)	over 10 y
Remediation of 201 houses in Pennsylvania for radon[d]	490 (averted)	over 10 y
MED/AED worker exposures, 1940–1960 (this work)	1,720	over 20 y

[a] Battist et al. 1979.
[b] Mettler et al. 1990.
[c] Beebe et al. 1977.
[d] Strom et al. 1991.

Interventions for radiation protection purposes may be used to reduce or avert collective dose (ICRP 1991). Two series of interventions in the form of residential radon remediations have been studied by Strom et al. (1991). In the first, 104 houses in Eastern Pennsylvania with very high radon concentrations (usually with potential alpha energy concentration greater than 0.2 WL) were remediated under the supervision of the Pennsylvania Department of Environmental Resources, saving an estimated 1,700 person-Sv among 416 persons over the first 10 y following remediation. In the second series, 201 houses in Western Pennsylvania with radon concentrations greater than 148 Bq m^{-3} (4 pCi L^{-1}) were remediated by a private contractor, averting an estimated 490 person-Sv among 804 persons over the first 10 y following remediation.

The figures discussed above and shown in Table 7 can be used to put the occupational exposures of MED/AEC workers into perspective. From an occupational radiation protection standpoint, 1,720 person-Sv is a significant collective dose. However, many other human practices and conditions dwarf this collective dose, and even a small number of interventions can avert comparable doses in non-occupational radiation protection.

CONCLUSIONS

There are gaps in the data for radiological exposures to workers at the dawn of the nuclear age. These gaps are due to the relatively "new" nature of radiation hazards at the time and the inability to measure and record data for large numbers of workers (especially during wartime). The records that do exist show relatively good control of external radiation hazards. The low number of radiation injuries and fatalities, compared to injuries in other industries, is testimony to the effectiveness of safety programs in place during that period.

The estimated occupational collective dose due to external irradiation for all MED and AEC activities for 1940–1960 is 1,720 $\times\div$ 2 person-Sv, a figure that is small compared to collective doses associated with other human practices, conditions, and interventions.

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APPENDIX A: DETERMINING AVERAGE AND COLLECTIVE DOSES FROM CATEGORIZED DATA

The summaries of data shown in Table 1 and this appendix include numbers of workers in dose categories, e.g., the number who received doses between 0–10 mSv, 10–50 mSv, etc. Since occupational exposure data have been shown to be lognormally distributed (Strom 1986 and references therein), fitting a lognormal distribution function to the categorized data is arguably the most accurate way of deducing the collective dose, especially in lower dose ranges. For lognormally distributed data, most of the workers are clustered in the lower portion of each range above the mode.

The worst-case (that is, highest collective dose case) estimate is made by assuming each worker received the maximum dose in each range (top of interval). A less controversial assumption is that each worker received a dose that is in the midpoint of each dose range (middle of interval). Both of these assumptions have been used to compute alternative collective doses, and these numbers are given in this appendix. Both of these approaches significantly overestimate the collective dose given by a least-squares fit of a lognormal distribution function to categorized dose data, as shown in Table A1.

Table A1. Summary of doses at MED and AEC sites for years for which summary data are available.

Dose interval (mSv)	1947–1955[a,d]	1955[a]	1958[b]	1959[c]	1960[c]
0–10	186,836	56,708	59,455	71,630	77,522
10–50	8,468	3,157	6,271	3,912	4,629
50–100	569	285	159	66	41
100–150	73	41	11	2	2
>150	19	3	11	1	3
Total number of workers[d]	195,965	60,194	65,907	75,611	82,197
Collective dose (lognormal fit; person-Sv)	490	177	300	237	278
Median dose (lognormal fit; mSv)	0.80	0.91	2.44	1.78	2.04
Mean dose (lognormal fit; mSv)	2.50	2.94	4.55	3.14	3.38
Geometric standard deviation	4.41	4.63	3.05	2.90	2.73
Collective dose (top of interval; person-Sv)	2363	760	929	919	1012
Collective dose (middle of interval; person-Sv)	1231	400	497	480	530

[a] AEC (1957).
[b] FRC (1960).
[c] Parker (1962).
[d] For 1947–1955 this is worker-years; some workers are included for up to nine different years.

APPENDIX B: COMPREHENSIVE EPIDEMIOLOGIC DATA RESOURCE (CEDR) DATA USED

Files used from the Comprehensive Epidemiologic Data Resource (CEDR) in compiling this report are listed in Table B1. External dose data were summed for all individuals and all records by year for each of these data sets. For SRS, neutron doses were added to gamma doses. For Mound and ORNL, neutron doses had been included in the *ywbody* and *pendose* fields, respectively, even though they were available as separate fields. In these working files, LANL and Zia doses were in centirems, all others known or assumed to be in millirems. All flags, codes, etc., were ignored for this analysis. Fernald data in the CEDR included no non-zero external doses during 1940–1960. A total of 98 megabytes of ASCII files were downloaded from CEDR using Telnet. Summation was carried out by a program called CEDR-TOT.BAS written by Daniel J. Strom[§] in Microsoft QuickBASIC 4.5. The program in place at this writing was not able to count unique ID numbers within years or across years, so only the total number of records processed was known.

Table B1. Working files and variables used from the CEDR, as downloaded on 9 June 1994, in alphabetical order by filename.

Site	File	Variable
LANL	1afacw01.d2	orauid, syear, mvalue
Mound	mdfacw01.d3	orauid, expyear, yneutron, ywbody
Fernald	orisewds.d11	id, resuldte, gamma
Linde	orisewds.d14	id, weekbeg, gamma
K-25	orisewds.d15	id, monyear, gamma
SRS	orisewds.d20	id, neutron, gamma, dateyear
ORNL	orisewds.d22	id, fbyear, pendose
Rocky Flats	rffacw01.d3	orauid, expyear, pendose
Zia Corp.	zafacw01.d2	orauid, syear, mvalue

[§] Hudgins, T. T.; Strom, D. J. Y1FB0414 Computer Program Output, 11:37 Friday 9 September 1983, pp. 5–6. Chapel Hill, NC: University of North Carolina at Chapel Hill; written for Oak Ridge Associated Universities' (ORAU) Center for Epidemiologic Research and U.S. Department of Energy Health and Mortality Studies, C. C. Lushbaugh, S. A. Fry, C. M. Shy, and J. E. Watson, Jr., investigators; 1983. Note added in April 1995: these data are now available from the CEDR.