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WORKER RADIATION DOSES IN THE UNITED STATES
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 U.S. 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 ten MED/AEC sites for all years were available from the U.S. Department of Energy's (DOE) Comprehensive Epidemiologic Data Resource (CEDR). These data are combined to produce an estimate of external collective dose equivalent to 172,000 person-rem (1720 person-Sv) for 1940-1960. During this period there were 41 overexposures, 19 criticality incidents, and 3 deaths due to acute radiation syndrome among several hundred thousand workers.

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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 atomic piles and natural uranium began shortly thereafter. Nuclear efforts in the United States from 1939 through 1946 were largely conducted by the U.S. Army under the name "Manhattan Engineer District." In 1947, the 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 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 facilities and uranium facilities, personal dose measurement devices were not issued and data are not available because uranium chemical toxicity was believed to be more of a problem than radiation exposure. The periods for which dosimetry was not available are short and later data indicate the hazards were under control. In this presentation, data are limited to external radiation exposures and normal operations. There were accidental criticalities and other accidents that resulted in high worker exposures and 3 worker deaths.

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 (1940-43) took place at major universities such as the University of Chicago, Columbia University, and the University of California. Activities of the Manhattan Engineering District (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. After the war (1947-1960), responsibility for special nuclear material production was given to the AEC. 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" was used as the basis for the majority of limits discussed in this paper. During the war years, the limit was 0.1 R per day based on a six-day work week. Table 2 details the limits recommended for the 1947-1960 period by the National Council on Radiation Protection and Measurements (NCRP) and International Commission on Radiation Protection (ICRP). 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 at the time, some sites, such as Hanford, utilized administrative limits that were lower than recommended limits. Such limits allowed a safety margin to account for the poor ability to measure neutron exposure.

TABLE 1. Major MED and AEC Sites, 1940-1960

Site	Date of Initial Operation	Activities
University of California Radiation Laboratory (later Lawrence Berkeley Laboratory)	1930s	Research
Columbia University	1930s	Research
University of Chicago, Argonne National Laboratory	1940	Reactor Design Chemical Separations
Oak Ridge National Laboratory (X-10)	1942	Research
Oak Ridge Y-12 Plant	1943	Uranium Enrichment and Fabrication
Oak Ridge Gaseous Diffusion Plant (K-25)	1943	Uranium Enrichment
Hanford	1943	Plutonium Production
Los Alamos/Zia Corp.	1943	Weapons Development
Mound Laboratory	1943	Isotope Separation
Sandia National Laboratory	1945	Weapons Development
Brookhaven National Laboratory	1947	Research
Knolls Atomic Power Laboratory	1947	Reactor Development
Idaho National Engineering Laboratory	1949	Reactor Development
Pantex Plant	1950	Weapons Assembly/Disassembly
Savannah River Plant	1950	Nuclear Materials Production
Nevada Test Site	1951	Weapons Testing
Fernald	1951	Feed Materials
Rocky Flats Plant	1951	Plutonium Fabrication
Lawrence Livermore National Laboratory	1952	Weapons Development
Paducah Gaseous Diffusion Plant	1954	Uranium Enrichment
Portsmouth Gaseous Diffusion Plant	1956	Uranium Enrichment

TABLE 2. Radiation Protection Recommendations and Limits, 1947-1960
(National Bureau of Standards 1947, 1949, 1954, 1957; ICRP 1958).
Table entries are in rems unless otherwise noted (R = roentgen).
Age in years is denoted by N; $5(N - 18)$ is a cumulative dose limit
in rems that may supersede the 3 rem/quarter limit.

Year	NCRP				ICRP			
	per day	per week	per qtr	per year	per day	per week	per qtr	per year
1947	0.1 R	0.5 R			0.2 R	1 R		
1949		0.3 R			"	"		
1950		"				0.3 R		
1954		"		15		"		
1957				5 ave, 12 max		"		
1958		0.3	3	$5(N - 18)$		0.1	3	$5(N - 18)$

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 milliroentgen (mR), film badges had detection thresholds of 30-40 mR during the 1940s and as low as 10 mR by the late 1950s (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 (Hornung 1993).

OCCUPATIONAL EXPOSURES

Exposure data for workers is not available for all sites for all periods of time in the early years. External exposure data from some individual sites are available from the DOE's Comprehensive Epidemiologic Data Resource (CEDR) (DOE 1993). With the exception of 1956 and 1957, summary data for AEC facilities were reported in the CEDR. Data in single year increments were only available for 1955, 1958, 1959, and 1960. There are no records of committed effective dose equivalent from intakes of radioactive materials in MED, AEC, Energy Research and Development Administration (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 during 1940-1960.

EXPOSURES AT ATOMIC ENERGY COMMISSION FACILITIES

Table 3 provides a summary of the external dose equivalent data for AEC facilities between 1947 and 1960. The number of workers in five dose ranges is given for the time period 1947-55 inclusive, and for the single years 1955, 1958, 1959, and 1960 (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.

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 (rems)	1947-55	1955	1958	1959	1960
0-1	186,836	56,708	59,455	71,630	77,522
1-5	8,468	3,157	6,271	3,912	4,629
5-10	569	285	159	66	41
10-15	73	41	11	2	2
>15	19	3	11	1	3
Total	195,965	60,194	65,907	75,611	82,197
Collective Dose (person-rems)	49,000	17,700	30,000	23,700	27,800
Average Dose (mrem)	250	294	455	314	338

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

FIGURE 1. Distribution of Individual 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 455 mrem (4.55 mSv) and the collective dose was approximately 30,000 person-rem (300 person-Sv), including 11 individuals exposed over 15 rem (five were involved in the 1958 Y-12 criticality incident; one worker at Los Alamos received 4400 rem from a criticality incident).

EXPOSURES AT TEN SITES FOR WHICH ANNUAL DATA ARE AVAILABLE

Table 4 shows collective doses due to external exposures for the Hanford Site, the Oak Ridge Gaseous Diffusion Plant (K-25), the Los Alamos National Laboratory (LANL), the Linde Plant, the Mound Laboratory, the Rocky Flats Plant (RF), the Savannah River Site (SRS), the Oak Ridge National Laboratory (ORNL, X-10), the Oak Ridge Y-12 Plant, and the Zia Corporation during 1944-1960. Neutron doses are probably underestimated. Working files and variables from CEDR used in this table are listed in Appendix B.

Data were not available for the Argonne National Laboratory, Brookhaven National Laboratory, Idaho National Engineering Laboratory, Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory, Nevada Test Site, Paducah

TABLE 4. Collective Penetrating Dose Equivalent at Ten MED or AEC Sites in the CEDR. All entries are in person-rem. Blanks indicate zeroes or no monitoring or facility not in operation. K-25=Oak Ridge Gaseous Diffusion Plant; LANL=Los Alamos National Laboratory; 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 (1983). 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								108			108	108
1944	207		6					1,228			1,441	1,550
1945	1,310	1	399					286		2	1,997	3,547
1946	584	9	942					260		14	1,809	5,355
1947	420	3	401		43			241		61	1,169	6,524
1948	329	24	278	21	43			315	13	35	1,058	7,583
1949	436	41	347	6	157			385	44	82	1,499	9,082
1950	584	22	437		150			414		74	1,681	10,763
1951	770	33	1,133		136			569		81	2,721	13,484
1952	1,193	51	686		180		21	997	311	97	3,536	17,020
1953	1,773	91	689		109	86	42	870	299	89	4,047	21,067
1954	1,566	32	911		75	44	57	885	216	147	3,934	25,001
1955	1,918	13	679		66	125	309	1,118	169	150	4,547	29,548
1956	1,944	12	1,124		48	145	629	1,147	187	184	5,420	34,967
1957	1,951	48	538		82	305	1,094	1,752	183	134	6,088	41,055
1958	2,613	52	5,599		146	546	871	1,921	2,468	222	14,439	55,494
1959	2,211	89	384		102	805	1,010	1,882	380	85	6,949	62,443
1960	2,630	100	424		158	579	1,869	1,012	410	162	7,344	69,787
Total	22,441	622	14,976	27	1,494	2,636	5,902	15,390	4,681	1,619	69,787	

Gaseous Diffusion Plant, Pantex Plant, Pinellas Plant, Portsmouth Gaseous Diffusion Plant, and Sandia National Laboratory. Data were also not available 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 ten facilities listed in Table 4 had external collective doses of 52,829 person-rem during the years 1947-1955 and 1958-1960, during which time our analysis indicates the entirety of the AEC facilities would have recorded 130,500 person-rem. 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 172,000 person-rem as shown in Table 5.

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 172,000 person-rem (in italics). The year 1955 is only included once in the totals.

Year	AEC	10 sites	Ratio
1947-55	49,000	24,100	2.03
(1955)	(17,700)	(4,547)	(3.89)
1958	30,000	14,439	2.08
1959	23,700	6,946	3.41
1960	27,800	7,344	3.79
1947-55, 58, 59, 60	130,500	52,829	2.47
1940-1960	172,390 (calculated)	69,787	2.47

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 were recorded during 1940-1960. Exposures exceeding 25 rems whole body, 600 rems to skin/extremity, 75 rems to other tissues, or 0.5 times the NCRP maximum organ burden totaled 41 during the same time period. Criticality incidents accounted for 24 overexposures, eight overexposures were due to total body irradiation, one overexposure was due to radionuclide intake, and eight overexposures were due to local (extremity) exposure (Hubner and Fry 1980).

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

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 ability to measure and record data for large numbers of workers (especially during wartime). The records that do exist show relatively good control of radiation hazards. The low number of injuries and fatalities, compared to other industries, is testimony to the effectiveness of safety programs in place at the time.

Estimated occupational collective dose due to external irradiation for all MED and AEC activities for 1940-1960 is 172,000 person-rem (0.17 million person-rem). In comparison, there were 2 million person-rem among Japanese bomb survivors, 60-90 million person-rem globally from the Chernobyl accident, 0.0033 million person-rem from the accident at Three Mile Island, and 1100 million effective person-rem every year from indoor radon (United Nations Scientific Committee on the Effects of Atomic Radiation 1988).

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APPENDIX A

DETERMINING AVERAGE AND COLLECTIVE DOSES FROM CATEGORIZED DATA

The summaries of data shown in Table A-1 and this appendix include numbers of workers in dose categories, e.g., the number who received doses between 0-1 rem, 1-5 rem, etc. Since occupational exposure data have been shown to be lognormally distributed (Strom 1986), 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 A-1.

TABLE A-1. Summary of Doses at MED and AEC Sites for Years for Which Summary Data are Available

Dose Interval (rems)	1947- 1955 (a,d)	1955 (a)	1958 (b)	1959 (c)	1960 (c)
0-1	186,836	56,708	59,455	71,630	77,522
1-5	8,468	3,157	6,271	3,912	4,629
5-10	569	285	159	66	41
10-15	73	41	11	2	2
>15	19	3	11	1	3
Total Number of Workers (a)	195,965	60,194	65,907	75,611	82,197
Collective Dose (lognormal fit; person-rems)	49,000	17,700	30,000	23,700	27,800
Median Dose (lognormal fit; rems)	0.08	0.091	0.244	0.178	0.204
Mean Dose (lognormal fit; rems)	0.250	0.294	0.455	0.314	0.338
Geometric Standard Deviation	4.41	4.63	3.05	2.90	2.73
Collective Dose (top of interval; person- rems)	236,341	76,018	92,785	91,900	101,167
Collective Dose (middle of interval; person-rems)	123,090	39,963	49,733	48,046	52,956

(a) AEC (1957).

(b) FRC (1960).

(c) Parker (1962).

(d) For 1947-55 this is worker-years; some workers are included for up to nine different years.

APPENDIX B

COMPREHENSIVE EPIDEMIOLOGIC DATA RESOURCE (CEDR) DATA USED

Working files and variables used from the CEDR, downloaded 6/9/94:

Site	File	Variable
LANL	lafacw01.d2	oraid, syear, mvalue
Mound	mdfacw01.d3	oraid, 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
Rucky Flats	rffacw01.d3	oraid, expyear, pendose
Zia Corp.	zafacw01.d2	oraid, syear, mvalue

Notes: External dose data were summed for all individuals and all records by year for each of these data sets. For SRS, we added neutron doses 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.

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