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Collection, Validation, and Treatment of Data for a Mortality Study of Nuclear Industry Workers

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To investigate the long-term health effects of protracted occupational exposure to low levels of ionizing radiation, a combined facility mortality study was initiated for 118,588 workers hired between 1942 and 1982 by three Department of Energy facilities in Oak Ridge, Tennessee. The primary objectives of the study were: (1) to evaluate and compare the mortality experience of separate subcohorts delineated by facility of employment, and (2) to conduct detailed dose–response analyses of the combined facilities subcohort having potential for external radiation exposure. Presented here are issues involving validation and treatment of data for study members, and characteristics of their radiation exposure. To verify data accuracy a stratified random sample was chosen, and original source documents containing demographic and radiation exposure data were reviewed. Health physicists investigated monitoring policies and practices in place at each facility over the 42 years of follow-up (1943 to 1984) before combining exposure data over time and across facilities. One outcome of the validation process was limiting dose–response analyses to 28,347 potentially exposed white male employees of two of these facilities, who had received 90 percent of the total recorded external dose for the population, 405 Sv. Also revealed was possible underestimation of external doses for early years of operation at these same two plants. Procedures were developed for preliminary adjustments to these doses. Data for this cohort are available in the Comprehensive Epidemiologic Data Resource of the U.S. Department of Energy.

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This article describes the data collection and validation process for a mortality study of workers hired before January 1, 1983, by three Department of Energy nuclear facilities in Oak Ridge, Tennessee. The primary objectives of the study were: (1) to evaluate and compare the mortality experience of separate subcohorts delineated by facility of employment, and (2) to conduct detailed dose–response analyses for the combined facilities subcohort having potential for external radiation exposure. We emphasize the importance of acquiring detailed background knowledge of the available data, and summarize critical information uncovered during data validation that significantly impacted the use and interpretation of data when conducting the study. Demographic and radiation exposure attributes of this population are presented along with the rationale and details of adjusting certain external doses. Previous studies have examined cause-specific mortality for subcohorts of white males[1–7] and selected groups of workers from single Oak Ridge plant populations.[8–13] The current study included all workers of both genders, all races, and employees of more than one facility. Inclusion of multiple facility workers increased both population size and radiation dose, and required a uniform approach to radiation assessment applied across facilities. The results of all analyses will be presented in a separate article.[14]

The three Department of Energy facilities in Oak Ridge included: (1) the Oak Ridge National Laboratory (referred to as X-10); (2) the Y-12 facility (involving two separate worker populations, referred to as TEC and Y-12); and (3) the Oak Ridge Gaseous Diffusion Plant (referred to as K-25).

X-10

Under management of the University of Chicago, X-10 began operation early in 1943 to provide research and development for the atomic pile project. In March 1948, Union Carbide Corporation-Nuclear Division (UCCND) assumed operation of this national laboratory, emphasizing applied as well as pure research. Potential exposures for X-10 workers included external ionizing radiation, plutonium, uranium dust, a variety of other radionuclides, lead, beryllium, and many chemicals associated with research and development laboratories.

Y-12

While operated by Tennessee Eastman Corporation (TEC) from June 1943 through May 1947, the Y-12 facility produced enriched uranium by the electromagnetic separation process. Possible occupational exposures included uranium dust, external radiation, carbon dust, chlorinated and fluorinated uranium compounds, solvents, lubricants, nitric acid, hydrogen peroxide and fluoride, chlorinating agents, oxidized uranium compounds, and uranyl nitrate.

When UCCND assumed management of Y-12 in 1947, the function of this production facility changed to nuclear materials fabrication, which involved converting uranium^{235} compounds to metal and fabricating weapons and aerospace products. Only 3147, or 6.7 percent of the TEC work force, were employed at Y-12 both before and after the process change in 1947. Potential exposures encompassed those from the earlier process and extended to beryllium, thorium, asbestos, 4,4′-methylene bis(2-choloroaniline), mercury, chromium, nickel, cadmium, lead, and zinc.

Because of the change in work force and mission, workers employed at the Y-12 facility were considered to be two separate populations in all descriptions and analyses. The subcohort referred to as TEC includes those workers employed at the facility until May 1947, and Y-12 refers to the subcohort employed at Y-12 after May 1947.

K-25

The K-25 site, which began full-scale operation in 1945, also produced enriched uranium, but used a gaseous diffusion process. After WWII, production at K-25 increased as the tense world political situation made the extraction of uranium^{235} a matter of high priority in the national defense strategy. K-25 workers had potential for exposure to uranium dust, oxidized uranium compounds, uranium hexafluoride, external radiation, fluoride, lead, nickel, cadmium, chromium, perchloroethylene, mercury, lubricants, and laboratory chemicals.

Methods

Data Collection

In 1965 the Computer Sciences Division of UCCND was asked by the Atomic Energy Commission to assemble and computerize employee demographic and exposure information from hard-copy records for the pilot project of a comprehensive Health and Mortality Study (HMS), which would investigate effects of long-term exposure to low level radiation.[15] In 1979 data for the Oak Ridge facilities were released on a series of magnetic tapes to Oak Ridge Associated Universities' Center for Epidemiologic Research (CER), and these data were developed into a dynamic, integrated database. The original magnetic tapes, prepared by UCCND, contained separate source data files for demographic, work history, and occupational exposure records. These files provided internal and external radiation personal monitoring data and other information such as name, social security number (SSN), vital status, gender, race, birth date, pay codes, various chemical exposures, and dates for entering and terminating employment and transferring to other facilities.

After the original transfer of data, machine-readable updates were received regularly until 1992, and error detection and corrections were performed on a continuing basis.[16] Of the 1,336,746 personal monitoring data records received from X-10, Y-12, and K-25, 99 percent were linked to employees through an algorithm using SSN, name, dates of employment, and badge numbers. Because medical records and occupational history records for the TEC workers are stored in a vault at CER, extensive validation has been done for all TEC employees.

Vital Status Follow-Up

This study population, as part of the HMS, was included in routine vital status updates, which were conducted for all active and former employees every 2 to 3 years from 1979 through the end of the study. Prior to 1979, the Social Security Administration was the predominant agency used to ascertain vital status, while afterward a number of additional sources were employed.[15] Death certificates were retrieved from either facility of employment or state of death.

Completeness of Roster

To check on completeness of the rosters, the number of workers employed at each Oak Ridge facility each year was obtained independently from UCCND annual human resources reports. Separate annual facility totals were combined and compared with the total number in the demographic analysis file.

Current Data Verification

To verify that study data accurately represented data in plant records, a stratified random sample was taken of 500 workers in the same race/gender proportions as the study cohort. Their data were verified by comparing values to those in archived hard copy and other source records. Demographic and work history data were checked for all 500 workers. For the 210 workers in the sample who were X-10 or Y-12 employees, radiation monitoring data were retrieved independently by plant personnel for X-10, Y-12, and K-25 employment-years.

Radiation Exposure Data

Historically, the main purpose of radiation monitoring programs was to ensure that each worker's exposure to radiation was kept well below the prescribed occupational limit each year (the current limit being 50 mSv). Because of this aim, data collected in early years were sparse for workers considered to have low exposure potential. Each facility had its own radiation safety personnel, followed its own procedures for monitoring and recording results, and concentrated resources on greatest potential hazards. Internal radiation was the primary concern for Y-12 and K-25. Figure 1 summarizes both internal and external monitoring policies in place at the facilities by year. No personal monitoring data are available for TEC. Because of contemporary policies, external dose data are not available for most Y-12 workers before 1961 and for most K-25 workers before 1975. X-10 had personal monitoring available for all employees by the end of 1947; however, only workers entering with a prescribed frequency into areas of potential external radiation exposure were actually badged. In 1947 all workers entering a radiation area more than three times a week were assigned a permanent film badge, and by 1949 permanent film badges were issued if entering at least once a week. By the end of 1951 all workers entering the main area at the X-10 site were required to have a film badge, and the film badge and security badge needed for entry were combined into one before 1954.[17] Neutron doses were not estimated for several reasons. Potential for neutron exposure at both K-25 and Y-12 was minimal. Neutron exposures at X-10 were believed to be insignificant relative to gamma exposures, and the limited neutron monitoring data available from this facility were of questionable quality.

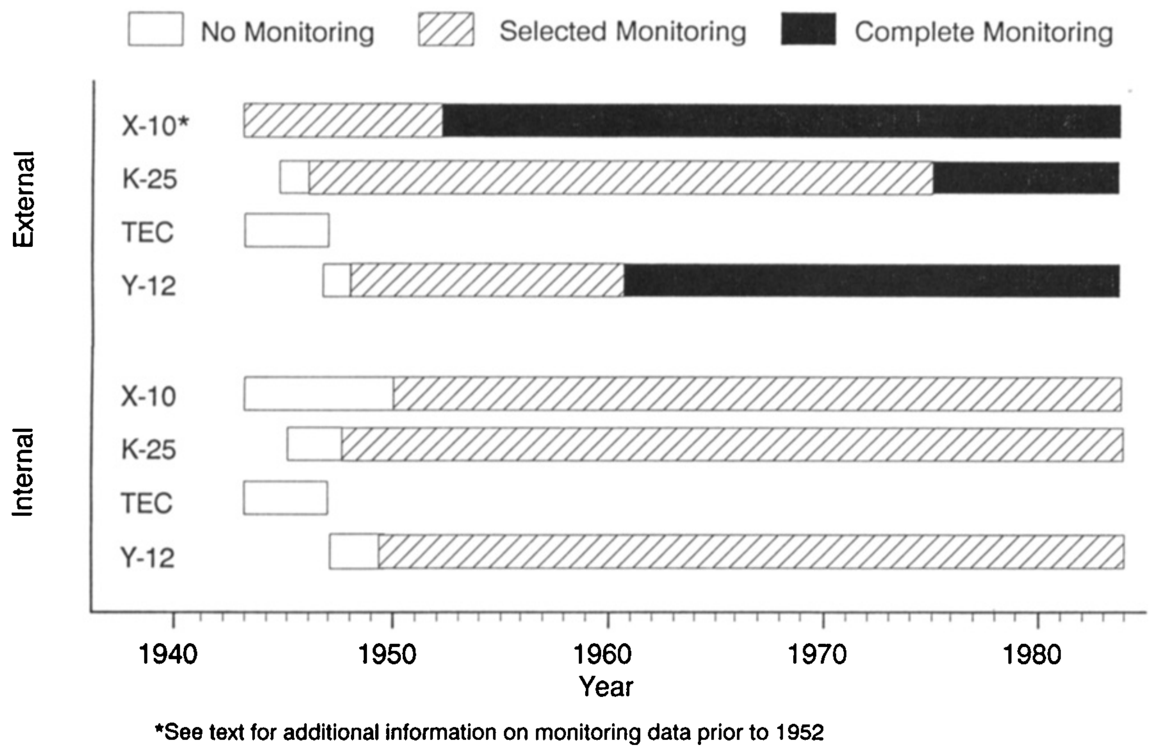

FIGURE 1. Personnel monitoring policies for Oak Ridge facilities, 1943–1984.

During the entire study period, workers were monitored for internal exposure at all facilities only if judged to have exposure potential. Internal monitoring programs were begun in 1948 by K-25, in 1950 by Y-12, and in 1951 by X-10.

External Radiation Exposure

External radiation doses for Oak Ridge workers were obtained from personnel integrating dosimeters, most frequently photographic film dosimeters (film badges) prior to 1975 and thermoluminescent dosimeters (TLDs) afterward. For early film badges the minimum detectable exposure was approximately 0.25 ± 0.10 mSv,[18] and the practical useful range for sensitive film badges was 0.30 to 1000 mSv.[19] TLDs were able to measure X rays and gamma rays as low as 0.10 mSv.[20] Pocket ionization chambers (pocket meters) have also been used since the plants opened, particularly to obtain interim values between film badge readings. Their use continued through the end of the study period whenever high exposure potential was suspected. Figure 2 summarizes by facility and year the types of dosimeters generally in use and the frequency at which they were read.

Annual recorded doses were calculated by summing all film badge readings taken throughout the year. Because of variability in dosimeter types, reading frequencies, and monitoring policies and procedures over time and across facilities, annual doses obtained in this way were not always comparable and some may have underestimated actual doses received. To compensate for likely missed dose in recorded doses for certain employment-years, adjusted annual doses were produced with the aim of reducing the effect of these systematic errors.

Adjustments to External Radiation Doses

Because of contemporary decisions of health physicists that none but a few K-25 workers were at risk of external radiation exposure, an extremely low percentage of K-25 workers was monitored during any year during the 30 years between plant opening and 1975. Determining which employees were at risk for external exposure involved decisions based on detailed knowledge of processes and materials. From 1975 to 1977, the first 3 years of complete monitoring at K-25, 99 percent of the workers received annual doses equal to or less than 1.2, 2.1, and 1.8 mSv, respectively. There was no evidence to indicate that K-25 doses should be adjusted upward and no data upon which to base an adjustment process. Upward adjustments were made to selected X-10 annual recorded doses from 1944 through 1956, years when film badges were read weekly. Dose estimates were made for unmonitored Y-12 employment-years from 1947 through 1960, when the policy was to monitor only those employees with higher exposure potential. Also, dose estimates were made for the 3 percent missing X-10 and Y-12 annual doses for the remaining years through 1984. All dose estimates and adjusted doses were prorated by the number of days employed during the year.

Procedures for Adjustments to X-10 External Radiation Doses

External radiation monitoring in 1943 consisted almost entirely of pocket meters. No adjustments were made to recorded doses based on these readings. However, unmonitored 1943 employment-years were replaced with estimated doses using procedures described below. From mid-1944 through mid-1956, film badges for X-10 workers were read weekly,

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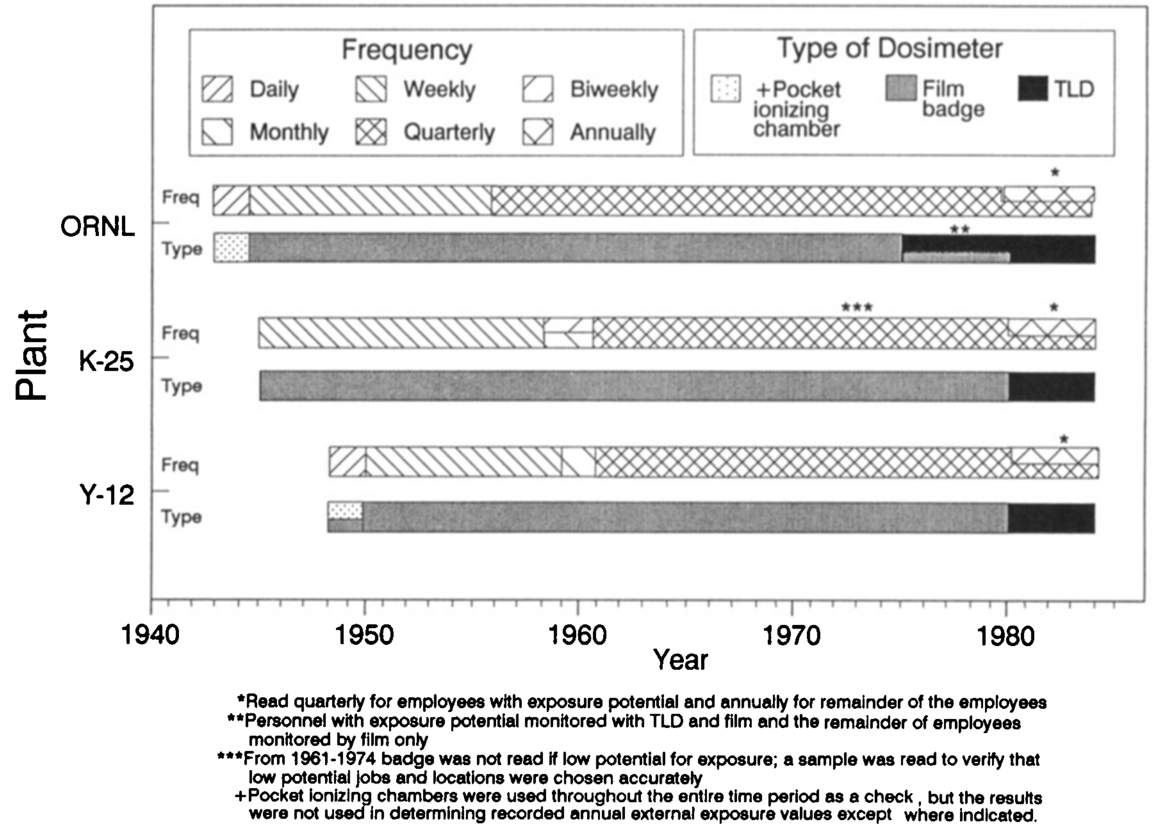

FIGURE 2. Types of dosimeters and frequency of readings for Oak Ridge facilities, 1943–1984.

allowing only a short time to accumulate exposure. It was general practice to record as zero those readings below the detection limit of the badge, which was taken to be 0.30 mSv through 1951 and 0.50 mSv or less during other periods, depending upon the sensitivity of the specific batch of film.[21] The combination of weekly readings and the zero recording practice made it likely that annual recorded doses for many employment-years were underestimations of actual doses. Once film badges were read quarterly rather than weekly, the magnitude of missed dose was probably much smaller than previously. As a preliminary attempt to compensate for likely missed dose, the adjustment procedures described below were implemented.

Not all doses from 1944 through 1956 required adjustment because certain employment-years had no occupational exposure associated with them. The following criteria were formulated by health physicists to select employment-years that should retain a dose of zero:

- If all annual recorded doses for a worker employed 5 or more years were zero, then they remained zero.
- If the department of employment for the majority of a given year had at least 75 percent annual recorded doses of zero that year, then the dose remained zero.

The remaining doses were adjusted upward by an algorithm created for this purpose. A sample of 211 employment-years of hard-copy dosimetry records before 1955 were archived and computerized for use in the adjustment process. These hard-copy records contained weekly film badge readings as well as corresponding pocket meter readings. Health physicists discovered weekly recorded doses of zero when concurrent skin doses and pocket chamber readings indicated positive dose. They replaced weeks having zero or missing film badge readings with available weekly pocket meter readings before summing to obtain the film badge–pocket meter estimate of annual dose. The difference between this estimate and the annual recorded dose was the estimate of missed dose (EMD). More details on the hard-copy records and their use in the dose adjustment procedure are available.[22]

Procedures for Estimation of Unmonitored External Radiation Doses at Y-12

From 1947 through 1960 at Y-12, between 80 and 95 percent of employment-years (depending upon the year) were unmonitored for external radiation since emphasis was placed on monitoring for internal radiation exposure. To replace these unmonitored employment-years with dose estimates, health physicists familiar with the facility first determined which of them would be assigned zero doses using the following criterion: If the department of employment for the majority of a given year had fewer than 10 percent monitoring that year, then the annual dose estimate was zero.

Unmonitored employment-years having an annual recorded dose within 2 years were replaced with estimated doses using procedures described below. For remaining employment-years, departments were grouped into three categories by

TABLE 1. Demographic Data Information for the Study Cohort

	Males		Females	
	White	Nonwhite	White	Nonwhite
Number of workers (% of total cohort)	68,666 (65)	4238 (4)	29,805 (28)	3311 (3)
Number of workers by facility (% of number in race/gender group)				
X-10 only	11,349 (17)	1021 (24)	3902 (13)	464 (14)
TEC only	16,503 (24)	942 (22)	14,483 (49)	1627 (49)
Y-12 only	8591 (12)	629 (15)	1465 (5)	283 (9)
K-25 only	21,279 (31)	945 (22)	6870 (23)	533 (16)
MUL (worked in multiple facilities)	10,944 (16)	701 (17)	3085 (10)	404 (12)
Number employed only during WWII (% of number in race/gender group)	31,337 (46)	1750 (41)	20,164 (68)	2065 (62)
Total person-years of follow-up (% of total)	1,824,000 (65)	82,700 (3)	833,100 (30)	70,400 (2)
Total person-years of employment (% of total)	462,824 (79)	23,055 (4)	91,757 (15)	9596 (2)
Total person-years of employment by facility (% of number in race/gender group)				
X-10	130,780 (28)	8163 (35)	27,747 (30)	2708 (28)
Y-12	157,994 (34)	7649 (33)	19,095 (21)	2688 (28)
K-25	148,020 (32)	6394 (28)	28,365 (31)	2727 (29)
TEC	26,030 (6)	849 (4)	16,550 (18)	1472 (15)
Vital status (% of number in race/gender group)				
Alive	41,748 (61)	2499 (59)	19,648 (66)	1944 (59)
Dead	22,724 (33)	1121 (26)	3595 (12)	542 (16)
Unknown	4194 (6)	618 (15)	6562 (22)	825 (25)
Number with death certificate retrieved (% of deceased in race/gender group)	22,283 (98)	1072 (96)	3452 (96)	510 (94)

exposure potential. Using medians of groups of doses from 1961 to 1965, when monitoring data were readily available, values of 0.45, 0.70, and 1.30 mSv were calculated as dose estimates for unmonitored employment-years through 1960 for employees in departments classified as having lower, moderate, or higher potential, respectively.

Replacement of Missing Doses at X-10 and Y-12

An algorithm was developed to replace the 3 percent missing values after 1956 at X-10 and after 1960 at Y-12.[23] First, a nearby procedure assigned an estimated dose based on an individual's doses for up to 2 years before or after the missing year. This technique averaged chronologically equidistant doses or copied the nearest eligible available dose. When no doses were recorded within 2 years of the missing value, the median dose of workers in the same department that year was assigned. If the departmental median was unavailable, the estimate was the annual plant median.

Internal Radiation Exposure

Monitoring for internal exposure is performed at specific points in time and can be used to calculate estimates of body or organ burden at the time of measurement. The two primary methods of internal monitoring used to obtain data on the study population were urinalysis and *in vivo* gamma spectrometry. Monitoring programs tested for 36 radioisotopes at X-10, for 5 at Y-12, and for 7 at K-25. Fewer than 40 percent of the workers at any facility were generally monitored during a year.

Personnel working in locations or administrative groups judged to have internal exposure potential were monitored. Periodically, a small number of randomly selected workers classified as not having exposure potential were also monitored by X-10 and K-25 to verify that they were indeed unexposed.[24] The stated policy at Y-12 was to increase monitoring frequency as internal exposure potential increased.

Because of great differences in potential for internal exposure among facilities, a common annual indicator of potential internal exposure for X-10, Y-12, and K-25 was assigned having one of three values. Values assigned were "not monitored" when no bioassay results and no *in vivo* counting results existed in that year, "not exposed" when an employee's monitoring results indicated an annual internal dose of less than 1 mGy, and "exposed" when results indicated a dose of 1 mGy or more total from all monitored isotopes.

Results

Analysis Files

Six analysis files were produced for the study. The first contained demographic and work history data for 118,588 Oak

TABLE 2. Monitoring Data Information for the Study Cohort

	Males		Females	
	White	Nonwhite	White	Nonwhite
Number monitored for external or internal radiation (% of race/gender group monitored)	33,088 (48)	2392 (56)	7809 (26)	1161 (35)
Number monitored for external dose (% of race/gender group monitored)	31,587 (46)	2354 (56)	7607 (25)	1154 (35)
Number of workers by final cumulative external dose (% of number monitored in race/gender group)				
<10 mSv	24,661 (78)	2109 (90)	7305 (96)	1119 (97)
≥10 to <50 mSv	5565 (18)	201 (8)	272 (4)	35 (3)
≥50 mSv	1361 (4)	44 (2)	30 (0)	0 (0)
Total external dose (Sv) (% of total)	376.19 (93)	12.20 (3)	15.37 (4)	1.68 (0)
Total external dose (Sv) by facility (% of total dose in race/gender group)				
X-10	238.85 (64)	7.89 (65)	7.87 (51)	0.75 (45)
Y-12	125.37 (33)	3.77 (31)	6.82 (45)	0.80 (48)
K-25	11.97 (3)	0.54 (4)	0.68 (4)	0.13 (7)
Total employment-years by facility (% of these unmonitored)				
X-10 (1943–1984)	146,229 (3)	9287 (4)	33,007 (6)	3232 (6)
Y-12 (1948–1960)	51,854 (86)	1500 (97)	7843 (96)	606 (98)
(1961–1984)	121,069 (2)	7056 (4)	14,162 (4)	2475 (4)
K-25 (1948–1974)	132,838 (89)	4206 (96)	1371 (100)	2058 (5)

Ridge facility workers hired by December 31, 1982. Of these workers, 12,568 were eliminated from the study cohort; 11,002 of those rejected were employed for less than 30 days.

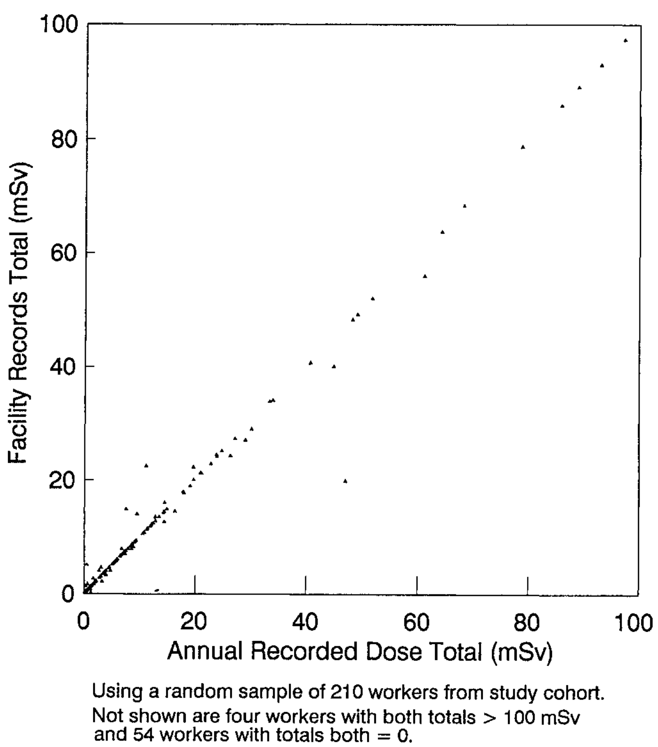

FIGURE 3. Comparison of cumulative external dose from plant records and analysis files for a sample of X-10 and Y-12 employees.

The remaining exclusions had data containing critical errors, such as unknown gender or hire date before birth date.

Radiation exposure analysis files were constructed for X-10, Y-12, and K-25. Each of these files contained an annual code to indicate whether the worker was employed and, for each employment-year, an indicator variable for internal exposure, and the annual recorded external dose if the worker had been monitored. Two additional analysis files were produced containing adjusted annual external doses for white male employees of X-10 and Y-12 as described in Methods.

Descriptive Statistics for the Study Population

The study cohort consisted of 106,020 workers hired by December 31, 1982, employed for at least 30 days, and having data free of critical errors. Of the 27,982 known to have died by December 31, 1984, death certificates were retrieved, verified, and coded for 97.9 percent. Table 1 provides descriptive demographic information for the study cohort by race and gender. White males had only 6 percent unknown vital status, while percentages for the other groups are substantially higher. Deaths may have been underascertained in females, since over 20 percent of the females of both races were lost to follow-up, most shortly after WWII.

Table 2 summarizes radiation monitoring data characteristics of the study population by race and gender. The distribution of unadjusted annual recorded doses shows that white males received 93 percent of the total recorded dose of 405.44 Sv. Of the dose received by the white male employees, 64 percent was attributed to X-10 workers, 33 percent to Y-12 workers, only 3 percent to K-25 workers, and none to TEC workers. Because deaths were possibly underascertained for all workers except white males, and 90 percent of total dose came from the

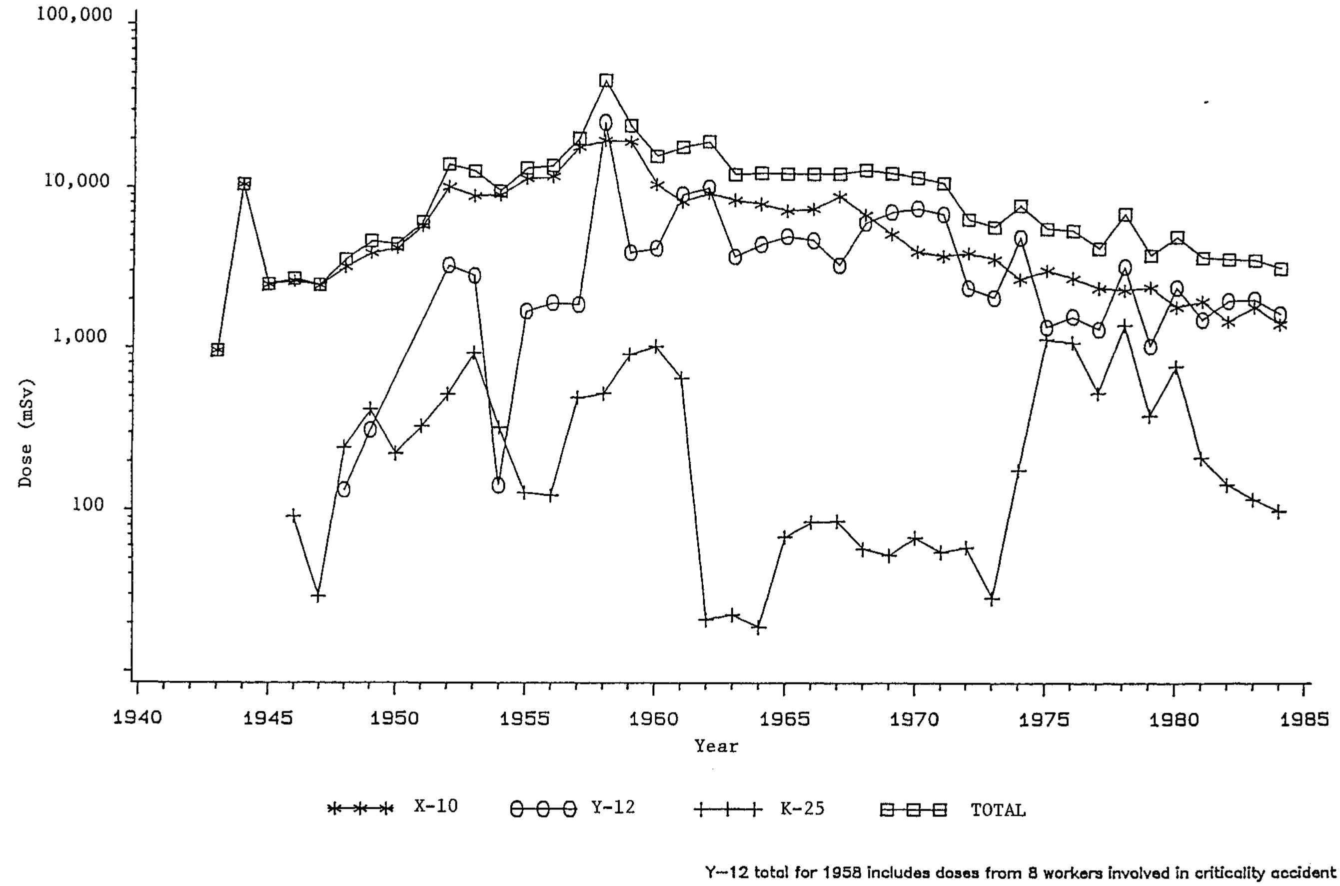

FIGURE 4. Total annual collective external dose by facility, 1943–1984.

monitoring data of 28,347 white male X-10 and Y-12 employees, dose–response analysis was restricted to white males known to be alive 365 days after first hire at X-10 or Y-12. This subcohort is referred to as X-10/Y-12 evers.

Completeness of Roster

There was very close agreement between the yearly numbers of Oak Ridge facilities employees from the demographic analysis file and UCCND reports. The only discrepancies occurred for years before 1948, when analysis file totals were greater than report totals because no corporate reports could be obtained on personnel figures from TEC, and because UCCND did not assume management of X-10 until March 1948. This check substantiated the completeness of the study cohort. From 1952 through 1984 the number of employees in the Oak Ridge facilities was fairly stable, varying from 12,000 to 15,000 through 1975 and gradually increasing to 18,000 by 1980.

Current Data Verification

The random sample data verification confirmed the high quality of the demographic and work history data with exact matches out of 500 as follows: gender, 500; race, 500; paycode, 499; birthdate, 498; hire/term dates, 483. Figure 3 compares the total external annual recorded dose from all facilities taken from analysis files with the total retrieved from checking plant records for the 210 who were X-10 or Y-12 employees. Very close agreement is observed for nearly all of these workers between the two totals for cumulative dose. For the four workers with cumulative doses between 100 and 155 mSv, there was a less than 4 percent difference for each between the analysis file total and the value from the plant check. Final cumulative internal category was in agreement for 205 of the 210.

Annual External Dose by Facility

Figure 4 depicts the total external dose by year and facility and shows that K-25 contributed the least dose in nearly every year of operation. Figure 4 also shows a trend of decreasing dose at X-10 from the peak between 1957 and 1959. External dose at Y-12 began to decline in 1961, but not monotonically.

Adjusted External Doses for X-10 and Y-12

Figure 5 is a graph of EMD versus annual recorded dose from film badges at X-10 (see Methods). The dashed line shows the fit obtained from a variable span smoother[25] using S-PLUS supersmu.[26] Although there is uncertainty involved because of the spread of the data, the graph suggests that an algorithm for preliminary adjustment of X-10 doses might contain two distinct parts, a quadratic curve for doses below 16 mSv and a horizontal line 3 mSv above the x axis for doses between 16 and 50 mSv. Based on background knowledge of the monitoring and dose recording practices at this facility, this pattern

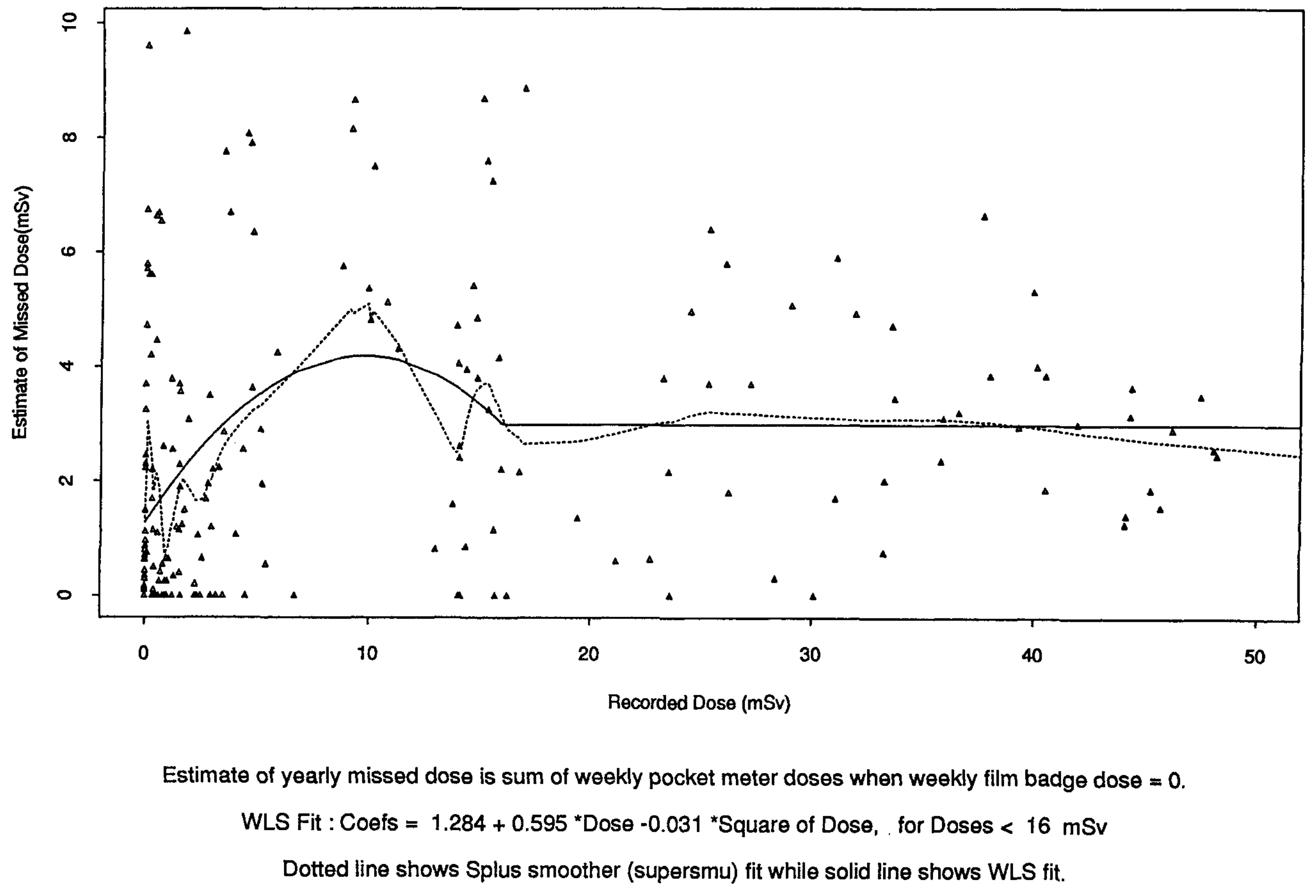

FIGURE 5. Adjusting X-10 external doses, 1944–1956: estimate of missed dose versus annual recorded dose.

appeared reasonable for preliminary dose adjustments. A second-degree polynomial was fit using weighted least squares to doses below 16 mSv (shown in a solid line), and resulted in the following equation:

$$EMD = 1.28 + 0.595X - 0.0306X^2$$

where: X = the unadjusted annual recorded dose in mSv.

Additional details on obtaining this equation are available.[22]

Tables 3 and 4 show numbers of adjusted and estimated

TABLE 3. Number of Annual External Doses and Unmonitored Years Adjusted for X-10

1943 (682 possible annual doses)	
Nearby	210
Plant median	97
1944–1956 (31,048 possible annual doses)	
Set to zero by criterion 1[A]	631
Set to zero by criterion 2[B]	5976
Adjusted by formula[C,D]	23,149
Adjusted by constant value[E]	1147
1957–1984 (114,499 possible annual doses)	
Nearby procedure	410
Annual department medians	96
Annual plant median	73

[A]Employed for 5 or more years and having no recorded doses greater than zero.
[B]Department of employment for majority of the year had 75 percent or more zero doses.
[C]Estimate of missed dose = $1.28 + 0.595X - 0.0306X^2$, where X is annual recorded dose in mSv.
[D]9322 doses adjusted by the formula were former zero doses.
[E]3 mSv.

TABLE 4. Number of Annual External Doses and Unmonitored Years Adjusted for Y-12

1947–1960 (51,854 possible annual doses)[A]	
Nearby procedure	4242
Set to zero[B]	20,671
Higher exposure departments[C]	5677
Moderate exposure departments[D]	5154
Lower exposure departments[E]	8648
Revised (1948 and 1949)	104
1961–1984 (121,069 possible annual doses)	
Nearby procedure	2104
Annual department medians	52
Annual plant median	128

[A]7358 not adjusted because annual recorded doses were based on film badge records.
[B]Department of employment for the majority of the year had less than 10 percent monitoring during that year.
[C]Dose estimate was 1.30 mSv.
[D]Dose estimate was 0.70 mSv.
[E]Dose estimate was 0.45 mSv.

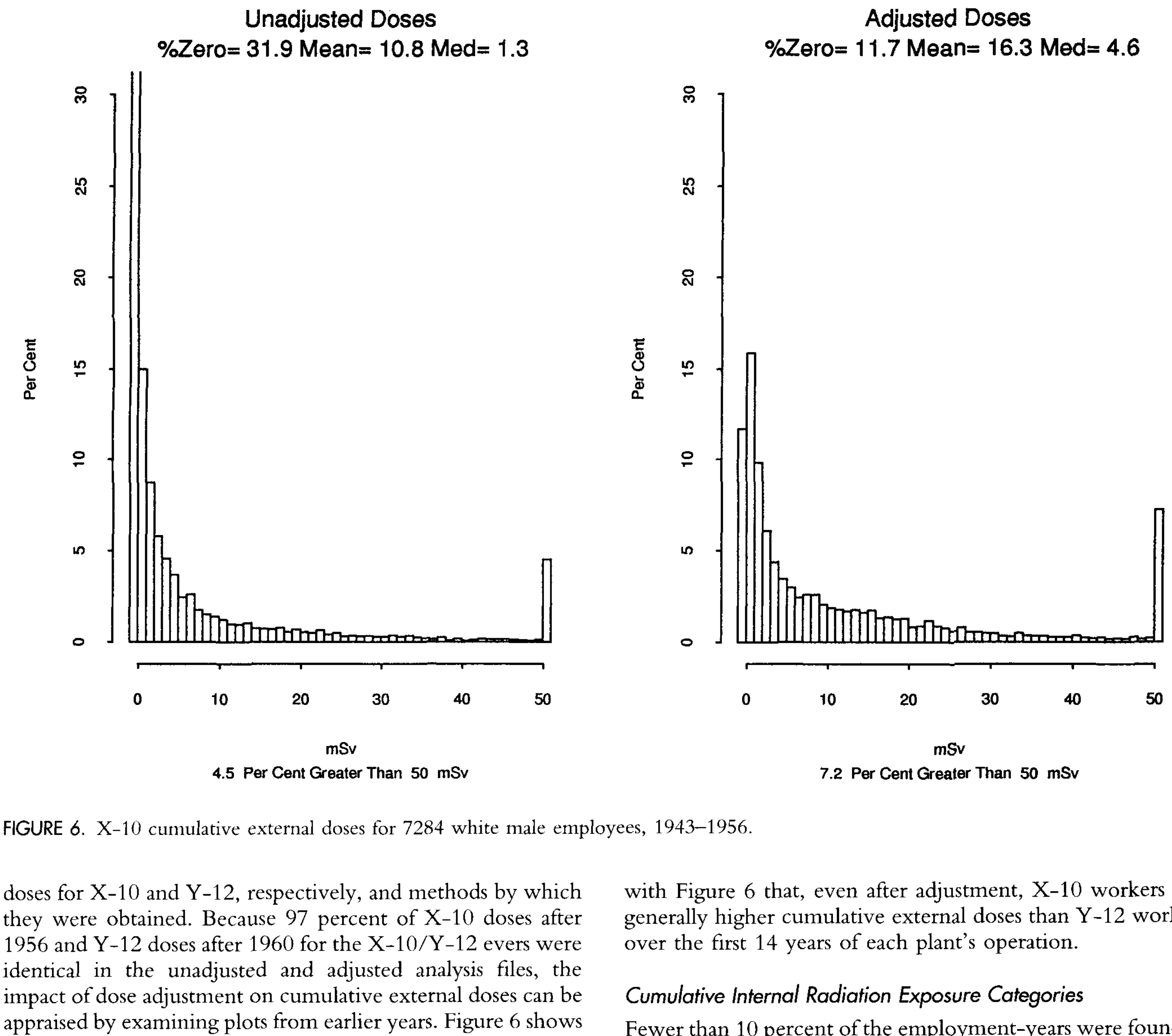

FIGURE 6. X-10 cumulative external doses for 7284 white male employees, 1943–1956.

doses for X-10 and Y-12, respectively, and methods by which they were obtained. Because 97 percent of X-10 doses after 1956 and Y-12 doses after 1960 for the X-10/Y-12 evers were identical in the unadjusted and adjusted analysis files, the impact of dose adjustment on cumulative external doses can be appraised by examining plots from earlier years. Figure 6 shows distributions of unadjusted and adjusted annual X-10 doses accumulated through 1956, while Figure 7 displays distributions of unadjusted and adjusted Y-12 cumulative doses through 1960.

Figure 6 depicts a smooth, gradual shift toward higher values of cumulative dose resulting from the dose adjustment process. Except for the large drop in percent of workers with a cumulative dose of zero through 1956 (from 31.9 to 11.7%), there were no major changes. The cumulative dose mean for X-10 white males increased from 10.8 to 16.3 mSv, the median from 1.3 to 4.6 mSv, and the total dose from 238.7 to 279.4 Sv.

Because few Y-12 workers were monitored before 1961, the adjustment process resulted in a striking change in percentage of workers with a zero cumulative dose (from 74.3 to 10.1%), as shown in Figure 7. The cumulative dose mean for Y-12 white males increased from 5.1 to 8.7 mSv, the median from 0.0 to 2.0 mSv, and the total from 125.3 to 160.3 Sv. However, after adjustment most Y-12 workers still had cumulative doses through 1960 of less than 10 mSv, and 50 percent were less than 2 mSv. It is apparent when comparing Figure 7 with Figure 6 that, even after adjustment, X-10 workers had generally higher cumulative external doses than Y-12 workers over the first 14 years of each plant's operation.

Cumulative Internal Radiation Exposure Categories

Fewer than 10 percent of the employment-years were found to be "not exposed." The data validation also revealed that "not monitored" had different implications before and after the implementation of internal monitoring programs. Therefore, the following annual indicators of cumulative internal exposure were used to form three time-dependent internal monitoring categories for use in analysis:

NE: Not eligible for monitoring
  Before 1951, when internal monitoring was first available at all three facilities.
EN: Eligible but not monitored
  For 1951 and later, assigned until reaching a year when monitoring occurred.
EM: Eligible and monitored
  For 1951 and later, assigned the year first monitored and all subsequent years.

These broad categories, necessitated by the substantial differences in internal exposure potential by plant and time period, were used to allow consideration of internal exposure as

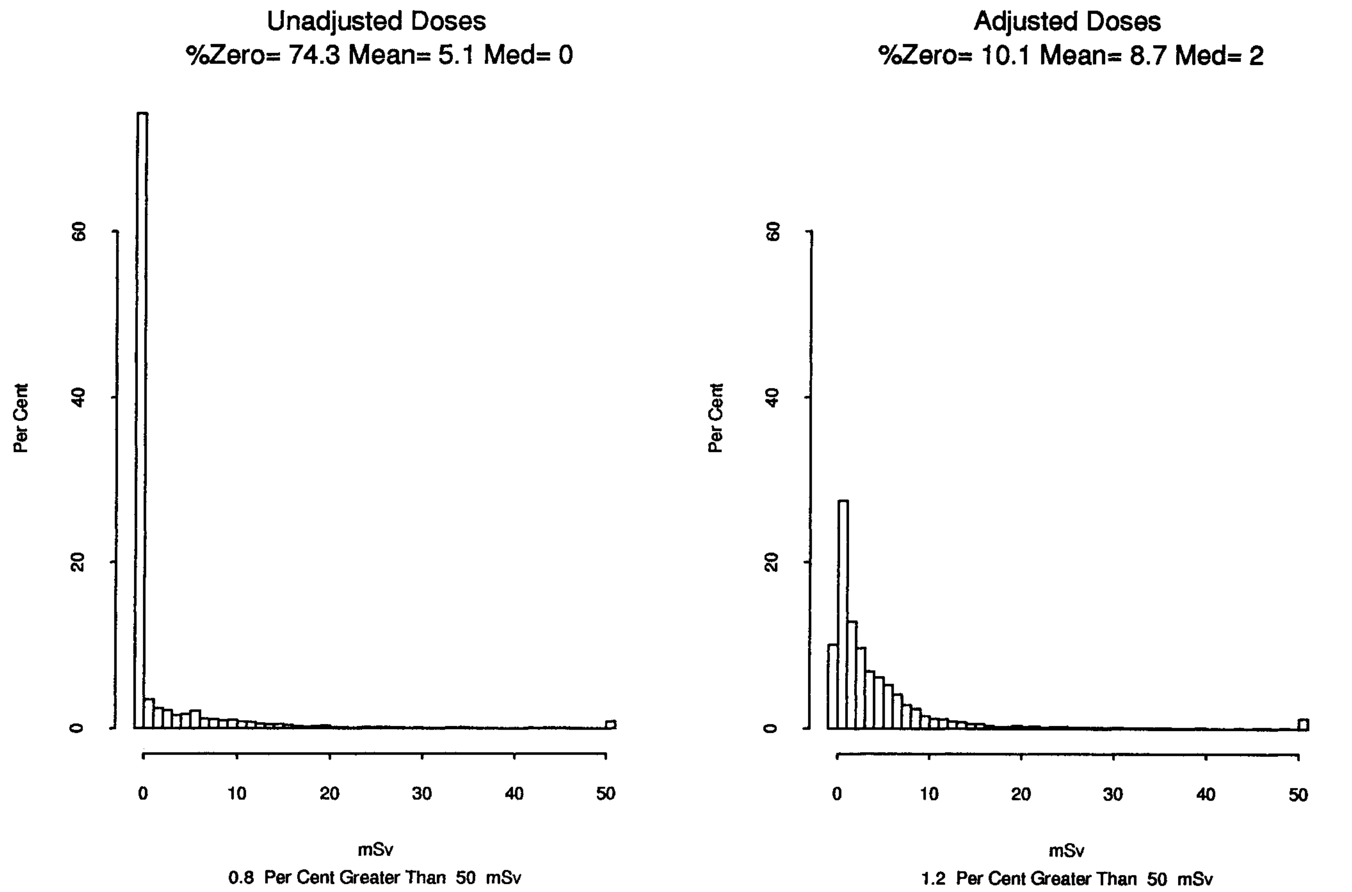

FIGURE 7. Y-12 cumulative external doses for 8490 white male employees, 1947–1960.

a possible confounder when performing dose–response analyses based on external radiation dose.

Discussion and Recommendations

We affirmed that the available data were an acceptable basis for the planned mortality study if carried out thoughtfully using the information obtained from the thorough background investigation. Validation checks confirmed that rosters were comprehensive and that demographic data were complete and reliable for the vast majority of the study cohort, although vital status was probably underascertained for females and nonwhite males. Characteristics of the varied internal exposure data allowed the calculation of three categories of annual internal exposure indicators. External dose data used in the study were compiled accurately from the originally recorded film badge and TLD data. However, external monitoring data were not complete, especially during early years for workers considered to be at low risk for radiation exposure. Personal monitoring did not occur for the TEC subcohort. Complete monitoring was not initiated at K-25 until 1975, 30 years after the plant began operating, because health physicists managing the K-25 monitoring program determined that most workers were not at risk from external radiation. Doses obtained when K-25 initiated complete monitoring support their decision, since 99 percent of the annual doses obtained from 1975 to 1977 were 2 mSv or less. Although there were no monitoring data for K-25 upon which to base a dose adjustment process, it is unlikely that dose adjustment was necessary.

We determined that underascertainment of external dose at X-10 and Y-12 during certain early years was likely because of contemporary monitoring policies and recording practices. The decision was made to calculate preliminary adjusted doses to obtain information on the potential impact of dose adjustment on dose–response estimates. It was speculated that using upwardly adjusted doses might in general lower dose–response estimates. Development of dose adjustment procedures, while based on extensive historical knowledge, was hampered by the small size of the sample of hard-copy records obtainable from X-10 and by the complete lack of hard-copy records from early years at Y-12.

If a more definitive dosimetry assessment is needed in future epidemiologic studies for X-10 workers, Kerr[27] recommends that all available data be used. Detailed hard-copy exposure records, which contain daily pocket meter and weekly film badge data for approximately 30,000 employment-years at X-10 prior to 1957, have not been computerized. More sophisticated and accurate adjustment techniques could be implemented for future studies if these individual monitoring data are computerized.[28] Alternatively, an epidemiologic study employing a nested case–control or case–cohort design would require computerization of complete radiation monitoring data for only a subset of the X-10 workers. Similar external radiation monitoring data in hard-copy records are not available for other Oak Ridge facilities.

Further details are available[17,22] on background information, distributions of data for the study cohort, and procedures used in dose adjustment. These two technical reports are available over the Internet at http://www.orau.gov/ehsd/cer.htm.

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