Journal of Exposure Analysis and Environmental Epidemiology (2000) **10,** 27–35

www.nature.com/jea

Evaluation of annual external radiation doses at values near minimum detection levels of dosimeters at the Hanford nuclear facility

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In epidemiological studies of workers exposed to ionizing radiation, recognition of the limitations of available radiation dosimetry data is important to interpretation of a study's findings. This paper provides an investigation of external radiation dosimetry data for workers at the Hanford nuclear facility, focusing on changes over time in practices for recording dosimetry measurements that were between zero and the minimum detectable level of a radiation dosimeter. Reported annual external radiation doses for the years 1944–1989 were examined for 33,459 workers; these records are the sum of periodic dosimetry measurements within a calendar year. For each year, the proportion of annual external doses with values in the range of minimum detectable level was examined. Contrary to previous researchers, we conclude that there is evidence that dosimetry measurements with values between zero and the minimum detectable level may have been recorded as zero in some historical periods. This conclusion is supported by evidence drawn from historical documentation about radiation dosimetry practices at the Hanford facility. Although workers at the Hanford facility have relatively complete and detailed external radiation dosimetry data compared to some other nuclear facilities that began operation in the 1940s, these data may suffer limitations related to dosimetry recording practices at the facility. *Journal of Exposure Analysis and Environmental Epidemiology* (2000) **10,** 27–35.

Keywords: *dosimetry, epidemiology, Hanford, radiation.*

Introduction

The Hanford Site, located in Richland, Washington, began operation in 1944 as a plutonium production facility for the United States nuclear weapons program. External radiation monitoring data for workers at Hanford have been collected primarily for worker protection, rather than for research purposes. Consequently, there was not a standardized protocol used for collecting exposure information for all workers included in epidemiological analyses over the entire period of study. Rather, there have been changes over time in the type of external radiation dosimeter used at Hanford, changes in the frequency of exchanging dosimeters, and changes in the units to which dosimetry results were rounded when recording measurements (Gilbert, 1990; Wilson et al., 1990). When using these data for epidemiological studies, therefore, it is necessary to give attention to potential limitations of these data, and inconsistencies over time, in recording practices and radiation dosimetry methods that could bias estimates of radiation–mortality associations.

External radiation exposures were typically accrued at the Hanford facility at low dose rates; and, radiation dosimeters were periodically exchanged during a calendar year. Given this environment of protracted, low dose rates exposures, we examined evidence about practices for recording dosimetry measurements when values were near the minimum detectable level (MDL) of a radiation dosimeter.

For a single dosimeter, recording a zero when a measurement was less than a dosimeter's MDL leads to only a slight underestimate of exposure. However, at Hanford, prior to 1958 workers exchanged dosimeters on a weekly or biweekly schedule. Furthermore, during this period dosimeters were not allowed to be taken from a work area; consequently, people were issued a separate dosimeter for each area in which they worked. In contrast to many other DOE nuclear facilities, some workers at Hanford were issued several hundred film badge dosimeters in a calendar year (Gilbert, 1990; Wilson et al., 1990). Since workers typically were issued many dosimeters over their period of employment, recording practices for doses near MDL can be an important issue for consideration when evaluating sources of dosimetry error (Tankersley et al., 1996).

In previous evaluations of the Hanford external radiation dosimetry data, it has been asserted that there was no

1. Abbreviations: DOE, Department of Energy; MDL, minimum detectable level; mSv, milliSievert; ORNL, Oak Ridge National Laboratory.
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Received 19 November 1998; accepted 20 May 1999.

evidence that doses below a threshold value had been recorded as zeros (Gilbert, 1990; Gilbert and Fix, 1995; Fix et al., 1992; Cardis et al., 1995). It has been suggested that the Hanford dosimetry program followed a consistent policy of recording all positive external radiation dose measurements throughout its period of operation (Fix et al., 1997).

In contrast, K.R. Heid, who was in charge of Hanford's personnel dosimetry program, described dosimetry recording practices at the facility as follows: "The actual dose, as measured, was rounded off to the nearest 10 mrem [0.10 mSv]. If the rounding off brought the dose up to the detection level, it was reported as positive for that amount (i.e., a dose of 18 mrem [0.18 mSv] would be rounded to 20 mrem [0.20 mSv]. If 20 mrem [0.20 mSv] was the detection level for that particular dosimeter it would be included as 20 mrem [0.20 mSv]. A dose of 14 mrem [0.14 mSv] would be rounded down to 10 mrem [0.10 mSv] and since this is less than the 20 mrem [0.20 mSv] detection level, it would be entered as zero dose for the record.)"[1]

At Oak Ridge National Laboratory, another DOE facility that operated during the same period, investigations have suggested inconsistencies over time in practices for recording external radiation doses with values between zero and the MDL (Wing et al., 1994). Using similar methodology to that used in investigations of ORNL dosimetry data, this paper examines evidence of inconsistencies over time in recording values for dosimetry measurements between zero and MDL using annual external radiation dosimetry data for Hanford workers.

Methods

Minimum Detection Level

Radiation exposure is measured using a film badge dosimeter by examining the blackening (change in optical density) of the film due to radiation exposure. Typically, the optical density of the dosimeter worn on-the-job is compared to the density of a film exposed for the same period of time to background radiation. The MDL of a radiation film badge dosimeter is the smallest change in optical density that can be distinguished from exposure due to background radiation. Because there is some variation in dosimeter measurements, the MDL for a dosimeter is based upon a decision about the level of statistical confidence for an indication of a positive dose. The customary procedure is to establish a critical value for optical density readings above which the dosimeter reading is considered to indicate a positive dose at a specified confidence level (National Research Council, Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests, 1989; Wilson et al., 1990). Exposures below this level are not distinguished from zero with certainty. Translating an optical density reading from a film badge dosimeter to a unit of radiation dose depends upon the calibration of the densitometer for each film batch. Historically, the dose value associated with the minimal detectable level from film badge data has been estimated to be in the range of 0.25 (±0.1) mSv (Maienschein and Peele, 1992).

At different facilities, and at different historical periods, practices have varied for recording values that are in the range between zero and the MDL. All dosimeter readings below the MDL were recorded as zero at some facilities during the early years of operation. At other facilities, zeros were recorded for those readings that favored the lower end of the range between zero and the MDL, while the value of the MDL was recorded for readings at the upper end of the range between zero and the MDL (National Research Council, Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests, 1989). At the Hanford facility, the procedures for recording doses near the MDL have not been sufficiently well documented to determine how recording practices may have changed over time (Wilson et al., 1990; Gilbert and Fix, 1995).

Study Cohort

Analyses in this report focus on those workers who will be included in upcoming epidemiological analyses of radiation–cancer associations among Hanford workers. Similar to previous analyses of workers employed at the Hanford facility, our study cohort includes workers who were employed at least 180 days at the Hanford nuclear facility, who were hired as operations workers by prime contractors before 1979, and who had at least one annual external dosimetry record. In addition, two workers with annual external doses greater than 250 mSv were excluded from our study cohort; and, two additional workers involved in radiation accidents that led to substantial internal and external radiation exposures were excluded (Gamertsfelder et al., 1962; Palmer et al., 1983).

External Radiation Dosimetry Data

Beginning in 1944, two-element film dosimeters were used at the Hanford facility, supplemented by ionization chamber readings (Hart, 1967). Initially the Hanford film badge dosimetry program used DuPont 502 sensitive film. A multielement film dosimeter was introduced in 1957, and, beginning in 1960, DuPont 508 sensitive film was used, which provided better information about low-level exposures (Wilson et al., 1990). In 1962, improvements in the multifilm dosimeter and densitometer technology were introduced, and film calibration was changed in order to improve accuracy when measuring low doses. In 1972, thermoluminescent dosimeters began to be used (Gilbert and Fix, 1995).

[1]Heid, K.R. "Letter to R.H. Mole: Details of the Hanford dosimetry program," June 22, 1979.

Reported annual whole-body doses were obtained by summing the periodic external dosimetry measurements made for a worker within a calendar year. Initially, dosimeters were exchanged weekly or biweekly. Workers may have had multiple dosimeters during a monitoring period if they were employed in several locations at the Hanford facility. In 1957 dosimeters began to be read monthly, and, in 1964 dosimeters began to be exchanged quarterly (Gilbert, 1990). Each annual whole-body dosimetry record includes an estimate of the dose received from photons (with X-ray and gamma radiation doses combined), neutrons; and, after 1962 internal tritium contamination (Gilbert et al., 1992).

Annual external doses were originally compiled as part of the AEC Health and Mortality Study; documentation for the AEC study indicates that annual doses were rounded to the nearest 0.1 mSv (Kirklin et al., 1969). A computerized file describes annual whole-body radiation doses for Hanford workers monitored during the years 1944–1989 (Buschbom and Gilbert, 1993). Computerized records of the periodic individual dosimeter measurements that were used to calculate annual external radiation doses were not available for these analyses.

We examined reported annual external radiation doses as an approach to evaluating dosimetry recording practices when values were near the MDL of a dosimeter. We examined trends over calendar time in the proportion of reported annual external doses at intervals between zero and 0.4 mSv.

Since these analyses of Hanford external dosimetry data examine reported annual external doses (which are the sum of more frequent periodic dosimetry measurements) these analyses rely on indirect evidence about recording practices at the Hanford facility. At any facility there may be inconsistencies in recording practices, as well as recording and data-entry errors; however, a practice of not recording values below the MDL would lead to few reported annual external radiation doses with values between zero and the MDL. This deficit of annual external radiation doses at these low values should be apparent when compared to the percentage of annual external radiation doses at values slightly above the MDL. In contrast, if all dosimetry measurements were entered in the record, there should not be a substantial difference in the proportion of reported annual external doses with values in the range of 0.1 mSv above or below the MDL.

In our investigations of Hanford dosimetry recording practices we examined the penetrating dose due to gamma, X-ray, and beta radiation. We did not include the component of recorded whole-body dose due to neutron exposure or tritium exposure (which were typically low doses that might give a false impression about recording practices for external doses below minimum detectable values). Examination of gamma radiation doses, separately from beta and X-ray doses, was not possible with the available data for all periods, since X-ray doses were recorded separately from other penetrating doses only during the period 1957–1971.

Results

There were 33,459 workers in the study cohort; these workers accrued a total of 847,504.8 mSv external penetrating ionizing radiation dose. One-third of the reported annual doses were zero; and, 68% of the annual doses were 1 mSv or less. The mean annual external radiation dose for Hanford workers was 2.3 mSv and the median was 0.4 mSv.

Film badges were exchanged on a weekly/biweekly schedule during the period 1944–1956. Annual external radiation doses were reported with values of 0.1, 0.2, 0.3, and 0.4 mSv, with no annual doses reported with values between these intervals (Table 1). Between 1944 and 1952, a small percentage of annual doses (0.7–2.2%) had a value of 0.1 mSv, and a larger percentage of annual doses had a value of 0.2 mSv (Table 1).

Between 1953 and 1956 a very small percentage of all nonzero annual doses had values less than 0.3 mSv; in contrast, a relatively large percentage of annual doses had a value equal to 0.3 mSv (1.3–9.8%). In 1956, 0.3% of all annual doses had values between 0 and 0.3 mSv, while 9.7% of all annual doses were reported to be equal to 0.3 mSv.

In 1957, a multifilm dosimeter began to be used, dosimeters began to be exchanged on a monthly schedule for some workers, and dosimeter film processing became automated. During the period 1957–1963, a substantial percentage of nonzero annual doses had values of 0.1, 0.2, 0.3, and 0.4 mSv (Table 2).

In the period 1964–1971 dosimeters were exchanged for some workers on a quarterly schedule. During this period, few nonzero annual external doses had values below 0.2 mSv (Table 2). In contrast, a substantial percentage of annual doses had values of 0.2, 0.3, and 0.4 mSv. The percentage of annual doses reported to be equal to zero ranged from 2.9% to 59.9% between 1957 and 1971. The years with the lowest proportion of annual doses equal to zero (1962–1966) were the calendar years when annual whole-body doses tended to be highest (Buschbom and Gilbert, 1993).

In 1972, thermoluminescent dosimeters were introduced at Hanford. Between 1972 and 1988, annual doses were reported in 0.1 mSv intervals (Table 3). A substantial percentage of annual dose were recorded at values of 0.1, 0.2, 0.3, and 0.4 mSv suggesting that recording practices during this period were to round dose values to 0.1 mSv and to record values as low as 0.1 mSv. At the end of 1988, the personnel dosimetry program at Hanford was contracted to

Table 1. Percentages of annual doses in specified ranges, by calendar year.

Year	Annual dose =0 mSv	Annual dose 0<–0.1 mSv	Annual dose =0.1 mSv	Annual dose <0.1–0.2 mSv	Annual dose =0.2 mSv	Annual dose <0.2–0.3 mSv	Annual dose =0.3 mSv	Annual dose <0.3–0.4 mSv	Annual dose =0.4 mSv	Annual dose >0.4 mSv
1944	55.1	.	2.2	.	2.0	.	1.8	.	2.7	36.1
1945	36.9	.	1.8	.	4.3	.	4.9	.	3.7	48.3
1946	16.9	.	1.8	.	4.0	.	4.6	.	4.3	68.4
1947	28.2	.	0.7	.	8.4	.	7.1	.	5.0	50.6
1948	39.2	.	2.0	.	10.9	.	9.4	.	6.2	32.3
1949	29.9	.	0.9	.	7.8	.	8.0	.	6.7	46.8
1950	28.8	.	0.4	.	6.3	.	9.0	.	6.3	49.1
1951	39.3	.	0.3	.	6.9	.	8.5	.	5.6	39.3
1952	37.7	.	0.1	.	1.8	.	2.8	.	6.1	51.5
1953	26.3	.	.	.	0.3	.	1.3	.	6.0	66.2
1954	35.6	.	0.0	.	0.2	.	7.2	.	6.3	50.7
1955	31.2	.	0.1	.	0.1	.	7.9	.	6.7	53.9
1956	51.3	.	0.2	.	0.1	.	9.7	.	3.8	34.8

1944–1956, period of weekly/biweekly exchange of film badge dosimeters.
Note: "." indicates no annual records with values in this range; "0.0" indicates less than 0.05% of records with values in this range.

Table 2. Percentages of annual doses in specified ranges, by calendar year.

Year	Annual dose =0 mSv	Annual dose 0<–0.1 mSv	Annual dose =0.1 mSv	Annual dose <0.1–0.2 mSv	Annual dose =0.2 mSv	Annual dose <0.2–0.3 mSv	Annual dose =0.3 mSv	Annual dose <0.3–0.4 mSv	Annual dose =0.4 mSv	Annual dose >0.4 mSv
1957	59.9	.	0.1	.	4.1	.	2.6	0.0	2.5	30.9
1958	49.7	0.0	1.1	.	3.9	.	3.3	.	2.6	39.4
1959	52.3	0.0	2.0	0.0	3.6	0.0	2.9	0.1	2.3	36.8
1960	45.8	0.0	4.4	0.1	4.5	0.0	3.4	0.1	2.4	39.4
1961	18.4	.	2.8	0.0	6.9	.	8.7	0.0	7.0	56.1
1962	2.9	0.0	2.2	0.0	2.8	0.1	3.2	0.1	3.7	84.9
1963	3.4	0.1	3.5	0.3	4.5	0.7	4.7	0.7	4.9	77.4
1964	7.1	0.0	0.6	0.0	1.0	0.0	0.9	0.0	1.1	89.2
1965	7.3	0.0	0.0	0.0	0.5	0.0	0.3	0.0	0.4	91.3
1966	9.5	0.0	0.0	0.0	2.2	0.0	2.1	0.0	2.0	83.9
1967	16.4	0.1	0.0	0.1	9.4	0.1	4.6	0.2	5.6	63.5
1968	11.5	0.1	.	0.0	5.2	0.1	2.9	0.1	3.7	76.5
1969	27.9	0.4	0.0	0.1	7.9	0.3	5.8	0.3	4.5	52.7
1970	48.0	0.1	0.0	.	2.4	0.0	2.4	0.0	1.3	45.7
1971	31.6	0.0	0.0	.	1.0	0.0	0.8	0.0	0.6	65.9

1957–1971, period of monthly (1957–1963) and monthly/quarterly (1964–1971) exchange of film badge dosimeters.
Note: “.” indicates no annual records with values in this range; “0.0” indicates less than 0.05 percent of records with values in this range.

Table 3. Percentages of annual doses in specified ranges, by calendar year.

Year	Annual dose =0 mSv	Annual dose 0<−0.1 mSv	Annual dose =0.1 mSv	Annual dose <0.1−0.2 mSv	Annual dose =0.2 mSv	Annual dose <0.2−0.3 mSv	Annual dose =0.3 mSv	Annual dose <0.3−0.4 mSv	Annual dose =0.4 mSv	Annual dose >0.4 mSv
1972	9.8	.	2.1	.	4.0	.	4.3	.	5.1	74.6
1973	11.4	.	3.5	.	6.5	.	7.9	.	8.7	61.9
1974	22.1	.	1.4	.	1.5	.	1.8	.	1.9	71.2
1975	16.3	.	4.8	.	5.1	.	5.1	.	2.3	66.5
1976	31.8	.	6.2	.	5.1	.	4.4	.	4.0	48.4
1977	37.1	.	8.2	.	4.9	.	4.4	.	3.1	42.2
1978	27.4	.	10.9	.	4.9	.	6.9	.	5.9	44.0
1979	31.6	.	8.6	.	7.5	.	7.6	.	6.9	37.8
1980	19.6	.	15.7	.	15.0	.	10.7	.	7.8	31.3
1981	42.3	.	11.4	.	8.6	.	6.5	.	4.7	26.4
1982	37.4	.	11.9	.	8.2	.	6.5	.	4.8	31.3
1983	62.7	.	8.6	.	5.0	.	3.3	.	2.0	18.3
1984	47.3	.	12.9	.	8.9	.	6.0	.	4.5	20.4
1985	61.0	.	12.2	.	6.2	.	3.8	.	2.1	14.6
1986	76.4	.	5.7	.	2.7	.	1.5	.	0.9	12.7
1987	32.4	.	18.5	.	16.9	.	9.3	.	5.3	17.6
1988	73.4	.	10.1	.	4.6	.	2.5	.	1.6	7.9
1989	41.6	0.1	20.4	0.1	13.2	0.0	9.8	0.1	5.3	9.5

1972–1989, period of monthly/quarterly/annual exchange of thermoluminescent dosimeters.
Note: "." indicates no annual records with values in this range; "0.0" indicates less than 0.05 percent of records with values in this range.

Battelle Pacific Northwest Laboratory (Wilson et al., 1990); beginning in 1989, annual external doses were reported at values between 0.1 mSv intervals.

Discussion

Overall, recorded annual external radiation doses among Hanford operations workers tended to be low. Nearly a third of the annual external radiation doses were reported to be equal to zero. This pattern of generally low-dose-rate exposures, means that there are important implications to recording practices for doses accrued near the minimum detection level, since many of the workers have recorded zero or near-zero external radiation doses.

The consequences of recording zeros for doses below MDL are most serious for historical periods at Hanford when dosimeters were exchanged frequently, and for workers who were issued a separate dosimeter for each work location in which they were employed (Gilbert, 1990; Wilson et al., 1990).

At other nuclear facilities in the US and in Britain, researchers have reported that results of external radiation dosimeters that were between zero and MDL were, in some periods, recorded as zero (Strom, 1986; Inskip et al., 1987; National Research Council, Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests, 1989; Cardis and Esteve, 1991; Taylor, 1991; Kerr, 1994; Wing et al., 1994; Tankersley et al., 1996; Mitchell et al., 1997; Watkins et al., 1997). Similar concerns have been raised about the Hanford dosimetry data (Kneale et al., 1991).

However, previous published reports about the Hanford radiation dosimetry program have asserted that "there was no indication that doses less than some specified threshold value had been set equal to zero;" or, stated differently, that although the practice of recording zero values for doses below a threshold of detection "has been identified as a problem in early years at some nuclear facilities, there is no evidence that this was a problem at Hanford" (Gilbert, 1990; Gilbert and Fix, 1995; Fix et al., 1992). Wilson et al. have cautioned, however, that examination of the proportion of dosimetry readings recorded as zero in this sample of 139 workers "suggests that practices for handling very low recorded exposures may have varied from year to year" (Wilson et al., 1990). Kneale et al. also noted that the changes over time in dosimetry practice, and the observation of inconsistencies in dosimetry recording practices at ORNL, suggested that such problems might affect the Hanford dosimetry data (Kneale et al., 1991).

Since the periodic dosimetry results used to calculate annual external doses at Hanford have not been computerized, we examined the reported annual external doses for indirect evidence about recording practices at Hanford. During the data collection for the AEC's Health and Mortality study, annual external dosimetry results were rounded to the nearest 0.1 mSv when reporting annual external radiation doses (Tables 1 and 2). Rounding also occurred when recording periodic dosimetry measurements; according to Gilbert et al., doses were rounded to nearest 0.05 mSv during the period 1944–1956, to the nearest 0.01 mSv in the period 1957–1964, and to the nearest 0.1 mSv in the period 1965–1989 (Gilbert, 1990; Gilbert et al., 1992; Gilbert and Fix, 1995).

In previous evaluations of the Hanford external dosimetry data, it has been noted that, while documentation of recording procedures at Hanford is not sufficient to determine whether there was a consistent policy over time, an examination of individual dosimetry measurements for 139 workers, found that values as low as 0.05–0.1 mSv were recorded during the period 1944–1956 (Gilbert, 1990; Gilbert and Fix, 1995). While we also observed that some annual external doses had values as low as 0.1 mSv, we observed an extremely small percentage of doses with values between zero and 0.3 mSv in the years 1953–1956. In contrast, a relatively substantial percentage of the annual doses had values equal to 0.3 and 0.4 mSv.

During the period 1957–1963 dosimeters were exchanged on a monthly schedule. The percentage of annual doses reported at 0.1, 0.2, 0.3, and 0.4 mSv was relatively comparable during this period. There was a substantial decline in the percentage of annual external radiation doses reported as equal to 0 mSv in 1962. While changes in dosimetry practice occurred in 1962 (changes in the type of densitometer used, and changes in the methods of calibration to improve detection of low level doses), this decline in the percentage of zero doses appears to be accounted for primarily by the increase in annual radiation doses with values above 0.4 mSv. The period of Hanford's operation between 1962 and 1965, when the smallest percentage of annual doses were reported as zero, corresponds to the historical period when occupational exposures to external ionizing radiation were highest.

In 1964, film badge dosimeters began to be exchanged on a quarterly schedule for some workers. Also, in that year, the contractor responsible for processing film badge dosimeters at Hanford changed from General Electric to a subcontractor, United States Testing (Wilson et al., 1990). During the period 1964–1971, we observed very little evidence of dosimetry measurements with values between zero and 0.2 mSv. The apparent deficit of annual external radiation doses with values between zero and 0.2 mSv conforms to Heid's description of dosimetry recording practices at Hanford, in which values below 0.2 mSv were reported as zero.[1] In Gilbert's review of individual dosimetry measurement records for 139 workers, no nonzero dosimetry measurements were recorded with values less than 0.2 mSv in the years 1965, 1967, 1969, and 1970.

Beginning in 1972, thermoluminescent dosimeters began to be used. During the 1972–1989 period, there is a substantial percentage of doses reported with values of 0.1, 0.2, 0.3, and 0.4 mSv. The percentage of annual doses with values equal to zero changed substantially during the period 1972–1989. Between 1986 and 1987, for example, the percentage of annual doses equal to zero fell from 76.4% to 32.4%; this change was largely accounted for by an increase in the percentage of annual doses reported with values equal to 0.1, 0.2, and 0.3 mSv.

These findings of historical changes in recording practices at Hanford are similar to observations about inconsistencies over time in dosimetry recording practices at ORNL, another DOE nuclear facility operated during the same historical period. Evidence of similarities in practices among health physics staff at these two facilities is not surprising. Over the decades of operation there has been substantial communication between health physics staff at these two facilities. At ORNL there is evidence that, in some years, doses with values between zero and 0.3 mSv were recorded as zero (Wing et al., 1994).

Understanding of potential limitations in the available external radiation dosimetry data are particularly important for understanding limitations of epidemiological studies of these workers. In epidemiological analyses, for example, one consequence of such practices may be the poor ability to distinguish workers with zero doses from those whose exposure was below MDL. At ORNL researchers have examined ways to evaluate the effects of dosimetry recording practices on estimates of radiation–mortality associations. Similar evaluations could be conducted using Hanford's dosimetry records.

These observations suggest that, over time at Hanford, different practices were followed for recording values of dosimetry measurements between zero and the MDL. Most notably, we observed a deficit of annual external doses reported with values between zero and 0.3 mSv in the years 1953–1956; and, we observed a deficit of annual doses reported with values between zero and 0.2 mSv in the years 1964–1971. Our conclusions are limited by the fact that we have relied on examination of annual external doses since records of periodic dosimetry results were not available. Nonetheless, these findings suggest that in some calendar years, values between zero and MDL may have been recorded as zero; and, these empirical observations are supported by a historical description of recording practices provided by one of the managers of the facility's health physics program.[1]

While whole-body dose data are of high quality for workers at the Hanford facility, there are limitations to measurements of doses received at low levels (and low dose rates). Over time there have been significant changes in the external radiation monitoring program, which includes changes in the types of dosimeters used, changes in the frequency of exchanging dosimeters, and changes in recording practices. Such historical variation in information about an exposure is an important consideration in evaluations of epidemiological findings. In contrast to the data available for many occupational cohort studies however, these external radiation dosimetry data provide individual, quantitative exposure estimates that may be used in epidemiological analyses provided that the limitations of these data are recognized. This investigation of the Hanford dosimetry data is part of a larger research project to examine the association between low levels of whole-body ionizing radiation and specific causes of death among workers at Hanford with follow-up extended through 1994. The research will improve the use of this valuable cohort data for investigating the effects of low level radiation exposure.

Acknowledgments

This project was supported by grant R01 OH12931 from the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention.

References

Buschbom R.L., and Gilbert E.S. Summary of recorded external radiation doses for Hanford workers, 1944–1989. PNL-8909/AD-1902, Pacific Northwest Laboratory, Richland, WA, 1993.

Cardis E., and Esteve J. Uncertainties in recorded doses in the nuclear industry: identification, quantification and implications for epidemiologic studies. *J. Radiat. Prot. Dosim.* 1991: 36: 279–285.

Cardis E., Gilbert E., Carpenter L., Howe G., Kato I., Fix J., Salmon L., Cowper G., Armstrong B., Beral V., Douglas A., Fry S., Kaldor J., Lave C., Smith P., Voelz G., and Wiggs L. Combined analyses of cancer mortality among nuclear industry workers in Canada, the United Kingdom and the United States of America. IARC Technical Report No. 25, World Health Organization, International Agency for Research on Cancer, Lyon, France, 1995.

Fix J.J., Gilbert E.S., Wilson R.H., Baumgartner W.V., and Nichols L.L. Comments on evidence of biased recording of radiation doses of Hanford workers. *Am. J. Ind. Med.* 1992: 22 (2): 281–283, 285.

Fix J.J., Salmon L., Cowper G., and Cardis E. A retrospective evaluation of the dosimetry employed in an international combined epidemiological study. *Radiat. Prot. Dosim.* 1997: 74: 39–53.

Gamertsfelder C., Larson H., Nielson J., Roesch W., and Watson E. Dosimetry investigation of the recuplex criticality accident. HW-SA-2730, Hanford Laboratories, Richland, WA, 1962.

Gilbert E.S. A study of detailed dosimetry records for a selected group of workers included in the Hanford Mortality Study. PNL-7439/UC-407, Pacific Northwest Laboratory, Richland, WA, 1990.

Gilbert E.S., Buchanan J.A., and Holter N.A. Description of the process used to create 1992 Hanford Mortality Study Database. PNL-8449/UC-605, Pacific Northwest Laboratory, 1992.

Gilbert E.S., and Fix J.J. Accounting for bias in dose estimates in analyses of data from nuclear worker mortality studies. *Health Phys.* 1995: 68 (5): 650–660.

Hart J.C. Derivation of Dose Data from Hanford-DuPont Personnel Meter Exposure Records Applicable to the Mancuso Study. Oak Ridge National Laboratory, Oak Ridge, TN, 1967.

Inskip H., Beral V., Fraser P., Booth M., Coleman D., and Brown A. Further assessment of the effects of occupational radiation exposure in the United Kingdom Atomic Energy Authority mortality study. *Br. J. Ind. Med.* 1987: 44: 149–160.

Kerr G.D. Missing dose from mortality studies of radiation effects among workers at Oak Ridge National Laboratory. *Health Phys.* 1994: 66 (2): 206–208.

Kirklin C.W., Heid K.R., Nuss B.D., Rising F.L., Adley F.E., and Lavelle E.B. The AEC Health and Mortality Study: Its Purpose, Scope, and Design and the Supporting Data Systems from the Hanford Operations. Accession number 13429, Hanford Environmental Health Foundation, Richland, WA, 1969.

Kneale G.W., Sorahan T., and Stewart A.M. Evidence of biased recording of radiation doses of Hanford workers. *Am. J. Ind. Med.* 1991: 20 (6): 799–803.

Maienschein F.C., and Peele R.W. Radiation dosage estimation and health risk. *J. Am. Med. Assoc.* 1992: 267: 929.

Mitchell T., Ostrouchov G., Frome E., and Kerr G. A method for estimating occupational radiation dose to individuals, using weekly dosimetry data. *Radiat. Res.* 1997: 147: 195–207.

National Research Council, Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests. Film Badge Dosimetry in Atmospheric Nuclear Tests. National Academy Press, Washington, DC, 1989.

Palmer H.E., Rieksts G.A., and Icayan E.E. 1976 Hanford americium exposure incident: in vivo measurements. *Health Phys.* 1983: 45 (4): 893–910.

Strom D.J. Estimating individual and collective doses to groups with "less than detectable" doses: a method for use in epidemiologic studies. *Health Phys.* 1986: 51 (4): 437–445.

Tankersley W.G., West C.M., Watson J.E., and Reagan J.L. Retrospective assessment of radiation exposures at or below the minimum detectable level at a federal nuclear reactor facility. *Appl. Occup. Environ. Hyg.* 1996: 11 (4): 330–333.

Taylor N.A. Estimation of dose received when dosemeter results are recorded below a threshold level. *J. Radiol. Prot.* 1991: 11 (3): 191–198.

Watkins J., Cragle D., Frome E., Reagan J., West C., Crawford-Brown D., and Tankersley W. Collection, validation, and treatment of data for a mortality study of nuclear industry workers. *Appl. Occup. Environ. Hyg.* 1997: 12 (3): 195–205.

Wilson R.H., Fix J.J., Baumgartner W.V., and Nichols L.L. Description and evaluation of the Hanford personnel dosimeter program from 1944–1989. PNL-7447/UC-606, Pacific Northwest Laboratory, Richland, WA, 1990.

Wing S., West C.M., Wood J.L., and Tankersley W. Recording of external radiation exposures at Oak Ridge National Laboratory: implications for epidemiological studies. *J. Exposure Anal. Environ. Epidemiol.* 1994: 4 (1): 83–93.