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A Study of Detailed Dosimetry Records for a Selected Group of Workers Included in the Hanford Mortality Study

E. S. Gilbert

September 1990

Prepared for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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A STUDY OF DETAILED DOSIMETRY RECORDS FOR A SELECTED GROUP OF WORKERS INCLUDED IN THE HANFORD MORTALITY STUDY

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ABSTRACT

Detailed dosimetry data from microfiche and microfilm source records for the years 1944-1978 for 139 Hanford workers were examined. Information on these records was compared with computerized dose equivalent estimates used in mortality analyses. Because of difficulties in reading some early source records, and because of variation in the format of records and in algorithms for calculating whole body dose, this validation was difficult. However, apparent discrepancies in cumulative dose were less than 0.1 rem for 88% of the workers in this study, never exceeded 1.5 rem, and would be unlikely to distort conclusions of dose-response analyses. Most discrepancies occurred in early years of Hanford operations, especially 1944-46, with very few problems with dose estimates from the 1960's and 1970's. The study also provided data on dosimetry practices, by calendar year, on frequency of monitoring, the number and proportion of dosimeters yielding positive results, and the magnitude of doses recorded for individual dosimeters.

ACKNOWLEDGMENTS

This study would not have been possible without the cooperation of the Dosimetry Records Group (Hazards Assessment and Records Section, Health Physics Department) under Matthew Lyon. The supervisory help of Vicki Berndt and clerical assistance by Marcella Combs, Patricia Johnson, and Ruth Walker is especially appreciated. I would also like to thank Janice Kaschmitter for managing the database and Lisa Mehlenbacher for entering the data.

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TABLES

1.0 INTRODUCTION

The Hanford mortality study is an ongoing study of workers at the Hanford Site conducted jointly by the Hanford Environmental Health Foundation (HEHF) and Pacific Northwest Laboratory (PNL). Several journal articles have described its findings with the most recent analyses including deaths through 1981 (Gilbert et al. 1989).

A major reason for conducting this study has been an interest in possible adverse effects resulting from exposure to external radiation. Analyses have included tests for an association of cumulative radiation dose and mortality from many specific diseases, and have also included the estimation of excess risk per unit of dose[a]. Thus, adequate data on external radiation exposure is an extremely important component of the study.

Data on external radiation exposure, used in published analyses, were obtained from computerized summaries of dosimetry for each worker and each year of monitoring. These data were provided in 1978 by PNL's Dosimetry Records Group, currently part of the Hazards Assessment and Records Section, Health Physics Department, and were obtained from the Hanford Occupational Radiation Exposure (HRO) system.

The HRO was initially developed in 1965 by HEHF as part of the Atomic Energy Commission Health and Mortality Study (HEHF 1969). This system served as a repository for Hanford historical exposure records, and included annual estimates of the whole body penetrating dose for each worker included in the mortality study. The HRO system was transferred from HEHF to PNL in 1979, and in 1983 was absorbed into the Occupational Radiological Exposure (ORE) database management system (Wilson 1987). The ORE is the current system for maintaining individual radiological exposure records for past and present Hanford workers.

The main objective of the study described in this report was to examine detailed source records (available on microfiche and microfilm) for selected groups of workers, and to determine the extent to which information on source records agreed with dose estimates obtained from the HRO and used in mortality

(a) Throughout this report, the word "dose" is used generically, and no attempt is made to address whether recorded doses are intended to estimate deep dose equivalent, effective dose equivalent, etc.

2.0 STUDY DESIGN AND PROCEDURES

2.1 SELECTION OF STUDY SUBJECTS

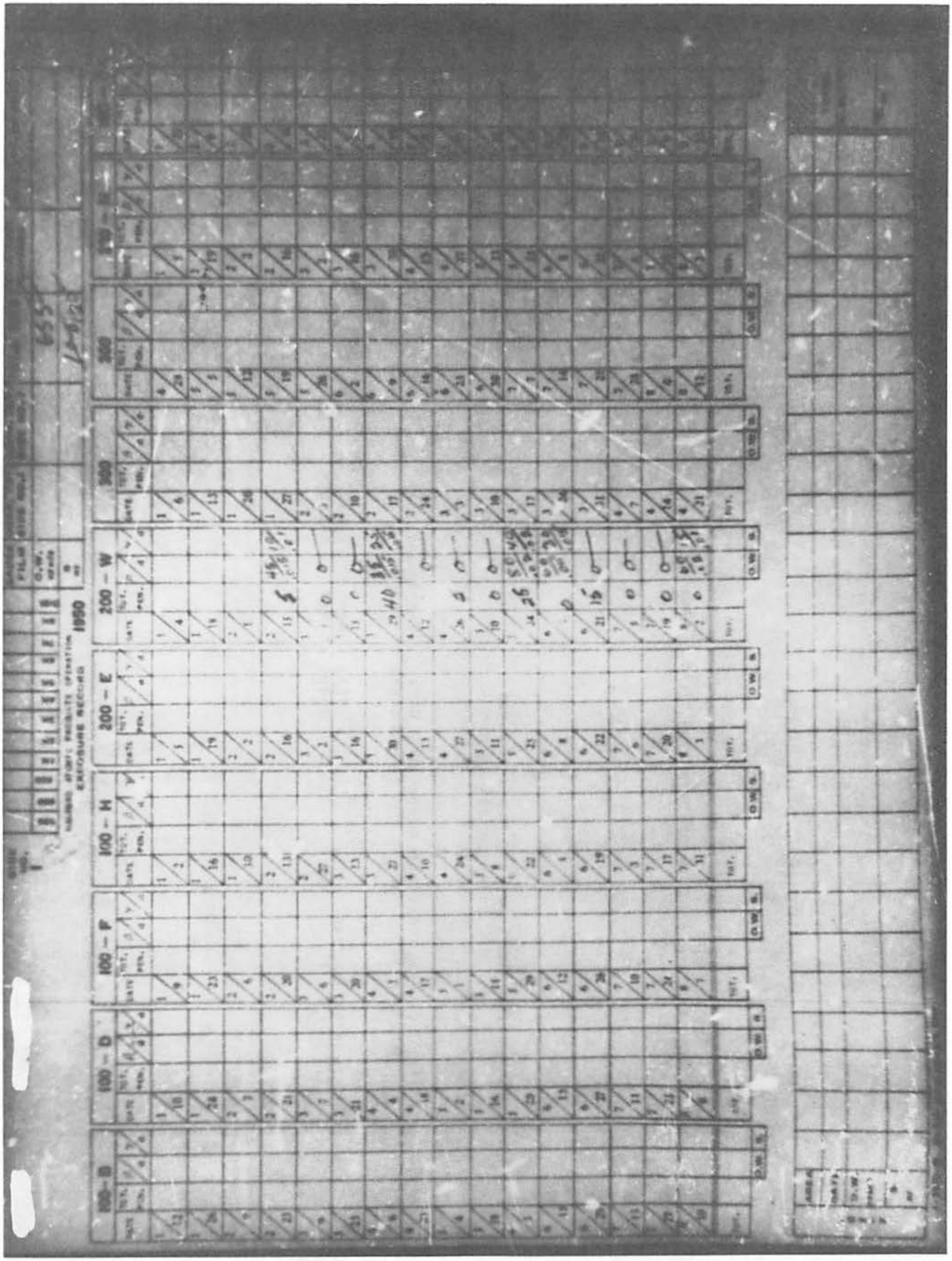
Records of 139 workers representing eight special groups were examined including 16 leukemia deaths, 12 multiple myeloma deaths, 39 randomly selected controls, 19 additional cancer deaths with relatively high doses, 28 workers in job categories with high potential for external radiation exposure, six workers with high potential for neutron exposure, 16 workers in job categories with little potential for radiation exposure, and three additional workers (see below for further description). In general, the selected workers were more highly exposed and came from earlier birth year cohorts than the average Hanford worker. For this reason, the specific quantitative results presented may not be typical of the Hanford population as a whole. However, the understanding of dosimetry practices gained from this study should be more generalizable. The eight groups are described in detail below.

1. Leukemia deaths. All deaths from leukemia (excluding chronic lymphatic leukemia) in males with at least five years of monitoring for external radiation (16 workers) were selected. Deaths occurring through 1985 were included even though cohort-based mortality analyses included only deaths through 1981 (Gilbert et al. 1989). In addition, records for deaths from leukemia in male workers employed at least five years, but not meeting the criteria noted above, were examined to verify that the low recorded doses were correct. This latter group included four deaths in males and one female death. The low doses were found to be correct. Data from these latter five workers were not included in the analyses presented in this chapter, and controls were not selected for these workers.
2. Multiple myeloma deaths. All deaths from multiple myeloma in males with at least five years of monitoring for external radiation (12 workers) were selected. Multiple myeloma has been linked with occupational radiation exposure both in Hanford workers (Gilbert et al. 1989) and in Sellafield workers (Smith and Douglas 1986). Deaths occurring through 1985 were included, and in addition, deaths noted on the certificate but not considered to be the underlying cause of death were included; two such deaths occurred and were noted in recent analyses. As with leukemia,

For the job categories considered to be of special interest, all lung cancer deaths and three controls were selected for the dosimetry study. Controls were selected randomly from those available in each category. All selected subjects were monitored at least five years for external radiation. The distribution by job category was as follows: radiation monitors (one case, three controls), reactor operators (three cases, three controls), process or chemical operators (five cases, three controls), steamfitters (three cases, three controls), and millwrights (one case, three controls).

6. Neutron workers. Six workers with potential for neutron exposure were selected. Shortly after introduction of the TLD in 1972, a special study of workers employed at the Z-plant and considered to have high potential for neutron exposure was conducted. The study included 14 operations workers; six were randomly selected for the dosimetry record study.
7. Workers with low exposure potential. Sixteen workers whose job histories indicated little potential for radiation exposure were selected. Specifically, these workers were chosen from those who had been classified only as managers and administrators, clerical and kindred workers, or service workers over a specified time period. The Bureau of Census (1971) codes for these groups were 201-244, 301-344, and 901-965. Workers with the code 245 ("managers and administrators, not elsewhere classified") were not selected for this group, because this code had sometimes been used for supervisors of persons performing radiation work. Five workers in this group were chosen from those employed at least five years over the period 1944-1956, and whose occupational codes fell in the categories indicated during this period. Eleven workers were chosen from those employed at least five years over the period 1957-1978, and whose codes fell in the designated categories during this later period. The reason for including these workers was to learn more about dosimetry practices for those with minimal exposure potential.
8. Other workers. Three workers were included who did not fall into any of the groups above. One worker was selected as a process operator dying of lung cancer, but subsequent examination of his occupational history indicated this designation was an error, and the worker had actually been a patrolman. Two workers dying of cancer had their records extracted

Figure 1. Example of Record From the Period 1944-56



HANFORD OCCUPATIONAL DOSE RECORD FOR   FILE NO.   DATE PREPARED 2- 4-71

SUFFIX CONST.ID SOC.SEC. SEX JOB CODE BIRTHDATE SER.DATE TERM.DATE   PU BIOASSAY SCHEDULE J F M A M J J A S O N D   YR

M   - -   2   2

ADDRESS   WASH   BADGE EXCHANGE SCH. 1

DOSE FOR LAST 12 MONTHS (MREM)

FILM BADGE DOSIMETERS

PERIOD ENDING	-B-	-G-	-X-	F-N	S-N
1-30-70		100	60		20
2-27-70		40	20		
3-27-70		50			
4-24-70	80	90	20	220	
5-28-70		190	50	100	
6-26-70		50	20	110	
7-31-70		130	110		20
8-28-70			10		
9-25-70		80	30		20
10-30-70		350	60		60
11-25-70		200	60	250	
12-23-70		60	10		

FILM RINGS

PERIOD ENDING	GAMMA (MREM)
1-30-70	170
2-27-70	100
3-27-70	100
4-24-70	100
5-28-70	300
6-26-70	100
7-31-70	100
8-28-70	100
9-25-70	100
10-30-70	430
11-25-70	360
12-23-70	100

CURRENT CALENDAR YEAR TOTAL DERMA- 2670 PENET- 2300 GAMMA- 1500 YR-

FILM RING CAL YR TOTAL 2060 MREM

	-B-	-G-	-X-	F-N	S-N	-TR-
OCCUPATIONAL DOSE EXCLUDING PRESENT EMPLOYMENT (MREM)	3120	20410	3040	7620	540	
ACCUMULATED OCCUPATIONAL DOSE (MREM)	4590	26160	5030	10110	1490	

Figure 3. Example of Record From the Period 1959-71

HANFORD OCCUPATIONAL DOSE RECORD FOR [redacted] PAYROLL NO. [redacted] DATE PREPARED 0?-11-78

SUFFIX	CONST.ID	SOC. SEC. NO.	SEX	JOB CODE	BIRTH DATE	SERVICE DATE	TERM. DATE	BIO-ASSAY SCHEDULE	IVC SCHEDULE	MASK FIT	TRAINING
[redacted]	.	[redacted]	M	[redacted]	[redacted]	[redacted]	- -	[redacted]		UV77	

ADDRESS [redacted] WA BUILDING [redacted] DATE OF DEATH - -

BADGE C PE *CALENDAR YEAR 77 DOSE HISTORY-MR [redacted] *

BADGE FREQ	C C	NC	PE MO	NONPEN	PEN	SN	FN	RING
M	0		07					10
M	0	61	07		10			
M	0		08					80
M	0	61	08		220			
M	0		09					30
M	0	61	09		170			
M	0		10					10
M	0	61	10		100		150	
M	0	61	11		10			
M	0	61	12		100			

TOTALS IN -MREM-

	SKIN	WB	EXT
CALENDAR YEAR	2130	2130	3660
ALL TIME	66460	57240	73120
CURRENT HANFORD EMPLOYMENT	760	760	890
PAST HANFORD EMPLOYMENT	65700	56480	72230
OFF-SITE OTHER THAN HANFORD			

PERIOD ENDING 12-30-77

Figure 5. Example of Record From the Period 1975-78

in summary spaces on the records, and a summary of the individual dosimeter readings. The latter included the number of dosimeters and the sum of the recorded doses for each radiation type. In addition, for gamma and beta radiation (or for "penetrating" and "non-penetrating" in the years 1972-78), the number of zero readings and the minimum and maximum of the positive readings were extracted.

3.0 VALIDATION OF DOSES USED IN MORTALITY ANALYSES

The main reason for conducting this study was to determine the extent to which dose estimates used in analyses relating cause-specific mortality to external radiation dose could be verified by examining information included in the annual pump-outs. The dose estimates used in mortality analyses were obtained from the Hanford Occupational Radiation Exposure (HRO) system, and provided in 1978 by PNL's Dosimetry Records Group, currently part of the Hazards Assessment and Records Section, Health Physics Department. As noted in Section 1.0, this validation effort was addressed only at assessing errors in record keeping, and did not address bias and uncertainties in the performance of the dosimeters.

3.1 INTERNAL CONSISTENCY OF SOURCE RECORDS

Analyses to examine internal consistency were performed, and were aimed at determining if the sums of individual readings agreed with the summary numbers provided on the records. Because dose-response analyses have been concerned only with penetrating radiation, we did not examine internal consistency for beta or non-penetrating radiation.

3.1.1 Description of Edits for Internal Consistency

For the years 1944-56, the sum of the individual gamma readings was required to be within 10% of the recorded summary gamma total to pass the test for internal consistency. Because of readability problems, a more stringent criterion (such as that used for later records) would have resulted in a large number of records that did not pass this test and, thus, would have needed re-examination.

In both 1957 and 1958, summary numbers labeled GAMMA and X-RAY were given, but monthly results were available on the annual pumpouts only for gamma radiation. For these years, it was determined that the summary number labeled GAMMA reflected the sum of the individual gamma readings and the summary number under X-RAY. Our edit required the sum of the individual gamma readings to be within 20 mrem of GAMMA - 65% X-RAY. Exact agreement was not required because of rounding to the nearest centirem that sometimes occurred (although mostly in later years).

doses. In several of these cases, the summary number had failed to include entries on one of the two pages of the record.

In 1957, the summary numbers entered under GAMMA were larger than the sums of the individual readings for 46 of 109 records examined (42%). It was not clear how these summary numbers had been calculated, but in most cases, the correct sum appeared elsewhere on the record. Since it appeared that deliberate adjustment of the total had taken place in these records, TRUDOS was assigned a value equal to the summary number. By 1958, this apparent discrepancy was not found, and the sums of the individual readings agreed with the summary numbers presented.

In 1959, the value "59" appeared in the column for x-ray exposure in 73 of the 110 (66%) records examined. In no case examined, did any other value for x-ray appear. These 59's had not been included in calculating the summary numbers given on the records, but in seven (7) cases, comparison of the entry under GAMMA with the sum of monthly gamma readings indicated that some x-ray dose had been included. In these cases, TRUDOS was assigned the value of PENET.

In addition to separate records for 1962 and 1963, most workers also had a joint record giving readings for the last part of 1962 and the first part of 1963. Also, records were in two parts when a worker had changed the contractor he worked for during the year. For some two-part records, the second part of the record gave the cumulative dose from the first part as the initial entry.

In records for several of the later years, particularly 1972-78, dashes sometimes followed entries for individual readings, and these readings were subtracted rather than added to obtain the summary totals. Since this was done consistently, it was assumed that the procedure was intentional (perhaps a correction) and TRUDOS was set to correspond to the value obtained by treating these entries as negative values.

Certain other features of the records needed attention before comparing TRUDOS with entries on the analysis file. First, although there was no place on the 1958 annual pumpouts for neutron dose, analysis files indicated neutron doses for 16 workers in 1958. These neutron doses were included in calculating TRUDOS. Second, although a place for tritium dose was provided only for pumpouts for 1962-1971, the analysis file showed tritium dose for one worker

Table 1. Number (and percent) of annual records by calendar year and status of agreement of source records and entries on analysis file.

(1) Number and percent where TRUDOS (from source records) agrees with ANALDOS (from analysis file).
(2) Number and percent with discrepancies less than 0.1 rem in TRUDOS (from source records) and ANALDOS (from analysis file).
(3) Number and percent with discrepancies greater than or equal to 0.1 rem in TRUDOS (from source records) and ANALDOS (from analysis file).
(4) Number and percent with source records but no corresponding entries on analysis file.
(5) Number and percent with entries on analysis file but no corresponding source records.
(6) Total number of workers with annual source record or entry on analysis file.

Calendar Year	(1)	(2)	(3)	(4)	(5)	(6)
1944	23 (76.7)	1 (3.3)	1 (3.3)	0	5 (16.7)	30
1945	40 (81.6)	0	4 (8.2)	0	5 (10.2)	49
1946	43 (89.6)	1 (2.1)	2 (4.2)	0	2 (4.2)	48
1947	63 (96.9)	0	0	0	2 (3.1)	65
1948	74 (98.7)	0	0	0	1 (1.3)	75
1949	71 (94.7)	3 (4.0)	0	0	1 (1.3)	75
1950	74 (100.0)	0	0	0	0	74
1951	84 (95.5)	4 (4.5)	0	0	0	88
1952	83 (94.3)	4 (4.5)	1 (1.1)	0	0	88
1953	93 (98.9)	1 (1.1)	0	0	0	94
1954	88 (93.6)	4 (4.3)	2 (2.1)	0	0	94
1955	95 (96.0)	2 (2.0)	2 (2.0)	0	0	99
1956	97 (97.0)	2 (2.0)	1 (1.0)	0	0	100
Subtotal (1944-1956)	928 (94.8)	22 (2.2)	13 (1.3)	0	16 (1.6)	979

corrections made for reasons that are not obvious, and that ANALDOS was correct.

Only two discrepancies exceeding 0.1 rem (of -0.22 and -0.41 rem) occurred in the years 1957-78. In both cases, the discrepancies resulted because the worker changed contractor during the year, and the dose from the second part of his record had not been included in ANALDOS. This problem also accounted for several of the smaller discrepancies. Of the smaller discrepancies (Column 2), seven were only two centirem (0.02 rem).

Column 4 of Table 1 shows the number of instances where source records were found, but the worker was indicated as unmonitored in that year on the analysis file. There were 10 such records, all after 1965, with four of the records from 1978, the last year for which dosimetry data was supplied in making our analysis file. The 10 records came from six workers, with one worker missing data in 1966, and 1975-78. The dose missed from these records was zero in eight cases, 0.1 rem in one case, and 1.03 rem in another case.

Column 5 of Table 1 shows instances where the analysis file indicated a worker had been monitored in the particular year, but no source records were found. There were no missing records after 1950, and 10 of the 16 missing records occurred in 1944 and 1945. The missing source records came from 10 different workers with total doses from the missing years (as indicated on the master file) of 0.0, 0.0, 0.0, 0.03, 0.09, 0.12, 0.41, 0.69, 1.18, and 1.46 rem.

In addition to the records for the 139 records summarized in Table 1, source records for 1945 were sought for 10 workers with annual doses on the analysis file exceeding one rem. The number of doses exceeding one rem in 1945 appeared unusual because there were few doses of this magnitude in the 1940's or early 1950's. Source records for five of the ten workers could not be found. Of the five that were found, it was determined that in all cases, dose estimates obtained from pencils had been recorded, and were much higher than the estimates from film badges that should have been recorded.

3.3 CONSISTENCY OF CUMULATIVE DOSES OBTAINED FROM SOURCE RECORDS AND CUMULATIVE DOSES USED IN MORTALITY ANALYSES

Mortality analyses have been based on cumulative dose, or dose summed over the relevant period of workers' exposure histories. Table 2 presents a therefore, these workers can be regarded as more representative of the full cohort, or at least of males with at least five years of monitoring for external exposure. For the combined group of leukemia deaths and controls, exact agreement was found for 75%, and agreement within 0.1 rem for 93% of the 55 subjects. However, for the combined groups of high dose cancer deaths, radiation workers, and neutron workers, exact agreement was found for only 60%, and agreement within 0.1 rem was found for 81% of 53 subjects. As might be expected, there is more opportunity for discrepancies among those with larger doses.

Table 3. Number of subjects by study group and absolute differences in the cumulative dose from analysis file and cumulative dose from source records.

Group	Absolute difference (in rem)							
	≤ -1	> -1 ≤-.1	>-.1 < 0	0	> 0 < .1	≥ .1 < 1	≥ 1	
1. Leukemia deaths	0	0	0	13	1	2	0	16
2. Multiple myeloma deaths	1	0	1	9	1	0	0	12
3. Controls	0	0	5	28	4	1	1	39
4. High dose cancer deaths	0	1	2	12	1	3	0	19
5. Radiation workers	0	2	0	19	4	2	1	28
6. Neutron workers	0	0	0	1	4	1	0	6
7. Workers with low exposure potential	0	1	2	11	1	0	1	16
8. Other workers	0	0	1	2	0	0	0	3

Table 4 lists the 17 workers with discrepancies exceeding 0.1 rem, and indicates the reason for each discrepancy. Nine of these discrepancies, including all but one of those exceeding 0.5 rem, resulted from difficulties with doses from 1944-46. Only two of the discrepancies resulted from difficulties within the 1957-78 period.

Table 5 compares cumulative doses from the analysis file and source files using various alternative methods for calculating these doses. In the second row of the table, the comparison is made with 1944-46 doses excluded. This improves the percent that agree within 0.1 rem from 88% to 94%, and reduces the number with discrepancies exceeding one rem from four to one.

Table 5. Number (and percent) of subjects by absolute differences in the cumulative dose from analysis file and cumulative dose from source records.*

	Absolute value of difference			
	0	> 0 rem < 0.1 rem	>= 0.1 rem < 1 rem	>= 1 rem
1. Cumulative dose calculated as in Tables 2-4*.	95 (68.3)	27 (19.4)	13 (9.4)	4 (2.9)
2. As in 1., but doses in 1944-46 excluded.	104 (74.8)	27 (19.4)	7 (5.0)	1 (0.7)
3. As in 1., but source record cumulative dose uses 1957 dose obtained as sum of entries on record	67 (48.2)	38 (27.3)	30 (21.6)	4 (2.9)
4. As in 1., but dose calculated through 1970.	98 (70.5)	24 (17.3)	13 (9.4)	4 (2.9)

* Except as noted, cumulative doses were calculated through 1978 using TRUDOS and ANALDOS as described in text. In calculating the cumulative dose from analysis file, doses with missing entries were taken to be zero. In calculating the cumulative dose from source records, doses for years with missing source records were taken to be zero

It was noted in Section 3.1 that in 1957, the summary numbers from the source records were larger than the sums of the individual readings for 46 of 109 records examined. For results presented in the first row of Table 5, TRUDOS was assigned a value equal to the summary number in these cases, and this value agreed with doses on the analysis file. In the third row of Table 5, the source record cumulative dose used the sum of the individual readings for the 1957 dose, instead of the summary number. This reduced the percent that agree within 0.1 rem from 88% to 76%, but did not change the number of workers with discrepancies exceeding one rem. As noted above, it appeared that an intentional correction had been made to the 1957 readings and, thus, the summary numbers, and the comparison in the first row of Table 5 (and in Tables 2-4) are more likely to be correct.

Most dose-response analyses of the Hanford data (Gilbert et al. 1989) have incorporated a 10-year lag and have included deaths only through 1981. Thus, these analyses have not included doses received after 1970. For this reason, the fourth row of Table 5 shows a comparison of doses calculated

Table 7. Analyses of multiple myeloma based on cumulative dose (10-year lag) from analysis file and cumulative dose from source records.

	Source records	Analysis file
Total dose for cases (12)	117.81 rem	117.83 rem
Total dose for matched controls (adjusted to allow for multiple controls per case)	27.68 rem	28.83 rem
Trend test statistic (approximately normally distributed)	2.61	2.58
Maximum likelihood estimate of linear excess relative risk coefficient (percent increase per rem)	58.6%	46.7%
90% confidence limits for risk coefficient	(5.2%, 2700%)	(4.3%, 860%)

Results of analyses based on source records and those based on the analysis file did not differ substantially. Differences in the estimated excess relative risk were negligible in comparison to the statistical uncertainty in these estimates as reflected in the confidence limits.

3.4 CONCLUSIONS AND RECOMMENDATIONS

From the results described above and quantified in Tables 1-7, it is clear that there are many instances in which the dose estimates on our analysis file could not be verified exactly. However, most of the apparent discrepancies led to only minor modifications of cumulative dose, and 88% of the doses could be verified to be within 0.1 rem of the correct dose. Even if all discrepancies were errors, they would be unlikely to seriously distort conclusions of dose-response analyses. This is illustrated by the leukemia and multiple myeloma analyses presented in Tables 6 and 7.

Because of difficulties in reading some early source records, and because of the variation in the format of records and in algorithms for calculating whole body dose, interpreting available source records was not simple. Our resources did not permit a thorough investigation of each case in our study, and had this been done, it is possible that additional doses would have been verified.

Most of the discrepancies occurred in the early years of the study, especially 1944-46, with very few problems in the 1960's and 1970's. Source records could not be found for many of the 1944-46 records, and frequently doses on the analysis file appeared to be based on pencil readings, which

4.0 DETAILED DOSIMETRY CHARACTERISTICS

The material in this section focuses on dosimetry characteristics that could not be obtained from computerized summaries that are available for the full cohort. The analyses presented were conducted before the completion of the validation study described in Section 3. Because the validation study resulted in resolution of some discrepancies, in locating some additional records, and in excluding a few records, some numbers presented in this section do not agree exactly with those presented in Table 1.

Table 8 summarizes certain features of dosimetry for each calendar year 1944-1978 for the entire group of 139 workers. Table 9 shows the same information for leukemia deaths and controls only. The selection of these subjects was not based on exposure characteristics and, thus, this group can be considered as more representative of the full cohort than the total study group. Table 10 shows results for workers selected because of their high doses or potential for high doses, and includes the high dose cancer deaths, neutron workers, and radiation workers. These workers may not have been in jobs involving high exposure for their entire history. Table 11 shows results for workers with low exposure potential. Only the five workers with low exposure over the period 1944-1956 are included in the results for 1944-1956, while only the 11 workers with low exposure potential over the period 1957-1978 are included in the results for 1957-1978. Tables 12 and 13 show results for annual doses less than 0.5 rem, and annual doses greater than or equal to 0.5 rem, respectively; data for a given worker can contribute to Table 12 for some years and to Table 13 for other years.

4.1 FREQUENCY OF MONITORING

During the period 1944-1956, monitoring generally occurred weekly or bi-weekly, and workers could have more than one dosimeter for a given week if they worked in more than one location. The median number of dosimeters was about 52 for the years 1945-1947 and 1955-1956, and ranged from 28 to 40 for the years 1948-1954. However, as indicated by the maximum numbers, a few workers had much larger numbers of dosimeters. The maximum identified in this study over all years was 399, which occurred in 1947. Workers with larger

Table 9. Characteristics of external dosimetry for leukemia deaths and controls

(1) Number of annual records
(2) Number of dosimeter results per worker*
(3) Percent dosimeter results with positive gamma dose**
(4) Number of dosimeter results with positive gamma dose per worker
(5) Gamma dose (in mrem) per dosimeter result with positive gamma

Calendar year	(1)	(2)			(3)	(4)		(5)	
		Median	Mean	Max.		Mean	Max.	Mean	Range
1944	9	3	4.3	11	7.7	0.3	1	53	40-60
1945	16	51.5	64	182	1.0	0.6	2	35	20-90
1946	19	64	97	251	6.3	6.1	26	36	5-1170
1947	24	55	101	399	5.9	6.0	27	24	5-105
1948	28	37.5	55	205	5.2	2.9	19	25	1-70
1949	26	37	53	138	8.6	5.5	26	29	10-85
1950	25	34	59	180	6.3	3.7	17	29	10-65
1951	31	30	49	175	5.0	2.4	26	38	10-250
1952	30	36	49	170	6.6	3.3	27	61	20-240
1953	34	36.5	45	195	9.1	4.0	22	62	15-230
1954	31	45	46	205	9.7	4.5	31	68	10-220
1955	32	46	55	234	8.4	4.6	30	65	10-220
1956	33	45	58	227	7.3	4.2	39	67	15-325
1957	33	12	12.0	12	15	1.8	11	136	20-518
1958	36	12	12.0	12	29	3.5	12	126	8-626
1959	35	2	4.0	12	29	3.5	12	104	2-540
1960	35	2	4.6	13	31	4.1	13	97	1-505
1961	36	3.5	5.5	13	40	5.2	13	94	2-547
1962	34	8.5	8.6	13	62	8.1	13	81	1-669
1963	32	6.5	7.2	13	49	6.4	13	68	1-673
1964	34	7	7.4	12	76	5.6	12	93	1-455
1965	32	4	5.9	12	77	4.5	12	171	20-850
1966	33	4	5.7	12	69	3.9	12	122	20-520
1967	28	4	5.8	12	60	3.5	12	117	20-570
1968	26	4	4.9	12	78	3.8	12	109	20-560
1969	20	4	5.6	12	55	3.1	12	130	20-520
1970	19	2	4.2	12	51	2.1	11	128	20-510
1971	18	1.5	3.3	12	52	1.7	10	104	10-920
1972	11	1	3.5	12	95	3.4	12	78	10-270
1973	10	2.5	3.6	12	86	3.1	12	65	10-600
1974	9	3	3.7	12	64	2.3	12	52	10-120
1975	9	2	3.8	13	71	2.7	11	70	10-370
1976	8	2.5	3.8	12	77	2.9	12	48	10-250
1977	7	4	5.6	14	82	4.6	13	38	10-170
1978	6	4.5	6.3	12	87	5.5	11	26	10-120

* See Table 8.
** See Table 8.

Table 11. Characteristics of external dosimetry for workers with low exposure potential

(1) Number of annual records
(2) Number of dosimeter results per worker*
(3) Percent dosimeter results with positive gamma dose**
(4) Number of dosimeter results with positive gamma dose per worker
(5) Gamma dose (in mrem) per dosimeter result with positive gamma

Calendar year	(1)	(2) Median	(2) Mean	(2) Max.	(3)	(4) Mean	(4) Max.	(5) Mean	(5) Range
1944	1	1	1.0	1	0.0	0.0	0	—	—
1945	3	43	31	45	0.0	0.0	0	—	—
1946	3	52	50	54	4.0	2.0	4	23	10–40
1947	3	52	52	53	6.4	3.3	4	30	15–40
1948	5	33	30	53	2.0	0.6	1	15	5–25
1949	4	30	35	52	5.0	1.8	3	21	15–45
1950	4	36	38	52	5.3	2.0	3	26	15–40
1951	4	38.5	39	52	3.2	1.3	2	26	10–55
1952	4	35	38	52	2.7	1.0	2	63	55–75
1953	4	44	43	54	4.1	1.8	3	46	25–55
1954	4	53.5	49	60	1.5	0.8	2	28	25–35
1955	4	52	67	133	2.2	1.5	2	32	25–55
1956	4	50	67	135	0.0	0.0	0	—	—
1957	10	12	12.0	12	0.0	0.0	0	—	—
1958	11	12	12.0	12	0.0	0.0	0	—	—
1959	9	1	1.1	2	2.8	0.3	1	27	7–44
1960	7	1	1.0	1	1.1	0.1	1	15	15–15
1961	10	1	1.2	2	2.3	0.3	2	15	7–27
1962	8	6	6.0	8	42	5.5	7	16	1–50
1963	8	6	6.0	8	30	3.9	6	14	3–41
1964	11	7	5.5	8	72	4.0	6	26	1–108
1965	11	5	3.9	6	74	2.9	4	133	20–700
1966	11	4	3.9	6	37	1.5	4	123	20–400
1967	11	4	3.4	5	14	0.5	1	124	20–360
1968	11	4	3.3	5	47	1.5	4	42	20–170
1969	11	4	2.9	4	31	0.9	2	37	30–60
1970	11	2	2.0	4	4.5	0.1	1	60	60–60
1971	10	2	2.0	4	50	1.0	2	78	50–140
1972	10	1	1.1	2	73	0.8	2	76	20–140
1973	10	1	1.2	3	75	0.9	1	46	20–100
1974	10	1	1.1	2	64	0.7	1	71	50–90
1975	10	1	1.1	2	45	0.5	1	24	10–50
1976	10	1	1.0	1	30	0.3	1	20	10–30
1977	10	1	1.1	2	18	0.2	1	20	10–30
1978	10	2.5	2.4	4	71	1.7	4	24	10–60

*See Table 8.
**See Table 8.

Table 13. Characteristics of external dosimetry when total annual dose greater than 0.5 rem.

(1) Number of annual records
(2) Number of dosimeter results per worker*
(3) Percent dosimeter results with positive gamma dose**
(4) Number of dosimeter results with positive gamma dose per worker
(5) Gamma dose (in mrem) per dosimeter result with positive gamma

Calendar year	(1)	(2)			(3)	(4)		(5)	
		Median	Mean	Max.		Mean	Max.	Mean	Range
1944	0	--	--	--	--	--	--	--	--
1945	0	--	--	--	--	--	--	--	--
1946	5	138	129	251	9.6	12.4	26	79	10-1800
1947	3	119	190	399	13	24.0	27	25	10-105
1948	2	131.5	132	205	9.9	13.0	18	57	15-575
1949	3	74	76	101	31	23.3	26	33	10-80
1950	5	66	73	103	18	13.2	18	40	10-180
1951	12	44.5	52	103	28	14.8	45	60	10-500
1952	17	53	57	105	29	16.5	27	65	20-310
1953	28	46.5	50	104	29	14.7	31	68	10-340
1954	30	51	56	106	32	18.0	46	69	10-315
1955	37	70	79	134	26	20.8	39	67	5-340
1956	41	71	79	141	30	23.6	45	68	5-325
1957	46	12	12.0	12	77	9.3	11	170	3-717
1958	58	12	12.0	12	88	10.5	12	169	8-781
1959	57	12	11.0	12	90	10.8	12	151	1-540
1960	58	12	12.1	13	92	12.0	13	147	2-532
1961	60	13	12.3	13	94	12.2	13	158	3-679
1962	60	13	12.5	13	96	12.5	13	151	1-715
1963	54	13	12.5	13	94	12.3	13	149	1-957
1964	60	12	11.3	12	95	10.8	12	164	1-1228
1965	71	12	9.9	12	88	8.7	12	186	20-990
1966	53	12	11.0	13	89	9.8	12	166	10-910
1967	45	12	11.1	12	95	10.6	12	178	20-850
1968	49	12	10.8	13	94	10.1	13	174	10-1260
1969	40	12	11.6	13	89	10.3	13	189	20-1490
1970	30	12	11.1	15	89	9.9	12	193	20-1660
1971	28	12	10.4	12	81	8.4	12	193	20-950
1972	27	12	11.7	12	96	11.2	12	153	10-970
1973	23	12	11.7	12	97	11.3	12	170	10-830
1974	22	12	11.1	12	95	10.6	12	159	10-1150
1975	18	12	15.6	25	67	10.5	14	162	10-910
1976	14	13.5	15.4	26	70	10.8	14	130	10-860
1977	13	14	16.0	23	80	12.8	16	112	10-900
1978	7	12	13.4	17	95	12.7	16	117	10-840

*See Table 8.
**See Table 8.

For the period 1957-1978, a larger proportion of dosimeters showed positive results than during the earlier period, and this probably resulted primarily because dosimeters were exchanged less frequently. Some years, notably 1964 and 1965, showed very high proportions with positive results even among those who probably had no occupational exposure (Table 11). The variation in the proportion of positive dosimeters by calendar year very likely reflects variation in dosimetry practices in measuring and recording very low doses.

4.3 MAGNITUDE OF POSITIVE RECORDED GAMMA DOSES

The average positive gamma dose per dosimeter increased over the period 1944-1956. Doses during this period were reported to the nearest five mrem. The lowest reported positive gamma dose by year never exceeded 10 mrem; thus, it appears that all indicated doses were recorded, without setting doses below some specified threshold value equal to zero.

With less frequent dosimeter exchange, the average positive gamma dose per dosimeter was larger during the period 1957-1978 than in earlier years. As would be expected, larger values were found for those with higher doses (Tables 10 and 13). For the years 1957-1964, doses were reported to the nearest mrem. Beginning in 1965, doses were reported to the nearest centirem. Again, there was no indication that doses less than some specified threshold value had been set equal to zero.

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