as part of the special study referred to under 6.
doses.

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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.

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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

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(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.

analyses. This study was not addressed at evaluating bias and uncertainty in the measurement of dose, but only at evaluating the extent to which doses used in analyses agreed with information from source records. However, another report is in preparation that describes and evaluates the technical aspects of historical dosimetry practices at Hanford. An historical review of the development of personnel dosimetry at Hanford is provided by Wilson (1987).

A second objective of this study was to examine detailed dosimetry characteristics, such as the frequency of dosimeter exchange and the distributions of readings from individual dosimeters. The computerized summaries on HRO included only annual doses, and did not provide this level of detail.

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,

records of workers dying from multiple myeloma and employed at least five years at Hanford, but not meeting other criteria, were also examined. This group included three deaths from multiple myeloma in males and two in females. The low recorded doses were found to be correct.

3. Controls. At least one matched control for each of the leukemia and multiple myeloma deaths noted in 1. and 2. was selected (39 workers). These controls were selected from males with at least five years of monitoring. For each leukemia and multiple myeloma death, controls were randomly selected from workers who were alive at the age the death occurred, and who had reached this age in the same five-year calendar year period as the death. Because recent analyses (Gilbert et al. 1989) have been controlled for age in single year intervals, and for calendar year in five-year intervals, this matching was equivalent to selecting controls from the risk sets used in dose-response analyses. In preliminary work, we had already examined records for some workers. For this reason, a few extra controls were available, so some leukemia and multiple myeloma deaths were assigned multiple controls.
4. High dose cancer deaths. Nineteen workers who had died from cancer and who had relatively high doses were selected. Six of these workers had been included in a preliminary investigation. Thirteen workers were added later so that the study (including groups 1-6) would include all workers dying of cancer 1981 or earlier with cumulative doses exceeding 20 rem 10 years prior to death.
5. Radiation workers. Twenty-eight workers with occupational data indicating a job title with relatively high potential for external radiation exposure were selected. Occupational data were collected at the Hanford Environmental Health Foundation (HEHF) independently of the dosimetry data. This group was selected from workers included in a lung cancer case-cohort study, designed to examine smoking data and other factors in relation to lung cancer risks (Petersen et al. 1990). For each subject in this study, the work history had been examined, and a job category corresponding to the job held longest had been assigned. All subjects in this study were males who were initially employed before 1960, terminated 1965 or later, and were monitored for external radiation.

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

as part of the special study referred to under 6., but did not have high doses.

2.2 DESCRIPTION OF THE RECORDS EXAMINED

The records examined for this investigation consisted of summary records, known as "annual pump-outs" and stored on microfiche or microfilm, for each worker for each year of employment. These records showed results of individual dosimeter readings for each component of radiation exposure measured. In many cases, workers' dosimetry files included additional records such as notations about special incidents or information on the original values read from dosimeters before converting to dose. For this investigation, it was not feasible to examine this additional information in detail.

Data from the source records or "annual pump-outs" were entered into a database system. These data included name, social security number, calendar year of the record and information obtained from dosimeter readings as indicated below. Examples of records for the periods 1944-56, 1957-58, 1959-71, 1972-74, and 1975-78 are reproduced in Figures 1-5.

The 1944-56 records were handwritten with estimates of beta and gamma dose, and the net optical densities associated with these estimates. Results of pencil readings were also given for the years 1944-51. These records consisted of two pages for each year. Dosimeters were exchanged either every week or every two weeks with separate dosimeters issued for different work locations. The worker whose record is shown in Figure 1 worked only in the 200-W area, but in other instances, workers had readings for several areas. The records also had designated spaces for summary information including the total estimated beta and gamma doses for the year. Records were handwritten, and copies made from microfiche were often difficult to read. For these records, the beta dose, gamma dose, and work location were entered into the data base. The summary totals for beta and gamma dose were also entered.

From 1957-1978, annual pump-outs were computerized (but are currently available only in hard copy). Records were more easily read than in the earlier period, but "smeared" entries resulted in occasional reading difficulties. Dosimeters were exchanged monthly (or every four weeks). Beginning in 1964, some workers were put on a quarterly exchange schedule, and beginning in 1972, some workers were put on a yearly exchange schedule.

Figure 1. Examples of Record 2 in the period 1941-60.

Figure 2. Example of Record From the Period 1957-58

MANPOWER APP. NATIONAL INCOME RECORD FOR				1958	PAYROLL NO.
SICITY	REV	SOC SEC	IND CORE	RIGHT-DATE	YEAR DATE
BASE FOR LAST 12 MO. BETA GAMMA 00000 00000					
CURRENT ADJUSTED YEAR TOTAL BETA GAMMA X-RAY 00000 00000 00000					
ACCUMULATED INCOME FOR PERIOD MANPOWER EXPENDITURE BETA GAMMA 00000 00000					
ACCUMULATED ACCUMULATED INCOME BETA GAMMA X-RAY 00000 00000 00000					

BIOASSAY SCHEDULE		J F M A M J J A S O N D YR	
		1 00	

FILM RANGES		PERIOD ENDING	
BETA GAMMA		BETA GAMMA	
JAN.	0000	FEB.	0000
MARCH	0000	APRIL	0000
MAY	0000	JUNE	0000
JULY	0000	AUG.	0000
SEPT.	0000	OCT.	0000
NOV.	0000	DEC.	0000

[illegible]

Figure 4. Example of Record From the Period 1972-74

PERSONAL OCCUPATIONAL DOSE RECORD FOR		FILE NO:	DATE PREPARED	1-25-74
SERIAL CUST. ID NO. REC. SEX JOB CODE BIRTHDATE SER. DATE TERM. DATE		817ASSAY SCHEDULE	1	2
				YR
A. L. S.			RADIO EXCHANGE SCH. 1	
DOSE TO LAST 12 MONTHS (MREM)				
PERIOD ENDING	MP	TLD BADGE DOSIMETERS	S-N	TLD RINGS
1-26-73	20	PEM	107	PERIOD ENDING
2-23-73	20	110	40	1-26-73
3-30-73	20	120	10	2-23-73
4-27-73	20	130	10	3-30-73
5-24-73	20	140	10	4-27-73
6-21-73	20	150	10	5-24-73
7-18-73	20	160	10	6-21-73
8-15-73	20	170	10	7-18-73
9-12-73	20	180	10	8-15-73
10-9-73	20	190	10	9-12-73
11-6-73	20	200	10	10-9-73
12-3-73	20	210	10	11-6-73
		220	10	12-3-73
		230	10	
		240	10	
		250	10	
		260	10	
		270	10	
		280	10	
		290	10	
		300	10	
		310	10	
		320	10	
		330	10	
		340	10	
		350	10	
		360	10	
		370	10	
		380	10	
		390	10	
		400	10	
		410	10	
		420	10	
		430	10	
		440	10	
		450	10	
		460	10	
		470	10	
		480	10	
		490	10	
		500	10	
		510	10	
		520	10	
		530	10	
		540	10	
		550	10	
		560	10	
		570	10	
		580	10	
		590	10	
		600	10	
		610	10	
		620	10	
		630	10	
		640	10	
		650	10	
		660	10	
		670	10	
		680	10	
		690	10	
		700	10	
		710	10	
		720	10	
		730	10	
		740	10	
		750	10	
		760	10	
		770	10	
		780	10	
		790	10	
		800	10	
		810	10	
		820	10	
		830	10	
		840	10	
		850	10	
		860	10	
		870	10	
		880	10	
		890	10	
		900	10	
		910	10	
		920	10	
		930	10	
		940	10	
		950	10	
		960	10	
		970	10	
		980	10	
		990	10	
		1000	10	
		1010	10	
		1020	10	
		1030	10	
		1040	10	
		1050	10	
		1060	10	
		1070	10	
		1080	10	
		1090	10	
		1100	10	
		1110	10	
		1120	10	
		1130	10	
		1140	10	
		1150	10	
		1160	10	
		1170	10	
		1180	10	
		1190	10	
		1200	10	
		1210	10	
		1220	10	
		1230	10	
		1240	10	
		1250	10	
		1260	10	
		1270	10	
		1280	10	
		1290	10	
		1300	10	
		1310	10	
		1320	10	
		1330	10	
		1340	10	
		1350	10	
		1360	10	
		1370	10	
		1380	10	
		1390	10	
		1400	10	
		1410	10	
		1420	10	
		1430	10	
		1440	10	
		1450	10	
		1460	10	
		1470	10	
		1480	10	
		1490	10	
		1500	10	
		1510	10	
		1520	10	
		1530	10	
		1540	10	
		1550	10	
		1560	10	
		1570	10	
		1580	10	
		1590	10	
		1600	10	
		1610	10	
		1620	10	
		1630	10	
		1640	10	
		1650	10	
		1660	10	
		1670	10	
		1680	10	
		1690	10	
		1700	10	
		1710	10	
		1720	10	
		1730	10	
		1740	10	
		1750	10	
		1760	10	
		1770	10	
		1780	10	
		1790	10	
		1800	10	
		1810	10	
		1820	10	
		1830	10	
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		2070	10	
		2080	10	
		2090	10	
		2100	10	
		2110	10	
		2120	10	
		2130	10	
		2140	10	
		2150	10	
		2160	10	
		2170	10	
		2180	10	
		2190	10	
		2200	10	
		2210	10	
		2220	10	
		2230	10	
		2240	10	
		2250	10	
		2260	10	
		2270	10	
		2280	10	
		2290	10	
		2300	10	
		2310	10	
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		2800	10	
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		2920	10	
		2930	10	
		2940	10	
		2950	10	
		2960	10	
		2970	10	
		2980	10	
		2990	10	
		3000	10	
		3010	10	
		3020	10	
		3030	10	
		3040	10	
		3050	10	
		3060		

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

HANFORD OCCUPATIONAL DOSE RECORD																						
SUFFIX	CONST.	ID	SOC.	SEC.	SEX	JOB	BIRTH	SERVICE	YEAR	DATE	DATE	DATE	DATE	DATE								
NO.						CODE	DATE	DATE	DATE	DATE	DATE	DATE	DATE	DATE								
M																						
ADDRESS	NA	BUILDING	DATE OF DEATH																			
BADGE NO.	PE	CALENDAR YEAR	77 DOSE HISTORY-MR	TOTALS IN -HREM-																		
4	0	07	10	SKIN	NO	EXT																
4	0	61 77	10	2130	2130	3660																
4	0	61 77	220	60460	57240	73120																
4	0	61 77	179	760	760	890																
4	0	61 10	190																			
4	0	61 10	150																			
4	0	61 11	10																			
4	0	61 12	180																			
				OFF-SITE OTHER THAN HANFORD																		
				PERIOD ENDING 12-30-77																		

For 1957-1963, it was not possible to determine the number of dosimeters with zero readings unless it was assumed that the total number of dosimeters was 12 (or 13). For 1957-58, records for all workers examined had exactly 12 readings, and it appeared that the computer program automatically printed zeros, with positive dosimeter results overriding zeros. For 1959-63, only positive results (either beta or gamma dose positive) were recorded with no entries for workers with zero readings.

Records for 1957 and 1958 included estimates of beta and gamma doses from each of the 12 dosimeters with summary spaces provided for the sums of the beta and gamma doses for the entire year. A space for annual x-ray dose was also provided. For each of the 12 dosimeters, the beta and gamma doses were entered into the database. Summary numbers were also entered.

Records for 1959-1971 included readings from each dosimeter for beta, gamma, x-ray, fast neutrons, and slow neutrons. Summary numbers were also given and were designated by "GAMMA", obtained as the sum of the gamma readings plus 35% of the sum of the x-ray readings, "PENET", obtained as "GAMMA" plus the sum of the readings for fast neutrons and slow neutrons, and "DERMA", obtained as the sum of beta, gamma, x-ray, fast neutrons, and slow neutrons. Beginning in 1962, the variable "TR", indicating tritium dose, was added. Again, readings for each radiation type for each dosimeter were entered into the database, as well as the summary numbers. The terms "GAMMA", "PENET", "DERMA", and "TR" were those used on the records, and will be used in the remainder of this report without quotations.

Records for 1972-1978 included individual dosimeter readings for penetrating, non-penetrating, fast neutrons, and slow neutrons. Summary numbers were as follows (quotations are used with the first introduction of a term, and subsequently omitted): "WB", obtained as the sum of penetrating, fast neutrons and slow neutrons, "SKIN", obtained as WB plus the sum of non-penetrating readings. For the years 1975-78, readings from rings were added and a summary number "EXT" was included, and obtained as SKIN plus the sum of readings from rings. Readings for each radiation type for each dosimeter were entered, as well as the summary numbers WB, SKIN, and EXT.

From the detailed information included in the database and described above, a working file of data for each worker for each year was prepared. This file included social security number, year, all dose estimates included

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).

For the years 1959-71, the sum of the individual gamma readings plus 35% of the sum of the individual x-ray readings, was required to be within 20 mrem of the summary number recorded under GAMMA. In addition, the sum of the individual gamma readings, plus 35% of the sum of the individual x-ray readings, plus the sum of the neutron readings, plus the recorded values for tritium (TR), was required to be within 20 mrem of the summary number recorded under PENET.

For the years 1972-78, the sum of the individual penetrating dose readings, plus the sum of the neutron readings, was required to be within 20 mrem of the summary number recorded under WB.

Records that did not pass all tests for internal consistency were re-examined. In some cases, the record failed to pass because of incorrect data entry on our part; in these cases, the working file was corrected. In other cases, the nature of the error was coded, and a dose reflecting what appeared to be the most likely "correct" whole body penetrating exposure was assigned. This dose is referred to as "TRUDOS" in subsequent discussions. Usually TRUDOS was taken to be the summary number unless an obvious error could be identified. In later years, the complexity of the records sometimes required consultation with persons in PNL's Dosimetry Records Group to understand the nature of apparent discrepancies and to determine the appropriate assignment of TRUDOS. Several features of these records, which sometimes led to difficulties in interpretation, are described below.

3.1.2 Results of Edits for Internal Consistency

For the years 1944-56, 963 records were examined. In many cases, copies made from microfiche or microfilm were difficult to read and, thus, it was not always possible to determine with certainty that the summary number reflected the correct total. After re-examination of records failing to pass the test for internal consistency, those records where it was judged that readability problems might have accounted for the observed discrepancy were assigned a TRUDOS equal to the summary number; usually the summary numbers could be read without difficulty. Such readability problems were found for 23 of the 963 records (2.4%). TRUDOS was also assigned the summary number for seven (0.7%) records where only one of two pages of the record was found. For an additional 11 records (1.1%), entries were reasonably clear but a discrepancy remained, and in these instances TRUDOS was assigned the sum of the individual gamma

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

in 1961, and for another worker in 1951, 1953, and 1954. These doses were also included in calculating TRUDOS.

3.2 CONSISTENCY OF ANNUAL DOSES ON SOURCE RECORDS AND ANNUAL DOSSES USED IN MORTALITY ANALYSES

Table 1 shows the number of annual records examined for each calendar year, and also indicates the number of records exhibiting various problems. Whenever doses were available from both source records and the analysis file, the two values were compared. Specifically, the dose on the analysis file, which we will call "ANALDOS", was compared with TRUDOS, our best assessment of the correct penetrating dose estimate based on source record data as discussed in Section 3.1. ANALDOS was available only to the nearest centirem. For comparison, TRUDOS was rounded to the nearest centirem, and differences of just one centirem were not counted (because of the possibility of different rounding conventions).

The number of times that ANALDOS differed from TRUDOS is indicated in Columns 2 and 3. Column 3 gives the number of times that disagreement was greater than 0.1 rem, while Column 2 gives the number of times smaller differences occurred.

Of the 13 larger discrepancies (Column 3) in the years 1944-56, four exceeded 0.5 rem with the difference between ANALDOS and TRUDOS equal to -0.56, 0.64, 0.67, and 1.35 rem. The three positive discrepancies exceeding 0.5 rem all occurred in 1945, and it appeared that ANALDOS was based on the total of pencil rather than the total of film badge readings. Another smaller discrepancy (of 0.10) also occurred for this reason in 1944. For two workers, the annual pumpouts could not be found for 1944 and 1945, but other handwritten source records were found; in these cases, only one of the four annual records agreed with ANALDOS.

The fourth largest discrepancy (-0.56 rem) came about because the summary total had included only one of two pages of the record. In at least one instance, the value of ANALDOS appeared on the source record but had been crossed out with another value written in. In at least two other instances, the value that agreed with the sum of the individual readings (and taken to be TRUDOS) had been crossed out in the summary, and another entry written in, which agreed with ANALDOS. It is possible that these changes were, in fact,

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	

Table 1. (cont.)

- (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)
1957	109 (100.0)	0	0	0	0	109
1958	113 (100.0)	0	0	0	0	113
1959	110 (100.0)	0	0	0	0	110
1960	108 (100.0)	0	0	0	0	108
1961	107 (100.0)	0	0	0	0	107
1962	102 (100.0)	0	0	0	0	102
1963	101 (100.0)	0	0	0	0	101
1964	106 (100.0)	0	0	0	0	106
1965	101 (99.0)	0	1 (1.0)	0	0	102
1966	96 (97.0)	1 (1.0)	0	2 (2.0)	0	99
1967	89 (95.7)	3 (3.2)	0	1 (1.1)	0	93
1968	89 (100.0)	0	0	0	0	89
1969	77 (95.1)	3 (3.7)	0	0	1 (1.2)	81
1970	75 (94.9)	3 (3.8)	1 (1.3)	0	0	79
1971	69 (98.6)	1 (1.4)	0	0	0	70
1972	56 (93.2)	1 (1.8)	0	0	0	57
1973	51 (100.0)	0	0	0	0	51
1974	48 (100.0)	0	0	0	0	48
1975	43 (97.7)	0	0	1 (2.3)	0	44
1976	40 (97.6)	0	0	1 (2.4)	0	41
1977	36 (97.3)	0	0	1 (2.7)	0	37
1978	28 (87.5)	0	0	4 (12.5)	0	32
Subtotal (1957-1978)						
1754 (98.6)	12 (0.7)	2 (0.1)	10 (0.6)	1 (0.1)	1779	
Total (1944-1978)						
2682 (97.2)	34 (1.2)	15 (0.5)	10 (0.4)	17 (0.6)	2758	

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

comparison of cumulative doses calculated through 1978 obtained from the analysis file and comparable cumulative doses obtained from the source records. The latter were calculated by summing the annual doses that appeared to be the most likely "correct" whole body penetrating exposure, that is, TRUDOS as defined above. When the annual TRUDOS differed from the annual ANALDOS by one centirem or less, TRUDOS was set equal to ANALDOS for the purpose of calculating cumulative dose. Years with missing source records or missing doses on the analysis file (as in Columns 4 and 5 of Table 1) were counted as zero for the summation.

Table 2. Number of subjects (and percent) by absolute and relative differences in the cumulative dose from analysis file and cumulative dose from source records.

Absolute difference (in rem)	Relative difference (as percent of source record dose)				Total
	0.0%	> 0% < 1%	> 1% < 10%	> 10%	
≤ -1.0	0	0	1	0	1 (0.7)
> -1.0, ≤ -0.1	0	2	1	1	4 (2.9)
> -0.1, < 0	0	6	5	0	11 (7.9)
= 0.0	95	0	0	0	95 (68.3)
> 0.0, < 0.1	0	12	3	1	16 (11.5)
≥ 0.1, < 1	0	3	6	0	9 (6.5)
≥ 1.0	0	0	0	3	3 (2.2)
Total	95 (68.3)	23 (16.5)	16 (11.5)	5 (3.6)	139 (100.0)

Table 2 categorizes both the absolute and relative differences in cumulative doses obtained from the analysis file and the source records. The relative difference was obtained by expressing the absolute difference as a percentage of the source record cumulative dose. Exact agreement was found for 95 (68%) of the 139 subjects. For another 27 workers, agreement was within 0.1 rem resulting in a total of 122 (88%) with discrepancies less than 0.1 rem. On a relative scale, 118 (85%) of doses agreed within 1%.

Table 3 presents the absolute differences for each group of subjects selected. As noted earlier, the selected subjects generally over-represent workers with large doses. However, the selection of leukemia deaths and controls was not based on potential for exposure or magnitude of doses and,

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	$>-.1$	0	> 0	$\geq .1$	≥ 1	
		$\leq -.1$	< 0		$< .1$	< 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 4. Workers with discrepancies in cumulative doses based on analysis file and cumulative doses based on source records exceeding 0.1 rem.
Ordered from highest to lowest absolute difference.

- (1) Cumulative dose (in rem) through 1978 calculated from analysis file.
- (2) Cumulative dose (in rem) through 1978 calculated from source record data.
- (3) Difference in (1) and (2).
- (4) Group (see group numbers from Table 3).
- (5) Reason for discrepancy.

(1)	(2)	(3)	(4)	(5)
1.79	0.31	1.48	3	1944-45 doses on analysis file obtained from pencil readings.
6.46	5.00	1.46	5	1944-46 source records not found.
1.79	0.33	1.46	7	1944-45 source records not found, 1946 dose on analysis file higher than that on source record.
29.44	30.88	-1.44	2	Part of dose from 1965 and dose from 1966 not included on analysis file (worker changed contractor in mid-1965).
12.47	11.68	0.79	3	1944 source record not found, 1945-46 doses on analysis file obtained from pencil readings
12.07	11.43	0.64	5	1945 dose on analysis file probably obtained from pencil readings.
49.12	48.51	0.61	5	1944-45 source records not found.
28.69	29.25	-0.56	4	1955 summary number on source record did not agree with sum of individual entries. Dose on analysis file taken from summary number.
15.70	15.29	0.41	4	1944-45 source records not found.
39.68	39.32	0.36	4	1954 dose on analysis file higher than summary number on source record, no obvious explanation found.
32.28	32.55	-0.27	5	1955 summary number on source record did not agree with sum of individual entries. Dose on analysis file taken from summary number.
35.99	36.21	-0.22	5	Part of dose from 1970 not included on analysis file (worker changed contractor in mid-1970).
10.75	10.57	0.18	4	1956 summary number on source record did not agree with sum of individual entries. Dose on analysis file taken from summary number.
11.44	11.28	0.16	1	1946 dose on analysis file higher than summary number on source record, no obvious explanation.
47.36	47.23	0.13	1	1951-52 doses on analysis file higher than summary numbers on source records, no obvious explanation.
58.46	58.36	0.10	6	1955-56 doses on analysis file higher than summary number on source record, 1953 dose lower, no obvious explanation.
0.40	0.50	-0.10	7	1945 dose on analysis file higher than summary number on source record, no obvious explanation (does not appear to be obtained from pencils).

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	<u>> 0 rem</u> <u>< 0.1 rem</u>	<u>>= 0.1 rem</u> <u>< 1 rem</u>	<u>>= 1 rem</u>
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

through 1970. Results are very similar to those based on doses calculated through 1978.

Tables 6 and 7 present analyses of leukemia and multiple myeloma, respectively, and are based on deaths from these diseases and matched controls as described in Section 2.1. Results based on doses from source records and on doses from the analysis file are presented. The score statistic and risk estimates were obtained using PECAN (Storer et al. 1983), a computer program for analyzing case-control data. Risk estimates were based on the linear relative risk model with confidence limits calculated using the likelihood ratio statistic. Further description of the statistical methods is provided in Gilbert et al. (1989). It should be noted that the results presented here differ from those based on the full cohort (Gilbert et al. 1989) in that they use only a small number of controls (one to three) per case, and in that cases and controls from the period 1982-1985 were included. The inclusion of recent deaths potentially biases results because only deaths occurring in Washington state (with generally higher doses) could be identified as cases for this time period. However, for the purpose of comparing results based on the analysis file and those based on source records, this was not judged to be of great concern.

Table 6. Analyses of leukemia based on cumulative dose (2-year lag) from analysis file and cumulative dose from source records.

	<u>Source records</u>	<u>Analysis file</u>
Total dose for cases (16)	95.33 rem	95.67 rem
Total dose for matched controls (adjusted to allow for multiple controls per case)	81.71 rem	81.67 rem
Trend test statistic (approximately normally distributed)	0.29	0.33
Maximum likelihood estimate of linear excess relative risk coefficient (percent increase per rem)	0.79%	0.88%
90% confidence limits for risk coefficient	(-2.0%, 16%)	(-1.9%, 16%)

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

	<u>Source records</u>	<u>Analysis file</u>
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

were much larger than film badge readings. Recall that besides the results presented in Table 1, an additional 10 records from 1945 (with doses on analysis file greater than one rem) were examined; of these 10, only five records could be found, and the remaining five doses on the analysis file had been erroneously obtained from pencil readings. Because of these problems, excluding these dose estimates, and limiting the study to workers monitored 1947 or later, should be considered in future analyses.

Although extensive additional checking of doses does not seem needed, it is recommended that the doses of high dose cancer deaths continue to be validated. These cases are especially influential in analyses, and this small study does not exclude the possibility of occasional gross errors that could affect results substantially if they occurred in doses of workers dying from causes of special interest. Validation of doses from all deaths from leukemia and multiple myeloma would also be desirable, and if resources are available, validation of doses of other cancer deaths and a sample of other monitored employees should be considered.

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 8. Characteristics of external dosimetry for all subjects in study

- (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	23	3	3.7	11	10.5	0.4	1	64	10-115
1945	42	50	50	182	2.3	1.1	12	36	10-140
1946	47	52	72	251	8.1	5.9	26	36	5-1800
1947	63	53	73	399	6.9	5.0	27	24	5-105
1948	74	40.5	48	205	6.7	3.2	19	27	1-575
1949	74	28.5	42	138	7.9	3.4	26	28	10-85
1950	73	30	46	180	7.8	3.6	18	34	10-195
1951	87	31	43	175	9.6	4.1	45	47	10-500
1952	88	36	49	170	10	4.9	27	60	5-310
1953	94	34.5	43	195	15	6.4	31	62	10-340
1954	94	40	45	205	16	7.2	46	65	10-315
1955	99	52	60	234	16	9.3	39	63	5-340
1956	100	52	65	227	17	10.8	45	65	5-325
1957	110	12	12.0	12	38	4.6	11	152	3-717
1958	115	12	12.0	12	50	0.0	12	156	8-781
1959	111	8	6.7	12	52	6.2	12	141	1-540
1960	108	11	7.7	13	56	7.3	13	134	1-532
1961	107	11	8.4	13	62	8.1	13	139	2-679
1962	103	12	10.3	13	77	10.0	13	117	1-715
1963	99	11	9.7	13	69	9.0	13	117	1-957
1964	106	11	9.3	12	88	8.2	12	132	1-1228
1965	101	10	8.4	12	84	7.1	12	173	20-1320
1966	99	12	8.5	13	79	6.7	12	141	10-910
1967	93	12	8.2	12	77	6.4	12	151	20-850
1968	90	12	8.1	13	85	6.8	13	149	10-1260
1969	81	12	8.4	13	74	6.2	13	164	20-1490
1970	80	8.5	7.4	15	66	4.9	12	163	20-1660
1971	70	7.5	7.0	12	64	4.5	12	160	10-950
1972	57	12	7.2	12	93	6.7	12	133	10-970
1973	51	11	7.3	12	92	6.7	12	138	10-830
1974	48	4.5	6.8	12	87	5.9	12	138	10-1150
1975	44	5	8.1	25	66	5.3	14	140	10-910
1976	41	5	8.1	26	70	5.7	14	98	10-860
1977	37	4	8.2	23	77	6.3	16	89	10-900
1978	29	4	6.4	17	84	5.4	16	78	10-840

* For 1959-1963, only the number of dosimeters with positive dose (either beta or gamma) could be determined; for records with no entries, the number of dosimeters was taken to be one.

**For 1959-1963, this percent was calculated under the assumption that all workers had 13 dosimeters per year (12 for 1959).

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

<u>Calendar</u> <u>year</u>	(1)	(2)			(3)	(4)		(5)	
		<u>Median</u>	<u>Mean</u>	<u>Max.</u>		<u>Mean</u>	<u>Max.</u>	<u>Mean</u>	<u>Range</u>
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 10. Characteristics of external dosimetry for high dose workers (high dose cancer deaths, radiation workers, and neutron workers)

- (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	2	2.9	9	19	0.6	1	61	10-115
1945	17	50	42	59	4.9	2.1	12	36	10-140
1946	19	52	54	111	14	7.3	21	25	10-150
1947	24	53	58	140	9.2	5.4	24	24	5-90
1948	25	46	45	97	9.5	4.3	14	29	10-575
1949	30	27	33	131	8.6	2.8	19	28	10-80
1950	34	43	39	136	11	4.4	18	39	10-195
1951	32	30	79	102	17	6.1	45	49	10-500
1952	42	34	47	115	13	6.3	24	59	5-260
1953	44	32	40	104	22	8.6	31	61	10-295
1954	48	33	41	106	23	9.4	29	62	10-315
1955	51	52	64	134	20	13.0	34	61	5-340
1956	51	46	71	141	23	16.5	45	64	5-280
1957	51	12	12.0	13	64	7.7	11	154	3-717
1958	51	12	12.0	12	84	10.1	12	163	17-781
1959	51	11	10.4	12	83	10.0	12	152	1-537
1960	51	12	11.7	13	88	11.5	13	142	1-510
1961	51	13	11.9	13	90	11.7	13	152	2-679
1962	50	13	12.3	13	93	12.1	13	137	2-715
1963	49	13	11.9	13	88	11.5	13	138	1-957
1964	51	12	11.4	12	94	10.7	12	149	1-1228
1965	50	12	11.0	12	88	9.7	12	169	20-990
1966	49	12	11.3	13	87	9.8	12	146	20-910
1967	48	12	10.9	12	89	9.6	12	161	20-850
1968	47	12	10.9	13	91	9.9	13	162	10-1260
1969	45	13	11.3	13	81	9.2	13	173	20-1490
1970	45	12	10.1	15	73	7.4	12	164	20-1660
1971	39	12	10.2	12	66	6.8	12	165	20-950
1972	33	12	10.5	12	93	9.8	12	137	10-970
1973	28	12	11.0	12	94	10.4	12	147	10-830
1974	26	12	10.2	12	92	9.4	12	144	10-1150
1975	22	12	13.5	25	66	8.8	14	148	10-910
1976	20	12.5	13.9	26	71	9.9	14	102	10-860
1977	17	13	13.9	23	78	10.8	16	95	10-900
1978	11	12	10.1	17	85	8.5	16	106	10-840

*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

<u>Calendar</u>		(2)			(3)	(4)		(5)	
<u>year</u>	(1)	<u>Median</u>	<u>Mean</u>	<u>Max.</u>		<u>Mean</u>	<u>Max.</u>	<u>Mean</u>	<u>Range</u>
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 12. Characteristics of external dosimetry when total annual dose less 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	23	3	3.7	11	10.5	0.4	1	64	10-115	
1945	42	50	50	182	2.3	1.1	12	36	10-140	
1946	42	52	65	232	7.8	5.1	17	24	5-30	
1947	60	52.5	67	312	6.1	4.1	17	24	5-90	
1948	72	40	46	171	6.4	3.0	19	24	5-60	
1949	71	28	41	138	6.1	2.5	15	26	10-85	
1950	68	29.5	44	180	6.6	2.9	12	32	10-195	
1951	75	30	42	175	5.8	2.4	12	35	10-120	
1952	71	33	47	170	4.7	2.2	10	51	5-150	
1953	66	30	40	195	7.3	2.9	11	51	15-130	
1954	64	30.5	39	205	5.4	2.1	9	48	10-165	
1955	62	35	48	234	5.0	2.4	13	43	25-210	
1956	59	47	55	227	3.6	2.0	9	42	5-140	
1957	64	12	12.0	13	10	1.3	8	58	18-331	
1958	57	12	12.0	12	12	1.5	9	61	9-274	
1959	54	1	2.2	12	11	1.3	8	53	2-284	
1960	50	1	2.7	12	15	2.0	11	39	1-242	
1961	47	2	3.3	13	22	2.8	12	33	2-207	
1962	43	7	7.2	12	50	6.5	12	26	1-179	
1963	45	6	6.4	13	39	5.1	11	24	1-160	
1964	46	7	6.7	12	71	4.8	10	38	1-258	
1965	30	4	4.7	12	66	3.1	6	91	20-310	
1966	46	4	5.7	12	57	3.2	10	58	20-360	
1967	48	4	5.5	12	44	2.4	11	42	20-360	
1968	41	4	4.9	12	60	2.9	10	45	20-250	
1969	41	4	5.4	12	42	2.3	9	51	20-290	
1970	50	3	5.1	12	36	1.8	8	54	20-240	
1971	42	2	4.8	12	40	1.9	9	64	10-170	
1972	30	1	3.2	12	83	2.7	12	58	10-400	
1973	28	1.5	3.6	12	80	2.9	12	36	10-300	
1974	26	2	3.2	12	63	2.0	12	40	10-230	
1975	26	1	2.9	14	60	1.7	8	48	10-370	
1976	27	1	4.4	23	69	3.0	12	40	10-250	
1977	24	1.5	3.9	14	69	2.7	11	30	10-120	
1978	22	3.5	4.2	14	74	3.1	11	28	10-350	

*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	(1)	(2)			(3)	(4)		(5)	
year		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.

doses tended to have more dosimeters than those with smaller doses, as can be seen by comparing corresponding means (or medians) from Tables 12 and 13.

For the period 1957-1978, Column 2 of Tables 8-13 is based on the number of results reported on the summary record. This number may not always be identical to the number of dosimeters. Detailed examination of some records indicated a few cases in which a single entry summarized several dosimeters in an earlier record, or in which an entry provided a correction. A detailed examination of these records on a case by case basis would probably allow one to determine the actual number of dosimeters more accurately. For the purposes of this study, however, reporting the number of results should provide an adequate general indication of the number of dosimeters. As noted earlier, the years 1957 and 1958 always had 12 results, while for the years 1959-1963, only dosimeters yielding positive results were entered into the record. Workers with annual doses of zero in these years had records, but there were no entries in the place where individual dosimeter results were ordinarily reported.

From Tables 10 and 13, it is seen that workers with higher doses were fairly consistently monitored on a monthly basis throughout the period 1957-1978, although, in the period 1975-1978, a few workers were monitored more frequently. Starting in 1964, most lower dose workers (Tables 11 and 12) were monitored quarterly, and in 1972, yearly monitoring was implemented for some workers.

4.2 NUMBER AND PROPORTION OF DOSIMETERS WITH POSITIVE GAMMA RESULTS

During the period 1944-1956, when dosimeters were exchanged frequently, only a small proportion of dosimeters showed positive results. This proportion increased over the period. Because the increase is seen mainly for those with potential for higher doses, it is plausible that this increase resulted from an increase in true exposure rather than from a change in dosimetry practices. For the leukemia deaths and controls, which can be considered a representative group, the proportion of dosimeters with positive results was always less than 10%. This low proportion may suggest underestimation of dose during this period, because chance fluctuation would generally yield a higher proportion of positive results even among those with no true occupational exposure.

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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