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LOW-LEVEL RADIATION AND CANCER DEATHS*

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Abstract—Although the proportion of cancer deaths among males is somewhat higher for Hanford employees with recorded occupational radiation exposure compared with males in the general population of the state of Washington, there is no indication that radiation is the cause of this difference.

For exposed male employees hired at Hanford from 1944 to 1971, the mean radiation dose increases progressively from 142 mrem in 1944 to 3745 mrem in 1972 (the true gradient would have been sharper); whereas, the percentage of deaths from cancer is 19.85 for 1944–1959 and 20.27 for 1960–1972. For the 1944–1945 cohorts (those hired in 1944 or 1945), the observed dose gradient rises progressively from 142 mrem in 1944 to 3762 mrem in 1972 (with a sharper gradient in true dose), and the percentage of cancer deaths is 20.67 for 1944–1959 and 19.10 for 1960–1972. The percentage of deaths from cancer is 20.35 for exposed males hired from 1946 to 1971 and 20.05 for those hired in 1944–1945 from the time of hire to October 1972. For each year the mean dose level of those who died from cancer is not significantly different from the mean of those who died from other causes. The mean dose level for the majority of those who died in a specific year is lower than the mean for the survivors in the year of death, in the year preceding the year of death, or in the two years preceding the year of death. This is true whether the mean was for those dying from cancer or from other causes.

These relationships are similar for female exposed employees and agree with other similar studies.

The latest analysis of exposed male Hanford employees vs those nonexposed and the out-of-plant controls from the date of hire to April 1974 shows the following often statistically significant differences:

1. Higher longevity for exposed employees vs the identified siblings of such employees. This advantage of employees over the siblings becomes more pronounced if the comparison is restricted to employees with one or more identified siblings.
2. Exposed employees have higher longevity when compared with nonexposed employees.
3. Exposed employees have higher longevity when compared with their matched controls.
4. Nonexposed employees have lower longevity when compared with identified siblings of such employees. If the comparisons are restricted to employees with one or more identified siblings, the longevity advantage of the siblings over the employees is enhanced.
5. Nonexposed employees have lower longevity when compared with their matched controls.

Crude disability claim rates for benefits among the population groups delineated above fully support the findings based on longevity; therefore, all observations available so far give no firm indication of any lasting adverse health effects among Hanford employees attributable to occupational exposure to radiation within permissible limits. Inferentially, these findings are likely to prevail at least until the early 1980's. Adverse effects beyond 36 yr cannot be denied or affirmed at this time.

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INTRODUCTION

SINCE 1964 a follow-up study* of the employees who have worked in atomic plants has been conducted to determine whether these employees have suffered any discernible health damage from exposure to occupational radiation within permissible limits. This paper will be limited to an evaluation of possible evidence of cancer deaths from external whole-body radiation among Hanford Works employees in Richland, Washington, with recorded exposure to occupational radiation.

Hanford employees and their out-of-plant controls were chosen because of the preservation of past records by the Hanford Works and the cooperation of the staff of the Hanford Environmental Health Foundation. Information was also available for employees at the three installations in the Oak Ridge, Tennessee, Mallinckrodt in the area of St. Louis, Missouri, Mound Laboratory in Miamisburg, Ohio, and a limited amount for employees at National Lead of Ohio.

The study population of Hanford has consisted of 33,000–34,000 employees; some 2500 nonstarts (applicants that were offered a job which they declined); 1500 identified siblings of these applicants; about 21,000 identified siblings of the employees (siblings of the same sex as the employee); and recently about 28,000 matched controls† for Hanford employees. The maximum follow-up period has been about 30 yr, and the average has ranged from 20 to 25 yr. Consistent provisional findings have appeared in all recent annual and special reports to ERDA (Ma71a–75, Sa72 and 74).

Although the proportion of cancer deaths for male Hanford employees is higher for certain types of cancers in the age range between 20 and 64 *vis-a-vis* all male deaths in the state of Washington in the same age range (Mi75), exposure to radiation is not the cause of this difference. Comparisons based on actual and expected numbers of deaths of exposed and nonexposed males are presented in tabular form below:

Observed versus the expected deaths from cancer (ICDA)

Ages*	Observed	Expected	χ^2	Significance
	Exposed male Hanford employees			
20–64	266	235	3.911	<5%
65+	157	144	1.194	
20+	423	379	4.545	<5%
	Nonexposed male Hanford employees			
20–64	155	147	0.420	
65+	80	87	0.625	
20+	235	235	0.000	
	All nonexposed males†			
20–64	385	386	0.001	
65+	198	191	0.245	
20+	583	577	0.068	

*The actual comparison between Hanford male employee deaths and male deaths in the state of Washington was in terms of five-year intervals and in age at the time of death except for those in ages 65+; these were then pooled into the summaries shown.

†Nonexposed Hanford employees, plus all the siblings of Hanford employees, plus the nonstarts and the identified siblings of the nonstarts.

Precise dose levels for Hanford employees with a record of occupational radiation exposure and for nonexposed employees are not available. In all probability the life-time cumulative dose that we have for these employees is incomplete. There has been no mechanism to centrally keep track of employee exposure to radiation so as to have a complete cumulative life-time dose if the employee worked for different contractors and in different plants. For the installations that are within the present study this presents no problem, but there is no information if employees in our study worked in plants not included in the study‡ (Ma71b). Cognizant of

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†These matched controls were derived from the 1% Continuous Work History Sample maintained by the Social Security Administration.

‡Since early 1960's Hanford questions every new employee whether he (she) has ever worked where he (she) could have been exposed to occupational radiation; where the response is affirmative, a request is sent to the former employer(s) for the record of exposure. The information supplied as to prior exposure to radiation is made a part of the employee's record. There is no way, however, of obtaining radiation exposure dose from post-Hanford employment of these employees. In addition many employees at the inception of the atomic age had occupational exposure before monitoring for radiation was widely adopted.

this limitation of the cumulative life-time dose level from occupational exposure to radiation. I have in my analyses relied more on gross differences in dose levels which would be less affected by deficiencies in dose information. In this paper my observations on possible causal relationship between external whole-body penetrating radiation* and cancer will be restricted to those Hanford employees who have recorded exposure to occupational radiation with a measurable recorded annual dose. This sample consists of 17,600 exposed Hanford males and 3900 females hired from 1944 to 1971.

CANCER DEATH EXPERIENCE

Table 1 shows all the deaths (with a death certificate) for male Hanford employees from 1944 to October 1972 who had a record of exposure to occupational radiation. These deaths are divided into deaths in which the underlying cause was cancer (Ic68) and

Table 1. Comparison of the proportion of deaths with the underlying cause as cancer (ICDA 140–209) in different years among the exposed* male Hanford employees. Also a year by year comparison of the mean cumulative lifetime dose for deaths from cancer vs the corresponding mean for deaths from causes other than cancer in 1944–1971 cohorts for all the years 1944–1972

Year	Cancer	No. of deaths other than cancer	All (2) & (3)	Cancer deaths (%)	Cancer	Mean exp. other than cancer (mrem)	Difference (6–7)	Pooled SD of dose (mrem)	t value	Sign (%)	Rank of (5)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1944	1	0	1	100.00	30						29
1945	1	4	5	20.00	110	718	–	125	1.67		18
1946	0	7	7	0.00		253					1
1947	1	7	8	12.50	130	170	–	158	0.24		3
1948	4	2	6	66.67	450	75	+	536	1.54		28
1949	4	20	24	16.67	268	567	–	400	0.38		9
1944–1949	11	40	51	21.57							
1950	2	19	21	9.52	315	506	–	606	0.37		2
1951	4	26	30	13.33	350	291	+	234	0.47		5
1952	6	33	39	15.38	422	433	–	443	0.06		6
1953	9	38	47	19.15	350	553	–	512	1.07		15
1954	9	28	37	24.32	639	543	+	690	0.36		23
1950–1954	30	144	174	17.24							
1955	9	30	39	23.08	1342	748	+	1444	1.09		21
1956	8	42	50	16.00	466	566	–	820	0.12		8
1957	12	46	58	20.69	355	564	–	674	0.96		19
1958	19	53	72	26.39	726	521	+	1128	0.31		25
1959	15	65	80	18.75	435	717	–	1728	0.57		14
1955–1959	63	236	299	21.07							
1944–1959	104	420	524	19.85							
1960	15	70	85	17.65	747	573	+	611	0.96		12
1961	17	79	96	17.71	918	1017	–	2105	0.17		13
1962	18	85	103	17.48	1631	1516	+	1208	0.14		11
1963	26	79	105	24.76	581	1106	–	2786	0.99		24
1964	23	88	111	20.72	1307	1338	–	3325	0.04		20
1960–1964	99	401	500	19.80							
1965	21	86	107	19.63	1545	849	+	1755	1.39		16
1966	17	115	132	12.88	4695	2124	+	5581	1.77	<10	4
1967	33	92	125	26.40	2270	1833	+	5007	0.53		26
1968	23	122	145	15.86	2377	2038	+	5084	0.29		7
1969	37	122	159	23.27	3201	2821	+	5879	0.53		22
1965–1969	131	537	668	19.61							
1970	35	143	178	19.66	1861	3786	–	6840	1.10		17
1971	45	121	166	27.11	4141	2080	+	5402	2.19	<5	27
1972	21	100	121	17.36	5793	3007	+	7366	1.58		10
1970–1972	101	364	465	21.72							
1960–1972	331	1302	1633	20.27			14+				
Total	435	1722	2157	20.17			13–				$r_s = 0.171$

*Exposed refers to employees with recorded occupational exposure to external whole body penetrating radiation.

†Only the first 9 months of 1972.

‡Deaths with a death certificate have been excluded, altogether 48 deaths, 25 of them in 1970–1972. For deaths without a death certificate the date reported by SSA is not the date of death, often it may be the date of the last benefit check, or the date of last reported employment subject to taxes, etc.

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*I have not analyzed Hanford data for internal radiation; however, I was advised by Hanford that every employee with recorded internal radiation is one of those who also has a record of external radiation. We, therefore, have no basis to assume that the study of internal radiation could lead to radically different results. Furthermore, a recent comparative analysis of Hanford employees with known plutonium deposition (452 of them) indicates no adverse effects from such internal exposure, at least for the first 30 years or so (No76).

deaths from other causes. Since the base population from which these deaths come is one with increasing dose levels and with an increasing proportion of the workers with long-term exposure to radiation, one would expect an increasing proportion of deaths from cancer with the passage of years if there was any causal relationship between exposure to radiation and cancer. Table 1 for exposed male Hanford employees fails, however, to corroborate this expectation, thus contradicting any causal connection between exposure to occupational radiation within permissible limits and deaths from cancer.

The cancer deaths are 19.85% of all deaths for 1944–1959 and 20.27% for 1960–1972. Correlating the ranks of percentage of cancer deaths in column (5) [these ranks are shown in column (12) with time], a coefficient of correlation of 0.171 is derived which is not statistically significant even at the 10% level (Za72). Such low correlation would be unlikely if exposure to occupational radiation had induced cancer among a large number of Hanford employees within the time span included in this study. There is no question that in the parent population the cumulative lifetime dose was increasing with time. This increase, in fact, is reflected in column (6) of Table 1. The mean dose level of the deceased increases with years. The rank coefficient of correlation between the mean dose level shown for the deaths in column (6) and time is 0.929, which is statistically highly significant at <0.1% level. Column (7) shows the mean dose level of deaths from causes other than cancer. These dose levels also increase with time. The rank coefficient correlation of these dose levels with time is 0.918, also highly significant. Notwithstanding these, there is no statistically significant correlation between the proportion of deaths from cancer and time. One would expect some increase on account of the advancing age of the population but there is no indication of that either.

If exposure to radiation within permissible limits were a causal factor, there would be a significantly higher mean cumulative dose for the deaths from cancer *vis-a-vis* the deaths from causes other than cancer. Column (8) shows, however, that this is not true. In 27 pairs of comparisons, the mean cumulative dose is higher in 14 for deaths from causes other than cancer and lower in 13. If for each year one compares the two means using the pooled standard deviation (SD), there are only two years in which the two means are statistically significantly different: one in 1966, for which the significance in the difference is at the 10% level, and the other for 1971, for which the difference is statistically significant at the 5% level. If, however, one uses the separate SDs for 1966 the *t* value drops to 1.33, that is, statistically nonsignificant, and for 1971, 1.77, significant at 10% level only. With 27 pairs of comparisons, this could easily arise by chance and cannot be deemed statistically significant.

There is another element in Table 1 that is not completely discordant with the hypothesis of a possible positive relationship between radiation exposure and cancer deaths. If one examines the mean dose levels for cancer deaths *vis-a-vis* the noncancer deaths, it is apparent that in the first 14 yr (1944–1959) the mean cumulative dose levels are higher for noncancer deaths in 10 yr and lower only in four: other than chance we cannot explain this disparity. For the last 13 yr (1960–1972) the mean cumulative dose levels are higher for noncancer deaths in four yr and lower in nine. One might be led to infer a possible adverse influence from occupational radiation, becoming apparent after a latent period. Comparing 10/4 vs 4/9 approaches the statistical significance (<10%) level. But since we have no plausible explanation for 10/4 and must attribute it to chance, by the same token, without additional evidence, the 4/9 ratio must also be attributed to chance at this time.*

Table 2 presents a parallel comparison for deaths of female employees with a record of occupational exposure to radiation. Admittedly the data are skimpy, but the evidence is consistent with that shown by Table 1. The

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*The interrelationships between length of employment at Hanford, dose level, and age of employee at time of death may account for this apparent anomaly.

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Table 2. Comparison of the proportion of deaths with the underlying cause as cancer (ICDA 140–209) in different years among the exposed female Hanford employees. Also a year by year comparison of the mean cumulative lifetime dose for deaths from cancer vs the corresponding mean for deaths from causes other than cancer in 1944–1971 cohorts all the years with any deaths 1951–1972†‡*

Year	Cancer	No. of deaths other than cancer	All (2) & (3)	Cancer deaths (%)	Cancer	Mean exp other than cancer (mrem)	Difference (6–7)	Pooled SD of dose (mrem)	t value	Sign (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1951	1	0	1		50					
1952	0	1	1			1250				
1953	0	2	2			470				
1954	0	1	1			40				
1951–1954	3	4	7	42.86						
1955	1	1	2	50.00	60	740	–			
1956	0	3	3			427				
1957	2	0	2		1163					
1958	0	1	1			310				
1959	1	2	3	33.33	1970	155	+			
1955–1959	4	7	11	36.36						
1960	0	4	4			228				
1961	1	6	7	14.29	85	528	–			
1962	2	3	5	40.00	140	597	–	13	1.50	
1963	1	2	3	33.33	1910	385	+			
1964	3	8	11	27.27	40	1116	–	153	1.04	
1960–1964	7	23	30	23.33						
1951–1964	14	34	48	29.17						
1965	4	2	6	66.67	693	400	+	39	0.86	
1966	0	5	5			416				
1967	1	8	9	11.11	720	1621	–			
1968	4	3	7	57.14	383	177	+	31	0.56	
1969	3	8	11	27.27	697	434	+	19	1.00	
1965–1969	12	26	38	31.58						
1970	3	6	9	33.33	2607	417	+	157	1.97	<10
1971	2	11	13	15.38	2400	973	+	543	2.44	<5
1972	3	1	4	75.00	687	1010	–			
1970–1972	8	18	26	30.77						
1965–1972	20	44	64	31.25						
Total	34	78	112	30.36						

*Exposed refers to employees with recorded occupational exposure to external whole body penetrating radiation.

†Only the first 9 months of 1972.

‡Deaths without a death certificate have been excluded, altogether 11 deaths, 6 of these in 1971–1972. For deaths without a death certificate the date reported by SSA is not the date of death, often it may be the date of the last benefit check, or the date of last reported employment subject to taxes, etc.

percentage of cancer deaths is 29.17 for 1951–1964 and 31.25 for 1965–1972, which is not a statistically significant difference. Comparing the mean cumulative dose shows six instances in which the average dose is higher for noncancer deaths and seven in which it is lower. This again is not statistically significant. It may be noted, however, that there is a similar concentration of the minus signs in column (8) in the early years and plus signs in more recent years as was observed in Table 1. For females these disparities between the two halves are not statistically significant even at the 10% level; were it not that they parallel the results in Table 1, they would call for no explanation other than chance. Comparison of the mean cumulative dose for cancer deaths with that for noncancer deaths shows a statistically higher mean for cancer deaths for the year 1970 at the 10% level, and for 1971 at the 5% level. This is, however, if we use the pooled SD. If we use the separate SDs then none of the paired means are significantly different from one another.

Some may feel that by including all those hired we have diluted the pool of employees who have had exposure to occupational radiation over a protracted period of time. To test this hypothesis, in Table 3 I give the experience of employees who were hired as production workers in 1944 and 1945. Table 3 is limited to male employees with recorded occupational exposure to external wholebody penetrating radiation from the year of hire to the year of death. As has been indicated, at least in some instances the known exposure may be only a fraction of the total life-time exposure to occupational radiation, especially for deaths from population most of whom have been followed for a minimum of 20 yr subsequent to their initial exposure. The

Table 3. Comparison of the proportion of deaths with the underlying cause of cancer (ICDA 140–209) in different years among the exposed* male Hanford employees. Also a year by year comparison of the mean cumulative lifetime dose for deaths from cancer vs the corresponding mean for deaths from causes other than cancer—1944–1945 columns for all the years 1944–1972†‡

Year	Cancer	No. of deaths other than cancer	All (2) & (3)	Cancer deaths (%)	Cancer	Mean exp. other than cancer (mrem)	Difference (6) − (7)	Pooled SD of dose (mrem)	t value	Sign (%)	Rank of (5)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1944	1	0	1	100.00	50	0					29
1945	1	4	5	20.00	110	718	–	325	1.67		15.5
1946	0	5	5	0.00	0	298					1
1947	1	7	8	12.50	150	170	–	158	0.24		4.5
1948	4	2	6	66.67	450	75	+	280	1.54		28
1949	4	15	19	21.05	268	395	–	332	0.42		17
1944–1949	11	33	44	25.00							
1950	2	14	16	12.50	315	561	–	250	0.61		4.5
1951	2	18	20	10.00	480	332	+	262	0.76		2
1952	5	26	31	16.13	490	486	+	450	0.02		7
1953	7	28	35	20.00	431	591	–	440	0.86		15.5
1954	6	20	26	23.08	897	689	+	738	0.59		23
1950–1954	22	106	128	17.19							
1955	6	19	25	24.00	1268	1041	+	1667	0.29		24
1956	6	30	36	16.67	665	868	–	904	0.46		9
1957	7	26	33	21.21	554	545	–	823	0.83		19
1958	11	32	43	25.59	552	703	–	781	0.35		26
1959	11	38	49	22.45	567	973	–	2160	0.55		20
1955–1959	41	145	186	22.04							
1944–1959	74	284	358	20.67							
1960	12	53	65	18.46	873	582	+	657	1.20		13
1961	9	46	55	16.36	558	1073	–	2305	0.49		8
1962	8	59	67	11.94	429	858	–	961	1.19		3
1963	14	48	62	22.58	930	1222	–	2014	0.35		21
1964	14	59	73	19.18	1296	749	+	1463	1.25		14
1960–1964	57	265	322	17.70							
1965	11	51	62	17.74	754	773	–	1178	0.05		10
1966	12	66	78	15.38	1666	2256	–	6183	1.24		6
1967	19	51	70	27.14	2222	1712	+	4652	0.41		27
1968	14	63	77	18.18	1444	1220	+	3912	1.90	<10	11.5
1969	20	67	87	22.99	2115	2278	–	4085	0.11		22
1965–1969	76	298	374	20.32							
1970	23	86	109	21.10	1843	2719	–	5857	0.64		18
1971	22	66	88	25.00	1590	1894	+	4472	1.54		25
1972	12	54	66	18.18	1844	2477	+	5840	1.28		11.5
1970–1972	57	206	263	21.67							
1960–1972	190	769	959	19.10							
Total	264	1053	1317	20.05			14– 13+				$r_s = 0.108$

*Exposed refers to employees with recorded occupational exposure to external whole body penetrating radiation.

†Only the first 9 months of 1972.

‡Deaths without a death certificate have been excluded, altogether 40 deaths, 19 of them in 1970–1972. For deaths without a death certificate the date reported by SSA is not the date of death, often it may be the date of the last benefit check, or the date of last reported employment subject to taxes, etc.

overwhelming majority of these former employees had their recorded initial exposure to occupational radiation prior to 1950. Table 3, like Table 1, shows no increased proportion of cancer deaths in relation to all deaths in recent years vis-a-vis the early years, which would have to be true if a significant number of cancers in this population were induced by their exposure to occupational radiation. The percentage of deaths attributed to cancer as the underlying cause is 20.67 for 1944–1959 and 19.10 for 1960–1972. The mean dose level of the employee population was, however, much higher in the 1960–1972 period and the years lapsed following the initial exposure much longer. The rank coefficient of correlation between the percentage of deaths attributable to cancer in a given year and time is 0.108, statistically nonsignificant. On the other hand the ranks of the mean cumulative life-time dose for the deaths in the different years correlated with time give a coefficient of 0.888 for cancer deaths and 0.863 for the noncancer deaths—both statistically highly significant, although not as high as the comparable coefficients for the observations in Table 1.

When the mean cumulative life-time doses in cancer deaths are compared with the corresponding means for noncancer deaths the ean is higher for the noncancer deaths in 14 id lower in 13. This overall picture is the me as in Table 1. In a sense this should not too surprising, since over 60% of the eaths in Table 1 are deaths given in Table 3. n the other hand this close similarity beveen the two tables is a clear indication that e length of exposure to radiation for a aximum period less than 30 yr does not ppear to be a differential factor in cancer eaths. This would be true, of course, if the nfluence of radiation within permissible imits on cancer deaths were nil—which the vailable evidence from Hanford so far tends o support. The distribution of the signs in column (8) again conforms to the pattern of Table 1; most of the minuses are in the early years and the pluses in the most recent years. The disparities in Table 3, however, are less sharp (9/5 for 1944–1959 and 5/8 for 1960–1972) than those in Table 1. These disparities are not statistically significant even at the 10% level.

Comparing the two sets of means [columns (6) and (7)] in terms of the pooled SDs shows that only for 1968 does the difference attain statistical significance at the 10% level. In 1968 the mean cumulative dose level is higher for cancer deaths; however, the t value of comparison of these two means drops from 1.90 to 0.94 if the two separate SDs are used. Using the separate SDs shows a statistically significant difference between the two means for 1962, but in this instance the larger mean is for the noncancer deaths.

COMPARISONS WITH THE PARENT POPULATION

So far our comparisons have been between the deaths for which cancer is given as the underlying cause and deaths from other causes. In Table 4 I show the parent population

Table 4. Cumulative mean dose level at the inception of each year for exposed male Hanford employees that have survived to that date, comparing the mean dose of the population along the time axis and comparing the population mean with the corresponding mean for deaths from cancer and the mean for deaths from causes other than cancer in the year of death and in the year preceding the year of death. All cohorts 1944–1971 and for all years 1944–1972† ‡*

Year	No. employees	Cumulative dose (mrem)		Cancer deaths	Cumulative dose (mrem)		Difference (3) − (6)		Other than cancer deaths	Cumulative dose (mrem)		Difference (3) − (10)	
		Mean	S.D.		Mean	S.D.				Mean	S.D.		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)	(10)	(11)	(12)	
1944	1309	142.04	132.02	1	10		+		0				
1945	3345	409.46	466.71	1	110		+	+	4	718	325	−	−
1946	4574	410.33	328.85	0	0				7	253	410	+	+
1947	5483	412.14	375.43	1	130		+	+	7	170	158	+	+
1948	5668	383.08	511.60	4	450	321	+	+	2	75	78	+	+
1949	7400	397.60	513.28	4	258	123	+	+	25	367	500	+	+
1950	7982	413.75	534.36	2	315	78	+	+	19	506	715	−	−
1951	9025	466.61	609.28	4	150	118	+	+	25	791	222	+	+
1952	9612	529.46	718.10	6	422	386	+	+	33	433	452	+	+
1953	10,382	657.98	880.08	9	350	432	+	+	38	153	127	+	+
1954	10,648	778.82	1103.43	9	639	571	+	+	58	143	721	+	+
1955	11,446	954.75	1326.89	9	1342	1678	−	−	50	748	1358	+	+
1956	11,914	988.66	1509.79	8	666	228	+	+	42	566	881	+	+
1957	12,028	1133.31	1908.12	12	355	266	+	+	46	544	740	+	+
1958	12,181	1321.95	2221.70	19	775	822	+	+	53	521	1217	+	+
1959	12,327	1474.98	2591.67	15	435	572	+	+	65	717	1009	+	+
1960	12,641	1637.10	3130.91	15	747	614	+	+	70	574	636	+	−
1961	13,222	1795.14	3577.69	17	418	1798	+	+	79	1017	2162	+	+
1962	13,762	2010.67	4057.13	18	1611	1125	+	+	85	1516	3224	+	+
1963	14,253	2203.01	4474.21	25	561	530	+	+	79	1306	3167	+	+
1964	14,782	2379.18	4940.34	23	1307	2628	+	+	88	1338	5480	+	+
1965	14,616	2819.79	5399.20	21	1545	2160	+	+	86	349	1645	+	+
1966	14,893	3015.67	5768.11	17	4695	9162	−	+	115	2124	4873	+	+
1967	15,349	3134.61	6127.95	33	2270	6506	+	+	92	1833	4159	+	+
1968	15,704	3287.78	6492.45	22	3377	7003	−	−	122	2038	4651	+	+
1969	15,764	3413.74	6880.29	37	3201	5979	+	+	133	2621	3849	+	+
1970	15,728	3537.21	7166.82	35	3861	3293	−	−	143	1256	7443	+	+
1971	15,903	3624.85	7402.56	45	4141	7678	−	−	121	2980	4274	+	+
1972	15,786	3745.15	7668.48	21	3793	10,764	−	−	100	3087	5467	−	+
		$r_s = 0.993$			$r_s = 0.929$		5−	5−		$r_s = 0.918$		3−	3−
							23+	22+				25+	25+

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*Exposed refers to employees with recorded occupational exposure to external whole body penetrating radiation.

†The deaths are only those occurring in the first 9 months.

‡Included are only deaths with a death certificate.

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lation and their mean cumulative occupational exposure dose *vis-a-vis* the mean dose of deaths from cancer and deaths from other causes.

Table 4 is for male Hanford employees with known recorded occupational exposure to external whole-body penetrating radiation. Every employee in this population in any year has a recorded radiation exposure in that year and/or in prior year(s).* Table 4 represents the parent population from which all the death cases shown in Table 1 came.

The mean cumulative dose level increases progressively with time [column (3)] for this population. To the extent that some exposure in plants not included in our study would be unknown to us, this missing fraction would increase in the more recent years in comparison to the earlier years; in other words the true rising trend in dose level with time in all probability is sharper than that shown by Table 4. Even as it stands, there is almost a consistent progression in the mean cumulative dose with time. The average known dose rises from 142 mrem in 1944, when the Hanford Plant first opened, to 3745 mrem in 1972. The rank coefficient of correlation between the mean cumulative dose in the different years and the time is 0.993, essentially a perfect correlation. The mean dose shown in column (3) for a small number of employees may represent only one or two years of exposure; for most of them it probably represents 12-15 years of exposure; and perhaps for a small number as much as 29 years of exposure. The mean cumulative annual dose varies widely for different employees, this may be inferred from the large SDs shown in column (4). It would be natural, therefore, that any sample drawn from this population would have a very wide variation in cumulative life-time dose. Cancer deaths represent such a sample (not a random one, however). If there were a causal connection between death from cancer and radiation, a higher mean life-time dose for cancer deaths, on the average at least, would be expected in comparison to the mean of the population in a specific year; however, in comparing the mean dose for cancer deaths [column (6)] with the corresponding mean for all the exposed employees at the inception of each year [column (3)], the converse is true. Out of 28 paired comparisons only in five does the mean cumulative dose for cancer deaths in a year exceed the general population mean; in the other 23 yr it is lower. These differences are shown as minuses and pluses on the left side of column (8). The disparity of five versus twenty three is statistically significant at a level lower than 1%. It is quite improbable that this could have been the case had there been a marked causal connection between occupational radiation exposure within permissible limits and deaths from cancer. Comparing the two means for the years in which the cancer mean is larger, in no instance does the difference attain statistical significance even at 10% level.

Some might think this disparity between the two means [column (6) subtracted from column (3)] in a given year may arise from the improbability that in the year of death one who died from cancer could have been exposed to radiation, or at least to as much radiation as the average employee who survived that year. This has some merit, at least in theory. But if we assumed no exposure at all in the year of death and, therefore, compare the mean dose for the cancer deaths in a given year with the aggregate population mean in the year before, we

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*It is conceivable that in a few instances the true occupational dose might be zero. In the early years at Hanford to overcome the possibility of overlooking doses below the sensitivity level of the film that was being used, it was customary to show this minimal value as a dose every time the badge was read if it had no exposure. In the early years the badges were often read even more frequently than monthly; therefore, it is likely some of the doses could be overstated, particularly for those employees who were only infrequently or intermittently in radiation areas. It is believed, however, that in most instances the recorded lifetime dose is an understatement, especially for employees with a short tenure at Hanford, who had greater opportunity to work in atomic plants not included in the current ERDA study, and also, perhaps, for the earliest employees who worked in atomic plants before routine personnel monitoring for radiation came into general practice.

still find no change in their relative position, except that we have reduced our observa- tions to five minuses indicating years in which the mean is higher for cancer deaths and 22 pluses indicating years in which the mean is lower. This disparity is still statistic- ally highly significant below the 1% level. These minuses and pluses are shown on the right side of column (8).* One may be suspi- cious in that although there are only five instances out of 28 in which the mean cumu- lative dose for cancer deaths is higher than the mean for the population .o of these five are in the most recent years, 1971 and 1972. This could easily occur by chance. On the other hand, as of now, I am not prepared to say conclusively that there are no cancer deaths in the study population where the exposure to radiation could have played at least a contributory role. It is still plausible that if observations are continued beyond the thirtieth year, there may be a positive in- dication of a measurable adverse effect. There is no basis for any prognostication of this in terms of longevity at this time. It is also plausible that in other installations the findings may be markedly different from those found at Hanford. The evidence that is being examined is so far incompatible with the likelihood that the 14% excess in cancer deaths shown among these employees, when compared with the proportion of cancer deaths of males in the general population of the state of Washington, could be attributed to the occupational radiation exposure experienced by these employees, especially if we could limit this to occupational exposures within permissible limits. It is also possible that a small fraction of the employees in this study may have had dose levels (unknown to ust far above the permissible level. Others may have had exposure to some other toxic substances which combined with radiation could have synergistic effects that could in- duce cancer. It is, of course, always conceivable that there may be rare genetic strains in the population that are highly sensitive to radiation. These and many others are possibilities which could account for the exceptions which we encounter and which I am inclined to attribute primarily to chance at this stage in the study. Given time and resources to extend the study along the ori- ginal design, I believe many of these un- certainties could be resolved. As far as more complete information on life-time cumulative dose is concerned, the only way we could have overcome this deficiency would have been to extend the study to all the employees of all the atomic plants and to continue long enough so that there would be available employees with complete life-time cumula- tive dose information. This was the scheme I recommended originally before I realized there was no mechanism to cumulate the life-time dose for individuals who worked in differe plants or even in certain circum- stances if they worked in the same plant but for different contractors, such as the con- struction maintenance workers at Hanford and Oak Ridge. In fact, in some instances even if they worked for the same contractor but in different plants their exposure records were not consolidated. Under these circum- stances the extension of the study to all the employees of all the atomic plants is all the more imperative for firm conclusions.

Going back to Table 4, I also compare the mean cumulative life-time dose of those dy- ing from causes other than cancer with the cumulative mean dose of the population surviving to the inception of the year in which the death occurs. It is seen that in general the mean dose is lower for the deceased. This is shown in column (12). Out of 28 pairs of comparisons for 1945 and 1950 there are 26 pluses indicating a higher dose for the population, and two minuses indicat- ing the dose is higher for the deceased. In these two instances the excess is not statis- tically significant. On the other hand the dis- parity of 2/26 is statistically highly significant, much below the 1% level. The same may be said for the disparity of 3/25. As we saw in Tables 1 and 3, the mean dose for deaths

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*Even if the mean cumulative life-time dose for cancer deaths were compared with the population mean in the second year preceding the year of death, the population mean in 19 instances is larger and in seven, small. This disparity is statistically significant at the 5% level.

from cancer vs the mean dose for death from other causes was not statistically significantly different. This is corroborated by comparing columns (8) and (12) in Table 4: 5/23 is not significantly different from 2/26, nor 5/22 from 3/25.

Table 5 is for female employees. It parallels Table 4 for males. It does not show as sharp an ascent in the mean cumulative dose for all employees from 1951 to 1972 as that for males (eliminating the years with no deaths whatsoever). The progression in the mean cumulative life-time dose is not only much more moderate, but there are many more exceptions to the rule: the overall upward trend in the mean dose with time is similar. Table 5, like the one for males, shows marked positive skewness in dose levels indicated by the large SDs in comparison to the means. When the mean dose of those dying in a given year from cancer is compared with the corresponding mean for the population at the inception of that year, the mean for the deceased is higher in five instances and lower in ten instances. This disparity, showing higher mean dose for the population, is not statistically significant; nevertheless, it is consistent with the relationship we observed among the males. The disparity is not changed markedly if the mean dose for the deceased is compared with the mean dose of the population in the year preceding the deaths. In this comparison we have six minuses indicating a higher mean and eight pluses indicating a lower mean for the deceased. Parallel comparison between the mean cumulative dose of those who died from other causes with the population mean shows eight instances in which the mean for the deceased is higher and twelve in which it is lower. This disparity does not change at all if the mean for the deceased is compared with the population mean of the preceding year. Of course these disparities are not statistically significant, although they lean in the same direction as those shown in Table 4 for males, where parallel disparities were statistically highly significant.*

Table 6 is for males; however, it is limited to employees hired as production workers at Hanford in 1944 and 1945; otherwise it parallels Table 4. For this population over 94% of the employees had their initial exposure to occupational radiation prior to 1950. The mean cumulative dose for all employees shows a perfect ranging with time, giving rank coefficient of correlation of 1. The ascent in the mean cumulative dose is about as sharp as that for all male employees, rising from 142 mrem in 1944 to 3762 mrem in 1972. The SDs are of the same general magnitude as in Table 4 although with a much smaller number of cases, especially in recent years. The relationships between the mean cumulative dose for deaths, whether from cancer or other causes, are significantly lower *vis-a-vis* the means for the total population at the inception of each year, regardless of whether one uses the mean for the same year or for the preceding year as far as the population is concerned. The disparities between the mean of the deceased and the population are highly significant for both those dying from cancer and from other causes. In other words, as we

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*This could suggest that a higher job mobility by the deceased *vis-a-vis* the survivors could be at least one of the causes of their showing a lower mean cumulative life-time dose (Ma73). I show that for those hired in 1944, for instance, male employees with a record of exposure to occupational radiation had been employed at Hanford on the average for 13.06 years. The corresponding mean for the employees that were monitored for radiation but had no record of being exposed to occupational radiation was 2.29 years. Finally, for the employees who were not monitored for radiation and had no record of exposure to occupational radiation, the mean duration of employment at Hanford was 1.47 years. The corresponding averages for the female employees were 9.45, 4.14, and 2.14 years, respectively. It would be reasonable to infer that among the occupational radiation-exposed employees there is also a gradation—on the average those with the lowest cumulative life-time radiation dose have a shorter period of employment at Hanford; conversely, those with the highest cumulative life-time dose have a longer period of employment. Employees with a record of exposure to occupational radiation have the greatest longevity, and those with no monitoring for radiation and no record of exposure to occupational radiation have the lowest.

Table 5. Cumulative mean dose level at the inception of each year for exposed* female Hanford employees that have survived to that date, comparing the mean dose of the population along the time axis and comparing the population mean with the corresponding mean for the deaths from cancer and the mean for deaths from causes other than cancer in the year of death and in the year preceding the year of death (all cohorts 1944–1972 and for all years with deaths 1944–1972†‡)

Year	No. exp. emp.	Cumulative dose (mrem) Mean	Cumulative dose (mrem) S.D.	Cancer deaths	Cumulative dose (mrem) Mean	Cumulative dose (mrem) S.D.	Difference (3)–(6)		Other than cancer deaths	Cumulative dose (mrem) Mean	Cumulative dose (mrem) S.D.	Difference (3)–(10)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)	(10)	(11)	(12)	
1951	1403	508	434	1	60	61	+		0			+	
1952	1449	370	364	0					1	1250		−	−
1953	1744	380	463	0					2	470	283	−	−
1954	1898	419	730	0					1	40		−	−
1955	2041	442	846	1	60		−	+	1	740		−	−
1956	2174	466	957	0					8	427	454	−	+
1957	2212	482	1012	2	1165	1218	−	−	0				
1958	2298	499	1091	0					1	310		+	−
1959	2330	521	1174	1	1070		−	−	2	155	22	−	−
1960	2364	515	1247	0					4	228	66	+	−
1961	2512	544	1138	1	88		−	+	6	128	667	−	+
1962	2511	566	1422	2	148	127	−	−	3	597	197	−	−
1963	2773	587	1518	1	1910		−	−	2	185	10	−	−
1964	2863	614	1632	3	27	7	−	+	8	1116	1737	−	−
1965	2996	729	1783	4	690	407	−	+	2	427	354	−	−
1966	3166	758	1872	0					5	436	268	+	+
1967	3316	734	1923	1	720		−	+	8	1622	2983	−	+
1968	3477	761	1944	4	583	198	+	+	3	153	81	+	+
1969	3510	785	2009	3	697	335	−	−	8	434	138	−	+
1970	3549	791	2172	3	2507	2762	−	−	6	417	811	−	−
1971	3688	788	2154	2	1400	4985	−	−	11	873	1766	−	−
1972	3775	795	2177	3	667	131	+	+	1	1210		−	−
							5−	6−				8−	5−
							10+	6+				12+	12+

*Exposed refers to employees with recorded occupational exposure to external whole body penetrating radiation.

†The deaths are only those occurring in the first 9 months.

‡Included are only deaths with a death certificate.

saw in Table 3, limiting the observation to employees with long years of exposure does not perceptibly alter the picture, which in itself is a strong indication that radiation has had no general harmful effect on the survival of Hanford employees with occupational radiation.

Increase in age normally would mean an increasing proportion of cancer deaths in later years, but there is no evidence of this. This absence would suggest that perhaps for homogenous segments of the population the proportion of deaths from cancer remains constant at least over the age span 30–35 yr to 60–65 yr; and that the apparent increase in cancer deaths with age is the result of differential longevity of different segments in the population for whom the proportion of cancer deaths is different. Furthermore, there is a strong indication of reduced mortality among the long-term Hanford employees. This perhaps at least partly may account for the distinctly higher longevity of the exposed Hanford employees *vis-a-vis* the nonexposed employees and the matched controls. It could be the principal differential showing significantly higher longevity for exposed Hanford employees *vis-a-vis* their siblings. This improvement in longevity for the long-term Hanford employees could also account for the negative association between the cumulative life-time dose and the probability of death in a given year (Ma74, Ma75). There is also the possibility of some beneficial effects from low-level radiation to which some animal experimentations have attested; however, as far as the differences between the exposed and the nonexposed Hanford employees are concerned, selective factors are in all probability the major differential.

The absence of increases in the proportion of cancer deaths with advancing age seems to characterize this population; thus the age at the time of hire for those hired in 1944–1945 was about 10 yr older than that for employees hired in subsequent years. Nevertheless, the percentage of known cancer deaths (including all the deaths) is 19.45 for those hired in 1944–1945, with a total of 1357 deaths, and 20.17 for those hired in 1946–1971, with a

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total of 848 deaths, despite an age differential of over 20 yr for those hired in 1944–1945.

The following derived facts refute the hypothesis that the 14% higher deaths from cancer among the exposed Hanford male employees, over the expected number based on over 300,000 Washington State deaths among males over 20, could have been caused by radiation exposure:*,†,‡

1. The lack of any statistically significant association between the proportion of deaths from cancer in relation to time in a population that shows a progressive increase in mean dose level over time and a progressively longer post-exposure period.

2. The absence of any significantly higher cumulative mean dose for deaths from cancer *vis-a-vis* the corresponding mean for deaths from other causes, compared year by year.

3. The significantly lower mean cumulative dose for deaths, whether caused by cancer or other than cancer, when compared with the mean for the survivors, reinforced by the additional evidence (demonstrated by Tables 3 and 6) of no perceptible change in any of these relationships whether all the occupationally exposed employees are used or only those employees who were hired in 1944–1945 and who had been exposed to occupational radiation for many years.

LONGEVITY AND DISABILITY

If occupational radiation was the cause of cancer, then there would be a reduced longevity among exposed Hanford employees. The contrary is true, the longevity of exposed Hanford employees, age adjusted, generally exceeds that for the nonexposed, particularly for males. For example, the comparative death rate per year for males in the 1944 cohort from the year of exposure to occupational radiation until October 1972 is 10.84 per 1000. The corresponding rate for employees with no record of occupational exposure to radiation, adjusted by age and the years at risk, from the year of hire to the cutoff date is 17.33 per 1000. Compared to their own siblings, the exposed employees have a higher longevity (males only), while the opposite is true with nonexposed employees. This relationship also holds in a comparison of the longevity of occupationally exposed male Hanford employees with that of their matched controls. These comparisons based on the common year of hire show consistently statistically significant differences in longevity in favor of the exposed Hanford employees. Parallel comparisons in longevity between the nonexposed male employees and their matched controls show just the opposite. The nonexposed Hanford employees have also statistically significantly lower longevity *vis-a-vis* their identified siblings—which is opposite to that between exposed employees and their siblings. The longevity of the matched controls of exposed employees on

not necessarily true
non-specific life span
shortening may not
be supportable
however, life span
shortening for specific
causes may be true
(IAEA Symposium 1978)

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*The "Atlas of Cancer Mortality for U.S. Counties: 1950–1969" (Mas75) shows sharp differences in deaths from cancer in contiguous counties throughout the United States, suggesting that many different etiological and other factors account for high or low cancer death rates.

†The distribution of disability claims by cause of disability among those allowed such benefits by SSA in a given year shows a statistically highly significant concentration in the highest Primary Insurance Amount (PIA) group by those disabled from cancer. Thus, for 1970, the last year for which such a report was published (Le70), the expected number of allowances because of cancer was 8028, while the actual number was 10,480. The latest available frequencies for 1973, obtained through personal correspondence, show 10,102 as the expected number of such allowances as against 12,467 as the actual, with the highest PIA $250 or more for the beneficiary per month. PIA is, of course, dependent on (a) continuity of employment in covered industry and (b) taxable earning level over the years; it may be regarded, therefore, as a socio-economic index, suggesting a higher prevalence of cancer among the relatively well-to-do. Probably a small part of this concentration is attributable to age, since the comparisons given are not age-specific. At this time no age-specific data are available.

‡Reference Ma74 demonstrates a strong negative correlation (statistically highly significant) between cumulative life-time occupational radiation dose level in a given year and the probability of dying in that year. Reference Ma75 shows that the extent of this negative correlation is reduced when age is taken into consideration, but it is not eliminated.

Table 6. Cumulative mean dose (rem) at the inception of each year for exposed* white Hanford employees that have survived to that date, comparing the mean dose of the population along the time axis, and comparing the population mean with the corresponding mean for deaths from cancer and the mean for deaths from causes other than cancer in the year of death and in the year preceding the year of death in 1944–1945 cohorts and for all years 1944–1972†‡

Year	No. exp. emp.	Cumulative dose (mrem) Mean	S.D.	Cancer deaths	Cumulative dose (mrem) Mean	S.D.	Difference (3)–(6)		Other than cancer deaths	Cumulative dose (mrem) Mean	S.D.	Difference (3)–(10)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)	(10)	(11)	(12)	
1944	1149	142	132	1	30		+		3	0			
1945	3343	204	444	1	600		+	+	4	718	325	−	−
1946	4377	431	540	0	0				5	298	492	+	+
1947	4191	466	554	1	130		+	+	7	170	158	+	+
1948	4455	512	568	4	450	121	+	+	2	75	78	+	+
1949	4511	549	583	4	256	128	+	+	15	105	567	+	+
1950	4537	600	614	3	315	8	+	+	14	663	778	−	−
1951	4540	662	702	3	280	481	+	+	18	332	244	+	+
1952	4551	737	826	6	500	189	+	+	26	466	459	+	+
1953	4548	839	977	7	431	462	+	+	28	391	415	+	+
1954	4532	928	1174	6	897	577	+	−	20	669	808	+	+
1955	4521	1022	1401	6	1268	[illegible]	−	−	19	1041	1645	−	−
1956	4501	1104	1660	6	465	[illegible]	+	+	30	968	955	+	+
1957	4471	1195	1990	7	354	300	+	+	25	645	815	+	+
1958	4461	1326	2245	11	552	300	+	+	32	703	882	+	+
1959	4409	1441	2582	11	567	968	+	+	38	973	2416	+	+
1960	4366	1558	2774	12	443	651	+	+	33	582	658	+	+
1961	4314	1780	3438	9	658	522	+	+	46	1077	2491	+	+
1962	4256	1963	3964	8	429	311	+	+	53	458	1011	+	+
1963	4201	2144	4399	14	346	360	+	+	48	1252	1167	+	+
1964	4144	2347	4831	14	1296	2758	−	+	49	729	456	−	−
1965	4077	2536	5298	11	784	779	−	−	43	773	1197	−	−
1966	4010	2847	5688	12	4666	9190	−	−	46	2256	5455	+	−
1967	3932	2992	6087	19	2222	5675	+	+	51	1712	4223	+	+
1968	3862	3164	6294	14	3464	8846	−	+	63	1220	1662	+	+
1969	3784	3325	6801	20	2415	3378	+	+	57	2278	5239	+	−
1970	3695	3465	7274	22	1843	3298	−	−	46	2719	6353	+	−
1971	3580	3654	7583	22	3590	7216	+	−	56	1899	3104	+	+
1972	3465	3782	7835	12	4668	7481	−	−	54	2477	5437	−	+
		$r_s = 1.000$			$r_s = 0.988$		4−	5−		$r_s = 0.861$		3−	3−
							24+	21+				25+	25+

*Exposed refers to employees with recorded occupational exposure to external whole body penetrating radiation.

†The deaths are only those occurring in the first 9 months.

‡Included are only deaths with a death certificate.

the average exceeds that for the matched controls of nonexposed employees. These relationships were established in the Twelfth Annual Report which the author prepared and which as of this writing has not been released. To a large extent these relationships between exposed employees vs their siblings *vis-a-vis* the nonexposed employees and their siblings are reflected in Table 7, which numerically is restricted to only a small segment of our study population, although the relationships shown by it are borne out by all of the observational data available so far.*

Table 7 demonstrates the comparative longevity of Hanford employees and their identified siblings of the same sex. In Table 7 the longevity of male and female employees can be compared with that of their respective siblings for all the Hanford employees (with identified siblings), as well as for the exposed and nonexposed employees with their respective siblings. To make this comparison as rigorous as possible, Table 7 is restricted to employees for whom we have an identified sibling (only about 30% of the Hanford employees have one or more identified siblings). Where an employee had more than one sibling, only the sibling nearest in age to the employee was used in this comparison. To reduce dilution effects, only those employee–sibling pairs are used in which either the employee, the sibling, or both had died prior to October 1972. These restrictions naturally eliminate a large part of our observational data. Nevertheless, Table 7 concisely bears out the key comparative relationships

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*In Table 7 internal radiation cases have not been separated from those with external radiation since that information was not available at the time that Table 7 was compiled.

Table 7. Comparative longevity of white Hanford employees with their [illegible] and siblings [illegible] for males and females, for radiation exposed and nonexposed employees [illegible]

Population	Pairs compared	Total yr lived*	Mean yr lived	S.D. of diff. in yr lived†	Mean age at time of hire (yr)	S.D. of age at time of hire	Mean age at time of death	S.D. of age at time of death	No. of deaths	S.E. of diff. in yr lived	Mean diff. in yr lived	S.E. × 1.96 (95% sig.)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
All Hanford emp.												
Males	1665			9.807						0.240	−0.082	±0.471
Employees		31,183	18.729		39.108	10.711	58.362	12.246	969			
Siblings		31,330	18.811		38.986	10.881	58.229	11.918	961			
Females	187			9.668						0.707	0.541	±1.386
Employees		3503	18.732		34.102	10.613	53.011	12.596	105			
Siblings		3604	19.273		35.561	12.218	55.278	13.602	98			
Exposed Hanford emp.												
Males	1259			9.511						0.268	0.376	±0.525
Employees		24,303	19.303		39.021	10.447	58.351	11.986	779			
Siblings		23,830	18.927		39.151	10.776	58.266	11.938	762			
Females	63			8.711						1.098	−0.969	±2.152
Employees		1258	19.968		34.262	9.862	54.430	11.474	18			
Siblings		1319	20.937		36.066	11.529	56.904	12.357	23			
Nonexposed Hanford emp.												
Males	406			10.557						0.524	−1.527	±1.027
Employees		6880	16.946		39.174	11.499	56.847	12.919	250			
Siblings		7500	18.473		38.473	11.201	57.508	11.540	219			
Females	122			10.148						0.918	−1.025	±1.799
Employees		2160	17.705		34.016	11.031	52.270	13.140	67			
Siblings		2285	18.730		35.503	12.451	54.467	11.913	60			

*For those who were living on 10 January 1972, the cutoff date for this analysis, the years lived, is the interval of time from the date of hire to 10 January 1972. For those who died within this time interval, years lived is the lapse of time from the date of hire to the date of death.

†This is the standard deviation of the difference in years lived when for each pair the years lived by the employee is compared with that for his or her sibling. When this S.D. is divided by the square root of the number of pairs (the number of such differences), it gives the standard error of the difference of the two mean number of years lived. The S.E. is shown in column (11).

indicated by all the observations on Hanford employees available to date.

With the restrictions indicated above we are left with 1665 male and 187 female employee–sibling pairs. Column (1) defines the population groups that are being compared. Column (2) gives the number of pairs in each population group available for comparison. Column (3) gives the total number of years lived from date of hire to the date of death, if death occurred prior to October 1972, and for those surviving the entire follow-up period.* A comparison of the years lived shows relatively close similarity between employees and siblings; thus for all males the years lived are 31,183 for the employees and 31,330 for the siblings. Column (4) is the mean years lived; i.e. column (3) divided by column (2). Column (5) gives the SD of the difference in the years lived between each employee and sibling pair. Column (6) gives the mean age of the employee at the time he was hired, and the corresponding mean age of the sibling on the date that the employee was first hired. It is to be observed that the mean ages are relatively close, thus making our comparisons of years lived more meaningful. Column (7) gives the SDs of the age at the time of employee's hire for employees and siblings, respectively. Again the SDs are quite close in magnitude between employees and the corresponding siblings. Column (8) gives the mean age at the time of death. The ages for employees and siblings are relatively close. One would expect this since the age at the time of hire and the years lived are close between

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*The proportion of deaths with a death certificate on the date when these tabulations were run was different for the different population groups, and to date these differences have not been removed. Thus for the groups represented in Table 7 for males, the exposed employees who had death certificates were 98.90%; their siblings, 90.16%; for the nonexposed employees, 98.85%; and for their siblings, 88.13%. For females these percentages are exposed employees, 92.11; their siblings, 75.86; nonexposed employees, 92.54; and their siblings, 78.26. Consistently, the percentage of deaths with a death certificate is lower for the siblings *vis-a-vis* that for the employees. This introduces a certain measure of uncertainty in comparing longevity of these respective population groups in which all the deaths are considered. For deaths without a death certificate the date of death is uncertain.

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employees and siblings in a given set, especially for males. Column (9) gives the SD of ages for employees and siblings, respectively, at the time of death. The magnitudes are close for employees and siblings, respectively. Column (10) gives the total number of deaths reported by the Social Security Administration (including deaths without death certificates). It is seen that for males there were 989 deaths among the 1665 employees and 981 deaths among the same number of siblings, who at the time of hire were on the average 0.122 yr younger. The close tolerances reflected in Table 7 are welcome in that they give some indication that perhaps there are no gross mechanical or other human errors which might vitiate the analyses. Column (11) gives the standard error of the mean number of years lived [column (5) divided by the square root of column (2)]. Column (12) gives the difference when the mean years lived [column (4)] by the siblings is subtracted from the corresponding mean for the employees. Finally, column (13) is the 95% confidence interval.*

Examining Table 7 for all males, the first set of employee-sibling comparisons shows the longevity of employees and their siblings about as close as one can come, keeping in mind that the siblings were somewhat younger. Since our first findings (Ma71), we have consistently found a very slight excess in longevity of male siblings over the employees, seldom attaining statistical significance, and introduced by the first two or three years of hire. When the comparison is restricted to employees with one or more identified siblings, however, then the differences, in any, tend to favor the employees when age differences are completely removed. This is not inconsistent with the relationship shown by Table 7. With the second set, for all females, the longevity of female Hanford employees is somewhat lower that that of their siblings. This is also true when the longevity of female employees is compared with that of the nonstarts. Matched controls also show a higher longevity when compared with the longevity of Hanford female employees.

The third set of comparisons between the longevity of male employees with recorded occupational exposure to external whole-body penetrating radiation and their siblings (with no exposure) shows higher longevity for the employees, although the difference is not statistically significant. In an unpublished report, I show that by and large higher longevity for male exposed employees over their siblings attains statistical significance, especially where the comparisons are limited to employees with identified siblings. In Table 7, the mean age is slightly higher for the siblings (0.130 yr). The fourth set is for exposed female employees and their siblings. It shows a higher longevity for the siblings, although the differential in this instance is not statistically significant. Again this is consistent with our findings, and often these differences are statistically significant in favor of the siblings. For females the siblings are appreciably older (1.784 yr). The disparity would, therefore, increase considerably if adjusted for age. The fifth set is a comparison for male nonexposed employees with their siblings. This comparison shows higher longevity for the siblings who are on the average somewhat younger than the employees (0.907 yr). The difference in favor of the siblings is statistically significant. The contrast in favor of the siblings would have been somewhat less had the siblings been of the same age as the employees. The findings shown by Table 7 are consistent with other findings, however, showing markedly lower longevity for nonexposed Hanford employees (statistically highly significant *vis-a-vis* their siblings when the age difference is completely eliminated).

The sixth set is for the nonexposed female employees, comparing the longevity of these with that of their siblings. In this instance the

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*Since only one set of comparisons has a frequency below 100, and that one shows no significant difference, I saw no need to use the *t* table in lieu of the normal curve for the tests of statistical significance. This is also true when the longevity of female employees is compared with that of the nonstarts. Matched controls also show a higher longevity when compared with the longevity of Hanford female employees.

siblings are older by more than a year (1.287 yr). This comparison again favors the siblings despite their older age. The difference, however, is not statistically significant; it would have been significant if adjusted for age. This finding again is consistent with other findings.

Table 7 is designed to compare within each set the longevity of employees in a given category with that of their siblings. Converting the years lived after hiring [column (3)] into percentage of years lived, using the years from the date of hire to the cutoff date as the base, allows comparisons across the sets, which we deem meaningful since the age differences for males and females, respectively, for the different sets are not too large. These percentages are:

Population	Males	Females
All employees	76.96	77.36
All siblings	77.56	81.43
Exposed employees	78.73	81.25
Siblings of exposed employees	77.17	84.11
Nonexposed employees	73.18	75.40
Siblings of nonexposed employees	77.78	79.76

The percentage of years lived by occupationally exposed male employees is higher than that for nonexposed employees; the difference is statistically significant at a level well below 1%. The nonexposed employees are somewhat older (0.353 yr); therefore, the difference is somewhat exaggerated. This differential between employees with records of occupational radiation compared with those with no record of such radiation is statistically significant for many years of hire when age differences are removed (Ma73). The longevity of the siblings of the exposed and nonexposed employees is about the same; the slight excess in favor of the siblings of nonexposed employees would be more than removed if adjusted for age. The siblings of nonexposed Hanford employees are somewhat younger (0.678 yr). For females the longevity of the exposed employees is higher, even though there is a slight age advantage favoring the nonexposed employees (0.246 yr). This difference, however, is not statistically significant. This finding is in agreement with our overall findings when age differences are removed (Ma73). For females the siblings of exposed employees have a distinctly higher longevity *vis-a-vis* the siblings of nonexposed employees in spite of the younger age of the siblings of the nonexposed (0.743 yr). This difference also is not statistically significant, although it might be were it adjusted for age.

In 1974 for the first time the study was able to add one set of matched controls. I have just compiled some preliminary data based on 5463 disability claim applications under the Social Security Disability Insurance program. Of these 4647 are for males; divided as follows: 1801 Hanford employees, 1788 the matched controls of these employees, and 1058 the identified siblings of these employees. Table 8 summarizes the result of dividing the total male employee population into exposed and nonexposed with their respective matched controls and siblings, dividing the respective population groups within each year of hire into quinquennial age groups, and comparing the claim rates for each of these. Table 8 also shows the comparative claim rates in terms of age-adjusted cohorts (years of hire).

The comparisons indicate:

1. Lower claim rate for all Hanford employees vs the matched controls; the

Table 8. Age-cohort specific and age-adjusted cohort claim rates for disability benefits from the Social Security Disability Insurance comparing the claim rates for the different population groups in the Hanford Works population for males, 1944–1971 cohorts inclusive and claims reported within the period 1955–1974 inclusive*

Population groups	Age-cohort specific Lower	Age-cohort specific Higher	Age-cohort specific Sign. %	Age-adjusted cohort Lower	Age-adjusted cohort Higher	Age-adjusted cohort Sign. %	Favoring
1. All Hanford employees vs matched controls	139	76	<0.05	24	4	<1	Employees
2. All Hanford employees vs identified siblings	111	104		16	12		Employees
3. Exposed Hanford employees vs nonexposed employees	87	49		18	10		Exp. employees
4. Exposed Hanford employees vs their matched controls	141	62	<0.05	27	1	<0.05	Exp. employees
5. Nonexposed Hanford employees vs their matched controls	96	94		8	17		
6. Exposed Hanford employees vs their identified siblings	107	82	<10	17	11		Exp. employees
7. Nonexposed Hanford employees vs their identified siblings	54	74	<10	11	12		Siblings

*All comparisons are limited to persons in ages 18–64 at the time of hire, a total of 4647 claimants: 1801 employees, 1788 matched controls, and 1058 identified siblings of Hanford employees.

difference in favor of the employees is statistically highly significant.

2. Slightly lower claim rate for all Hanford employees vs the identified siblings; the difference in favor of the employees is not statistically significant.

3. Lower claim rate for exposed Hanford employees vs the nonexposed; the difference in favor of the exposed is not statistically significant.

4. Lower claim rate for exposed Hanford employees vs their matched controls; the difference in favor of the exposed employees is statistically highly significant.

5. About the same claim rate for the nonexposed Hanford employees vs their matched controls.

6. Lower claim rate for exposed Hanford employees vs the identified siblings of such employees; the difference in favor of the exposed employees is statistically significant at 10% level only.

7. Higher claim rate for nonexposed Hanford employees vs the identified siblings of such employees; the difference in favor of the siblings is statistically significant at 10% level only.

The disability claim rates summarized in Table 8 do not make adjustments in the differential longevity of the population groups that are being compared. When these adjustments are made,[*] the findings based on disability claim rates will precisely parallel the findings based on comparative longevity. This confirmation strengthens my confidence in the validity of my findings to date for Hanford employees.

This exact agreement in the findings, whether one looks to comparative longevity of the different population groups or the comparative claim rates for disability benefits by these same groups, is very important. Claims for disability benefit may be regarded as a precursor of death with a lead of 6–8 yr.[†] (There would be a comparable time lead for early retirement in relation to premature deaths with a time lead of perhaps 11–13 yr.) The earliest application filed for disability freeze was in January 1955; therefore, we are comparing a series that began in 1955 at a comparatively low level of frequency with the series for longevity over the period 1944–1972. An exact agreement between the two such series as to the relative health of specified population groups indicates that the relative longevity advantage enjoyed by the radiation-exposed Hanford employees in relation to the different controls will remain essentially the same at least until the early 1980's, thus, confirming my interpretation that such apparent declines as we have observed for recent years are attributable to chance, possibly augmented by a small number of deaths due to the presence of certain exceptionally radiation-sensitive individuals in the population, and/or small number of workers with early or otherwise large doses of exposure well beyond the permissible limits, and/or synergistic effects when radiation exposure is combined with certain other toxicants. There is however, no indication that large numbers of workers exposed to occupational radiation well within the permissible limits are about to show adverse effects attributable to their exposure to such radiation.[‡]

On the basis of all the available evidence, there is no indication of any general adverse health effects assignable to occupational radiation exposure within permissible limits to Hanford employees during the years these

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[*] Disability claims include the claims for disability freeze as well, claims which were first filed on January 1955. Disability freeze maintains a worker's insured status and the Primary Insurance Amount as of the time when the worker becomes disabled. Other things being equal, population groups with higher longevity would have a higher disability claim rate. Therefore, had I adjusted for longevity the lower claim rate for exposed employees would have become more pronounced.

[†] This is judgmental, taking into consideration factors such as the longer relative longevity of disability applicants who are disallowed benefits for failure to meet the definition of disability and the progressive liberalization of this definition that has taken place over the years both through statutory changes and relaxation in administrative standards (Sm72, Ba69, Co74).

[‡] SSA has supplied 2400 additional claims for disability benefits filed mostly in the last quarter of 1974 and the first three quarters of 1975. To date these claims have not been analyzed.

employees were analyzed and projecting into the early 1980's. The analysis has not gone far enough nor are the observations prolonged enough to conclude that no Hanford employee has been harmed by exposure to radiation over the course of his or her life. Nevertheless, the evidence already obtained should quell the dread that any radiation exposure, however minimal, has a harmful effect on man.

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