Mortality of employees of the United Kingdom Atomic Energy Authority, 1946-1979

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Abstract

An analysis was conducted of 3373 deaths among 39 546 people employed by the United Kingdom Atomic Energy Authority between 1946 and 1979, the population having been followed up for an average of 16 years. Overall the death rates were below those prevailing in England and Wales but consistent with those expected in a normal workforce. At ages 15-74 years the standardised mortality ratios (SMRs) were 74 for deaths from all causes and 79 for deaths from all cancers. Mortality from only four causes was above the national average—namely, testicular cancer (SMR 153; 10 deaths), leukaemia (SMR 123; 35 deaths), thyroid cancer (SMR 122; three deaths), non-Hodgkin's lymphoma (SMR 107; 20 deaths)—but in none was the increase significant at the 5% level.

Half of the authority's employees were recorded as having been monitored for exposure to radiation, their collective recorded exposure being 660 Sv (65 954 rem). Among these prostatic cancer was the only condition with a clearly increased mortality in relation to exposure. Of the 19 men who had a radiation record and died from prostatic cancer at ages 15-74 years, nine had been monitored for several different sources of exposure to radiation. The standardised mortality ratios were 889 (six deaths) in employees monitored for contamination by tritium, 254 (nine deaths) in those monitored for contamination by other radionuclides, and 385 (nine deaths) in those with dosimeter readings totalling more than 50 mSv (5 rem); but the same nine subjects tended to account for each of these significantly raised ratios. Because multiple exposures were common and other relevant information was not available the reason for the increased mortality from prostatic cancer in this population could not be determined and requires further investigation.

Excess mortality rates of 2·2 and 12·5 deaths per million person years per 10 mSv (1 rem) were estimated for leukaemia and all cancers, respectively. The confidence limits around these estimates were wide, included zero, and made it unlikely that the International Commission on Radiological Protection's cancer risk coefficients were underestimated by more than 15-fold. Thus despite this being the largest British workforce whose mortality has been reported in relation to low level ionising radiation exposure, even larger populations will need to be followed up over longer periods before narrower ranges of risk estimates can be derived.

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Introduction

The magnitude of the risk of cancer in people exposed repeatedly to low levels of ionising radiation is the subject of considerable debate. Most estimates of risk, such as those published by the International Commission on Radiological Protection, are based to a large extent on linear extrapolation from the known effects in heavily exposed groups such as survivors of atomic bombs or patients treated with radiotherapy.[1] Such populations were exposed, over a relatively short period, to doses of ionising radiation often hundreds or thousands of times greater than the total doses typically accumulated over long periods by workers in the nuclear industry. In 1977 Mancuso *et al* suggested, on the basis of a study of workers at the Hanford nuclear plant in the United States, that extrapolation from highly exposed populations may underestimate cancer risk at low levels of chronic exposure by about 20-fold.[2] Their methods have been criticised and the data reanalysed.[3 4] Nevertheless, the ensuing controversy together with recognition of the need to examine the validity of existing risk estimates for low levels of radiation exposure has prompted several studies in the nuclear industry.

In 1978 the United Kingdom Atomic Energy Authority, desiring an independent inquiry, asked the Medical Research Council to appoint an epidemiological group to investigate the mortality of its employees. Members of the epidemiological monitoring unit at the London School of Hygiene and Tropical Medicine performed this task, the conduct, analysis, and findings of the study being reviewed yearly by an ad hoc subcommittee of the MRC's Protection Against Ionising Radiation Committee (latterly the Committee on the Effects of Ionising Radiation). The purpose of the study was to examine the mortality of employees of the United Kingdom Atomic Energy Authority, to see if there was any relation between mortality and recorded exposure to ionising radiation, and to compare the findings with risk estimates published by the International Commission on Radiological Protection. Before the investigation began it was recognised that the study would not have sufficient power to detect an increase in radiation related cancers unless the existing figures of the International Commission on Radiological Protection underestimated risk by a factor of about 20 or more.

Methods

The design of the study and methods of data collection and validation are described in our accompanying report (p 435). Personnel records were used to define the study population. Data were collected for all employees of the authority at its establishments at Harwell, Culham, London, Dounreay, Winfrith, Risley, and Culcheth who were in service at any time from 1 January 1946 to 31 December 1979 (except those who had been statutorily transferred, with their records, to British Nuclear Fuels, the Radiochemical Centre, and the Atomic Weapons Research Establishment at the time of their respective formations).

Radiation records held by the authority were used to construct files of employees who had been monitored for exposure to radiation. For those issued with a film badge or other personal dosimeter a yearly summary of the dosimeter recordings was extracted. This included the total "whole body dose," stated here in millisieverts (mSv), and the numbers of dosimeters issued, lost, with readings below the threshold of the measuring devices used, and with readings exceeding 10 mSv (1 rem). Dosimeter readings of whole body dose, which include contributions from x and γ rays and neutrons, indicate the amount of radiation from external sources which penetrates the body. Since the doses recorded on dosimeters are not direct measurements of the absorbed dose in the tissues, the term whole body "exposure" rather than "dose" is used here, the units of measurement remaining as mSv. Information on exposure from internal sources, such as ingested or inhaled radionuclides, was limited to noting the years in which subjects were monitored for possible contamination by tritium, plutonium, or other unspecified radionuclides or isotopes. The associated radiation doses were not included in measures of whole body exposure except for tritium at Harwell from 1977. Radiation records were linked to the personnel records with the result that nearly half of the authority's employees were identified as having a radiation record.

Details of employees leaving the United Kingdom Atomic Energy Authority on or before 31 December 1979 were submitted for tracing to the National Health Service's central registers in Southport and Edinburgh, the follow up period thus being limited to the end of 1979. When a death was identified the cause was coded by the Office of Population Censuses and Surveys or the General Register Office for Scotland and the details then sent directly to the Epidemiological Monitoring Unit. Information on deaths was not passed to the United Kingdom Atomic Energy Authority until the monitoring unit had received all the radiation data from the authority.

Various validation checks were carried out including assessment of the completeness of the study population and of the ascertainment of deaths, replication by staff of the monitoring unit of data abstraction for a random sample of personnel and radiation records, and remeasurement by Harwell staff of the dose on a sample of old film badges.[5] As a result of these checks we concluded that the completeness of the study population and the quality of data collection were satisfactory, with two exceptions. An administrative decision before the study began had led to the destruction of personnel records of employees leaving Risley and the neighbouring small establishment, Culcheth, before 1965. The magnitude of the deficit necessitated excluding from the analyses 9542 people who were last employed at these two establishments. A special check by the records branch of the Department of Health and Social Security on the vital state of 150 people aged over 80 and flagged as alive by the central registers disclosed that 27 (18%) had in fact died by the end of 1979. When the completeness of death notification was cross checked against the United Kingdom Atomic Energy Authority's files of deaths in serving staff and pensioners (see our accompanying report) some additional discrepancies came to light, but to maintain independence of follow up these deaths were not included in the analyses. The appendix lists the details of the 70 deaths identified by the various validation checks, or notified too late to be included. Since misclassification of death may occur at any age, but is most prevalent and affects death rates mostly in the elderly, all comparisons with national mortality rates (see tables II-IV, VII, VIII, and X and figures 1 and 2) are limited to the 15-74 age group.

The study used two main methods of analysis. The first compared the mortality of the study population with that of the general population. Person years at risk were calculated for men and women in each of 12 five year age groups (15-19, 20-24, etc) and seven calendar periods (1946-9, 1950-4, 1955-9, etc). Age, sex, and calendar period specific death rates for England and Wales for 1946 to 1979 (extracted from the Registrar General's annual reports[6 7] and computer files provided by the World Health Organisation) were used to calculate expected deaths and standardised mortality ratios (SMRs). For different categories of radiation exposure person years at risk were calculated from the date when a subject first entered that category. Analyses were based on the underlying cause of death, coded by the Office of Population Censuses and Surveys and General Register Office for Scotland, according to the rules of the eighth revision of the International Classification of Diseases (ICD).[8] Associated causes of death were also coded, and the appendix shows those from cancer. National rates were bridge coded to take account of the changes between ICD revisions. When an adjustment for social class and area of residence (defined by the establishment of last employment) was made social class and regional specific death rates for England and Wales[9] and for Scotland were used.[10]

The second method of analysis examined the relation between radiation exposure and mortality in employees who had a radiation record. Yearly dosimeter readings for whole body exposure were cumulated, lost film badges and readings below theshold being assigned zero doses. A standard test for trend with level of exposure was used.[11 12] Person years at risk and expected deaths in each exposure category were obtained in strata defined by age, sex, social class, calendar period, and establishment. The observed and expected deaths were then summed over all strata and a χ^2 test for linear trend with level of exposure performed. The divisions presented here have the lower limits of 0, 10, 20, 50, and 100 mSv, and the median doses of 1·6, 14·0, 30·5, 68·7, and 173·0 mSv respectively were used in the χ^2 test. All tests of significance were two sided.

After exclusion of Risley and Culcheth 39 914 subjects remained. Of these, 244 could not be traced by the NHS central registers or the DHSS and for a further 124 essential information such as sex, date of birth, or dates of employment was missing. The analyses presented here are based on the remaining 39 546 subjects.

Results

Table I shows the distribution of the population by current or last United Kingdom Atomic Energy Authority establishment, presence or absence of a radiation record, and, for those with a record, the final cumulative whole body radiation exposure. The 19 164 subjects without a radiation record contributed 310 399 person years of observation, and the 20 382 with such a record contributed 328 435 person years, an average follow up period of 16 years in each group. Two thirds of the subjects were last employed at Harwell, Culham, or the London office; these three establishments were grouped, since they are situated reasonably close together and the employees at Culham (2623) and London (1437) were too few to consider separately. The remainder of the population was almost equally divided between Dounreay and Winfrith. For those with a radiation record most (61%) were recorded as having accumulated a whole body exposure of less than 10 mSv (1 rem), and the collective exposure was 660 Sv (65 954 rem). The average occupational exposure at Dounreay and Winfrith was about twice that accumulated elsewhere (table I).

MORTALITY BY COMPARISON WITH NATIONAL RATES

From 1 January 1946 to 31 December 1979, 3373 subjects were reported to have died and 1417 to have emigrated. Table II shows the standardised mortality ratios for all causes of death for those aged 15-74 years by sex, United Kingdom Atomic Energy Authority establishment, and presence or absence of a radiation record. In general the ratios were low, varying from 64 to 92, with no consistent differences between establishments or between subjects with and without a radiation record. The overall standardised mortality ratio of 74 increased only slightly to 76 after adjusting for social class and region of residence, because of two opposing influences: social class adjustment raised the ratio by reducing the numbers of expected deaths, whereas regional adjustment for mortality in Dounreay increased the numbers of expected deaths, consequently lowering the ratio.

Table III shows the standardised mortality ratios for cancers in particular and other causes of death in general. Standardised mortality ratios for all malignant neoplasms, all diseases of the nervous, circulatory, respiratory, digestive, and genitourinary systems, and accidents

TABLE I—*Distribution of study population according to final place of employment and cumulative radiation exposure*

United Kingdom Atomic Energy Authority establishment	Total No of subjects	No without a radiation record	No with a radiation record: final cumulative exposure (mSv*)						Mean exposure in employees with a radiation record (mSv)
			<10	10–	20–	50–	100–	≥500	
Harwell, Culham, London	25 866	14 013	8 206	1 228	1 230	598	553	38	22·1
Dounreay	7 407	2 147	2 476	687	848	545	668	36	47·0
Winfrith	6 273	3 004	1 741	299	449	316	454	10	45·8
All establishments	39 546	19 164	12 423	2 214	2 527	1 459	1 675	84	32·4

*10 mSv = 1 rem.

TABLE II—*Standardised mortality ratios for all causes of death at ages 15-74 years, 1946-79*

United Kingdom Atomic Energy Authority establishment	Men		Women		Total†	
	Without a radiation record (observed deaths)	With a radiation record (observed deaths)	Without a radiation record (observed deaths)	With a radiation record (observed deaths)	Without a radiation record (95% confidence interval)	With a radiation record (95% confidence interval)
Harwell, Culham, London	76** (809)	70** (981)	69** (250)	75* (50)	79** (74-84)	76** (72-81)
Dounreay	79* (76)	89* (336)	72 (27)	88 (6)	62** (51-75)	77** (69-86)
Winfrith	80* (103)	64** (172)	84 (42)	92 (4)	83* (70-98)	69** (60-81)
All	76** (988)	73** (1489)	71** (319)	77* (60)	78** (73-82)	76** (72-79)

Significance of difference from 100: *$p<0.05$; **$p<0.001$.
†Standardised mortality ratio adjusted for sex, social class, and region of residence.

TABLE III—*Cause specific standardised mortality ratios at ages 15-74 years, 1946-79*

Cause of death (ICD code (8th revision))	Men		Women		Total (95% confidence interval)
	Without a radiation record (observed deaths)	With a radiation record (observed deaths)	Without a radiation record (observed deaths)	With a radiation record (observed deaths)	
All malignant neoplasms (140-209)	84** (277)	75** (393)	82* (129)	101 (28)	79** (74-85)
Stomach cancer (151)	73 (28)	79 (46)	21 (2)	— (0)	70** (55-88)
Intestinal cancer (152-153)	119 (24)	81 (26)	105 (13)	47 (1)	96 (74-122)
Rectal cancer (154)	121 (18)	68 (16)	18* (1)	104 (1)	80 (56-111)
Pancreatic cancer (157)	124 (17)	81 (18)	78 (4)	— (0)	93 (66-127)
Lung cancer (162)	74** (103)	69** (151)	99 (18)	64 (2)	72** (64-81)
Bone cancer (170)	56 (1)	73 (2)	141 (1)	— (0)	74 (20-190)
Connective and soft tissue cancer (171)	104 (1)	120 (2)	— (0)	— (0)	91 (19-266)
Breast cancer (174)	469 (2)	— (0)	93 (38)	55 (4)	89 (65-120)
Uterine and ovarian cancer (180-183)	—	—	68 (19)	183 (9)	85 (57-123)
Prostatic cancer (185)	79 (9)	115 (19)	—	—	100 (67-145)
Testicular cancer (186)	173 (4)	142 (6)	—	—	153 (73-281)
Bladder and urinary cancer (188-189)	88 (15)	66 (18)	27 (1)	— (0)	70* (49-98)
Brain and other central nervous system cancer (191-192)	85 (8)	30** (5)	66 (3)	353 (3)	60* (36-93)
Thyroid cancer (193)	158 (1)	192 (2)	— (0)	— (0)	122 (25-356)
All lymphatic and haematopoietic neoplasms (200-202)	99 (22)	92 (35)	136 (14)	159 (3)	102 (80-128)
Non-Hodgkin's lymphoma (200,202)	88 (5)	121 (12)	119 (3)	— (0)	107 (66-166)
Hodgkin's disease (201)	69 (3)	39 (3)	177 (3)	295 (1)	71 (34-131)
Multiple myeloma (203)	134 (4)	60 (3)	69 (1)	— (0)	83 (36-163)
Leukaemia (204-207)	115 (10)	110 (16)	160 (7)	247 (2)	123 (86-171)
All benign and unspecified neoplasms (210-239)	163 (7)	43 (3)	142 (4)	— (0)	96 (52-161)
All diseases of the nervous system (320-389)	50* (8)	62 (16)	42 (4)	— (0)	53** (35-76)
All diseases of the circulatory system (390-458)	82** (491)	80** (764)	70** (116)	65 (18)	80** (76-84)
All diseases of the respiratory system (460-519)	46** (69)	49** (109)	45** (16)	82 (5)	48** (41-55)
All diseases of the digestive system (520-577)	35** (13)	62** (35)	68 (9)	— (0)	52** (40-68)
All diseases of the genitourinary system (580-629)	42** (8)	81 (23)	59 (5)	65 (1)	65** (46-89)
Hyperplasia of prostate (600)	32 (1)	131 (5)	—	—	86 (32-187)
Accidents, suicide, and violence (800-999)	88 (80)	66** (102)	76 (22)	92 (5)	75** (65-86)

Significance of difference from 100: *$p<0.05$; **$p<0.01$.

were below those expected, based on mortality rates in England and Wales. At individual cancer sites four standardised mortality ratios were significantly low ($p<0.05$): these sites were the stomach, lung, bladder and other urinary organs, and brain. At four other sites the ratios were above 100, but in none of these (testicular cancer, leukaemia, thyroid cancer, and non-Hodgkin's lymphoma) was the increase significant at the 5% level. All 10 deaths from testicular cancer were in employees from Harwell and adjacent authority establishments, where the standardised mortality ratio was 232 with a 95% confidence interval (CI) of 111 to 427.

There were no major differences in mortality between those with and those without a radiation record. The only significant differences ($p<0.05$) between the two groups of workers were for uterine and ovarian cancer and benign and unspecified tumours. When examined separately standardised mortality ratios from each of the three main sites of genital tract cancer in women—the cervix (ICD 180), body of the uterus (ICD 182), and ovary (ICD 183)—were higher in women with a radiation record than in those without, only the excess of uterine body cancer being significant at the 5% level.

Table IV lists the standardised mortality ratios for all causes of death and certain cancers in relation to duration of continuous employment at the United Kingdom Atomic Energy Authority. Since there were so few deaths from bone, soft tissue, and thyroid cancer these sites have been grouped together in this and subsequent analyses. The standardised mortality ratios for all causes of death and leukaemia increased with the duration of employment in employees with a radiation record, whereas the trend was in the opposite direction in those without a radiation record. These trends were significantly different ($p<0.05$) when the two groups of workers were compared. Employees who stayed with the authority for less than two years and had no radiation record experienced high standardised mortality ratios for several cancers, notably leukaemia (SMR 234; 95% CI 121-409) and testicular cancer (SMR 361; 95% CI 98-923).

MORTALITY IN RELATION TO RECORDED RADIATION EXPOSURE

Tables V-VII give the results of analyses relating mortality to radiation exposure. Tables V and VI show the results of "internal" analyses in employees who had a radiation record, comparing mortality at all ages in each of five cumulative exposure categories, adjusting simultaneously for age, sex, social class, calendar period, and establishment. The numbers of expected deaths in tables V and VI were calculated from within the United Kingdom Atomic Energy Authority population, without reference to national mortality rates (see Methods), and thus differ from the numbers of expected deaths in the standardised mortality ratio analyses of the other tables. Although not presented here, standardised mortality ratios at ages 15-74 years were also calculated for each exposure category and exhibited similar trends to those shown in tables V and VI. Table VII shows the standardised mortality ratios in subjects who were monitored for possible contamination by radionuclides or who had any single dosimeter reading exceeding 10 mSv (1 rem). Many workers were monitored for exposure to more than one radionuclide.

The only striking findings were for cancer of the prostate. Mortality from this malignancy was significantly related to cumulative radiation exposure, as measured by personal dosimeter, irrespective of whether no latency (table V) or lag of 15 years (table VI) was assumed. The trends were significant both at Harwell and adjacent authority establishments ($p<0.01$) and at Winfrith ($p<0.01$) and persisted when other dose categories and latent periods were used and after adjustment for duration of employment. Mortality from prostatic cancer was also high in men who had any single dosimeter reading exceeding 10 mSv (SMR 594; 95% CI 163-1529) and in those monitored for possible exposure to tritium (SMR 889; 95% CI 329-1949) or other unspecified radionuclides (SMR 254; 95% CI 116-483). There was, however, overlap between these various exposure categories, and the highest mortality ratio for cancer of the prostate was in the men who both were monitored for possible exposure to tritium and had cumulative dosimeter readings exceeding 50 mSv (SMR 1277; 95% CI 272-2779) (table VIII). Among the men who were not monitored for possible contamination by tritium the mortality from prostatic cancer was higher in those whose cumulative exposure exceeded 50 mSv compared with those with lower exposures, but the trend with increasing exposure was not statistically significant.

Certain other features in the occurrence of prostatic cancer in United Kingdom Atomic Energy Authority employees should be noted. Table IX lists details of the 25 men (19 aged 15-74 years) with radiation records who died of prostatic cancer. Ten of these, including six of the seven youngest, had multiple special monitorings recorded, and they also tended to have the highest dosimeter readings. Although the standardised mortality ratio for prostatic cancer was 115 in men

TABLE IV—*Standardised mortality ratios (observed deaths) at ages 15-74 years, 1946-79, by duration of continuous employment at United Kingdom Atomic Energy Authority*†

Cause of death (ICD code (8th revision))	Radiation record	Duration of employment (years)		
		<2	2-9	≥10
All malignant neoplasms (140-209)	No	83* (140)	89 (162)	77* (92)
	Yes	69** (54)	72** (142)	81** (205)
Intestinal cancer (152-153)	No	61 (7)	174* (21)	116 (9)
	Yes	42 (2)	130 (16)	58 (9)
Pancreatic cancer (157)	No	161 (10)	87 (6)	99 (5)
	Yes	65 (2)	63 (5)	89 (10)
Lung cancer (162)	No	77 (37)	77 (45)	77 (35)
	Yes	67 (20)	61** (47)	71** (77)
Bone, soft tissue, and thyroid cancer (170, 171, 193)	No	— (0)	153 (3)	— (0)
	Yes	— (0)	87 (2)	141 (3)
Prostatic cancer (185)	No	66 (2)	112 (5)	54 (2)
	Yes	104 (2)	87 (5)	145 (12)
Testicular cancer (186)	No	361 (4)	— (0)	— (0)
	Yes	195 (2)	200 (4)	— (0)
All lymphatic and haematopoietic neoplasms (200-209)	No	159 (20)	91 (11)	76 (5)
	Yes	72 (5)	84 (13)	117 (18)
Non-Hodgkin's lymphoma (200,202)	No	129 (4)	33 (1)	169 (3)
	Yes	175 (3)	77 (3)	118 (5)
Multiple myeloma (203)	No	67 (1)	191 (3)	84 (1)
	Yes	— (0)	— (0)	115 (3)
Leukaemia (204-207)	No	234* (12)	82 (4)	40 (1)
	Yes	74 (2)	116 (7)	138 (8)
All (000-999)	No	82** (493)	74** (486)	72** (302)
	Yes	72** (223)	73** (568)	76** (709)

Significance of difference from 100: *$p<0·05$; **$p<0·01$.
†Table excludes 75 deaths in those who had more than one period of employment at United Kingdom Atomic Energy Authority.

TABLE V—*Relation of mortality from selected causes of death to cumulative radiation exposure (adjusted for age, sex, social class, calendar period, and United Kingdom Atomic Energy Authority establishment). Results expressed as ratio of observed to expected deaths (observed numbers of deaths in parentheses)**

Cause of death (ICD code (8th revision))	Cumulative exposure (mSv†)					p Value, test for linear trend (direction of trend)
	<10	10–	20–	50–	≥100	
All malignant neoplasms (140-209)	0·94 (291)	1·06 (54)	1·17 (58)	1·23 (35)	0·99 (35)	0·5 (+)
Stomach cancer (151)	1·01 (32)	1·41 (8)	0·70 (4)	0·87 (3)	0·89 (4)	0·7 (−)
Intestinal cancer (152-153)	0·95 (19)	0·80 (3)	0·85 (3)	0·93 (2)	1·99 (5)	0·1 (+)
Pancreatic cancer (157)	1·19 (17)	0·47 (1)	0·75 (2)	0·76 (1)	0·63 (1)	0·4 (−)
Lung cancer (162)	0·95 (103)	0·96 (19)	1·38 (25)	1·26 (13)	0·77 (10)	0·8 (−)
Bone, soft tissue, and thyroid cancer (170, 171, 193)	0·78 (2)	1·52 (1)	1·03 (1)	1·23 (1)	1·01 (1)	0·9 (+)
Breast cancer (174)	1·12 (4)	— (0)	— (0)	— (0)	— (0)	0·6 (−)
Uterine and ovarian cancer (180-183)	0·87 (7)	— (0)	3·39 (2)	— (0)	— (0)	0·5 (+)
Prostatic cancer (185)	0·70 (11)	0·35 (1)	1·14 (3)	1·91 (3)	3·24 (7)	<0·001 (+)
Testicular cancer (186)	0·86 (4)	2·00 (1)	— (0)	— (0)	5·49 (1)	0·1 (+)
Brain and central nervous system cancer (191-192)	1·03 (7)	3·45 (2)	— (0)	— (0)	— (0)	0·3 (−)
All lymphatic and haematopoietic neoplasms (200-209)	0·83 (21)	0·90 (4)	1·29 (6)	2·13 (6)	1·01 (3)	0·3 (+)
Non-Hodgkin's lymphoma (200, 202)	0·76 (6)	0·74 (1)	1·29 (2)	2·22 (2)	1·57 (2)	0·2 (+)
Multiple myeloma (203)	0·80 (2)	— (0)	1·72 (1)	3·57 (1)	— (0)	0·8 (+)
Leukaemia (204-207)	0·91 (10)	0·86 (2)	1·20 (3)	1·46 (2)	0·84 (1)	0·9 (+)
All (000-999)	0·99 (1136)	1·04 (210)	1·15 (220)	0·95 (107)	0·85 (116)	0·1 (−)

*Table includes deaths at all ages to employees with a radiation record, so numbers exceed those in tables II-IV.
†10 mSv = 1 rem.

TABLE VI—*Relation of mortality from selected causes of death to cumulative radiation exposure, lagged by 15 years (adjusted for age, sex, social class, calendar period, and United Kingdom Atomic Energy Authority establishment). Results expressed as ratio of observed to expected deaths (observed numbers of deaths in parentheses)*

Cause of death (ICD code (8th revision))	Cumulative exposure (mSv*)					p Value, test for linear trend (direction of trend)
	<10	10–	20–	50–	≥100	
All malignant neoplasms (140-209)	0·99 (424)	1·40 (25)	0·93 (13)	1·25 (8)	0·55 (3)	0·6 (−)
Intestinal cancer (152-153)	0·99 (29)	0·79 (1)	1·30 (1)	— (0)	5·60 (1)	0·2 (+)
Pancreatic cancer (157)	0·95 (19)	1·60 (1)	2·23 (2)	— (0)	— (0)	0·8 (−)
Lung cancer (162)	1·00 (155)	1·56 (10)	0·43 (2)	1·37 (3)	— (0)	0·2 (−)
Bone, soft tissue, and thyroid cancer (170, 171, 193)	0·95 (5)	3·33 (1)	— (0)	— (0)	— (0)	0·7 (−)
Prostatic cancer (185)	0·83 (18)	0·83 (1)	1·91 (2)	4·51 (2)	3·23 (2)	<0·01 (+)
All lymphatic and haematopoietic neoplasms (200-209)	1·04 (38)	0·68 (1)	0·83 (1)	— (0)	— (0)	0·4 (−)
All (000-999)	0·99 (1620)	1·07 (73)	1·14 (58)	1·16 (26)	0·64 (12)	0·4 (−)

*10 mSv = 1 rem.

TABLE VII—*Standardised mortality ratios (observed deaths) at ages 15-74 years in employees monitored for possible exposure to radionuclides or who had any dosimeter reading exceeding 10 mSv (1 rem)*

Cause of death (ICD code (8th revision))	Employees monitored for possible exposure to: Tritium (n=1418)	Plutonium (n=3154)†	Other unspecified radionuclides (n=5846)	Employees with any dosimeter reading exceeding 10 mSv (n=1492)
All malignant neoplasms (140-209)	77 (21)	64* (43)	85 (105)	88 (24)
Stomach cancer (151)	37 (1)	70 (5)	85 (11)	110 (3)
Intestinal cancer (152-153)	61 (1)	146 (6)	93 (7)	120 (2)
Pancreatic cancer (157)	84 (1)	— (0)	37 (2)	83 (1)
Lung cancer (162)	62 (7)	60* (17)	77 (40)	62 (7)
Bone, connective tissue, and thyroid cancer (170, 171, 193)	— (0)	152 (1)	81 (1)	714 (2)
Prostatic cancer (185)	889** (6)	152 (3)	254* (9)	594* (4)
Brain and other central nervous system cancers (191-192)	— (0)	— (0)	48 (2)	— (0)
All lymphatic and haematopoietic neoplasms (200-209)	146 (3)	61 (3)	100 (9)	197 (4)
Leukaemia (204-207)	132 (1)	— (0)	89 (3)	267 (2)
All (000-999)	59** (60)	69** (176)	69** (323)	76* (77)

Significance of difference from 100: *$p<0.05$; **$p<0.001$.
†One subject who died from leukaemia should have been included but the radionuclide monitoring data were located by United Kingdom Atomic Energy Authority too late to be analysed.

TABLE VIII—*Standardised mortality ratios (observed deaths/expected deaths) for prostatic cancer at ages 15-74 years among those with a radiation record, by cumulative radiation exposure and monitoring for tritium*

	Cumulative exposure (mSv†) <50	≥50	Total
Employees not monitored for tritium	71 (10/14·00)	160 (3/1·87)	82 (13/15·87)
Employees monitored for tritium	0 (0/0·20)	1277** (6/0·47)	889** (6/0·67)
Total	70 (10/14·20)	385* (9/2·34)	115 (19/16·54)

Significance of difference from 100: *$p<0.01$; **$p<0.001$.
†10 mSv = 1 rem.

aged 15-74 years with a radiation record, it was higher at younger ages (table X). At Winfrith the standardised mortality ratio was 246, at Harwell and adjacent United Kingdom Atomic Energy Authority establishments 88, and at Dounreay 56. Twelve additional incident cases of prostatic cancer were notified to the monitoring unit from cancer registration data held by the NHS central registers, eight of which were in men aged less than 75. Although cancer registration data are known to be incomplete, the pattern of exposure to radiation was similar to that shown in table IX. Four of the eight had multiple exposures to radionuclides or single dosimeter readings exceeding 10 mSv. Of the nine cases in which cancer of the prostate featured on the death certificate as an associated cause of death (see appendix), only three were in men aged less than 75, and in none was any special exposure recorded. Their inclusion in the analyses did not alter the findings in tables V and VI. Early cancer of the prostate may be difficult to distinguish from hyperplasia of the prostate, and there were six deaths at ages 15-74 years from this cause (ICD 600) in the population analysed, which included five men with a radiation record (table III). Two of the five were monitored for radionuclide contamination. At Harwell and adjacent establishments, but not overall, there was a significant trend ($p=0.05$) in mortality from prostatic hypertrophy with increasing cumulative dosimeter readings.

For causes of death which have been reported to be linked with low level exposure to radiation, notably leukaemia, multiple myeloma, and pancreatic, brain, and breast cancer,[3 4 13-18] no significant associations with exposure were found, although the trends for leukaemia and multiple myeloma were in the direction of an increasing risk with increasing exposure (table V). Of the 18 deaths from leukaemia, seven were described on the death certificate as being due to myeloid leukaemia, one as acute and three as chronic lymphatic leukaemia, and seven as unspecified or other leukaemia. Non-Hodgkin's lymphoma was significantly related to cumulative radiation exposure at Harwell and adjacent authority establishments, but not when all establishments were combined. Intestinal cancer at Winfrith, but not elsewhere, was also significantly related to cumulative exposure.

For comparison with risk estimates of the International Commission on Radiological Protection[1] the findings were expressed in a form similar to that used by the commission—as excess death rates per unit of radiation dose. Excess death rates for each exposure category were calculated as the observed minus the expected deaths, based on national mortality statistics, divided by the person years at risk; they are plotted in figures 1 and 2 for leukaemia and all cancers, respectively. Maximum likelihood methods were used to fit regression lines through the points in the figures. The intercepts of the regression lines were zero for leukaemia and −402 for all cancers. The slopes of the lines, expressed as excess deaths per million person years per 10 mSv (1 rem), were +2·2 and +12·5 for the leukaemia and all cancer data respectively. Neither slope differed significantly from zero, the 95% confidence limits being −2·7 to +12·4 for leukaemia and −22·0 to

TABLE IX—*Details of men with radiation records whose cause of death was prostatic cancer*

Age at death (years)	Duration of employment (years)	United Kingdom Atomic Energy Authority establishment where last employed	Final cumulative radiation exposure (mSv*)	Monitored for: Tritium	Plutonium	Other unspecified radionuclides	Any dosimeter reading exceeding 10 mSv (1 rem)
49	24	Harwell	175	Yes		Yes	Yes
52	9	Harwell	84		Yes	Yes	
54	5	Harwell	5		Yes	Yes	
55	22	Harwell	41				
55	24	Harwell	54		Yes	Yes	
58	25	Winfrith	223	Yes		Yes	
58	13	Winfrith	113	Yes		Yes	Yes
59	30	Harwell	31				
65	6	Harwell	3				
65	26	Harwell	11				
66	11	Winfrith	3				
67	<1	Harwell	0				
68	24	Harwell	164	Yes		Yes	
68	10	Winfrith	107	Yes		Yes	Yes
69	8	Winfrith	293	Yes		Yes	Yes
72	20	Harwell	1				
72	11	Dounreay	83				
74	8	Winfrith	8				
74	<1	Harwell	0				
76	21	Harwell	266			Yes	Yes
77	8	Harwell	4				
78	4	Winfrith	0				
79	8	Harwell	4				
79	4	Winfrith	1				
90	7	Harwell	27				

*10 mSv = 1 rem.

+52·2 for all cancers. The slopes of 2·2 for leukaemia and 12·5 for all cancers may be compared with the figures of 0·8 and 4·0 respectively, based on estimates of the International Commission on Radiological Protection of an excess of two deaths from leukaemia and 10 from cancer per million mSv,[1] assuming that these risks are spread over a 25 year period.

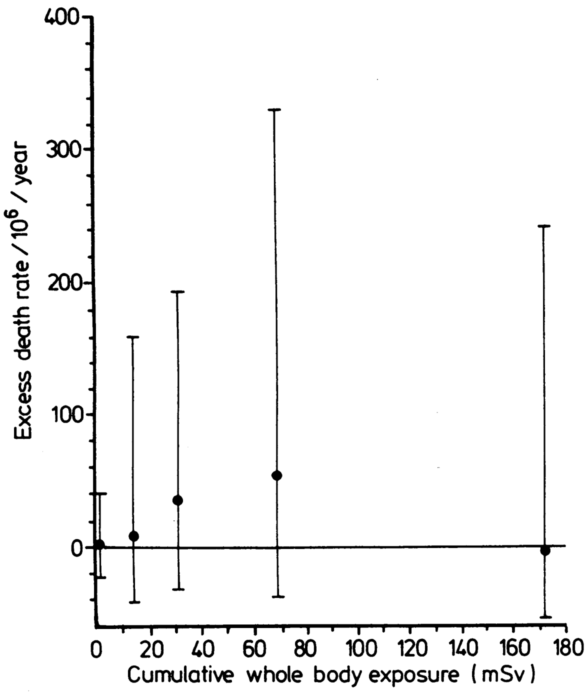

FIG 1—Death rates from leukaemia in excess of those expected on the basis of mortality in England and Wales, in relation to cumulative radiation exposure. Bars represent 95% confidence intervals for excess death rate. (10 mSv=1 rem.)

TABLE X—*Age specific standardised mortality ratios for prostatic cancer among those with a radiation record*

Age (years)	Observed deaths	Expected deaths	Standardised mortality ratio
45-49	1	0·24	412
50-54	2	0·80	250
55-59	5	1·76	285
60-64	0	3·40	—
65-69	7	5·00	140
70-74	4	5·20	77
15-74	19	16·54	115

Discussion

These 39 546 employees of the United Kingdom Atomic Energy Authority make up the largest British workforce whose mortality has been reported in relation to occupational exposure to low dose radiation. The Hanford study, from the United States, was of comparable size and concerned broadly similar exposures to penetrating radiation.[2-4] The mortality among 11 500 men employed by British Nuclear Fuels has also been described.[18] Validation of data and an independent ascertainment of the cause of death were considered to be important aspects of the United Kingdom Atomic Energy Authority study, and each stage of data collection was scrutinised and checked by the Epidemiological Monitoring Unit. The data analysed here were judged to be of good quality, after exclusion of subjects last employed at Risley and Culcheth, where data were missing. This necessarily meant the exclusion of an unknown number who had previously been employed at other United Kingdom Atomic Energy Authority establishments. Much of the work at Risley and Culcheth is administrative: only 30% of employees with existing personnel records also had a radiation record, and their mean cumulative exposure (8·4 mSv) was considerably lower than that in the remaining population (table I). Validation checks showed that a small number of employees regarded as alive in the analyses may in fact be dead. Inclusion of the 70 deaths (53 in those aged under 75) listed in the appendix, but not used in the analyses, would have increased the standardised mortality ratios for all causes by 3%, not altering the results substantially.

COMPARISON WITH THE GENERAL POPULATION

Employees of the United Kingdom Atomic Energy Authority have generally lower mortality rates than those prevalent in England and Wales, but in the range that might be expected given the nature of the population studied. Their favourable mortality ratios result partly from the social class distribution of the employees (see our accompanying report) and partly from the small underascertainment of deaths, but mostly because normal working populations are known to have low standardised mortality ratios, since they are initially selected from the healthy.[19] National statistics include the chronically sick and unemployed, who have higher mortality rates than average. Less is known about how selective forces determining who enters a workforce relate to cause of death, but large deficits in mortality from non-malignant and non-circulatory conditions are prominent in the United Kingdom Atomic Energy Authority population (table III). The significant deficits of stomach, lung, and bladder and other urinary tract cancers may be partly explained by the social class of the population. Reliable information on the smoking habits of the employees was not available, so the effect of smoking on mortality could not be assessed. The low standardised mortality ratio for brain cancer (table III) was an underestimate, since two deaths from this cause—11% of the total—were not included in the analysis (see appendix). Leukaemia and thyroid cancer, two of the four causes with a standardised mortality ratio above 100, are malignancies especially sensitive to induction by ionising radiation. A third, non-Hodgkin's lymphoma, was significantly related to

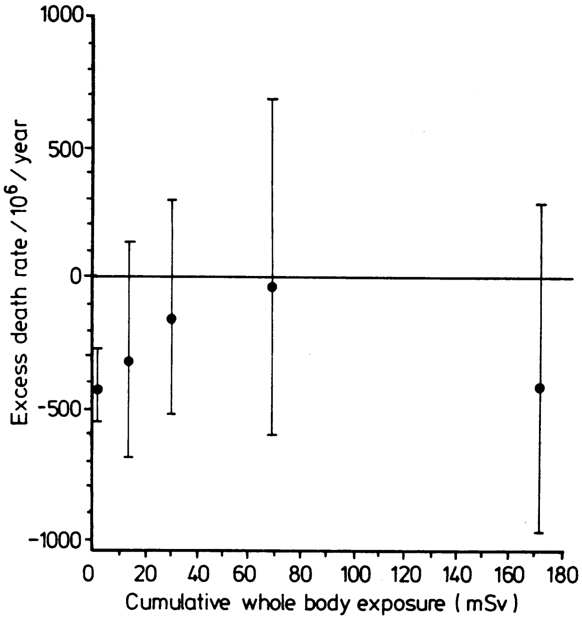

FIG 2—Death rates from cancers in excess of those expected on the basis of mortality in England and Wales, in relation to cumulative radiation exposure. Bars represent 95% confidence intervals for excess death rate. (10 mSv=1 rem.)

radiation exposure at Harwell and adjacent authority establishments.

Short term employees who had no radiation record were an anomalous group, experiencing high mortality from several causes, especially leukaemia (table IV). Furthermore, those with and without radiation records showed different trends in mortality from all causes and leukaemia, according to duration of employment. It is not clear why these differences existed and we plan to examine them further in a separate publication. Employees with a radiation record were predominantly scientists, technicians, and skilled workers who had relatively long durations of employment, whereas those without a radiation record were largely in clerical or administrative jobs and were employed for comparatively shorter periods (see our accompanying report). Also the two groups were defined in different ways. An employee "with a radiation record" was one for whom a positive link between a personnel and radiation record was established at the time of data collection, whereas one "without a radiation record" was defined by default if no such link could be made. Subjects may be misclassified and such errors are likely to predominate in one direction—workers "without a radiation record" being incorrectly assigned if, for example, insufficient identifying information existed on a radiation record. Such misclassification should not be expected to introduce serious biases, since only 293 radiation records (about 1% of the total) could not be linked to a personnel record (see accompanying report). Of these, 70% dated from before 1960, suggesting that the record linkage may be less certain for those employed in the 1940s and 1950s than later. It may be relevant that eight of the 12 short term employees who had no radiation record and died of leukaemia left the authority before 1960. Another consideration is that some short term employees may have moved later to other places where they were exposed to radiation. Until more is known about the reasons for the differences in mortality between those with and those without radiation records—which may be due to factors other than exposure to radiation—comparisons between the groups are strictly not valid.

MORTALITY IN EMPLOYEES WITH A RADIATION RECORD

The only cause of death showing a clear relation with exposure to radiation was cancer of the prostate (tables V-X). Not only was there a highly significant trend of increasing mortality with increasing cumulative exposure but standardised mortality ratios for this malignancy were significantly raised in workers monitored for contamination by tritium and other unspecified radionuclides and in those with any single dosimeter reading exceeding 10 mSv (1 rem). The excess mortality was in younger men and concentrated in the small group of workers who were both monitored for tritium and had accumulated exposures exceeding 50 mSv (SMR 1277). Neither the reasons for monitoring nor the doses acquired from tritium exposure were collected for this study, nor were such doses included in measures of whole body exposure except at Harwell from 1977. Doses attributed to tritium contamination were, however, small (United Kingdom Atomic Energy Authority, personal communication). Details of the "other unspecified radionuclides" were not collected, although this category generally included people who had urine analysis performed to detect α, β, or γ radioactivity or to identify uranium contamination (United Kingdom Atomic Energy Authority, personal communication). Clearly further investigations are required but clues might come from the high standardised mortality ratios for prostatic cancer at Winfrith (SMR 246) and in those monitored for exposure to tritium (SMR 889) and the fact that tritium monitoring is most prevalent at Winfrith (17% compared with 7% at Harwell and 3% at Dounreay). Tritium is not known to be concentrated in the prostate and so it may perhaps be a marker for another exposure which itself is responsible for the relationship, although no clear occupational causes of prostatic cancer are known.[20]

Most men with radiation records were not monitored for tritium and their mortality from cancer of the prostate was not raised (SMR 82) (table VIII). Despite this there was a suggestion that the men with dosimeter readings exceeding 50 mSv who were not monitored for tritium exposure may also have had increased mortality from prostatic cancer (SMR 160), but the trends with cumulative exposure were not statistically significant. Other populations exposed to high doses of ionising radiation do not show noticeable increases in prostatic cancer,[21 22] but the findings for workforces in the nuclear industry are less clear. At Hanford a group of workers described as "craftsmen and operators" were reported to have higher cumulative exposures and also higher mortality from cancer of the prostate than did other workers, but no relation between prostatic cancer and level of exposure was noted in the whole population.[4] Employees of the Oak Ridge National Laboratory were also found to have an excess of cancer of the prostate, which was, however, not significant nor related to level of radiation exposure.[23] In neither study was there comment on whether exposure to tritium had occurred.

Cancers which have been reported in some studies to be linked with exposure to low levels of ionising radiation and discussed in detail elsewhere,[24] notably leukaemia, multiple myeloma, and cancers of the pancreas, brain, and breast, showed no strong trend of increasing risk with cumulative whole body exposure. Except for the lung there were, however, few deaths from any single cancer site in each exposure category. The trend for mortality from non-Hodgkin's lymphoma to increase with dosimeter dose at Harwell and adjacent authority establishments needs further investigation, since this malignancy has been linked with high dose radiation exposure before[21] and the standardised mortality ratio for non-Hodgkin's lymphoma was above the national average in the United Kingdom Atomic Energy Authority population, especially in those with a radiation record (table III). Intestinal cancer was also associated with cumulative exposure at Winfrith, but not at other establishments. Given the number of significance tests carried out, however, these may be chance findings. The increased mortality from testicular cancer at Harwell and adjacent authority establishment and the excess of uterine and ovarian cancer in women with a radiation record compared with those without (table III) suggest that cancers of the genital tract in general warrant further investigation in this workforce.

One aim of the study was to compare the relation between level of radiation exposure and risk of leukaemia and all cancers in the workforce with estimates derived from figures of the International Commission on Radiological Protection.[1] The slopes of the regression lines fitted to the points in figures 1 and 2 and their sampling errors were consistent with a wide range of effects. The 95% confidence intervals included at their upper limit risk levels some 15 times greater than the commission's figures predict and, at their lower limit, a decrease in mortality in relation to increasing levels of exposure. Thus these data are of little help in distinguishing between extreme estimates of risk associated with exposure to low levels of ionising radiation. The wide confidence intervals are themselves subject to considerable uncertainty. They were based on exposures recorded by dosimeters worn outside the body and yet cancer risk is likely to be determined by doses absorbed by the tissues. The relation between tissue dose and occupational exposure is not straightforward. Secondly, tissue doses from ingested, inhaled, or other internal sources of radiation are not generally included in the dosimeter readings. Thirdly, lost dosimeters and readings below the threshold of the measuring devices were assigned zero dose. These two assumptions underestimate true exposure,[25] and the implications of assigning doses other than zero are currently being investigated and will be published later.

Finally, no specific account was taken of medical exposure to *x* rays, or background radiation, except that they were assumed to be similar in each exposure category. Occupational exposures before joining the United Kingdom Atomic Energy Authority were included, if known, but exposures after leaving were unknown. With an extended period of follow up, and by combining the results of this study with that of other occupa-

APPENDIX—*Additional information about deaths, especially with respect to cancer (see text)*

	Deaths included in analysis: cancers coded as associated causes of death		Deaths not included in analysis: underlying cause of death	
Cause of death (ICD code (8th revision))	Without a radiation record	With a radiation record	Without a radiation record	With a radiation record
Oral cavity cancer (140-149)	0	2	0	0
Stomach cancer (151)	1	5	1	2
Intestinal and rectal cancer (152-154)	5	8	0	0
Pancreatic cancer (157)	0	0	1	0
Lung cancer (162)	9	4	0	6
Bone and connective tissue cancer (170-171)	0	2	0	0
Breast cancer (174)	3	0	0	0
Uterine cancer (180-182)	2	0	1	0
Prostatic cancer (185)	7	9	0	0
Testicular cancer (186)	0	0	0	1
Bladder cancer (188)	4	6	0	0
Brain and other central nervous system cancer (191-192)	0	0	0	2
Secondary and unspecified (196-199)	0	0	0	1
Non-Hodgkin's lymphoma (200-202)	2	0	1	1
Hodgkin's disease (201)	1	0	0	0
Leukaemia (204-207)	1	0	0	0
Other haematopoietic (200-202)	2	1	0	0
Other cancers*	4	4	0	0
Other causes of death	Not applicable		16	29
Unknown cause of death	Not applicable		3	5

*Without a radiation record: oesophageal cancer (1); nasal cancer (1); melanoma (1); kidney cancer (1). With a radiation record: retroperitoneal cancer (1); ocular cancer (1); penile cancer (2).

tional groups exposed to low levels of ionising radiation—for example, at British Nuclear Fuels[18]—it should be possible to obtain more complete information on occupational exposure and more precise estimates of radiation associated risks. A study four times as large as this one, with findings similar to those in figures 1 and 2, would show that the figures of the International Commission on Radiological Protection do not underestimate risk by a factor of 10; a study 30 times as large, with such findings would show that the risks are significantly greater than the commission's estimates.

Members of the Epidemiological Monitoring Unit were funded by the MRC, which held a contract with the United Kingdom Atomic Energy Authority to perform the study. It was possible only because of the cooperation and advice of many people from different organisations, including the MRC, United Kingdom Atomic Energy Authority, Office of Population Censuses and Surveys, General Register Office for Scotland, NHS central registers, DHSS, Oxford Cancer Registry, and World Health Organisation. We thank all who helped us, especially the members of the MRC subcommittee and its chairman, Dr R Mole; the United Kingdom Atomic Energy Authority staff, who are too numerous to name individually; Peter Smith, Sarah Firsht, Sandra Speak, Anna Brown, Martin Shipley, and Helen Edwards.

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AN INTERPRETATION OF CERTAIN CRABBED NAMES WHICH YOU SHALL MEET WITH UNEXPLAINED IN THIS TREATISE

Accelerator, In plain English an Hastener. Physically tis used in this Treatise the Muscle that opens the passage of the Seed and Urin.
Allantois, The Skin that holds the Urin of the Child during the time it abides in the Womb.
Amnios, The inner skin that compasseth the Child in the womb.
Arteries, Proceed from the Heart, are in a continual motion, and by their continual motion quicken the Body. They carry the vital blood to every part of the Body, their motion is what is called the Pulse, you may feel it at your Temples, Wrist, Groyn, etc.
Arthrodia, is a Juncture, when the Head of the Bone is little which is received, and the Cavity which receives it is as a shallow.
Chorion, Is the outward skin which compasseth the Child in the Womb.
Corpus-Varicoform, Is an interweaving of the Veins and Arteries, which carry the vital and natural blood to the Stones to make Seed of.

Nicholas Culpeper (1616-54)
Directory for Midwives, 1671