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Mortality and Cancer Incidence 1952–1990 in UK Participants in the UK Atmospheric Nuclear Weapon Tests and Experimental Programmes

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Abstract

In order to study the long-term effects of participating in the United Kingdom's atmospheric nuclear weapon tests and experimental programmes which took place in Australia and the Pacific Ocean between 1952 and 1967, a total of 21,358 men who took part in the tests have been identified from archives of the Ministry of Defence and followed up to 1 January 1991. The mortality and incidence of cancer in these men were compared with those in 22,333 controls selected from the same archives. In the period more than 10 years after initial test participation, mortality was found to be low compared with that expected from national rates both for all neoplasms and for all other causes of death (SMRs of 0.84 and 0.82, respectively), and rates in test participants and controls were very similar (RR = 0.97, 90% CI 0.91, 1.04 for incidence of all neoplasms and RR = 1.02, 90% CI 0.96, 1.08 for mortality from all causes of death other than neoplasms). Rates were also examined for leukaemia and 26 other types of cancer, and for 15 other causes of death. It is concluded that participation in the nuclear weapon testing programmes has not had a detectable effect on the participants' expectation of life, or on their risk of developing cancer or other fatal diseases. The suggestion from a previous study that participants may have experienced small hazards of leukaemia and multiple myeloma is not supported by the additional data, and the excesses observed previously now appear likely to have been a chance finding, although the possibility that test participation may have caused a small risk of leukaemia in the early years after the tests cannot be completely ruled out.

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Executive Summary

A follow-up study has previously been carried out of the health of men who participated in the UK atmospheric nuclear weapon tests and experimental programmes that took place in Australia and the Pacific Ocean between 1952 and 1967. Participants were identified from archives of the Ministry of Defence and a matched control group was selected from the same archives. The rates of mortality and cancer incidence, as determined from death certificates and national records of cancer registration, were compared in the two groups. The numbers of deaths observed were also compared with those that would have occurred if the men had experienced the death rates recorded for all men of the same ages over the same years in England and Wales. The results of that study led to three hypotheses: that test participation may have caused small hazards of leukaemia (excluding chronic lymphatic leukaemia) and multiple myeloma; that test participation did not cause a detectable hazard of any other cancer or of any other disease that has an appreciable fatality rate; that test participants smoked less than other similar men in HM forces or employed by the Atomic Weapons Establishment.

The present report extends the follow-up of both test participants and controls by a further 7 years, with the object of testing the three hypotheses generated by the previous report and of further examining the long-term effects of participation in the tests on health. The men included comprise those that were studied previously, plus a few hundred further participants found in MOD archival material since the previous report, minus some fifteen hundred men who had no more potential for radiation exposure from the tests than the general public. In total 21,358 test participants and 22,333 controls have been studied, of whom 99.8% were traced to 1 January 1991.

A further 2488 deaths in test participants and controls recorded in the additional period of follow-up beyond 31 December 1983 provided data to test these hypotheses. During the additional period the mortality rates from all causes and all neoplasms and the incidence rate of all neoplasms were very similar in the two groups, with relative risks (RR) in the participants compared with the controls, respectively, of 0.99 (90% confidence interval (CI) 0.93, 1.06), 0.96 (90% CI 0.85, 1.08) and 0.99 (90% CI 0.90, 1.09). Only 6 additional deaths from leukaemia were observed in test participants, compared with 10.55 expected from national rates, and the RR of leukaemia incidence in test participants compared with controls in the additional period was 0.64 (90% CI 0.28,1.44). Three additional deaths from multiple myeloma were observed in test participants, compared with 6.50 expected nationally, and the corresponding RR of myeloma incidence in test participants compared with controls was 0.71 (90% CI 0.23, 2.07). Of the two chief smoking-related diseases, the incidence of one (lung cancer) continued to be somewhat less frequent in test participants than in controls (RR = 0.93, 90% CI 0.76, 1.13), whereas the mortality from the other (bronchitis, emphysema, and chronic obstructive lung disease) was significantly greater in test participants than in controls (RR = 1.57, 90% CI 1.05, 2.34).

Altogether 5692 deaths (78% more than previously) are now available for examination of the long-term effects on health of participants in the tests. For all neoplasms and all other diseases, mortality in comparison with that expected from national mortality rates was exceptionally low in the first 10 years after start of test participation (standardised mortality ratios (SMRs) of 0.72 and 0.54, respectively), owing in part to the selection of fit and healthy men to take part in the tests. Moreover, any effect of test participation on the incidence of neoplasms other than leukaemia is likely to be concentrated in the period more than 10 years after start of test participation. Evidence for any long-term effect of test participation has, therefore, been sought after excluding the first 10 years of observation. The mortality among test participants was

found to remain low after this exclusion both for all neoplasms and for all other causes of death (SMRs of 0.84 and 0.82, respectively), and rates in test participants and controls remained very similar (RR = 0.97, 90% CI 0.91, 1.04 for incidence of all neoplasms, and RR = 1.02, 90% CI 0.96, 1.08 for mortality from all causes of death other than neoplasms). Rates in the period more than 10 years after start of first test participation were examined for a total of 41 different causes of death (26 types of cancer other than leukaemia, and 15 other causes). Significant increases in test participants compared with controls were observed for the incidence of cancers of the bladder (RR = 1.45, 90% CI 1.03, 2.03), and liver (RR = 2.89, 90% CI 1.11, 7.94), and for mortality from 'other injury and poisoning' (RR = 1.35, 90% CI 1.02, 1.79), and there was a significant deficit of the incidence of skin cancers other than malignant melanoma (RR = 0.77, 90% CI 0.63, 0.95). This is exactly the number of significant differences that would on average be expected to occur by chance. Moreover, the significant excesses of bladder cancer and liver cancer seem to be largely due to unusually low rates among the controls (SMRs of 0.39 and 0.53, respectively).

For leukaemia, any effect of radiation exposure is likely to be greater in the period 2–25 years after the tests, rather than 10 or more years after. In the 2–25 year period, 20 deaths were observed from leukaemia against 16.29 expected from national rates (p = 0.38). The incidence was significantly greater than that in the controls (RR = 3.45, 90% CI 1.72, 7.10), but the risk was not concentrated in those most likely to have been exposed to radiation nor in those involved in any particular test, and the excess over the controls seems likely to have been attributable principally to a deficit in the controls, since the mortality in the controls was atypically low (SMR = 0.34 in the 2–25 year period), although it was close to the national mortality during the additional period of follow-up (SMR = 0.98 in the period from 1 January 1984 to 31 December 1990).

It is concluded that participation in the nuclear weapon testing programme has not had a detectable effect on the participants' expectation of life nor on their risk of developing cancer or other diseases. The excess of leukaemia in test participants compared with controls in the period 2–25 years after the tests is likely to be a chance finding, although the possibility that test participation may have caused a small risk of developing leukaemia in the early years after the tests, cannot be completely ruled out. The suggestions from the previous study that participants may have experienced a small hazard of multiple myeloma and that participants may have smoked less than their matched controls and so experienced lower rates of smoking-related diseases are not supported by the data available from the additional period of follow-up, and now also appear likely to have been chance findings.

Contents

1 Introduction

Between 1952 and 1958, the United Kingdom Ministry of Supply conducted a series of 21 atmospheric nuclear weapon tests in South and Western Australia and at Malden Island and Christmas Island in the Pacific Ocean. Other experiments in which radioactive materials were dispersed into the environment were carried out by the Ministry of Supply at the same sites in South Australia between 1953 and 1963. Survey and clean-up operations continued until 1967, when the sites were returned to Australian control. UK personnel also participated in a series of American tests based at Christmas Island in 1962, finally vacating the Island in 1964.

Although the Ministry of Defence has always believed that only a small proportion of the men who participated in these tests were exposed to ionising radiation as a result, some participants have expressed concern that attending the tests may have affected their subsequent health. In 1983 MOD, therefore, commissioned the National Radiological Protection Board to undertake a study of the health of the test participants. For this study the names of over 20,000 men who participated in the tests were identified from MOD archives, and a matched control group was selected from the same archives[1,2]. The rates of mortality and cancer incidence in the period up to 1 January 1984, as determined from death certificates and national records of cancer registration, were compared in the two groups, and the numbers of deaths observed were also compared with those that would have occurred if the men had experienced the same death rates as those of men of the same ages in England and Wales as a whole during the same period. The reasons for choosing to study mortality and cancer incidence were discussed in the first report[1]. The results of the study indicated that test participation had not had a detectable effect on the men's expectation of life or on their total risk of developing cancer, but for leukaemia and multiple myeloma both the mortality rate and the rate of incident cancers were higher among the test participants than among the controls. These differences were, however, difficult to interpret as they were chiefly due to extraordinarily low rates from these diseases among the controls.

In order to clarify the situation, MOD commissioned NRPB to carry out a further follow-up of these men. In the present report the period of follow-up has been extended for a further 7 years, almost doubling the number of deaths available for analysis. As previously, the study has been carried out jointly by the National Radiological Protection Board and the Imperial Cancer Research Fund.

2 Study population and data collection

2.1 Outline of the nuclear weapons testing programme and definition of a test participant

The UK programme of atmospheric nuclear weapon testing took place in the 1950s and 1960s and included a series of nine operations (involving 21 major explosions) from Hurricane in 1952 to Grapple Z in 1958 (see Table 2.1). Operations involving only devices with yields in the kiloton range took place off the Monte Bello Islands in Western Australia, or at Emu Field or Maralinga in South Australia. Later operations involving devices in the megaton range took place in the vicinity of Christmas and Malden Islands in the Pacific Ocean. In addition to these major operations there was an experimental programme, mostly at the Maralinga Range, which comprised a series of minor trials together with clean-up operations (see Table 2.2). UK personnel were based at the locations mentioned above for the trials, and personnel responsible for the aircraft that sampled radioactive clouds from the explosions were based at RAAF Pearce in Western Australia

TABLE 2.1 UK atmospheric nuclear weapons tests in Australia and the Pacific Ocean, 1952–1958[a]

Operation	Round and name	Location	Date of firing[b]	Yield	Height (m)	Explosion conditions
Hurricane		Off Trimouille Island, Monte Bello Islands, Western Australia	3 Oct 1952	25 kt	– 3	Ocean surface burst
Totem	1	Emu Field, South Australia	14 Oct 1953	10 kt	31	Tower mounted
	2	Emu Field, South Australia	26 Oct 1953	8 kt	31	Tower mounted
Mosaic	1	Trimouille Island, Monte Bello Islands, Western Australia	16 May 1956	15 kt	31	Tower mounted
	2	Alpha Island, Monte Bello Islands, Western Australia	19 Jun 1956	60 kt	31	Tower mounted
Buffalo	1	One Tree, Maralinga Range, South Australia	27 Sep 1956	15 kt	31	Tower mounted
	2	Marcoo, Maralinga Range, South Australia	4 Oct 1956	1.5 kt	0	Ground surface burst
	3	Kite, Maralinga Range, South Australia	11 Oct 1956	3 kt	150	Air dropped – air burst over land
	4	Breakaway, Maralinga Range, South Australia	21 Oct 1956	10 kt	31	Tower mounted
Grapple	1 Short Granite	Off Malden Island, Pacific Ocean	15 May 1957	0.3 Mt[c]	2200	Air dropped – air burst over ocean
	2 Orange Herald	Off Malden Island, Pacific Ocean	31 May 1957	0.72 Mt[c]	2400	Air dropped – air burst over ocean
	3 Purple Granite	Off Malden Island, Pacific Ocean	19 Jun 1957	0.2 Mt[c]	2400	Air dropped – air burst over ocean
Antler	1	Tadje, Maralinga Range, South Australia	14 Sep 1957	1 kt	31	Tower mounted
	2	Biak, Maralinga Range, South Australia	25 Sep 1957	6 kt	31	Tower mounted
	3	Taranaki, Maralinga Range, South Australia	9 Oct 1957	25 kt	300	Balloon suspended – air burst over land
Grapple X		Off Christmas Island, Pacific Ocean	8 Nov 1957	1.8 Mt[c]	2200	Air dropped – air burst over ocean
Grapple Y		Off Christmas Island, Pacific Ocean	28 Apr 1958	3 Mt[c]	2500	Air dropped – air burst over ocean
Grapple Z	1 Pennant	Christmas Island, Pacific Ocean[d]	22 Aug 1958	24 kt[c]	450	Balloon suspended – air burst over land
	2 Flagpole	Off Christmas Island, Pacific Ocean	2 Sep 1958	1 Mt[c]	2800	Air dropped – air burst over ocean
	3 Halliard	Off Christmas Island, Pacific Ocean	11 Sep 1958	0.8 Mt[c]	2600	Air dropped – air burst over ocean
	4 Burgee	Christmas Island, Pacific Ocean[d]	23 Sep 1958	25 kt[c]	450	Balloon suspended – air burst over land

Notes

(a) A series of 25 American tests, part of Operation Dominic, and known as Operation Brigadoon, took place off Christmas Island between 25 April and 11 July 1962[3]. UK personnel known to have attended are also included in the present study.

(b) Dates according to Greenwich Mean Time.

(c) MOD best estimates of the yields of the Christmas and Malden Island tests made available October 1993 together with revisions to heights of explosions.

(d) Over the southeast peninsula of the island.

TABLE 2.2 Maralinga Experimental Programme

Operation	Type	Dates
Kittens	Initiator trials	Sep 1953[a], Apr–Jun 1955, Mar 1956, Mar–Jul 1957, Apr–May 1959, May 1961
Tims	Timing experiments	Jul 1955, Mar–Jul & Sep–Nov 1957, Apr–Jul & Sep–Nov 1958, May–Nov 1959, Apr–Oct 1960, Aug–Dec 1961, Mar–Apr 1963
Rats	Timing experiments using gamma ray sources	Apr–Jul & Oct–Nov 1958, Mar–Jul 1959, Sep–Nov 1960
Vixen	Effects of fire or uncontrolled explosions	Jun–Aug 1959, May–Oct 1960, Mar–Jun & Sep–Nov 1961, Apr–May 1963
Ayres	Clean-up operation	Feb–Mar 1960, Mar 1963
Hercules	Clean-up operation	Aug–Nov 1964
Brumby	Clean-up operation	Mar–Aug 1967

Note
(a) The first Kittens trials took place at Emu Field.

for Operation Mosaic and at RAAF Edinburgh Field in South Australia for Operations Buffalo and Antler. These seven locations and the periods during which UK personnel were based at them in connection with the trials or with their associated clean-up operations are detailed in Table 2.3. The entry for Christmas Island includes the period when part of the American Dominic trials, known as Operation Brigadoon, took place on Christmas Island, and UK participants in those trials are also included in the present study. The main base for Operation Grapple, which took place off Malden Island, was on Christmas Island, and in the discussion that follows the term Christmas Island will be used to denote the area around both Christmas and Malden Islands.

Individuals who visited the Monte Bello Islands, Emu Field, Maralinga Range or Christmas or Malden Islands during the appropriate period as indicated in Table 2.3 will be referred to as test participants. Individuals based at RAAF Pearce or RAAF Edinburgh Field during the appropriate periods are also included as test participants if they are known to have been members of the squadron responsible for cloud sampling activities. The majority of test participants were Servicemen. A considerable number of employees of the AWE at Aldermaston were also closely involved in the test programme, as were a few employees of AERE Harwell, and employees of these two organisations who visited the test locations during the specified periods are included in the study. Some UK civilian employees of other organisations also visited the test locations at the relevant times, but difficulties in establishing a comprehensive list of those involved prevented their inclusion. The small number of women who participated in the tests and all non-UK nationals, other than those with regular engagements in the UK Services or who were permanent employees of AWE or AERE, have also been excluded. Australian, Canadian, and New Zealand nationals have been studied separately[4,5,6].

2.2 Test participants included in the present analysis

A total of 21,358 test participants have been included in the present analysis (see Table 2.4). The largest proportion of men (39.5%) came from the RAF, with rather smaller proportions from the RN, and the Army (29.5% and 27.1%, respectively). Less than 4% of the men were civilians. As in the first report, men from the RNVR, RM and NAAFI are included with the RN and employees of AERE Harwell with AWE. Only a minority of test participants (11.2%) were National Servicemen and two-thirds of these were in the Army. Overall, about one man in seven was an officer (here civilians of social class 1 are included with officers). The ratio of officers to other ranks was about one to ten in the RN and the Army but about one to five in the RAF.

The majority of the test participants included in this second report were identified by the extensive series of searches of archival material held by AWE and MOD carried out for the previous report, and were also included in the first analysis. There are, however, some differences between the men included as test participants in the first analysis and men included here, as given below.

(a) The addition of 50 participants in the American Dominic Tests at Christmas Island in 1962, identified from two extra listings. The first, from UK archives, contained only names, ranks and other personal identifiers. The second, made available by the American Defense Nuclear Agency, also contained information about doses received, from personal monitoring carried out by the American authorities. These dosimetric data are discussed in more detail in Section 2.4.

TABLE 2.3 Locations and periods for the UK atmospheric nuclear weapon testing programme

Location	Period	Comment
Monte Bello Islands, Western Australia	Oct 1952 – Jun 1956	Operation Hurricane took place on 3 October 1952. The last ships of the Royal Naval Task Force for Operation Mosaic left in June 1956
Emu Field, South Australia	Oct 1953 – Aug 1967	The first explosion in Operation Totem took place on 14 October 1953. The UK clearing-up operation was completed in August 1967
Maralinga Range, South Australia	Apr 1955 – Aug 1967	The first scientific personnel for activities involving the dispersal of radioactive material into the environment arrived at Maralinga in April 1955. The UK clearing-up operation was completed in August 1967
Christmas Island, Pacific Ocean	May 1957 – Jun 1964	The first explosion for Operation Grapple took place on 15 May 1957. The final clearing-up exercise finished in June 1964
Malden Island, Pacific Ocean	May 1957 – Jun 1964	The first explosion for Operation Grapple took place on 15 May 1957. The evacuation of Malden Island was completed by June 1964
RAAF Pearce, Western Australia	May 1956 – Aug 1956	UK personnel involved with cloud sampling for Operation Mosaic were based at RAAF Pearce during this period, including some who remained there for 2 months after June 1956 when the Royal Navy Task Force left the Monte Bello Islands
RAAF Edinburgh Field, South Australia	Aug 1956 – Oct 1957	UK personnel involved with cloud sampling for Operation Buffalo were based at RAAF Edinburgh Field from August 1956. Operation Antler took place in September and October 1957

Note
Only locations where there was a possibility of radiation exposure to UK personnel as a result of the weapon tests are included. For RAAF Pearce and RAAF Edinburgh Field only personnel specifically known to have been members of the squadron responsible for cloud sampling have been included as test participants. For other locations all UK Servicemen or AWE or UKAEA employees known to have visited during the periods specified have been included as test participants.

TABLE 2.4 Numbers of test participants and controls by Service or employer, rank or social class and, for the Services, whether or not on National Service

Service or employer	Rank	Test participants				Controls			
		National servicemen	Regular	Total number	%	National Servicemen	Regular	Total number	%
RN[a]	Officer	54	434	488		22	559	581	
	Other ranks	340	5,476	5,816		261	6,502	6,763	
	Total	394	5,910	6,304	29.5	283	7,061	7,344	32.9
Army	Officer	24	537	561		174	488	662	
	Other ranks	1,563	3,670	5,233		1,727	3,093	4,820	
	Total	1,587	4,207	5,794	27.1	1,901	3,581	5,482	24.5
RAF	Officer	17	1,594	1,611		43	1,755	1,798	
	Other ranks	404	6,429	6,833		765	6,139	6,904	
	Total	421	8,023	8,444	39.5	808	7,894	8,702	39.0
AWE[b]	Officer	0	380	380		0	361	361	
	Other ranks	0	436	436		0	444	444	
	Total	0	816	816	3.8	0	805	805	3.6
All Services and employers	Total officers/social class 1	95	2,945	3,040	14.2	239	3,163	3,402	15.2
	Total other ranks/social classes	2,307	16,011	18,318	85.8	2,753	16,178	18,931	84.8
	Total	2,402	18,956	21,358	100.0	2,992	19,341	22,333	100.0

Notes
(a) RN includes members of the RM, RNVR and NAAFI.
(b) AWE includes a few employees of AERE Harwell.

(b) The addition of some participants whose records had not been located previously by Service Records Offices. At the time of the first report there were 902 individuals mentioned in contemporary documents as possible participants, but whose records could not be located. As part of the preparation for the second analysis, further searches were made. A total of 127 additional sets of Service records were located. Test participation was confirmed for 75 men, and 52 others were found not to have met the criteria for inclusion in the study or to have been duplicate records for men already included.

(c) The addition of 389 men identified for the first time as participants during further searches carried out at the Service Records Offices since the time of the first analysis.

(d) The exclusion of 1503 men who had been counted previously as test participants, but who were judged to have had no more potential for radiation exposure from the tests than the general public. Men in this category had visited test locations but had left before the first detonation, or had worked at RAAF Pearce or RAAF Edinburgh Field but were not members of the squadron responsible for cloud sampling. Follow-up for these men has been continued and the results are given in Appendix A.

As a result of these changes, the number of test participants included in the study has decreased by 989. The newly identified test participants were predominantly (78%) from the RAF and Army (20%).

2.3 Controls

Men who were included in the study as test participants had been selected as fit and healthy for employment by the Services or by their civilian employers, and they had also been further selected as fit for deployment overseas to participate in the tests. Furthermore, all participants experienced at least a short period of life in a tropical or desert environment and, as Service personnel, experienced a lifestyle that differed materially from that of the majority of the population for the period of their engagement. Therefore it could not be assumed that, in the absence of any effect of test participation, the mortality and incidence of cancer in the test participants would be identical with that of others in the UK population of the same sex and age.

To overcome this difficulty, an approximately equal number of individuals who did not participate in the tests but who otherwise had similar characteristics were also identified from MOD archives to form a control group. For test participants in the Services, controls were chosen from Servicemen who had served in tropical or sub-tropical areas other than test locations during the period when the tests were being carried out. For employees of AWE, AERE, or their forerunners, controls were selected from AWE employees who had not visited a test location or attended tests at a test site in the USA. The methods used to identify men used as controls are described in detail in the earlier report[1].

A total of 22,333 men were included in the control group for this second analysis (see Table 2.4). Among them are included all 22,326 men used as controls for the first analysis, and 7 additional men who had been selected as controls at the time of the first analysis but whose Service record could not be identified at that time. As described in the previous report, the distributions of controls by Service/employer, rank/social class, year of birth, year of enlistment/employment, and year of discharge/termination are very similar to those of the test participants.

2.4 Test participation and possible radiation exposure

The 21,358 test participants included in the present analysis were identified as having a total of 27,501 test involvements* (see Table 2.5). About two-thirds of these were at Christmas Island, one-fifth were at Maralinga Range or Emu Field, and about one-tenth at the Monte Bello Islands. The later operations tended to involve more men than the earlier ones. The majority of visits to test locations were known to be connected with specific operations, but at both Maralinga and Christmas Island a substantial number of men were involved in general support tasks at a test location rather than with a specific operation.

TABLE 2.5 Numbers of men involved at each operation by Service or employer

	Service or employer				
Location and operation	RN	Army	RAF	AWE	Total
Monte Bello Islands					
Hurricane	1,075	206	21	95	1,397
Mosaic	1,134	72	128	49	1,383
Other Monte Bello	9	0	0	0	9
Total Monte Bello	2,218	278	149	144	2,789
Emu Field					
Totem	1	11	9	85	106
Maralinga Range					
Buffalo	5	194	883	203	1,285
Antler	60	136	1,156	196	1,548
MEP	2	174	49	330	555
Other Maralinga	324	630	1,554	47	2,555
Total Maralinga	391	1,134	3,642	776	5,943
Christmas Island					
Grapple	1,722	638	1,038	117	3,515
Grapple X	597	625	1,009	107	2,338
Grapple Y	851	1,331	1,426	114	3,722
Grapple Z	738	1,438	2,017	182	4,375
Brigadoon	63	228	395	43	729
Other Christmas Island	636	1,779	1,532	37	3,984
Total Chrismas Island	4,607	6,039	7,417	600	18,663
Total involvements	7,217	7,462	11,217	1,605	27,501

Notes

(a) Visits to RAAF Edinburgh Field in connection with Operation Buffalo or Antler and visits to RAAF Pearce in connection with Mosaic are included under the appropriate operation.

(b) Other involvements at Edinburgh Field are included with 'Other Maralinga'.

* The definition of a test involvement differs somewhat from that used previously. Involvement in the Maralinga Experimental Programme in two different years was previously counted as two separate involvements, although any doses incurred in different years were combined for the analysis. In the present tables, such an individual is counted as having a single involvement in connection with the Maralinga Experimental Programme.

The operations that took place at the Monte Bello Islands chiefly involved the RN (see Table 2.5). The RN also supplied almost half the personnel for Operation Grapple. For operations at the Maralinga Range, and also for the later operations at Christmas Island, the RAF supplied the largest number of men. The Army provided support in all test locations. The proportion of visits that were made by AWE personnel was small at all operations except Totem at Emu Field. About three quarters of test participants were involved in only a single operation, but a few participated in as many as eight (see Table 2.6). AWE employees tended to be involved in more tests (average 2 per man) than Servicemen (average 1.3 per man).

TABLE 2.6 Numbers of operations attended by each man, by Service or employer

Number of operations	Service or employer				
	RN	Army	RAF	AWE	Total
1	5,506	4,255	6,302	431	16,494
2	687	1,426	1,663	171	3,947
3	107	100	354	106	667
4	4	11	106	59	180
5	0	1	12	28	41
6	0	1	6	13	20
7	0	0	1	4	5
8	0	0	0	4	4
Total number of test participants	6,304	5,794	8,444	816	21,358
Mean number of visits	1.1	1.3	1.3	2.0	1.3

Most of the available information on radiation exposures to test participants came from AWE Health Physics records. These were records of the radiation dosemeters (film badges) issued and of the results assessed when the badges were returned. The exposure data available for the study had been compiled by AWE staff from original film badge records and summaries of radiation exposures recorded at the tests that had been prepared by the AWE Health Physics Group in the early 1960s. Dosemeters at the tests had been calibrated in terms of roentgen but, in collating the data, AWE staff made the conventional assumption that an exposure of 1 roentgen delivered a dose equivalent to the whole body of 10 mSv and, to avoid confusion, the term 'dose' will be used rather than 'exposure' in what follows. For operations listed in Table 2.1, doses were given as totals for each man for the operation, while for staff deployed at the Maralinga Range they were given as annual totals.

At the end of the testing programme in the 1960s the minimum level of dose recordable by the film badges was 0.1 mSv. However, for most of the operations in Australia it was 0.2 mSv, although, on occasions, it was 0.3 mSv, and for the Buffalo Indoctrinee Force (see below) at Buffalo Round 1 it was 4 mSv, as low sensitivity emulsion film badges had been issued which did not record lower doses. At Christmas Island the minimum recordable level was usually 0.2 mSv, with 0.5 mSv for the first two operations. With the exception of the Buffalo Indoctrinee Force, these

minimum recordable doses are all less than is normally received from background radiation in the course of a year. MOD reported that it was normal policy to record doses below the threshold of detection as zero.

Any gamma radiation from fallout would have been detected by personal film badges. Exposures to neutrons and doses from internal contamination by radioactive materials would not have been recorded on these dosemeters. MOD has made estimates, based on free-standing neutron dosemeters, of doses from neutrons to the Buffalo Indoctrinee Force, which was the one group where neutron doses were considered possible. MOD advised that in all cases the resulting dose estimates were negligible.

In addition to dose records available from AWE Health Physics, some dose records were made available from American programmes of monitoring for the Dominic series. At these tests the minimum recordable level was 0.2 mSv. Dose estimates from these records, involving 345 individuals with a collective dose totalling 224 man mSv, have been included with other doses for the present analysis. However, a proportion of them may be overestimates because it is known that some of the badges issued by the American authorities during the Dominic series were damaged, for example by light, heat or humidity. This caused darkening of the film which would have been interpreted as if it had been due to radiation exposure.

The total collective gamma dose recorded for test participants in the study was 16,995 man mSv (see Table 2.7). All the operations listed in Table 2.1 contributed, but the largest contribution was for Operation Grapple Z for which a collective dose of 3814 man mSv was

TABLE 2.7 Numbers of men mentioned in Health Physics (HP) records, with and without recorded doses as a percentage of all participants at each operation

Location and operation	Number of men					Collective dose (man mSv)
	Total test participants	Total mentioned in HP		Mentioned in HP with zero dose	Mentioned in HP with non-zero dose	
Hurricane	1,397	1,339	(96%)	1,133	206	2,470
Mosaic	1,383	599	(43%)	404	195	1,274
Other Monte Bello	9	0	(0%)	0	0	0
Totem	106	78	(74%)	19	59	1,209
Buffalo	1,285	786	(61%)	404	382	2,156
Antler	1,548	737	(48%)	418	319	1,874
MEP	555	510	(92%)	314	196	775
Other Maralinga	2,555	253	(10%)	228	25	111
Grapple	3,515	83	(2%)	4	79	1,018
Grapple X	2,338	179	(8%)	53	126	1,081
Grapple Y	3,722	114	(3%)	18	96	981
Grapple Z	4,375	618	(14%)	395	223	3,814
Brigadoon	729	379	(52%)	29	350	231
Other Christmas Island	3,984	11	(0%)	3	8	1
Total	27,501	5,686	(21%)	3,422	2,264	16,995

Note
The number of men with zero recorded dose may be an underestimate, as MOD advised that some lists of men who wore radiation dosemeters but for whom no dose was recorded had been destroyed.

recorded. The distribution of doses to individuals by Service or employer, together with the collective dose in each category, is shown in Table 2.8. Doses to individuals are calculated as a total for the entire test programme and so, in some cases, spread over several years. Only 483 individuals were recorded as having received 5 mSv or more, and 81 test participants were recorded as having received 50 mSv or more. Over half the total collective dose (9915 man mSv) was received by men in the RAF. AWE employees received the next largest fraction of the collective dose (3858 man mSv). Of the 21,358 test participants included in the study, only 1716 (8.0%) had non-zero recorded radiation doses. The proportion was very much higher for AWE personnel, 420 (51%) of whom had recorded doses above zero.

The study team was informed that, although some records indicating that a man had worn a film badge which recorded a zero dose had been destroyed, the information available from AWE Health Physics records included doses from every personal film badge dosemeter issued that had registered a dose greater than the minimum recordable level. The numbers involved are shown in Table 2.7, together with the total number of men known to be involved in each operation. For the entire programme, Health Physics records were available for about 21% of test participants. Less than half of these men had recorded a dose above threshold. The proportion of test participants known to have been monitored varied from 2% at Operation Grapple to 96% at Operation Hurricane. From the evidence available, it would appear that there was a greater tendency to monitor individuals at the earlier tests. This is in agreement with the MOD statement of the general policy that during the early trials in Australia almost all participants were monitored. For the later Pacific tests this policy was reviewed and, if it was judged from the experience of the previous trials that measurable exposure was unlikely to occur, then monitoring was not carried out.

For the majority of test participants, the information that was available on the duties they carried out at the test locations was very limited, and thus the scope for assessing the possibility of any unrecorded exposure to radiation was poor. At the time of the previous report MOD advised that four distinct groups of test participants were liable to have been exposed to radiation. These were:

(a) the members of the Buffalo Indoctrinee Force, a group of volunteer Army officers assembled to observe at first hand the effects of a nuclear explosion,

(b) RAF aircrews involved in sampling the radioactive clouds of the explosions,

(c) the RAF active handling flights, who decontaminated aircraft used in cloud sampling,

(d) members of the crew of HMS Diana, which sailed through the fallout plume in Operation Mosaic.

Since the previous report a further group has been identified:

(e) the Target Response Group at Buffalo (largely Army officers and AWE civilians) who re-entered the area of the explosion, in some cases shortly after the detonation, in order to recover data from experiments designed to determine the effects of the explosion on various kinds of target.

The members of the crew of HMS Diana could be identified from the relevant ship's ledger, while the members of the other four groups could be identified from AWE Health Physics records and contemporary reports. The numbers of men involved in each group are shown in Table 2.9 by operation. Except for the crew of HMS Diana, almost all the men had already been identified as having been exposed to radiation, and had recorded radiation exposures. Only one member of the crew of HMS Diana has a recorded radiation dose and MOD informed the study

TABLE 2.8 Numbers of men and collective dose (man mSv) in different dose categories by Service or employer

Dose category (mSv)	Service or employer									
	RN		Army		RAF		AWE		Total	
	No.	Dose	No.	Dose	No.	Dose	No.	Dose	No.	Dose
0.01–0.99	113	43	267	129	349	161	159	76	888	410
1.00–4.99	48	130	78	193	109	219	110	260	345	802
5.00–9.99	25	184	50	304	33	233	52	372	160	1,094
10.00–49.99	36	668	49	1,296	69	1,590	88	1,970	242	5,523
50.00–99.99	0	0	4	275	32	2,349	8	627	44	3,251
>100.00	0	0	0	0	34	5,363	3	553	37	5,915
Total	222	1,026	448	2,197	626	9,915	420	3,858	1,716	16,995

TABLE 2.9 Numbers of test involvements believed by MOD to have been liable to exposure to radiation by group and operation together with collective gamma dose recorded

Location and operation	Special group				
	Buffalo Indoctrinee Force	Aircrew sampling plumes	Active handling flight	Crew of HMS Diana	Target response group
Monte Bello Islands					
Hurricane	0	0	0	0	0
Mosaic	0	19	17	282	0
Emu Field					
Totem	0	3	0	0	0
Maralinga Range					
Buffalo	172	31	22	0	77
Antler	0	28	34	0	0
MEP	0	0	0	0	0
Christmas Island					
Grapple	0	23	28	0	0
Grapple X	0	14	25	0	0
Grapple Y	0	13	35	0	0
Grapple Z	0	34	44	0	0
Brigadoon	0	0	0	0	0
Total participants	172	165	205	282	77
Total with dose	172	161	198	1	77
Collective dose	358.2	8194.1	599.5	0.2	642.4
Mean dose	2.1	49.7	2.9	0.0	8.3

team that this had been incurred while the individual was on escort duties immediately after the first Mosaic test. About half the total collective dose recorded for all test participants (8,194 man mSv out of a total of 16,995 man mSv) was received by aircrew involved in cloud sampling. On average these men had the highest recorded doses in the groups shown in Table 2.9, and they accounted for over 80% of the test participants listed in Table 2.8 whose recorded doses were 50 mSv or more.

MOD also advised that undocumented inhalation or ingestion of radionuclides, if any, was most likely to have occurred among test participants employed by AWE or in men directly involved with the programme of minor trials at Maralinga.

3 Method of follow-up

3.1 Determination of deaths and emigrations

In the previous report, attempts were made to determine the vital status of all test participants and controls on 1 January 1984, and to identify as many as possible of those who had emigrated by that date. In the present analysis, the same information was sought for the period up to 1 January 1991. Details sufficient to identify all men not previously established as having died or emigrated were submitted to the National Health Service (NHS) central registers at Southport and

Edinburgh[7] where searches for these records were made. For men who were found to have died, both the underlying and the contributory causes of death, as stated on the death certificate, were coded according to the ninth revision of the International Classification of Diseases (ICD)[8].

For men who could not be traced on the NHS central registers, the available information was reviewed both at NRPB and by the Service Records Offices. A total of 305 men were found to be still in the Services at the end of the follow-up period. Attempts were made to find the remaining men, with the help of the Health Departments in Belfast, the Isle of Man, Jersey, or Guernsey, as appropriate.

It is widely recognised that the NHS central registers are not always aware of emigrations that have taken place, as the information will only be known if the individual's general practitioner is informed, or if the NHS card is returned. Therefore, details of men in the following categories were submitted to the Contributions Agency of the Department of Social Security (DSS) in Newcastle where a detailed check was carried out for evidence that the man had emigrated or that he had died:

(a) those untraced on the NHS central registers,

(b) those traced on the NHS central registers, but not currently registered with an NHS doctor,

(c) those who were thought to have died, but for whom the NHS central registers were unable to provide a death certificate.

3.2 Determination of cancer incidence

As in the previous report, information on the numbers of men in the study who had died from cancer was supplemented by information indicating that a man had developed cancer. Two sources of information were available on cancers that were not given as the underlying cause of death on a death certificate. Firstly, a proportion of death certificates listed cancer as a contributory cause of death, even when it was not the underlying cause. Secondly, a large proportion of cancers are registered in regional cancer registries and since 1971 this information has been linked with the NHS central registers. Information on cancer registrations for men in the study was passed to the study team whenever it was available from the NHS central registers.

As in the previous analysis, individuals were recorded as having at most one type of cancer in the analysis of cancer incidence. For men who had more than one type of cancer mentioned as an underlying or contributory cause of death or as a cancer registration, one was chosen for the analysis of cancer incidence as follows.

(a) For men whose underlying cause of death recorded on the death certificate was a tumour, this was normally accepted in preference to registrations and contributory causes. There were two exceptions to this rule. Firstly, if a leukaemia appeared as a registration or a contributory cause but not as the underlying cause, it was taken in preference to other tumours. Secondly, if the underlying cause was a tumour of unspecified site or a secondary cancer and information on site and date of diagnosis could be obtained from cancer registration data then the registration data was taken in preference to the death certificate data.

(b) For other men, preference was given to tumours other than non-melanomatous skin cancer, to malignant rather than benign conditions, and, in other circumstances, to the first type of tumour reported.

4 Validation

4.1 Introduction

Before the previous analysis, members of the study team personally carried out a large number of checks to ensure that the data supplied by MOD for use in the study were as complete and accurate as the available sources of information would allow. These included the following:

(a) checks of RN planning documents and ship's logs dating from the time of the tests to ensure that coverage of RN ships participating in the tests was complete and accurate,

(b) checks to ensure that individual names had not been omitted from important source documents containing lists of participants such as ship's ledgers, Army unit records, RAF squadron operational record books, AWE Health Physics material, AWE Trials Series reports, and AWE overseas travel registers,

(c) sample checks to verify that the Service Record Offices had completed the forms for Service personnel in accordance with the guidance notes supplied by the study team, and that doses recorded in the AWE Health Physics records had been correctly transcribed; similar checks were also carried out for AWE and AERE employees by staff of the Medical Research Council's Epidemiological Monitoring Unit[9,10],

(d) sample checks to examine whether the records of all Servicemen who had ever claimed a disability pension or for whom a claim had been made by a dependant were correctly stored in the Service Records Offices.

Details of these checks are given in the previous report[1]. In most cases the outcome was satisfactory. However, it was shown that the Service records of some men in the Army who had made claims or lodged appeals before 1976 had been sent on with the papers relating to the claim, and would not therefore have been found during the course of data compilation for the study[1].

In addition to manual checks of source material by members of the study team, including detailed checks of the available Health Physics material, many further checks of computerised material were carried out at NRPB to eliminate errors, omissions, and inconsistencies. All important information received at NRPB was entered on to the computer twice and the two versions compared for differences. These checks are described in detail in the earlier report and the same rigorous standards were applied in preparing for this second analysis.

4.2 Completeness of coverage of test participants

At the time of the previous report, the study team requested information about test participants from all other organisations known to have complied lists of test participants independently of archival material, and the resulting information was used to estimate the completeness of the coverage of test participants in the main study. The organisations that contributed to this exercise are shown in Table 4.1. For this second analysis, the number of independent respondents was increased by including new names from the current membership list of the British Nuclear Test Veterans Association, the British Atomic Veterans Association, and from lists of men who had been named in claims or appeals to the DSS or in correspondence received by other government departments. For all the new independent respondents the information supplied from these sources was reviewed, and any for whom there was insufficient detail to expect that they

TABLE 4.1 Sources of information on independent respondents

1	British Atomic Veterans Association – list of members and individual questionnaires
2	British Nuclear Test Veterans Association – list of members and individual questionnaires
3	Royal British Legion – individuals named in cases connected with the tests
4	British Broadcasting Corporation – test participants named in correspondence following 'Nationwide' television programme
5	Department of Social Medicine, University of Birmingham – list of test participants
6	Department of Social Security War Pensions Directorate – details of claimants
7	Oxford Eye Hospital – list of test participants with possible or definite diagnosis of cataract
8	Institution of Professional Civil Servants – list of test participants
9	Association of Scientific, Technical and Managerial Staffs – list of test participants
10	National Radiological Protection Board – test participants named in correspondence or inquiries received by NRPB
11	Ministry of Defence – test participants named in correspondence or inquiries received by NRPB
12	Ministry of Defence – individuals identified as test participants in claims or appeals to DSS
13	Ministry of Defence – test participants named in correspondence or inquiries received by various government departments

could be identified at the Service Records Offices or in AWE employment records, or whose test involvement would not have made them eligible in the present study, were discarded. For the remaining 752, identification details were compared with those of the 21,358 test participants enumerated for the main study. Identification details of the 414 independent respondents previously identified but found not to be in the main study were also rechecked against the main list. Two were found to have visited test areas but to have left before the first detonation, so that they had no more potential for radiation exposure than the general public and did not satisfy the revised definition of a test participant, and 48 more were found now to be included in the main study and were re-classified accordingly. Overall there was a total of 2335 independent respondents already included in the main study, compared with 1707 at the time of the previous analysis. Since the previous report, a further 124 men were identified who did not appear to be in the main study, and information about them was sought from MOD similar to that already obtained for the men in the main study. For 110 of these men the service or employment record confirmed test participation, for 7 men the service record was compatible with test participation, and for a further 7 men (including 3 from the NAAFI where there is a policy of destroying records 10 years after an individual leaves employment) the Service record could not be found. There were no new independent respondents for whom it was concluded that test participation was unlikely.

To estimate the percentage of all eligible test participants covered by the main study, the number of independent respondents who had not already been included, but whose test participation was confirmed or probable, was compared with the number of independent respondents who had been included, and the results are shown in Table 4.2. For AWE employees all had been included in the main study, and for the RN almost all. For the Army and the RAF, the proportions were 83% and 74%, respectively. From these data the overall proportion was estimated to be 85% after standardising for Service or employer to the proportions seen in the main study.

TABLE 4.2 Numbers and percentages of independent respondents not included in the main study and those included, by Service

Service or employer	Independent respondents				
	Not included in main study		Included in main study		
	Number	%	Number	%	Total number
RN	7	1	670	99	677
Army	130	17	652	83	782
RAF	337	26	948	74	1,285
AWE	0	0	65	100	65
Total	474	17	2,335	83	2,809
Total standardised to Service distribution of main study		15		85	

4.3 Completeness of ascertainment of mortality and emigration

After the procedures described in Section 3.1 to establish the vital status of the men in the study on 1 January 1991 and to establish which of them had emigrated, the following four independent checks of the completeness of the mortality and emigration data were carried out.

(a) Details of all men not otherwise established to have died or emigrated were submitted to the Contributions Agency of the DSS for a vital status check. For about 90% of the men submitted it was possible to carry out a computerised check based on National Insurance (NI) numbers. For the remaining 10% the NI number supplied by MOD could not be found by computerised search and a manual vital status check was carried out. All but 182 men were identified on DSS records. NHS central registers were able to locate a further 87 deaths with the information provided by DSS.

(b) The vital status checks described above using DSS records did not identify men who had emigrated from the UK, and would not have identified subsequent deaths among them. DSS can only identify a proportion of emigrations and these only by a detailed manual search of their records. It did not prove possible for DSS to carry out detailed emigration searches for all men in the study who were not already known to have died or emigrated. Such searches were, however, carried out for men for whom follow-up appeared unsatisfactory, as described in Section 3.1, and those found to have emigrated have been so recorded. As an additional cross-check, searches were also carried out for a 1% sample of remaining men for whom follow-up at the NHS central registers appeared satisfactory. Out of a total of 354 men in the sample, definite evidence of emigration was found for 7. This implies that the follow-up procedures have missed a total of about 700 emigrations and that the person-years at risk on the study have been overestimated by 1%, and consequently that the mortality rates underestimated by a similar amount. The follow-up procedures were, however, identical for test participants and controls so that the effect is likely to have been of comparable magnitude in each group.

(c) Searches were made on the databases held by the National Registry for Radiation Workers[11] and by the Medical Research Council's Epidemiological Monitoring Unit[10] for information on men in the present study who were AWE employees. One previously unknown death and nine emigrations were found.

(d) MOD Medical Statistics Department made available the data that it held on deaths of Servicemen. This covered the period 1952–1989 for the Army and 1965–1989 for other Services. A cross-check with data held for the present study revealed one additional death.

The vital status of the members of the study population, as determined by the procedures described in Section 3.1, together with the checks listed above, is summarised in Table 4.3. Some 79% of test participants and also 79% of controls were found to be alive and resident in the UK on 1 January 1991; 13% of test participants and also 13% of controls were found to have died; 8% of test participants and 7% of controls were known to have emigrated, and less than 0.5% of each group were lost to follow-up after discharge from full-time service or leaving employment at AWE or AERE. Follow-up to determine mortality was therefore practically complete and comparable in both groups.

TABLE 4.3 Status of test participants and controls on 1 January 1991

	Test participants		Controls	
Status	Number	%	Number	%
Alive	16,797	79	17,721	79
Dead	2,755	13	2,949	13
Emigrated	1,750	8	1,613	7
Lost to follow-up	56	0.3	50	0.2
Total	21,358		22,333	

4.4 Completeness of ascertainment of cancer incidence

Follow-up to determine cancer incidence was necessarily less complete then follow-up for mortality. Only a small proportion of non-fatal cancers are referred to on the death certificate when the individual dies. The national system for cancer registration was poorly developed before 1971, and is still incomplete for the easily treatable non-melatomatous cancers of the skin. Linkage with the NHS central registers has been attempted only for registrations since 1971, and delays in the system of cancer registration and with linkage to the NHS central registers means that, at the time of analysis, data processing by the NHS central registers was finished only for cancers diagnosed up to the end of 1987. At the time of the previous analysis it was reported that for the period for which data processing was nominally complete cancer registrations had not been received for approximately 30% of men for whom there was a mention of cancer on the death certificate[1]. When analysis for the present report commenced the position was broadly similar. Out of a total of 535 deaths in the period 1983–1987 for whom cancer was mentioned on the death certificate, there were 288 for whom no cancer registration information had been received. Details of these men were referred back to the NHS central registers for further investigation. For 144 of these men the NHS central registers had no record of a cancer registration being received, while for the remaining

144 men errors and limitations in the systems in operation at the NHS central registers had led to the registration not being reported to the study team.

Although the available information on cancer incidence is incomplete, it does provide substantially more data than would be obtained from considering mortality alone. If non-melatomatous skin cancers are excluded the number of incident cancers reported was 38% greater than the number of cancer deaths. This is somewhat greater than the 27% recorded nationally for the period 1975–1984, which suggests that the great majority of cancers in the study population must have been detected. The figures for 'incident cancers' are certainly lower than the true incidence of the disease, but the method by which they were obtained should have ensured that this has not introduced any bias against the reporting of cases in the test participants. Confidence that it has not done so is strengthened by the fact that the excess of incident over fatal cancers (excluding non-melatomatous skin cancer) was greater for the test participants (45%) than for the controls (37%).

5 Method of analysis

The methods of analysis used were similar to those for the previous report. Test participants were entered into the study on the date of their first test involvement. For controls the date of entry to the study was the first day such that, if the man had died on that day, he would still have been included in the study; for all groups except soldiers and civilians this was around the time of the overseas visit which led to their inclusion in the control group, while soldier controls were entered into the study on the date of termination of their reserve liability, and civilian controls were entered into the study on the date of the first test involvement of the test participant with whom they were matched.

For the analysis of mortality, men were regarded as at risk until their date of death or emigration, their 85th birthday, or 1 January 1991, whichever came earliest. For the analysis of cancer incidence, they were regarded as at risk similarly, except that men were also removed on their date of cancer registration where appropriate. A total of 14 test participants were excluded from the study on reaching their 85th birthday, among whom 2 deaths, attributed to heart failure and atherosclerosis (ICD code 428.0 and 440.9), and 2 incident cancers (ICD codes 173.4 and 173.8) occurred before the end of the follow-up period. A total of 21 controls were also excluded on reaching age 85, in whom 10 deaths (attributed to carcinoma of the caecal valve, carcinoma of the bronchus (2 deaths), adenocarcinoma of the prostate, anaemia, acute myocardial infarction, ischaemic heart disease, cerebral arteriosclerosis, chronic renal failure, and rheumatoid arthritis with ICD codes 153.4, 162.2, 162.9, 185.0, 285.9, 410.0, 414.9, 437.0, 585.0, 714.0) and 3 incident cancers (with ICD codes 162.2, 188.9, and 195.5) occurred.

In the analyses, each man contributed person-years at risk from the date of his entry to the date of his removal from the study. Person-years were subdivided, as appropriate, by Service or employer, rank, 5-year age group, and calendar year. To compare mortality rates in test participants and controls with those of the nation generally, the numbers of deaths expected in each group were calculated by multiplying the person-years at risk in each age and calendar year group by the corresponding specific mortality rates for men in England and Wales and the results summed. Standardised mortality ratios were then calculated for each disease by dividing the numbers of deaths observed by the corresponding numbers expected. For the years in which the national data were coded to revisions of the ICD earlier than the ninth, disease groups were constructed that approximated as closely as possible to those based on the ninth revision. The statistical significance

of the standardised mortality ratios (SMRs) was calculated by assuming that the number of deaths observed from any cause had a Poisson distribution. Two-sided tests were used for calculating the statistical significance of the SMRs, as both increases and decreases compared with the national rates were of interest.

To compare the mortality rates of the test participants directly with those of the controls, the deaths and person-years at risk were stratified by age, calendar year, Service or employer into four groups (RN, Army, RAF, AWE) and within each of the three Services by rank into officers and men and within AWE employees into social class 1 and others. The relative risk (RR) of mortality in test participants compared with controls was then estimated by maximum likelihood. For this purpose it was assumed that within each stratum the number of deaths among test participants, given the total number of deaths among participants and controls, had a binomial distribution. Significance tests for the RR were based on the score statistic[12]. When the total number of informative strata was less than 60, significance levels were calculated using 10,000 simulations. When the observed deaths were all among the test participants or all among the controls, exact significance levels were calculated. Confidence intervals for the RRs were based on the score function. The same method was used for the analysis of cancer incidence. One-sided tests were used to calculate the statistical significance of the RRs, as the study was designed to test the hypothesis that rates of mortality and cancer incidence were greater among test participants than among controls. When the RR was less than unity, one-sided tests of the hypothesis that rates of mortality and cancer incidence were greater among controls than among test participants were also carried out.

In the analyses comparing cancer incidence rates in test participants with different levels of recorded gamma dose, incident cancers or deaths and person-years were stratified as for the comparison of mortality rates in test participants and controls. The number of incident cancers or deaths expected in each dose category was then calculated internally assuming that within any stratum the death rate was the same in each dose category. Dose categories were indexed by the median dose recorded in each category, and a one-sided test for a trend in relative risk with increasing dose was carried out using the score statistic[12]. In this dose–response analysis each participant was regarded as being at risk from the date of his involvement in a test for which a dose was recorded. For the few men who had received a recorded dose in connection with more than one test, the date of entry was taken to be the latest relevant one.

6 Results

6.1 Introduction

As in the previous report, the question whether participation in the tests has adversely affected the subsequent health of those involved has been examined partly by comparing their mortality with that of the general population of the UK. The interpretation of such a comparison is not straightforward, however, because, even in the absence of any effect of test participation, mortality rates in the test participants would not be expected to be the same as in the general population. Servicemen who served abroad were selected for their physical fitness, so that their mortality from many diseases should be substantially less than average, at least in the early part of the study[13]. In addition, life in the Services involved specific hazards including an increased risk of accidents in all three Services, and an increased risk of mesothelioma and of diseases associated with alcohol in the RN[14]. Compared with the population at large, test participants also included an

unusually high proportion of officers or AWE employees who in civilian life would be allocated on the basis of their occupation to social class 1, in which mortality rates from many diseases have been substantially lower than for the general population[15]. The effect of test participation on health has, therefore, been examined by comparing both the mortality and the incidence of cancer in the test participants with that in the matched controls from the same Services or employer (see Section 2.3).

The present study was undertaken primarily to resolve the uncertainty about the reasons for the differences in the mortality and incidence of leukaemia and multiple myeloma between the test participants and the controls, although the total mortality and incidence of all neoplasms was almost identical in the two groups. On the basis of the earlier results, three hypotheses had been formulated[1], namely that:

(a) test participation caused small hazards of leukaemia (excluding chronic lymphatic leukaemia) and multiple myeloma,

(b) test participation did not cause a detectable hazard of any other cancer or of any other disease that has an appreciable fatality rate,

(c) test participants have smoked less than other similar men in HM forces or employed by AWE.

The new findings have, therefore, been examined, firstly, to see whether these hypotheses are supported by the experience of the subsequent 7 years and, secondly, to provide a comparison between the health of the two study groups over the whole of the period from first observation to the end of 1990, similar to that provided in the previous report to the end of 1983.

6.2 Comparison between old and new data

Tables 6.1–6.4 provide the data needed to test the three hypotheses: namely mortality and incidence of leukaemia, multiple myeloma, lung cancer, and other neoplasms, and mortality from the combined group of bronchitis, emphysema, and chronic obstructive lung disease, and from other diseases in the period covered by the previous report and in the subsequent 7 years. In presenting these data, also shown separately are the data for all the other conditions for which statistically significant differences in incidence or mortality between the participants and the controls had been recorded and which, it had been suggested, should be attributed to chance, and for all accidents and violence, which had been found to have a higher mortality than expected nationally both in participants and in controls. Those conditions for which statistically significant differences had been observed between participants and controls are listed in group A, and all other neoplasms, all neoplasms, all other diseases, and accidents and violence in group B. The numbers for the period up to 31 December 1983 differ slightly from those given in the earlier report, because of the slightly different definition of a test participant used in the present report (see Section 2.2), the inclusion of some men who were untraced at the time of the previous report, and the receipt of some additional cancer registrations for the period up to 31 December 1983 since the earlier report was prepared.

Table 6.1 shows the number of deaths in the test participants and controls, and the relative risks (RR) in the test participants compared with the controls in the two periods for the two groups of causes. Six of the seven diseases in group A (leukaemia, multiple myeloma, cancers of the prostate and kidney, the combined group of bronchitis, emphysema, and chronic obstructive lung disease, and 'other injury and poisoning') had shown statistically significant differences in mortality between the test participants and the controls in the previous report, and these findings remain in

TABLE 6.1 Observed deaths among test participants and controls, and relative risks (RR) of mortality among test participants compared with controls for selected causes of death, by calendar period

Cause of death	Calendar period up to 31 Dec 83					Calendar period 1 Jan 84 – 31 Dec 90				
	Observed deaths		Mortality rate in test participants relative to controls			Observed deaths		Mortality rate in test participants relative to controls		
	Test participants	Controls	RR	Probability[a]	90% CI[b]	Test participants	Controls	RR	Probability[a]	90% CI[b]
A Causes with significant difference between test participants and controls in previous analysis										
Leukaemia	23	6	3.93	0.002	1.71, 9.49	6	11	0.57	0.19	0.22, 1.46
Multiple myeloma	6	0	∞	0.006	1.96, ∞	3	6	0.57	0.33	0.13, 2.17
Cancer of lung	120	158	0.86	0.12	0.70, 1.06	122	145	0.89	0.19	0.72, 1.10
Cancer of prostate	9	22	0.44	0.03	0.21, 0.91	25	19	1.55	0.10	0.90, 2.70
Cancer of kidney	5	21	0.25	0.001	0.10, 0.62	16	15	1.08	0.49	0.56, 2.07
Bronchitis, emphysema and chronic obstructive lung disease	20	38	0.56	0.03	0.34, 0.92	48	33	1.57	0.03	1.05, 2.34
Other injury and poisoning[c]	101	75	1.38	0.03	1.05, 1.81	30	32	1.00	0.56	0.64, 1.57
B Other selected causes of death										
All neoplasms	392	439	0.96	0.31	0.86, 1.08	370	411	0.96	0.30	0.85, 1.08
All neoplasms not in group A	229	232	1.04	0.36	0.89, 1.22	198	215	0.98	0.44	0.83, 1.16
All diseases other than neoplasms	810	869	1.01	0.40	0.93, 1.10	754	793	1.02	0.35	0.94, 1.11
Accidents and violence	315	299	1.06	0.24	0.92, 1.22	57	60	1.03	0.46	0.75, 1.42
Unknown cause	39	41	–	–	–	16	27	–	–	–
All causes	1,556	1,648	1.01	0.39	0.95, 1.07	1,197	1,291	0.99	0.45	0.93, 1.06

Notes
(a) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).
(b) Confidence interval.
(c) Other injury and poisoning – ie other than motor vehicle traffic accidents, drowning and water transport accidents, air and space transport accidents or suicide.

TABLE 6.2 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) for test participants for selected causes of death, by calender period

	Calendar period up to 31 Dec 83				Calendar period 1 Jan 84 – 31 Dec 90			
Cause of death	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]
A Causes with significant difference between test participants and controls in previous analysis								
Leukaemia	23	18.47	1.25	0.29	6	10.55	0.57	0.17
Multiple myeloma	6	5.13	1.17	0.65	3	6.50	0.46	0.18
Cancer of lung	120	175.61	0.68	<0.001	122	153.92	0.79	0.01
Cancer of prostate	9	10.14	0.89	0.76	25	23.11	1.08	0.68
Cancer of kidney	5	10.45	0.48	0.09	16	11.14	1.44	0.17
Bronchitis, emphysema and chronic obstructive lung disease	20	63.64	0.31	<0.001	48	62.59	0.77	0.07
Other injury and poisoning[b]	101	78.71	1.28	0.02	30	22.98	1.31	0.17
B Other selected causes of death								
All neoplasms	392	485.37	0.81	<0.001	370	436.89	0.85	0.001
All neoplasms not in group A	229	264.41	0.87	0.03	198	231.65	0.85	0.03
Other diseases other than neoplasms	810	1,157.05	0.70	<0.001	754	811.66	0.85	<0.001
Accidents and violence	315	247.38	1.27	<0.001	57	57.93	0.98	0.95
Unknown cause	39	–	–	–	16	–	–	–
All causes	1,556	1,889.83	0.82	<0.001	1,197	1,386.47	0.86	<0.001

Notes
(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.
(b) Other injury and posioning – ie other than motor vehicle traffic accidents, drowning and water transport accidents, air and space transport accidents or suicide.

TABLE 6.3 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) for controls for selected causes of death, by calender period

Cause of death	Calendar period up to 31 Dec 83				Calendar period 1 Jan 84 – 31 Dec 90			
	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]
A Causes with significant difference between test participants and controls in previous analysis								
Leukaemia	6	19.04	0.32	<0.001	11	11.25	0.98	1.00
Multiple myeloma	0	5.59	0.00	0.01	6	6.94	0.86	0.85
Cancer of lung	158	193.63	0.82	0.01	145	163.98	0.88	0.14
Cancer of prostate	22	11.80	1.86	0.01	19	25.11	0.76	0.23
Cancer of kidney	21	11.26	1.86	0.01	15	11.84	1.27	0.38
Bronchitis, emphysema and chronic obstructive lung disease	38	72.87	0.52	<0.001	33	67.83	0.49	<0.001
Other injury and poisoning[b]	75	78.50	0.96	0.69	32	24.39	1.31	0.16
B Other selected causes of death								
All neoplasms	439	526.22	0.83	<0.001	411	466.23	0.88	0.01
All neoplasms not in group A	232	283.45	0.82	0.002	215	247.08	0.87	0.04
All diseases other than neoplasms	869	1,261.61	0.69	<0.001	793	957.35	0.83	<0.001
Accidents and violence	299	241.40	1.24	<0.001	60	61.34	0.98	0.90
Unknown cause	41	–	–	–	27	–	–	–
All causes	1,648	2,029.25	0.81	<0.001	1,291	1,484.90	0.87	<0.001

Notes
(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.
(b) Other injury and posioning – ie other than motor vehicle traffic accidents, drowning and water transport accidents, air and space transport accidents or suicide.

TABLE 6.4 Numbers of incident cancers among test participants and controls, and relative risks (RR) of incident cancer in test participants compared with controls for selected types of cancer, by calendar period

	Calendar period up to 31 Dec 83					Calendar period 1 Jan 84 – 31 Dec 90				
	Incident cancers		Incident rate in test participants relative to controls			Incident cancers		Incident rate in test participants relative to controls		
Type of cancer	Test participants	Controls	RR	Probability[a]	90% CI[b]	Test participants	Controls	RR	Probability[a]	90% CI[(b)]
A Types of cancer with significant difference between test participants and controls in previous analysis										
Leukaemia	29	10	2.92	0.002	1.51, 5.78	8	14	0.64	0.21	0.28, 1.44
Multiple myeloma	8	0	∞	0.002	2.48, ∞	5	8	0.71	0.37	0.23, 2.07
Cancer of lung	137	175	0.87	0.13	0.72, 1.06	138	158	0.93	0.28	0.76, 1.13
Cancer of prostate	20	25	0.88	0.39	0.51, 1.50	42	38	1.31	0.14	0.88, 1.95
Cancer of kidney	12	27	0.47	0.02	0.25, 0.87	25	27	0.98	0.52	0.60, 1.60
B Other neoplasms	404	438	0.98	0.38	0.87, 1.10	380	399	1.01	0.49	0.89, 1.13
All neoplasms	610	675	0.97	0.30	0.88, 1.07	598	644	0.99	0.44	0.90, 1.09

Notes

(a) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(b) Confidence interval.

the slightly revised data for the period up to 31 December 1983. For five of these six diseases, the direction of the difference between the participants and the controls was reversed in the second period of follow-up: those conditions that had shown a significantly higher mortality in the earlier period subsequently showed a lower one, and those that had shown a significantly lower mortality subsequently showed a higher one. In no instance, however, was the difference in risk in the second period significant. For other injury and poisoning, for which the RR had been significantly raised in the earlier period, mortality in the two groups was equal in the later one, while for lung cancer, for which the RR for mortality had been significantly below unity in the test participants in the previous report only when the first 10 years of observation were omitted, the RR was not significantly different from unity in either period. The conditions in group B had large numbers of deaths attributed to them in each period and, in contrast to group A, showed closely similar results in each period: the relative risk for test participants being, respectively, 0.96 and 0.96 for all neoplasms, 1.01 and 1.02 for other diseases, and 1.01 and 0.99 for all causes.

Table 6.2 shows similar data for test participants, the comparison in this case being made, not with the experience of the controls but with the numbers of deaths that would have been expected if the participants had experienced the same mortality as all men in the country in the same 5 year age groups in the same years. The table includes data for the four types of cancer in group A for which mortality differed significantly between test participants and controls in the earlier period. As in Table 6.1, the experience of the participants with regard to these cancers was reversed in the later period: the conditions for which the standardised mortality ratio (SMR) was initially greater than unity had SMRs less than unity in the second, while those for which the SMR had been less than unity initially subsequently had SMRs greater than unity. For none of these four types of cancer was the difference between the numbers of observed and expected deaths statistically significant in either period. For lung cancer the SMR was higher in the later period than in the earlier one, but the numbers of deaths observed were significantly lower than expected in both periods. For bronchitis, emphysema, and chronic obstructive lung disease, for which the SMR had been significantly below unity in the earlier period, mortality had increased relative to that of the general population, although it still remained low, while for other injury and poisoning mortality was high compared to the general population in both periods.

For the causes of death in group B, the results in Table 6.2 differ to some extent from those recorded in Table 6.1. The SMR for all neoplasms changed very little (from 0.81 to 0.85) , but the SMR for other diseases rose substantially (from 0.70 to 0.85), although still remaining significantly less than expected from national mortality rates, while the SMR for accidents and violence fell (from 1.27 to 0.95). These two last changes both have a natural interpretation. The mortality for all diseases other than neoplasms had been very low during the first 10 years of the study, as was to be expected from the fact that the men had been medically screened and found fit for active service abroad, and this healthy worker selection effect would be expected to wear off with the passage of time. No similar large effect would, however, have been expected to affect the trend in mortality from accidents and violence. On the contrary, the mortality from these latter conditions would have been expected to be raised during active service (for example, from air accidents in the RAF and drowning in the RN) and to fall towards normal as the men returned to civilian life. These opposing trends largely cancelled in the mortality from all causes which changed very little, the SMR increasing from 0.82 to 0.86, but remaining significantly less than unity even in the second period.

Table 6.3 gives the same set of data for the controls as Table 6.2 gave for the participants. As in the case of the participants, the SMRs for the types of cancer in group A that were higher than unity in the first period were reduced in the second, and those that were less than unity in the first period were increased. In particular the SMR for multiple myeloma, which had been zero, was close to unity in the second period. In no case was the difference between the numbers of deaths observed and expected in the second period statistically significant. For bronchitis, emphysema, and chronic obstructive lung disease mortality remained low in both periods, while for other injury and poisoning mortality did not differ significantly from the national rates in either period. For the conditions in group B the changes from the first to the second period closely paralleled those for the participants in Table 6.2: the SMR for all neoplasms increasing slightly, for all other diseases increasing substantially, and for accidents and violence decreasing. As with the participants the SMR for all causes rose slightly but remained statistically significantly less than unity.

Lastly, Table 6.4 shows the relative risks of incident cancers in test participants and controls for the same types of cancer given in Tables 6.1–6.3. As with the mortality, the relative risks that were significantly increased in the earlier period were less than unity in the second, while cancer of the kidney, which was significantly decreased in the first period, was close to unity in the second. For lung cancer, for which the incidence rate had been significantly lower in test participants than in controls in the previous report, the deficit was no longer statistically significant for the updated data set in the earlier period, and the RR was closer to unity in the later period than the earlier one. For all remaining neoplasms and for all neoplasms combined the RRs were close to unity in both periods.

6.3 Mortality in test participants and controls

The total mortality in test participants and controls, and that from three broad groups of causes of death (neoplasms, other diseases, and accidents and violence) over the whole period up to the end of 1990 are shown in Table 6.5. For 2% of the deaths in each group (55 deaths among test participants and 68 deaths among controls) no cause could be obtained. As the proportions are small and similar in both groups they are unlikely to have affected the comparison of mortality in the test participants directly with that of the controls (RRs), and they have generally been ignored. They can be taken into account when the mortality of test participants is compared with that in the general population by multiplying the cause-specific mortality of the test participants by 1.02, but this is a very crude adjustment as many of the deaths from unknown causes occurred abroad and so a disproportionate number may have been due to accidents or diseases of sudden onset, rather than to long-lasting diseases such as cancer.

From Table 6.5, it can be seen that mortality from all causes, from all neoplasms, and from all other diseases was substantially lower in both groups than in men of the same ages in England and Wales, but that mortality from accidents and violence was higher (all SMRs highly significantly different from unity). Very little difference was observed between the experience of the test participants and the controls (all RRs close to, and not significantly different from, unity). In so far as there was any difference in the total mortality and the mortality from neoplasms, they were lower in the participants.

As mentioned in Sections 6.1 and 6.2, the selection of physically fit men for participation in the tests means that for many diseases mortality among test participants would be expected to be lower than that of the general population, at least for the early period of the study, so that the

TABLE 6.5 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls and relative risks (RR) of mortality in test participants compared with controls, by broad cause of death

Cause of death (ICD Codes 9th Revision)	Test participants				Controls				Mortality rate in test participants relative to controls		
	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
All neoplasms	762	921.99	0.83	<0.001	850	992.06	0.86	<0.001	0.96	0.22	0.88, 1.04
Other diseases	1,564	2,048.12	0.76	<0.001	1,662	2,218.13	0.75	<0.001	1.02	0.32	0.96, 1.08
Accidents and violence	372	305.28	1.22	<0.001	359	302.72	1.19	0.002	1.06	0.24	0.93, 1.20
Unknown	55	–	–	–	68	–	–	–	–	–	–
All causes	2,753	3,275.40	0.84	<0.001	2,939	3,512.92	0.84	<0.001	1.00	0.46	0.96, 1.05

Notes

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(c) Confidence interval.

TABLE 6.6 Observed deaths (O) and standardised mortality ratios (SMR) among test participants by time since start of first test participation and broad cause of death

		Time since start of first test participation (years)			
Cause of death		<10	10–19	20–29	30+
Neoplasms	O	53	159	350	200
	SMR	0.72	0.85	0.81	0.87
Other diseases	O	97	319	755	393
	SMR	0.54	0.70	0.79	0.86
Accidents and violence	O	147	94	105	26
	SMR	1.34	1.09	1.24	1.08
Unknown	O	6	18	24	7
All causes	O	303	590	1,234	626
	SMR	0.84	0.81	0.83	0.88

existence of a hazard emerging many years after the tests might be masked by examining all periods combined. To investigate this possibility further, the mortality of test participants is compared in Table 6.6 with that of the general population for different periods after the start of test participation. For diseases, the patterns seen are typical of those found commonly in occupational studies: for non-neoplastic diseases the effect of the selection of healthy men for participation in the tests is especially pronounced in the first 10 years (SMR = 0.54) and then wears off progressively; for neoplasms the effect of selection is weaker in the initial period than for other diseases (SMR = 0.72) and there is little trend after the initial 10 year period, although SMRs remain considerably below unity for the entire period of the study. For accidents and violence the opposite effect is seen, and the SMR is highest in the first 10 years, with lower values in later periods as the men changed from Service to civilian life. In many studies of populations known to have received substantial exposures to ionising radiation, the resulting risk of radiation-induced cancer appears greater in the period more than 10 years after exposure than in the initial 10 year period[16]. Most of the data presented in the remainder of this section are, with the exception of leukaemia, limited to the period 10 or more years after initial test participation (ie after entry to the study), partly to avoid the period when the healthy worker selection effect is most pronounced, and partly to maximise the opportunity for detecting any cancer hazard attributable to test participation that was not apparent at the time of the earlier report. The corresponding tables including the entire follow-up period are given in Appendix B.

Table 6.7 shows that mortality from neoplasms and from all other diseases was substantially lower in officers (including AWE employees in professional occupations) than in other ranks, but that mortality from accidents and violence was higher. This was true both for test participants and for controls. Among both officers and other ranks mortality from neoplasms was slightly lower in test participants than in controls.

Table 6.8a compares the mortality in the study population with that of the nation generally, separately for the three Services and for AWE employees. The findings were similar for test participants and controls. For neoplasms, mortality in the RN was similar to that in the nation generally, while in the other two Services and among AWE employees it was lower. For other diseases mortality was lower than that of the nation generally in all three Services and among AWE employees, and for accidents and violence mortality tended to be higher than the national average

TABLE 6.7 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls for officers and other ranks more than 10 years after start of first test participation, together with relative risks (RR) of mortality in test participants compared with controls, by broad cause of death

		Test participants				Controls				Mortality rate in test participants relative to controls		
Cause of death	Status[a]	O	E	SMR	Probability[b]	O	E	SMR	Probability[b]	RR	Probability[c]	90% CI[d]
Neoplasms	Officers	166	258.20	0.64	<0.001	191	288.70	0.66	<0.001	0.95	0.35	0.79, 1.14
	Other ranks	543	590.62	0.92	0.05	596	611.87	0.97	0.53	0.95	0.22	0.86, 1.05
Other diseases	Officers	318	582.17	0.55	<0.001	333	655.18	0.51	<0.001	1.07	0.21	0.94, 1.23
	Other ranks	1149	1,287.50	0.89	<0.001	1,206	1,338.56	0.90	<0.001	0.99	0.41	0.92, 1.06
Accidents and violence	Officers	36	29.76	1.21	0.27	43	34.47	1.25	0.17	0.90	0.36	0.60, 1.34
	Other ranks	189	165.73	1.14	0.08	155	158.00	0.98	0.84	1.17	0.09	0.97, 1.41
Unknown	Officers	12	–	–	–	16	–	–	–	–	–	–
	Other ranks	37	–	–	–	45	–	–	–	–	–	–
All causes	Officers	532	870.13	0.61	<0.001	583	978.35	0.60	<0.001	1.01	0.43	0.91, 1.12
	Other ranks	1,918	2,043.83	0.94	0.01	2,002	2,108.40	0.95	0.02	0.99	0.38	0.94, 1.04

Notes

(a) Includes AWE employees in social class 1 with officers and other employees with other ranks.

(b) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(c) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(d) Confidence interval.

in the three Services and lower for AWE employees. Table 6.8b compares mortality among the test participants in the three Services and AWE employees with that of the nation after adjusting for the social class structure of each of the four groups. For neoplasms the SMR is slightly reduced for the RN and is slightly increased for the other two Services and for AWE employees, while for diseases other than neoplasms the use of social class specific national rates increases the SMRs in all four groups, although they still all remain less than unity. Table 6.8b also compares the mortality in test participants directly with that of the controls for the three Services and for AWE employees. For neoplasms the RR is slightly less than unity for all four groups, while for other diseases the RR is slightly less than unity in the RAF and slightly greater than unity in the other three groups. In no case is the RR significantly different from unity.

Not all organs are equally susceptible to the induction of cancer by ionising radiation, particularly if there is any possibility that they may have been irradiated as a result of the inhalation or ingestion of radionuclides that might lead to some organs of the body receiving much greater doses than others. Table 6.9 provides detailed results for 27 specific types of cancer. For leukaemia, for which the increase in relative risk has been observed to be at a maximum within the first 5 years of irradiation[17], data for the entire period of follow-up are given, and also for the period 2–25 years after first test participation, during which any effect of exposure to radiation is most likely to have been seen. For other sites of cancer, the period 10 or more years after first test participation is given. When compared with the nation as a whole, there were significant deficits for a number of types of cancer in both the test participants and the controls, and there was a significant excess only for cancer of the kidney among the controls. For some types of cancer, mortality in the test participants exceeded that in the controls, while for others the reverse was true. The mortality rate in test participants relative to controls was significantly greater than unity at the 5% level or less only for cancer of the bladder and leukaemia. For cancer of the bladder there were 27 deaths among test participants and 11 among controls, giving a mortality rate in test participants 2.69 times that in controls ($p = 0.004$; 90% confidence interval (CI) 1.42, 5.20). For leukaemia, when the entire follow-up period is included, there were 29 deaths in test participants and 17 among controls, giving a mortality rate in test participants 1.75 times that in controls ($p = 0.05$; 90% CI 1.01, 3.06). When only the period 2–25 years after start of first test participation is included, the mortality rate from leukaemia in test participants relative to controls is 3.38 (90% CI 1.45, 8.25). For both bladder cancer and leukaemia the numbers of deaths observed among test participants were similar to those expected from national rates [cancer of the bladder: SMR = 1.04, $p = 0.84$; leukaemia (whole follow-up period): SMR = 1.00, $p = 1.00$; leukaemia (2–25 years only): SMR = 1.23, $p = 0.38$]. For both diseases the numbers of deaths observed among controls were, however, substantially less than would be expected from national rates [cancer of the bladder: SMR = 0.39, $p < 0.001$; leukaemia (whole follow-up period): SMR = 0.56, $p = 0.01$; leukaemia (2–25 years only): SMR = 0.34, $p = 0.003$]. For cancer of the liver the mortality rate in test participants was estimated to be greater than that in controls by a factor of 2.46, but the increase did not quite reach statistical significance ($p = 0.07$). The relative risk in test participants was significantly less than unity at the 5% level only for cancers of the mouth, tongue and pharynx (RR = 0.45, $p = 0.03$) and for cancer of the lung (RR = 0.85, $p = 0.04$). For the remaining types of cancer shown in Table 6.9 the mortality rate experienced by the test participants was similar to that of the controls ($p > 0.10$ in all cases, including multiple myeloma).

Table 6.10 shows the results for specific causes of death other than neoplasms. For many of the individual causes mortality was lower than in men of the same ages in England and Wales

TABLE 6.8a Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls more than 10 years after start of first test participation by Service and broad cause of death

		Test participants				Controls			
Cause of death	Service	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]
Neoplasms	RN	268	259.71	1.03	0.62	305	290.78	1.05	0.41
	Army	127	169.98	0.75	<0.001	122	132.90	0.92	0.36
	RAF	271	349.59	0.78	<0.001	307	403.09	0.76	<0.001
	AWE	43	69.54	0.62	<0.001	53	73.79	0.72	0.01
Other diseases	RN	514	566.02	0.91	0.03	571	634.94	0.90	0.01
	Army	325	374.12	0.87	0.01	236	283.86	0.83	0.004
	RAF	532	771.36	0.69	<0.001	630	897.40	0.70	<0.001
	AWE	96	158.17	0.61	<0.001	102	177.53	0.57	<0.001
Accidents and violence	RN	84	60.77	1.38	0.005	94	70.92	1.33	0.01
	Army	57	51.19	1.11	0.44	33	31.53	1.05	0.79
	RAF	78	75.10	1.04	0.73	67	81.65	0.82	0.11
	AWE	6	8.42	0.71	0.49	4	8.37	0.48	0.13
Unknown	RN	13	–	–	–	23	–	–	–
	Army	16	–	–	–	8	–	–	–
	RAF	17	–	–	–	27	–	–	–
	AWE	3	–	–	–	3	–	–	–
All causes	RN	879	886.49	0.99	0.81	993	996.64	1.00	0.91
	Army	525	595.28	0.88	0.003	399	448.29	0.89	0.02
	RAF	898	1,196.05	0.75	<0.001	1,031	1,382.14	0.75	<0.001
	AWE	148	236.14	0.63	<0.001	162	259.69	0.62	<0.001

Note
(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

TABLE 6.8b Observed deaths (O), deaths expected from social class specific national rates (E_s), and standardised mortality ratios corrected for social class (SMR_s) more than 10 years after start of first test participation, together with relative risks (RR) of mortality in test participants compared with controls, by Service and broad cause of death

		Test participants[a]				Mortality rate in test participants relative to controls		
Cause of death	Service	O	E_s	SMR_s	Probability[b]	RR	Probability[c]	90% CI[d]
Neoplasms	RN	268	262.43	1.02	0.73	0.98	0.44	0.85, 1.13
	Army	127	161.75	0.79	0.01	0.84	0.09	0.67, 1.05
	RAF	271	329.25	0.82	0.001	0.98	0.42	0.85, 1.13
	AWE	43	62.07	0.69	0.01	0.91	0.38	0.63, 1.32
Other diseases	RN	514	550.47	0.93	0.12	1.01	0.44	0.91, 1.12
	Army	325	343.40	0.95	0.33	1.03	0.40	0.89, 1.19
	RAF	532	702.92	0.76	<0.001	0.97	0.32	0.88, 1.07
	AWE	96	138.18	0.69	<0.001	1.16	0.17	0.90, 1.50
Accidents and violence	RN	84	53.44	1.57	<0.001	1.04	0.41	0.81, 1.35
	Army	57	45.12	1.26	0.09	1.02	0.51	0.68, 1.54
	RAF	78	65.50	1.19	0.14	1.23	0.13	0.92, 1.64
	AWE	6	7.12	0.84	0.72	1.45	0.40	0.43, 5.14
Unknown	RN	13	–	–	–	–	–	–
	Army	16	–	–	–	–	–	–
	RAF	17	–	–	–	–	–	–
	AWE	3	–	–	–	–	–	–
All causes	RN	879	862.32	1.02	0.57	1.00	0.49	0.92, 1.08
	Army	525	548.00	0.96	0.34	0.98	0.39	0.87, 1.10
	RAF	898	1,094.32	0.82	<0.001	0.98	0.37	0.91, 1.06
	AWE	148	207.13	0.71	<0.001	1.09	0.25	0.89, 1.33

Notes

(a) E_s and SMR_s are based on national mortality rates among men in social class 1 for officers and for AWE employees with jobs in social class 1, and on national mortality rates among men in social class 3 (manual and non-manual combined) for other men.

(b) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(c) One-sided test that the RR is greater than unity ($RR \geq 1.00$) or less than unity ($RR < 1.00$).

(d) Confidence interval.

TABLE 6.9 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls, and relative risks (RR) of mortality in test participants compared with controls, for leukaemia and 26 other specific types of cancer. For leukaemia the whole follow-up period and the period 2 to 25 years after start of first test participation are considered, and for other specific cancers the period more than 10 years after start of first test participation is considered

	Test participants				Controls				Mortality rate in test participants relative to controls		
Type of cancer (ICD Codes 9th Revision)	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
Cancer of the mouth, tongue, pharynx (141,143-149)	10	14.05	0.71	0.29	22	14.76	1.49	0.09	0.45	0.03	0.22, 0.93
Cancer of the oesophagus (150)	39	32.47	1.20	0.25	35	34.39	1.02	0.93	1.19	0.26	0.79, 1.80
Cancer of stomach (151)	48	68.29	0.70	0.01	55	73.17	0.75	0.03	0.94	0.41	0.66, 1.32
Cancer of large intestine and rectum (153, 154 excl. 154.3, 159.0)	82	93.40	0.88	0.25	82	99.03	0.83	0.09	1.04	0.44	0.79, 1.36
Cancer of liver (155)	12	9.00	1.33	0.31	5	9.45	0.53	0.15	2.46	0.07	0.92, 6.92
Cancer of gallbladder (156)	1	4.25	0.24	0.14	4	4.52	0.89	0.83	0.24	0.17	0.01, 1.79
Cancer of pancreas (157)	38	37.77	1.01	1.00	35	40.05	0.87	0.43	1.11	0.37	0.74, 1.68
Cancer of larynx (161)	8	8.44	0.95	1.00	14	8.96	1.56	0.13	0.60	0.17	0.26, 1.34
Cancer of lung (162, 163)	228	309.25	0.74	<0.001	285	331.01	0.86	0.01	0.85	0.04	0.73, 0.99
Cancer of bone (170)	1	2.37	0.42	0.53	1	2.43	0.41	0.53	1.07	0.73	0.04, 29.19
Cancer of connective and soft tissue (171)	2	3.86	0.52	0.45	3	3.96	0.76	0.80	0.74	0.55	0.11, 4.37
Malignant melanoma (172)	15	9.28	1.62	0.10	13	9.39	1.38	0.25	1.22	0.37	0.61, 2.44
Other skin cancer (173)	0	2.13	0.00	0.18	0	2.27	0.00	0.18	–	–	–
Cancer of prostate (185)	34	32.78	1.04	0.86	41	36.19	1.13	0.45	0.93	0.44	0.62, 1.41
Cancer of testis (186)	4	4.81	0.83	0.83	3	4.41	0.68	0.64	1.23	0.54	0.27, 5.91
Cancer of bladder (188, 189.3-189.9)	27	26.08	1.04	0.84	11	28.22	0.39	<0.001	2.69	0.004	1.42, 5.20
Cancer of kidney (189.0-189-2)	21	20.26	1.04	0.91	32	21.31	1.50	0.03	0.68	0.11	0.41, 1.12
Tumours of central nervous system (191,192,224,225,239.6)	39	38.69	1.01	1.00	38	39.53	0.96	0.81	1.04	0.48	0.69, 1.56
Cancer of thyroid (193)	0	1.58	0.00	0.28	1	1.66	0.60	0.74	0.00	0.51	0.00, 13.14
Cancer of adrenals (194.0)[d]	1	0.64	1.57	0.47	2	0.65	3.10	0.14	0.58	0.55	0.03, 6.31
Hodgkin's disease (201)	3	8.02	0.37	0.08	8	7.87	1.02	1.00	0.41	0.15	0.10, 1.41
Non-Hodgkin's lymphoma (200,202.0-202.3,202.5-202.9)	19	22.46	0.85	0.53	17	23.26	0.73	0.21	1.02	0.56	0.55, 1.89
Multiple myeloma (203 excl. 203.1,238.6)	8	11.13	0.72	0.38	6	11.82	0.51	0.08	1.51	0.31	0.55, 4.26
Leukaemia: 2-25 yrs (202.4,203.1, 204-208)	20	16.29	1.23	0.38	6	17.63	0.34	0.003	3.38	0.005	1.45, 8.25
Leukaemia: whole follow up period	29	29.01	1.00	1.00	17	30.28	0.56	0.01	1.75	0.05	1.01, 3.06
Polycythaemia vera (238.4)[e]	1	0.77	1.30	1.00	1	0.82	1.22	1.00	1.12	0.71	0.04, 30.71
Other specified neoplasms (140-239 excl. above, 196-199 and 239)	13	18.96	0.69	0.17	16	19.79	0.81	0.43	0.90	0.46	0.46, 1.78
Unspecified neoplasms (196-199, 239, excl. 239.6)	31	44.65	0.69	0.04	42	47.47	0.88	0.47	0.83	0.25	0.54, 1.26
All neoplasms (140-239)	709	848.83	0.84	<0.001	787	900.56	0.87	<0.001	0.95	0.19	0.87, 1.04

Notes

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(c) Confidence interval.

(d) Cancers of the adrenal glands are included only from 1958 in the comparison with national rates, no deaths in participants and none in controls occurred before this.

(e) Polycythaemia vera is included only from 1968 in the comparison with national rates, no deaths in participants and none in controls occurred before this.

TABLE 6.10 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls, and relative risks (RR) of mortality in test participants compared with controls more than 10 years after start of first test participation, for causes of death other than neoplasms

Cause of death (ICD Codes 9th Revision)	Test participants				Controls				Mortality rate in test participants relative to controls		
	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
A Diseases related to smoking											
Coronary heart disease (410–414)	831	1,037.67	0.80	<0.001	905	1,101.52	0.82	<0.001	0.96	0.22	0.89, 1.04
Bronchitis, emphysema and chronic obstructive lung disease (491, 492, 496, 519)[d]	65	117.74	0.55	<0.001	68	129.96	0.52	<0.001	1.01	0.52	0.74, 1.36
Aortic aneurysm (441)	37	34.60	1.07	0.67	43	37.47	1.15	0.37	0.95	0.45	0.64, 1.41
B Diseases related to alcohol											
Cirrhosis of liver, alcoholism and alcoholic psychosis (303, 305.0, 291, 571)	49	32.50	1.51	0.01	50	33.29	1.50	0.01	1.07	0.40	0.75, 1.52
C Other diseases											
Infectious and parasitic diseases (1–139)	14	18.15	0.77	0.35	14	18.85	0.74	0.30	1.08	0.50	0.54, 2.14
Diseases of nervous system (320–389)	32	44.51	0.72	0.06	32	46.10	0.69	0.03	1.11	0.38	0.71, 1.73
Other diseases of circulatory system (390–459, excl. 410–414, 441)	265	330.80	0.80	<0.001	253	356.31	0.71	<0.001	1.11	0.14	0.95, 1.29
Other diseases of respiratory system (460–519, excl. 491–2, 496, 519)	65	99.97	0.65	<0.001	67	107.76	0.62	<0.001	1.08	0.37	0.79, 1.47
Other diseases of digestive system (520–579 excl. 571)	46	55.76	0.82	0.20	37	59.03	0.63	0.003	1.33	0.13	0.90, 1.96
Remaining diseases other than neoplasms (001–799.8 excl. above diseases in A and B and 140–239)	63	97.94	0.64	<0.001	70	103.41	0.68	<0.001	0.93	0.37	0.68, 1.26
D Accidents and violence											
Motor vehicle traffic accidents (E810–E819)	47	49.95	0.94	0.72	50	48.73	1.03	0.89	0.90	0.35	0.63, 1.30
Drowning and water transport accidents (E830–E838, E910, E984)	11	9.94	1.11	0.75	11	9.70	1.13	0.75	0.93	0.52	0.41, 2.09
Air and space transport accidents (E840–E845)	11	1.51	7.27	<0.001	10	1.43	7.01	<0.001	1.10	0.50	0.49, 2.46
Suicide (E950–E959)	64	61.34	1.04	0.75	60	60.65	0.99	0.95	1.05	0.44	0.76, 1.44
Other injury and poisoning (E800–E999 excl. above)	92	72.72	1.27	0.03	67	71.95	0.93	0.60	1.35	0.04	1.02, 1.79
All known causes, other than neoplasms	1,692	2,065.12	0.82	<0.001	1,737	2,186.18	0.79	<0.001	1.02	0.30	0.96, 1.08

Notes

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(c) Confidence interval.

(d) ICD code 519 (other diseases of respiratory system) is included as it is impossible to separate deaths attributed to this cause from those attributed to ICD code 496 (chronic airways obstruction, not elsewhere classified) in calculating expected deaths prior to 1979.

in both test participants and controls, and sometimes much lower. Mortality was significantly raised in both test participants and controls, however, for diseases related to alcohol and for air and space transport accidents. When the mortality of test participants was compared with that of controls, the RR was in some cases less than unity and in some cases greater. Only for the category 'other injury and poisoning' was the RR significantly greater than unity (RR = 1.35, p = 0.04). Inspection of the individual causes of death in this category showed that there were more deaths among test participants than controls from railway accidents (3 in test participants, 0 in controls), fires (9 in test participants, 2 in controls), electric currents (5 in test participants, 1 in controls), and from injuries with no external cause specified on the death certificate (eg specified only as multiple injuries) (12 in test participants, 6 in controls). For no other cause of death shown in Table 6.10 did either the increase or the deficit in participants reach statistical significance ($p > 0.10$ in all other cases).

6.4 Cancer incidence in test participants and controls

Table 6.11 shows the numbers of known incident cancers in test participants and controls and the relative risk of incident cancer in the two groups 10 or more years after entry to the study. When all neoplasms are considered together the incidence rate in test participants was slightly less than that in controls, although the difference is not statistically significant (RR = 0.97, $p > 0.27$). As in the analysis of mortality, rates in the test participants were higher than those in the controls for some individual types of cancer and lower for others. Types of cancer with significantly higher incidence rates among the test participants than the controls were liver cancer (RR = 2.89, p = 0.03), bladder cancer (RR = 1.45, p = 0.03), and leukaemia [RR (whole follow-up period) = 1.61, p = 0.05; RR (2–25 years only) = 3.45, $p < 0.001$]. In contrast, the incidence rate in test participants was significantly lower than in controls for skin cancers other than malignant melanoma (RR = 0.77, p = 0.02). Other types of cancer for which somewhat different rates were observed in test participants and controls, but for which the difference did not quite reach statistical significance, were lung cancer (RR = 0.88, p = 0.07) and tumours of the central nervous system (RR = 1.40, p = 0.06). For all other types of cancer, including multiple myeloma, the difference between the incidence rate in test participants and controls was no greater then might be expected by chance ($p > 0.10$ in all cases).

Review of the evidence on which the 61 diagnoses of leukaemia were based had no effect on the relative incidence of the disease in participants and controls, but it did have a minor effect on the distribution of cases by type. No information could be obtained about 12 cases (9 participants and 3 controls) because the hospital where the patient had been diagnosed could not be identified or the notes had been destroyed. In all but one of the others, the diagnosis of leukaemia had been satisfactorily established. In one case, affecting a participant certified as having chronic myeloid leukaemia, an independent haematological consultant preferred the diagnosis of chronic myeloproliferative disorder (ICD code 238.7) but as he suspected that the patient had some form of chronic leukaemia, here the diagnosis of chronic leukaemia has been retained and the case recorded as type unspecified (ICD code 208.1). In six other cases, review also led to a change in the classification of the leukaemia type: one participant and one control certified, respectively, as having acute lymphatic and acute monocytic leukaemia were reclassified as having acute myeloid leukaemia; one participant reported to have chronic myeloid leukaemia was reclassified as having acute myeloid leukaemia; one control reported to have unspecified myeloid leukaemia was reclassified as having chronic myeloid leukaemia; one control with unspecified leukaemia and

TABLE 6.11 Numbers of incident cancers (I) among test participants and controls, and relative risks (RR) of incident cancer in test participants compared with controls, for 27 types of cancer. For leukaemia the whole follow-up period, and the period 2–25 years after start of first test participation, are considered. For all other specific cancers the period more than 10 years after start of first test participation is considered

	Test participants	Controls	Incidence rate in test participants relative to controls		
Type of cancer	I	I	RR	Probability[a]	90% CI[b]
Cancer of tongue, mouth, pharynx	22	29	0.80	0.27	0.48, 1.33
Cancer of oesophagus	44	40	1.17	0.27	0.80, 1.72
Cancer of stomach	57	67	0.91	0.33	0.66, 1.24
Cancer of large intestine and rectum	112	127	0.93	0.30	0.74, 1.16
Cancer of liver	14	5	2.89	0.03	1.11, 7.94
Cancer of gallbladder	2	4	0.45	0.30	0.07, 2.35
Cancer of pancreas	39	37	1.08	0.41	0.72, 1.62
Cancer of larynx	25	29	0.93	0.45	0.57, 1.50
Cancer of lung	261	315	0.88	0.07	0.76, 1.02
Cancer of bone	4	2	2.32	0.27	0.45, 14.52
Cancer of connective and soft tissue	4	7	0.55	0.26	0.16, 1.77
Malignant melanoma	31	23	1.45	0.12	0.89, 2.36
Other skin cancer	123	164	0.77	0.02	0.63, 0.95
Cancer of prostate	62	63	1.12	0.29	0.82, 1.54
Cancer of testis	18	18	0.92	0.46	0.50, 1.69
Cancer of bladder	64	46	1.45	0.03	1.03, 2.03
Cancer of kidney	37	49	0.79	0.17	0.54, 1.16
Tumours of central nervous system	57	42	1.40	0.06	0.98, 2.00
Cancer of thyroid	3	3	0.92	0.61	0.18, 4.65
Cancer of adrenals	1	2	0.58	0.55	0.03, 6.30
Hodgkin's disease	9	15	0.57	0.14	0.25, 1.25
Non-Hodgkin's lymphoma	33	30	1.06	0.46	0.67, 1.67
Multiple myeloma	12	8	1.66	0.20	0.72, 3.94
Leukaemia: whole follow-up period	37	24	1.61	0.05	1.00, 2.57
Leukaemia: 2–25 years	28	9	3.45	<0.001	1.72, 7.10
Polycythaemia vera	4	5	0.80	0.50	0.22, 2.89
Other specified neoplasms	49	45	1.09	0.37	0.76, 1.58
Unspecified neoplasms	36	47	0.85	0.28	0.58, 1.26
All neoplasms	1,154	1,244	0.97	0.27	0.91, 1.04

Notes

(a) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(b) Confidence interval.

one with acute monocytic leukaemia were reclassified, respectively, as having acute lymphatic leukaemia and acute unspecified leukaemia. In the other 42 cases the diagnosis of leukaemia type was unchanged.

Although leukaemia is the type of cancer most closely associated with ionising radiation, not all subtypes are equally susceptible to induction by ionising radiation and chronic lymphatic leukaemia has not been shown to be increased in any irradiated population. The cases allocated to the four major types of leukaemia following the review have, therefore, been examined separately

TABLE 6.12 Numbers of incident leukaemias (I) among test participants and controls, and relative risk (RR) of incident leukaemia in test participants compared with controls classified by subtype of leukaemia following the review of diagnostic information

(a) Whole follow-up period

	Test participants	Controls	Incident rate in test participants relative to controls		
Subtype of leukaemia	I	I	RR	Probability[a]	90% CI
Acute myeloid[b]	18	14	1.39	0.23	0.72, 2.68
Chronic myeloid[b]	5	1	4.71	0.13	0.67, 81.25
Acute lymphatic	5	3	1.43	0.47	0.33, 6.57
Chronic lymphatic	7	4	1.89	0.24	0.59, 6.41
Unspecified myeloid	1	0	∞	0.47	0.09, ∞
Unspecified acute	0	2	0.00	0.31	0.00, 3.76
Unspecified chronic	1	0	∞	0.49	0.08, ∞
All subtypes	37	24	1.61	0.05	1.00, 2.57
All subtypes other than chronic lymphatic	30	20	1.55	0.08	0.92, 2.62

(b) Period 2–25 years after start of first test participation

	Test participants	Controls	Incident rate in test participants relative to controls		
Subtype of leukaemia	I	I	RR	Probability[a]	90% CI
Acute myeloid[b]	14	4	3.53	0.01	1.24, 10.93
Chronic myeloid[b]	5	0	∞	0.05	0.94, ∞
Acute lymphatic	4	1	5.45	0.11	0.69, 100.52
Chronic lymphatic	5	3	2.31	0.22	0.56, 10.39
Unspecified acute	0	1	0.00	0.53	0.00, 14.45
All subtypes	28	9	3.45	<0.001	1.72, 7.10
All subtypes other than chronic lymphatic	23	6	3.98	0.001	1.73, 9.62

Notes
(a) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).
(b) Monocytic leukaemia has been classed with myeloid.

to see if the pattern expected from exposure to ionising radiation is apparent. The results are shown in Table 6.12. When the entire period of follow-up is considered, the incidence rate in test participants exceeded that of controls for all four major subtypes of leukaemia, although for none of them does the increase reach statistical significance. When chronic lymphatic leukaemia is excluded, the magnitude of the relative risk among the test participants compared with the controls is slightly lower, and the increase no longer reaches statistical significance (RR = 1.61, p = 0.05 including chronic lymphatic leukaemia, and RR = 1.55, p = 0.08 excluding it). When only the period 2–25 years after first test participation is considered the incidence rate in test participants

again exceeds that in controls for all four major subtypes of leukaemia, and the excess reaches statistical significance for two of them (acute myeloid and chronic myeloid). When chronic lymphatic leukaemia is excluded, the relative risk among the remaining subtypes is slightly increased, and the excess in test participants compared with controls remains highly significant statistically (RR = 3.45, $p < 0.001$ including chronic lymphatic leukaemia, and RR = 3.98, $p = 0.001$ excluding it).

6.5 Mortality and cancer incidence in test participants by type and degree of exposure

The mortality from leukaemia and other neoplasms among test participants known to have been monitored for exposure to radiation is compared with national expected values in Table 6.13, according to whether or not a non-zero gamma dose had been recorded for them. For both diseases, and regardless of whether the entire period of follow-up or just the 2–25 year period is taken for leukaemia, mortality was lower than that expected from national rates. Furthermore, for both diseases mortality was lower relative to the national values for those with a recorded gamma dose than for those without. The relationship between malignant disease and recorded gamma dose is examined further in Table 6.14, where the numbers of incident cases of leukaemia and other neoplasms are shown for each category of recorded dose, together with the numbers expected under the hypothesis of no trend in cancer incidence with recorded dose. For both diseases, and regardless of whether the entire period of follow-up or just the 2–25 year period is considered for leukaemia, there is little evidence of a trend in incidence with recorded dose and, in so far as there is any trend at all, the tendency is for incidence to decrease with recorded dose.

Mortality from leukaemia and other neoplasms among the test participants is also shown subdivided by the nature of their test participation in Table 6.15. For leukaemia, the number of deaths observed was less than the number expected from national rates among test participants present at a major operation, test participants in groups identified by MOD as liable to exposure to radiation, and test participants employed by AWE or directly involved in the minor trials at Maralinga, ie those in whom undocumented inhalation or ingestion of radionuclides, if any, is most likely to have occurred. Only among test participants not in any of these three groups did the number of deaths observed from leukaemia exceed the number expected from national rates. For other neoplasms, the number of deaths observed was less than the number expected from national rates in all four groups.

6.6 Study of jobs held by those with leukaemia or multiple myeloma

At the time of the previous report, mortality and cancer incidence was significantly raised in test participants relative to controls for both leukaemia and multiple myeloma. In order to investigate whether these diseases were concentrated among individuals with any specific jobs, information was sought from MOD on the jobs carried out by all the men known to have developed leukaemia (other than chronic lymphatic leukaemia) or multiple myeloma. For comparison, similar information was also sought for three other test participants matched to each man who developed leukaemia or multiple myeloma by having a similar pattern of test involvement, birth in the same 5 year calendar period, and survival to the date of diagnosis of the affected man's disease, but otherwise selected at random. The relative risk of leukaemia or multiple myeloma within specific job categories was then examined using conditional logistic regression for matched sets[12]. The

TABLE 6.13 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among monitored test participants with and without a recorded gamma dose, for selected causes of death. For leukaemia the whole follow-up period, and the period 2–25 years after start of first test participation are considered. For other neoplasms the period more than 10 years after start of first test participation is considered

	Monitored test participants with no recorded gamma dose				Test participants with a recorded gamma dose			
Cause of death	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	4	5.08	0.79	0.68	2	2.91	0.69	0.78
Leukaemia: 2–25 years	2	2.51	0.80	0.79	1	1.52	0.66	0.75
Other neoplasms: 10+ years	134	162.90	0.82	0.02	64	96.93	0.66	<0.001

Note
(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

TABLE 6.14 Numbers of incident cancers observed (I) and expected (E_I) for monitored test participants by dose category, for selected types of cancer. For leukaemia the whole follow-up period and the period 2–25 years after start of first test participation are considered. For other neoplasms the period more than 10 years after start of first test participation is considered

Type of cancer		Dose category (mSv) <0.01	0.01–0.99	1.00–4.99	5.00–9.99	10.00–49.99	≥50.00	Probability[a]	Direction of trend[b]
Leukaemia: whole follow-up period	I	5	2	2	0	0	0	0.66	–ve
	E_I[c]	5.69	1.70	0.75	0.24	0.57	0.05		
Leukaemia: 2–25 years	I	2	2	1	0	0	0	0.79	–ve
	E_I	3.31	1.04	0.36	0.11	0.17	0.01		
Other neoplasms: 10+ years	I	212	47	17	11	25	2	0.76	–ve
	E_I	207.89	43.34	23.96	12.65	22.53	3.62		

Notes

(a) One-sided test that the trend is greater, or less than, zero.

(b) –ve: Rate tends to decrease with increasing recorded dose.
+ve: Rate tends to increase with increasing recorded dose.

(c) E_I is calculated internally, assuming no trend in cancer incidence with dose.

TABLE 6.15 Observed deaths (O) and standardised mortality ratios (SMR) for test participants by nature of test participation for selected types of For leukaemia the whole follow-up period and the period 2–25 years after start of first test participation are considered. For other neoplasms the period more than 10 years after start of first test participation is considered

	Test participants at a major operation (15,633 men)			Test participants in groups identified by MOD as liable to exposure to radiation (5,118 men)			Test participants employed by AWE or directly involved in the minor trials at Maralinga[a] (1,041 men)			Other test participants (5,165 men)			All test participants (21,358 men)		
Type of cancer	O	SMR	Probability[b]	O	SMR	Probability[b]	O	SMR	Probability[b]	O	SMR	Probability[b]	O	SMR	Probability[b]
Leukaemia: whole follow-up period	19	0.87	0.59	7	0.83	0.73	2	0.96	1.00	9	1.41	0.31	29	1.00	1.00
Leukaemia: 2–25 years	10	0.85	0.67	3	0.70	0.64	1	0.89	1.00	9	2.22	0.04	20	1.23	0.38
Other neoplasms: 10+ years	539	0.86	<0.001	209	0.77	<0.001	49	0.66	0.003	129	0.74	<0.001	685	0.83	<0.001

Notes

(a) Those in whom undocumented inhalation or ingestion of radionuclides, if any, is most likely to have occurred.

(b) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

TABLE 6.16 Numbers of cases of leukaemia (excluding chronic lymphatic leukaemia) and other test participants matched for age and test involvement, by job, and relative risk (RR) of leukaemia

Job	Number of: Test participants with leukaemia	Other test participants	RR	Probability[a]	95% CI[b]
Flying duties	1	11	0.25	0.28	0.01, 1.86
Cooks, caterers	0	13	0.00	0.04	0.00, 0.91
Mechanics/engineers	3	5	1.80	0.64	0.28, 9.25
Office workers	4	7	1.79	0.57	0.36, 7.68
Senior officers	2	2	3.00	0.52	0.22, 41.39
Fitters	2	5	1.22	1.00	0.11, 8.92
Electrical workers	2	10	0.58	0.77	0.06, 2.89
Drivers	1	1)			
Wireless operators	0	3)			
Sanitary dutymen	0	1)			
Balloon operators	0	1)			
Metal workers	1	1)	0.63	0.77	0.10, 2.79
Technicians	1	1)			
Marines	0	3)			
Carpenters	0	2)			
Sappers not otherwise specified	5	17	0.85	1.00	0.21, 2.90
Servicemen with no known speciality	6	3	6.00	0.02	1.28, 37.08
AWE employees with jobs such that they are likely to have been close to or handled radioactive material at the tests	1	2	1.73	1.00	0.02, 156.75
Other AWE employees	1	2	1.73	1.00	0.02, 156.75
Total	30	90			

Notes
(a) Two-sided test of RR = 1.
(b) Confidence interval.

TABLE 6.17 Numbers of cases of multiple myeloma and other test participants matched for age and test involvement, by job, and relative risk (RR) of multiple myeloma

Job	Number of: Test participants with multiple myeloma	Other test participants	RR	Probability[a]	95% CI[b]
Flying duties	1	3	1.00	1.00	0.02, 21.27
Cooks, caterers	0	1	0.00	1.00	0.00, 117.00
Mechanics/engineers	2	3	3.00	0.75	0.14, 196.39
Office workers	1	10	0.27	0.36	0.01, 2.12
Senior officers	3	4	3.00	0.45	0.32, 38.30
Fitters	1	4	0.72	1.00	0.01, 9.72
Electrical workers	0	1	0.00	1.00	0.00, 117.00
Drivers	0	1)			
Wireless operators	0	0)			
Sanitary dutymen	0	0)			
Balloon operators	0	1)			
Metal workers	0	0)	0.00	0.84	0.007, 7.26
Technicians	0	0)			
Marines	0	1)			
Carpenters	0	0)			
Sappers not otherwise specified	1	0	∞	0.50	0.108, ∞
Servicemen with no known speciality	1	3	1.00	1.00	0.02, 21.27
AWE employees with jobs such that they are likely to have been close to or handled radioactive material the tests	2	4	2.28	1.00	0.09, 169.99
Other AWE employees	1	3	1.00	1.00	0.01, 130.30
Total	13	39			

Notes
(a) Two-sided test of RR = 1.
(b) Confidence interval.

TABLE 6.18 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among independent respondents known at the time of the previous analysis, for selected causes of death, by calendar period

	Calendar period up to 31 Mar 86				Calendar period 1 Apr 86 – 31 Dec 90			
Cause of death	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]
All neoplasms	49	9.46	5.18	<0.001	4	4.95	0.81	0.82
Leukaemia	4	0.38	10.66	<0.001	0	0.12	0.00	1.00
Multiple myeloma	0	0.10	0.00	1.00	0	0.08	0.00	1.00
Other neoplasms	45	8.98	5.01	<0.001	4	4.75	0.84	0.83
Other diseases	24	22.09	1.09	0.67	13	9.74	1.34	0.33
Accidents and violence	1	5.08	0.20	0.07	0	0.69	0.00	0.65
Unknown	1	—	—	—	1	—	—	—
All causes	75	36.63	2.05	<0.001	18	15.38	1.17	0.52

Note
(a) Two-sided test.

results are summarised in Tables 6.16 and 6.17. For most jobs, the relative risk of developing leukaemia was not significantly different from unity. However, among the nine Servicemen with no known speciality there were six leukaemias compared with only three controls and the relative risk of leukaemia in this group was significantly raised (RR = 6.00, 95% CI 1.28, 37.08). The six men with leukaemia had attended a variety of tests, but all were in the RN compared with only one of the three controls, thus raising the question of whether the risk of leukaemia was raised among test participants in the RN generally. The analysis was therefore repeated classifying the cases of leukaemia and other test participants according to Service rather than job. A total of 11 cases of leukaemia and 19 controls were in the RN, giving a relative risk of 2.46, which was not significantly different from unity (95% CI 0.81, 7.92; p = 0.12). The men with leukaemia in the RN took part in a range of different operations. Seven of them were based on ships: HMS Narvik at Hurricane, HMS Warrior at Grapple (2 men), HMS Alert at Grapple, HMS Messina at Grapple X, HMS Ulysses at Grapple Y, and HMS Scarborough at Grapple Z. The remaining four men in the RN with leukaemia were shore-based: one was based on Christmas Island for Grapple X, Grapple Y, and Grapple Z, and three were based at Maralinga in 1958, 1963 and 1963, respectively.

For multiple myeloma, the results of the comparison of jobs for cases and other test participants is shown in Table 6.17. For no job category was the relative risk significantly raised.

6.7 Mortality in independent respondents

In the previous report, mortality up to 31 December 1983 was examined in the 412 independent respondents* who had been notified to NRPB prior to 31 March 1986 and found not to be in the main study. Mortality from all causes was significantly increased in this group, and the number of deaths observed was almost double the number expected from the corresponding age- and calendar-year-specific national rates. Cancer mortality was also significantly increased, and the number of deaths observed was over five times the number expected from national rates. It was not surprising that mortality in this group would be raised during this period, as the names of many of those concerned are likely to have been forwarded to the organisations listed in Table 4.1 specifically because the men had died. If selective reporting had been the reason for the increased mortality, then the mortality rates during the period after enrolment ceased would no longer be raised. In order to study this issue, mortality in the same 414 men was examined separately for the period up to the close of enrolment for the group and subsequently. The results, which are shown in Table 6.18, confirm the high level of mortality in the earlier period. For the period after enrolment ceased, however, mortality from all causes was close to that expected from national rates, mortality from all cancers was less than that expected from national rates and similar to that among test participants included in the study, and there were no further deaths from leukaemia.

Mortality was also examined in the 110 new independent respondents whose details had become available to NRPB only after 31 March 1986 and who were not already included in the main study, and the results are shown in Table 6.19. There was a total of 13 deaths observed from all neoplasms in the group, compared with only 4.22 expected, indicating that the same tendency to report selectively men who had died occurred among these men as had occurred in the earlier group.

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* A total of 414 independent respondents were included in the previous report, but 2 were found not to satisfy the revised definition of a test participant (see Section 4.2 for further details), and so were excluded.

TABLE 6.19 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among independent respondents not known at the time of the previous analysis, for selected causes of death

Cause of death	O	E	SMR	Probability[a]
All neoplasms	13	4.22	3.08	<0.001
Leukaemia	0	0.16	0.00	1.00
Multiple myeloma	2	0.05	37.02	0.001
Other neoplasms	11	4.01	2.74	0.003
Other diseases	10	9.22	1.08	0.87
Accidents and violence	0	2.01	0.00	0.19
Unknown	0	–	–	–
All causes	23	15.45	1.49	0.07

Note
(a) Two-sided test.

7 Discussion

7.1 General considerations

As described previously, no comprehensive list of test participants was compiled at the time of the tests. To identify test participants to be included in the study, it was therefore necessary to carry out a series of extensive searches of MOD records dating from the time of the tests. Inevitably, a list compiled in this way could not be complete. At the time of the previous report, it was estimated that approximately 83% of eligible men had been included. For the present analysis all additional MOD archival material that has subsequently been found has been used, and extensive searches were made for all test participants whose Service record could not previously be found. These efforts have raised the completeness of the study to an estimated 85%, but there still remain approximately 15% of eligible test participants that could not be identified from MOD archival material.

The failure to include all eligible men in the study inevitably raises the question of whether there is any potential for differential selection amongst those included, as Service records for men who have made claims for disability might have been differentially mislaid or, conversely, the fact that a man has made a claim might have ensured that his Service record was obtained. In the previous analysis, it was shown that some men in the Army who had made claims or lodged appeals before 1976 had been omitted from the study, as their Service records had been removed from the archive at the time of the claim and never replaced. Although this aspect was worrying, it could have had very little effect, both because deaths of men in the Army before 1976 contributed only 15% of the total, and because excluding the Army from the analysis had very little effect on the results. In the present analysis the period of additional follow-up, which provides a 73% increase in the number of deaths, is almost all prospective in that the names of the men to be included were available to NRPB at the beginning of the follow-up period and their inclusion is certainly unrelated to any diseases they subsequently developed, thus eliminating the possibility of differential selection during this period.

A clear example of the potential for difference between retrospective and prospective follow-up is illustrated by the experience of the 412 men who were identified at the time the previous analysis was being carried out but who were found not to have been included in the main study. These men were identified in the period up to 31 March 1986 and it is likely that the names of many of those concerned became known specifically because the men had died. It was therefore to be expected that their mortality up to the end of the enrolment period would be substantially raised (see Table 6.18). The subsequent period of follow-up shows a very different picture, however, with overall mortality now close to that expected from national rates and cancer mortality (for which the SMR had been 5.18 in the earlier period) having an SMR of 0.81 in the later period, similar to that for the test participants who had been included in the study (see Table 6.5).

An increased level of mortality or cancer incidence resulting from test participation could be obscured by including in the list of test participants men who were only peripherally involved. Although details of the precise role that each man played were usually not available, it has been possible to identify 1503 men who appeared to have had no more potential for radiation exposure than the general public because they left the test sites before any nuclear explosion occurred, and these have now been excluded from the main study, thus eliminating any dilution effect that the inclusion of this group might otherwise have had. Their follow-up has, however, been continued and the results are presented in Appendix A. In addition, results have been examined for various subgroups of test participants, including those known to have been exposed to radiation, those in whom undocumented inhalation or ingestion, if any, is most likely to have occurred, those witnessing a major operation, and also those involved in each operation (see Section 6.5 and Appendix C). In this way, the chance of detecting harmful effects associated with attending the tests generally, or with taking part in any particular operation has been maximised. Caution is needed, however, in interpreting these results, as some statistically significant excesses must be expected to be thrown up solely by the play of chance, when many subgroups are examined.

Another way in which harmful effects associated with the tests might have been obscured stems from the fact that all the men who took part were selected as being fit and healthy, not only for active Service or employment by AWE, but also for travel overseas specifically to take part in the tests. It was to be expected, therefore, that the SMRs for test participants would be lower than those of men in the nation as a whole in the years immediately after the tests, and would increase with the passage of time (see Table 6.6). To eliminate any dilution that the inclusion of this initial period might have in detecting harmful effects associated with the tests, the main tables in Sections 6.3–6.5 exclude the first 10 years after entry to the study for both test participants and controls, although the corresponding tables including the entire period of follow-up are also given in Appendix B. Exclusion of the initial 10 years after start of test participation also maximises the chance of detecting harmful effects appearing many years after test participation that had not yet become manifest at the time of the previous report as, in many studies of persons known to have received substantial exposures to radiation, the resulting increase in cancer risk is concentrated in the period more than 10 years after exposure for many types of cancer[10]. There are a few specific examples where the relative risk of radiation-induced cancer appears to be concentrated in the early years after exposure, notably leukaemia after exposure to the atomic explosions at Hiroshima and Nagasaki and irradiation for ankylosing spondylitis[17,18], and also bone cancer in patients injected with radium-224[19] and lung cancer following exposure to radon progeny[20]. For leukaemia, the results for the entire period of follow-up and also the period 2–25 years after start of first test

participation in all appropriate tables are included, whereas for bone cancer and lung cancer the previous study provided no suggestion of any increase in the period shortly after the tests.

7.2 Objectives of the present study

The primary objectives of the present study were to see whether the hypotheses that were formulated as a result of the earlier study could be confirmed or negated by extending the observations for a further period of 7 years, and to examine the long-term effects of participating in the weapon testing programme on the health of those involved. The hypotheses formulated from the earlier study were that:

(a) test participation caused small hazards of leukaemia (excluding chronic lymphatic leukaemia) and multiple myeloma,

(b) test participation did not cause a detectable hazard of any other cancer or of any other disease that has an appreciable fatality rate,

(c) test participants have smoked less than other similar men in HM forces or employed by AWE.

7.3 Leukaemia and multiple myeloma

The first hypothesis, that test participation may have caused small hazards of leukaemia (other than chronic lymphatic leukaemia) and multiple myeloma, was based mainly on the observation that during the period up to 31 December 1983 the relative risks of these diseases were significantly greater in the test participants than in their controls (see Tables 6.1 and 6.4). The evidence in support of this hypothesis was, however, weak because the magnitude and the statistical significance of both excesses were chiefly due to an exceptionally small number of men in the control group who had developed either disease, rather than to the occurrence of a large number among test participants, when comparison was made with the experience of the nation as a whole (see Tables 6.2 and 6.3). The finding of such low mortality rates in the controls was surprising, as there was no reason to think that men in the Armed Forces could have a particularly low incidence of either disease, and an alternative hypothesis was that the low incidence in the controls was due to chance. The experience of the additional period of follow-up has supported this alternative hypothesis: for both leukaemia and multiple myeloma the numbers of deaths observed in the controls in the period from 1 January 1984 to 31 December 1990 are close to those expected from national mortality rates (Table 6.3), whereas the numbers of deaths observed among test participants, which had been slightly greater than would be expected from national rates in the period up to 31 December 1983, were considerably below the numbers expected nationally during the extended period (see Table 6.2). Consequently the relative risk of each of these diseases in participants compared with controls is less than unity for the new period of follow-up (see Table 6.1).

At the time of the previous report, the evidence available from other studies indicated that there might be an unusually close link between multiple myeloma and radiation and this had contributed to the formulation of the hypothesis. This evidence is now less strong. The excess of multiple myeloma in the workers of the Hanford plant in the USA, which was striking when it was first reported[21], has subsequently ceased to be statistically significant[22], and the positive dose–response relationship in the survivors of the Hiroshima and Nagasaki atomic bombings, which was observed in a study based on death certificates[18] has not been confirmed in a new study based on registrations of confirmed cases[23].

The totality of the data now available on the rate of multiple myeloma among test participants indicates that the number of deaths that has occurred is somewhat lower than would be expected from national mortality rates, and furthermore that neither the incidence of nor the mortality from this disease appears exceptionally high in the test participants compared with the controls. It is therefore concluded that the apparent increase in multiple myeloma in test participants compared with controls present in the previous report was a chance finding, due primarily to the exceptionally low rate of the disease experienced by the controls.

The interpretation of the results for leukaemia is less straightforward. Firstly, there is conclusive evidence that the proportionate increase in risk from whole-body exposure to x-rays and gamma-rays is substantially greater for leukaemia than for other cancers, and that the proportionate increase is greatest within 10 years of exposure and continues, although at a lower level, for over 30 years. It was therefore anticipated, before any results were obtained, that if any risk had occurred it would most likely be revealed by an increased incidence of leukaemia between (say) 2 to 25 years after an individual's first test participation. Compared with national rates, a small excess was indeed observed in this period which has, not surprisingly, continued to be observed with the addition of the new data (20 deaths observed against 16.29 expected, SMR = 1.23, $p = 0.38$, see Table 6.9) as very few observations during this period were added. Secondly, the incidence of leukaemia in the participants in this 2–25 year period is significantly greater than that in the controls (28 against 9, RR = 3.45, $p < 0.001$, see Table 6.11). Thirdly, a report on the health of Royal New Zealand Navy (RNZN) personnel who participated in Operations Grapple, Grapple X, Grapple Y, and Grapple Z has been published[6] which shows that they experienced a statistically significant increase in deaths from leukaemia, whether compared with national rates (4 observed against 0.6 expected, $p = 0.003$) or with a control group of RNZN personnel who did not attend the tests (RR = 5.58, 90% CI 1.04, 41.6).

This evidence is, however, much weaker than it might appear. Firstly, continued observation to the end of 1990 (38 years from the first test and 23 years from the last clean-up operation) has shown that the mortality from leukaemia in the participants was almost precisely what would have been expected if they had experienced the normal mortality experienced by men of the same ages in the country as a whole (29 deaths observed against 29.01 expected, Table 6.9). Secondly, continued observation of the controls has shown that the very low mortality from leukaemia recorded in the first period (SMR 0.32 up to 31 December 1983) was atypical, the mortality in the extended period being very close to that expected from national rates (11 observed against 11.25 expected, SMR 0.98, see Table 6.3) so that the relative risk in the participants in the latter period was reduced from 3.93 to 0.57 (Table 6.1). Thirdly, the highest relative mortality in the participants compared to national rates (9 deaths observed against 6.38 expected; SMR = 1.41, see Table 6.15) was in men who were neither present at a major test, nor in groups identified by MOD as liable to exposure to radiation, nor among men employed by AWE or directly involved in the minor trials at Maralinga (ie those in whom undocumented inhalation or ingestion, if any, is most likely to have occurred); nor was there any evidence of an increasing risk with increasing dose (see Table 6.14). The recorded doses of external radiation were, moreover, very small (17 man Sv in total) and, on the best evidence now available, they would be estimated to have caused a less than 50% chance of the development of one fatal case in the entire cohort[24,25,26]. Fourthly, it is difficult to attribute the excess in the RNZN personnel to participation in the tests. According to MOD, the RNZN ships were at least 40 km from the hypocentre of the explosions which would have ensured that they did not receive any detectable amount of direct irradiation. Both ships visited

Christmas Island after the tests[6] but this can hardly have exposed crews to any material risk when the British who served on Christmas Island and participated in the Grapple series of tests experienced only a marginal increase in risk, if indeed they experienced any risk at all (16 deaths observed against 14.30 expected from national rates for all UK participants present at a Pacific ocean test). MOD has reported[27] that there was little measured fallout on Christmas Island which could be attributed to the UK tests; the levels of radioactive deposition that were found were generally consistent with the pattern of global fallout at the time. None of the leukaemias observed in RNZN personnel was a chronic lymphatic leukaemia and so certainly unrelated to radiation exposure. Three of the four, however, occurred more than 25 years after the tests, which would be unexpected if they were caused by irradiation at the time of the tests.

On balance, it seems most likely that the excess of leukaemia in the test participants compared with controls that was recorded in the previous report was, as with multiple myeloma, a chance finding due to the occurrence of an exceptionally low rate of disease in the controls. The possibility that the participants did experience some small risk of developing leukaemia in the first 25 years after the tests cannot be ruled out, but, if they did, there is no evident explanation for it.

7.4 Other diseases

The second hypothesis engendered in the previous report, that test participation did not cause a detectable hazard of other neoplasms or of any other disease that has appreciable fatality rate, is strongly supported in the further data. Most importantly, the mortality rates from all neoplasms and from all causes have continued to be almost identical in participants and controls in the extended period (RRs of 0.96 and 0.99, respectively, see Table 6.1) as they were in the initial period (RRs of 0.96 and 1.01) and they have continued, in both groups, to be less than expected from national mortality rates. As was to be expected, however, the SMR rose slightly in the extended period, because, by that time, the healthy worker effect would have largely, if not completely, worn off.

Compared with the experience of the nation generally, the test participants experienced significantly lower rates for the whole period of observation, even though mortality from accidents and violence was raised (see Table 6.5). Two factors in particular were responsible for this: the selection of fit and healthy men referred to above, and the relatively high proportion of officers and others in professional occupations compared to the proportion categorised in social class 1 in the nation as a whole (see Table 6.7). Adjustment has been made for these factors, by omitting the first 10 years after the start of test participation, when the impact of selection on diseases other than neoplasms was particularly marked, and by making comparison with social class specific rates. Mortality among test participants from neoplasms still remains low for all groups except the RN, in whom it is comparable to that of the nation generally, whereas overall mortality is close to that expected nationally for those in the RN and the Army, and remains low for those in the RAF or employed by AWE (see Table 6.8b). In all these groups, however, the experience of the test participants remains close to that of the controls.

When a large number of individual diseases are considered, it is to be expected that some differences will occur purely by chance. This is clearly illustrated in Tables 6.1–6.4 where the unexpectedly high mortality rates from cancers of the prostate and kidney in the controls in the period of follow-up to 31 December 1983 disappear in the extended period with the result that the corresponding deficits in the participants not only cease to be significant but disappear as well. In

the present analysis, the mortality of the test participants has been compared with that of the controls for a total of 42 different causes of death (27 cancer sites, and 15 other causes of death). As one-sided tests have been used to compare the mortality of test participants and controls, it is to be expected that in such a study an average of four significant differences would occur by chance. In fact five have occurred, including leukaemia which has been discussed above. The four additional ones are increases in mortality from bladder cancer and 'other injury and poisoning' in the test participants, and deficits in the numbers of deaths from lung cancer and cancers of the mouth, tongue and pharynx. If cancer incidence rather than mortality is considered, the number of significant differences remains the same, but the conditions vary and there are now increases of cancers of the liver and bladder, and of 'other injury and poisoning' in the test participants, and a deficit of skin cancers other than malignant melanoma. For 'other injury and poisoning' the excess was present in the previous report and has remained (see Table 6.1), and it is not surprising that this has occurred for 1 cause out of the total of 42 different causes of death examined. For cancer of the bladder the data are suggestive of a chance effect. The discrepancy between test participants and controls is greater for mortality (RR = 2.69, see Table 6.9) than for the larger number of incident cases (RR = 1.45, see Table 6.11), and is almost entirely due to an extremely low mortality (and presumably incidence) in the controls when compared to the nation as a whole (SMR = 0.39, see Table 6.9).

For liver cancer the excess mortality among test participants compared with controls is also largely caused by a low rate among the controls (SMR = 0.53, see Table 6.9), as was presumably the excess incidence, for which numbers were much the same (Table 6.11). Liver cancer is, however, an unsatisfactory diagnosis, as the liver is a common site for the metastatic spread of cancer from elsewhere. Such cancers should be classed as cancers of unknown primary site, as most of them usually are. Sometimes, however, they are classed as liver cancer, unspecified whether primary or secondary, and so combined with the true 'hepatomas' or 'hepatocellular carcinomas' that arise in the liver. Examination of the detailed description on the death certificates and cancer registration records shows that several of the so-called liver cancers should not have been so described and the numbers of definite primary liver cancers in the two groups were, respectively, 10 and 4. This difference is only of suggestive significance ($p = 0.09$), and could well be due to chance. Most liver cancers in the British population are due to viral hepatitis or alcoholic cirrhosis of the liver, while liver cancers in tropical Africa and Asia are due to a combination of viral hepatitis and the consumption of food contaminated by fungi that produce a powerful carcinogen (aflatoxin) as a product of their metabolism. Excess deaths from liver cancer were also recorded in the group of Servicemen who had visited the test sites but were excluded from the present study because they had left before the tests were carried out (3 deaths observed against 0.67 expected, $p = 0.03$, see Table A3) but there is no obvious reason why visits to these areas should have caused particular exposure to any of the known causes of the disease.

7.5 Smoking habits of test participants compared with controls

The third hypothesis formulated in the previous report, that the test participants may have smoked fewer cigarettes than their matched controls, arose because the relative risks of mortality from chronic obstructive lung disease and of the incidence of lung cancer, the two major diseases most closely related to smoking, were significantly lower in the participants than in the controls. This is not supported by the additional data. In the revised data set, the relative risk of incident lung

cancer is not significantly lower in the participants than in the controls either in the period up to 31 December 1983, or in the extended period (see Table 6.4), or in the whole period (RR = 0.88, p = 0.07, see Table 6.11). For bronchitis, emphysema, and chronic obstructive lung disease, rates in test participants exceeded those in controls in the extended follow-up period (see Table 6.1), and rates in test participants and controls for the entire period of follow-up are now very similar (see Table 6.10). It is concluded that the results in the previous report suggesting that test participants may have smoked fewer cigarettes than their matched controls were chance observations, and that it would be inappropriate to consider smoking-related diseases separately from other diseases in examining the effect of test participation on life expectancy or on rates of cancer generally.

8 Conclusions

It is concluded from this study that participation in the nuclear weapon testing programme has not had a detectable effect on the participants' expectation of life, nor on their risk of developing cancer or other fatal diseases. The possibility that the participants experienced a small risk of developing leukaemia in the first 25 years after the tests cannot be ruled out but, as the risk was not concentrated in those involved in any particular test, those known to have been exposed to radiation, or those with any particular job, possible explanations for such a risk are unknown and it is concluded that the excess of leukaemia in test participants compared with controls that was noted in the previous report is likely to have been a chance finding. The possible risk of developing multiple myeloma noted in the previous report was not confirmed in the longer follow-up period and, in the light of the additional evidence available, now also seems likely to have been a chance finding. The further data obtained in this study do not support the idea that the participants smoked less than the controls, a hypothesis based on the relatively low mortality from two diseases closely related to smoking that had been reported previously. Other statistically significant differences between the morbidity and mortality of the participants and their controls that had been noted previously and were attributed to chance were nearly all found to have disappeared in the extended data. Other differences were found in their place, as was anticipated would happen when so many conditions were studied. These, in their turn, are considered probably to be chance findings.

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10 References

1 Darby, S C, Kendall, G M, Fell, T P, O'Hagan, J A, Muirhead, C R, Ennis, J R, Ball, A M, Dennis, J A, and Doll, R. Mortality and incidence of cancer in UK participants in UK atmospheric nuclear weapons tests and experimental programmes. Chilton, NRPB-R214 (1988) (London, HMSO).

2 Darby, S C, Kendall, G M, Fell, T P, O'Hagan, J A, Muirhead, C R, Ennis, J R, Ball, A M, Dennis, J A, and Doll, R. A summary of mortality and incidence of cancer in men from the United Kingdom who participated in the United Kingdom atmospheric nuclear weapon tests and experimental programmes. *Br. Med. J.*, **296**, 332–338 (1988).

3 Carter, M W, and Moghissi, A A. Three decades on nuclear testing. *Health Phys.* **33**, 55 (1977).

4 Commonwealth Department of Health. Health of atomic test personnel. Canberra, Australian Government Publishing Service (1983).

5 Raman, S, Dulberg, C S, and Spasoff, R A. Mortality of Canadian military personnel exposed to radiation: Atomic test blasts and Chalk River nuclear reactor clean-ups, 1950s. Ottawa, University of Ottawa Department of Epidemiology and Community Medicine (1984).

6 Pearce, N, Prior, I, Methuen, D, Culling, C, Marshall, S, Auld, J, de Boer, G, and Bethwaite, P. Follow-up of New Zealand participants in British atmospheric nuclear weapon tests in the Pacific. *Br. Med. J.*, **300**, 1161–1166 (1990).

7 Office of Population Censuses and Surveys. The National Health Service Central Register as an Aid to Medical Research. A Guide for Potential Applicants. London, OPCS (1982).

8 World Health Organization. Manual of the International Statistical Classification of Diseases, Injuries and Causes of Death. 9th Revision. Geneva, World Health Organization (1977).

9 Beral, V, Inskip, H, Fraser, P, Booth, M, Coleman, D, and Rose, G. Mortality of employees of the United Kingdom Atomic Energy Authority, 1946–1979. *Br. Med. J.*, **291**, 440–447 (1985).

10 Beral, V, Fraser, P, Carpenter, L, Booth, M, Brown, A, and Rose, G. Mortality of employees of the Atomic Weapons Establishment 1951–82. *Br. Med. J.*, **297**, 757–770 (1988).

11 Kendall, G M, Muirhead, C R, MacGibbon, B H, O'Hagan, J A, Conquest, A J, Goodill, A A, Butland, B K, Fell, T P, Jackson, D A, Webb, M A, Haylock, R G E, Thomas, J M, and Silk, T J. Mortality and occupational exposure to radiation: First analysis of the National Registry for Radiation Workers. *Br. Med. J.*, **304**, 220–225 (1992).

12 Breslow, N E, and Day, N E. *Statistical Methods in Cancer Research*, Volume II. The Design and Analysis of Cohort Studies. Lyon, International Agency for Research on Cancer (1987).

13 Fox, A J, and Collier, P F. Low mortality rates in industrial cohort studies due to selection for work and survival in the industry. *Br. J. Prev. Soc. Med.*, **30**, 225 (1976).

14 Darby, S C, Muirhead, C R, Doll, R, Kendall, G M, and Thakrar, B. Mortality among United Kingdom Serviceman who served abroad in the 1950s and 1960s. *Br. J. Ind. Med.*, **43**, 793–804 (1990).

15 Office of Population Censuses and Surveys, Occupational Mortality. The Registrar General's Decennial Supplement for England and Wales, 1970-72. London, HMSO, Series DS No. 1 (1978).

16 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, effects and risks of ionizing radiation. Report to the General Assembly, with Annexes. New York, United Nations (1988).

17 Darby, S C, Doll, R, Gill, S K, and Smith, P G. Long term mortality after a single treatment course with x-rays in patients treated for ankylosing spondylitis. *Br. J. Cancer*, **55**, 179–190 (1987).

18 Shimizu, Y, Kato, H, and Schull, W J. Studies of the mortality of A-bomb survivors, 9: Mortality, 1950–1985; Part 2: Cancer mortality based on the recently revised doses (DS 86). *Radiat. Res.*, **121**, 120–141 (1990).

19 Mays, C W, Spiess, H, Chmelovsky, D, and Kellerer, A. Bone sarcoma cumulative tumour rates in patients injected with ^{224}Ra. IN *The Radiobiology of Radium and Thorotrast* (W Gössner, G B Gerber, U Hagen and A Luz, eds). Munchen, Urban and Schwarzenburg (1986).

20 Tomasek, L, Darby, S C, Fearn, T, Swerdlow, A J, Placek, V, and Kunz, E. Patterns of lung cancer mortality among uranium miners in West Bohemia with varying rates of exposure to radon and its progeny. *Radiation Research* (in press).

21 Gilbert, E S, and Marks, S. An analysis of the mortality of workers in a nuclear facility. *Radiat. Res.*, **79**, 122–148 (1979).

22 Gilbert, E S, Omohundro, E, Buchanan, J A, and Holter, N A. Mortality of workers at the Hanford site: 1945–1986. *Health Physics* (in press).

23 Preston, D, Kusumi, S, Tomonaga, M, Izumi, S, Ron, E, Kuramoto, A, Kamada, N, Dohy, H, Matsuo, T, Nonaka, H, Thompson, D E, Soda, M, and Mabuchi, K. The incidence of leukaemia, lymphoma and multiple myeloma among A-bomb survivors (in press).

24 International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection. ICRP Publication 60. *Ann. ICRP*, **21**, Nos 1–3 (1991).

25 Committee on the Biological Effects of Ionizing Radiation (BEIR V). Health effects of exposure to low levels of ionizing radiation. Washington DC, National Academy of Sciences, National Academy Press (1990).

26 National Radiological Protection Board. Estimates of late radiation risks to the UK population. *Doc. NRPB*, **4**, 15–157 (1993).

27 Clare, P M, Woods, S J, Woodville, A C, and Harrison, K G. Environmental monitoring at Christmas Island, 1957–1958. Aldermaston, AWE Safety Division Technical Note 16/93 (1993).

11 Abbreviations and acronyms used

AERE	Atomic Energy Research Establishment
AWE	Atomic Weapons Establishment (formerly Atomic Weapons Research Establishment)
CI	Confidence interval
DSS	Department of Social Security
ICD	International Classification of Diseases
ICRF	Imperial Cancer Research Fund
MOD	Ministry of Defence
NAAFI	Navy, Army and Air Force Institute
NHS	National Health Service
NI	National Insurance
NRPB	National Radiological Protection Board
OPCS	Office of Population Censuses and Surveys
RAAF	Royal Australian Air Force
RAF	Royal Air Force
RM	Royal Marines
RN	Royal Navy
RNVR	Royal Naval Volunteer Reserve
RNZN	Royal New Zealand Navy
RR	Relative risk
SMR	Standardised mortality ratio
Sv, mSv	Sievert, millisievert

APPENDIX A

Mortality in Test Participants with No More Potential for Radiation Exposure than the General Public

During the course of assembling the list of test participants for the study, a number of men were identified who satisfied the criteria for inclusion (Table 2.3) but who appeared to have no more potential for radiation exposure from the tests than the general public. These were men whose only visits to test locations were in the following categories:

(a) RAAF Edinburgh Field or RAAF Pearce, but who were not members of the squadron involved in cloud sampling,

(b) Monte Bello Islands, but departing before 3 October 1952, the date of Operation Hurricane,

(c) Christmas Island but departing before 15 May 1957, the date of the first explosion of Operation Grapple,

(d) the crew of HMS Comus or HMS Concord, both of which visited the Monte Bello Islands briefly in March and April 1956 before the first explosion of Operation Mosaic.

Such men were included as test participants in the analyses presented in the previous report, but have been excluded from the main tables in the present analysis. Follow-up for these men has continued, however, and their mortality is presented here. A total of 1520 men were involved, 17 more than had been identified at the time of the previous report. As shown in Table A1, no AWE employees were included, but otherwise all three Services were represented, with rather more men from the Army and RAF than from the Navy.

Table A2 gives the mortality of these men by broad cause of death and compares the rates with those in the controls. The number of deaths involved are much smaller than in the corresponding tables for test participants (Table 6.5) but the pattern is broadly similar. For all causes, for all neoplasms and for all other diseases mortality rates are lower than those of men in England and Wales generally, while for accidents and violence mortality is higher. However, only for non-malignant diseases was the difference statistically significant ($p = 0.003$). The mortality of these test participants was broadly similar to that of controls and no relative risk was significantly different from unity.

Table A3 gives the same information as Table A2, but for 27 specific types of cancer. Only for cancer of the liver is the SMR significantly above unity (SMR = 4.47, $p = 0.03$). For cancer of the oesophagus the SMR is elevated but the excess is not significant (SMR = 2.18, $p = 0.08$). When comparisons were made with the control group, liver cancer rates were again elevated (RR = 9.14, $p = 0.01$). Relative risk was elevated, but not to a statistically significant extent for leukaemia (RR = 3.02, $p = 0.10$). The relative risk was below unity for cancer of the kidney but the observation was not significant (RR = 0.0, $p = 0.11$). It may be noted that the elevated relative risks for liver cancer and leukaemia follow broadly the trends in test participants (Table 6.9), as was to be expected if the elevated risk in the participants was due principally to unduly low rates in the controls.

In addition to the three men indicated in Table A3 who had died from leukaemia, two further men in this group were known to have developed leukaemia. Review of these five cases of

leukaemia confirmed the diagnosis of four (one acute myeloid leukaemia, two chronic lymphatic leukaemias, and one hairy cell leukaemia). The hospital notes of the fifth man, reported to have had chronic myeloid leukaemia, could not be traced.

TABLE A1 Numbers of men with no more potential for radiation exposure than the general public by Service, rank and whether or not on National Service

Service	Rank	National Serviceman	Regular	Total number
RN	Officer	6	26	32
	Other ranks	16	349	365
ARMY	Officer	3	30	33
	Other ranks	231	257	488
RAF	Officer	1	115	116
	Other ranks	15	471	486
AWE	Officer	0	0	0
All Services	Officer	10	171	181
	Other ranks	262	1,077	1,339
	Total	272	1,248	1,520

Note
RN includes members of the RM, RNVR and NAAFI.

TABLE A2 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants with no more potential for radiation exposure than the general public, and relative risks (RR) compared with controls, by broad cause of death

	Test participants with no potential for radiation exposure				Mortality rate relative to controls		
Cause of death	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
All neoplasms	58	61.94	0.94	0.66	1.06	0.36	0.84, 1.34
Other diseases	102	136.04	0.75	0.003	0.97	0.40	0.81, 1.15
Accidents and violence	30	21.98	1.36	0.11	1.28	0.12	0.91, 1.79
Unknown	2	–	–	–	–	–	–
All causes	192	219.96	0.87	0.06	1.02	0.41	0.90, 1.16

Notes
(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.
(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).
(c) Confidence interval.

TABLE A3 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants with no more potential for radiation exposure than the general public and relative risks (RR) of mortality compared with controls, for 27 specific types of cancer

	Test participants with no potential for radiation exposure				Mortality rate relative to controls		
Type of cancer	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
Cancer of the mouth, tongue, pharynx	2	1.05	1.90	0.28	1.48	0.41	0.29, 5.48
Cancer of the oesophagus	5	2.30	2.18	0.08	2.04	0.11	0.80, 4.84
Cancer of stomach	5	4.89	1.02	1.00	1.57	0.24	0.63, 3.65
Cancer of large intestine and rectum	6	6.74	0.89	0.85	0.98	0.56	0.43, 2.07
Cancer of liver	3	0.67	4.47	0.03	9.14	0.01	2.08, 36.78
Cancer of gallbladder	0	0.31	0.00	1.00	0.00	0.96	0.00, 345.92
Cancer of pancreas	3	2.70	1.11	1.00	1.17	0.50	0.34, 3.40
Cancer of larynx	2	0.61	3.29	0.12	2.21	0.25	0.43, 8.53
Cancer of trachea, bronchus, lung and pleura	17	21.69	0.78	0.34	0.87	0.34	0.56, 1.35
Cancer of bone	1	0.27	3.75	0.23	9.76	0.33	0.15, 619.25
Cancer of connective and soft tissue	0	0.31	0.00	1.00	0.00	0.83	0.00, 25.76
Malignant melanoma	0	0.76	0.00	0.64	0.00	0.46	0.00, 4.89
Other skin cancer	0	0.15	0.00	1.00	–	–	–
Cancer of prostate	0	1.97	0.00	0.28	0.00	0.17	0.00, 20.14
Cancer of testis	0	0.59	0.00	0.67	0.00	0.42	0.00, 5.76
Cancer of bladder	1	1.75	0.57	0.73	1.49	0.52	0.09, 9.40
Cancer of kidney	0	1.52	0.00	0.29	0.00	0.11	0.00, 12.75
Tumours of central nervous system	5	3.28	1.53	0.39	1.62	0.22	0.64, 3.79
Cancer of thyroid	1	0.12	8.23	0.11	14.91	0.12	0.54, 409.53
Cancer of adrenals	0	0.05	0.00	1.00	0.00	0.89	0.00, 48.38
Hodgkin's disease	0	0.97	0.00	0.63	0.00	0.45	0.00, 4.87
Non-Hodgkin's lymphoma	1	1.79	0.56	0.73	0.48	0.40	0.03, 2.80
Multiple myeloma	0	0.79	0.00	0.64	0.00	0.64	0.00, 9.26
Leukaemia	3	2.03	1.48	0.46	3.02	0.10	0.83, 9.43
Polycythaemia vera	0	0.05	0.00	1.00	–	–	–
Other specified neoplasms	2	1.45	1.38	0.66	1.96	0.30	0.37, 7.70
Unspecified neoplasms	1	3.14	0.32	0.28	0.37	0.26	0.02, 2.06
All neoplasms	58	61.94	0.94	0.66	1.06	0.36	0.84, 1.34

Notes

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(c) Confidence interval.

APPENDIX B

Mortality and Cancer Incidence in Test Participants as in Sections 6.2 and 6.3 but for the Entire Period of Follow-up

TABLE B1 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls for officers and other ranks, together with relative risks (RR) of mortality in test participants compared with controls, by broad cause of death

		Test participants				Controls				Mortality rate in test participants relative to controls		
Cause of death	Status[a]	O	E	SMR	Probability[b]	O	E	SMR	Probability[b]	RR	Probability[c]	90% CI[d]
Neoplasms	Officers	177	281.46	0.63	<0.001	202	311.50	0.65	<0.001	0.97	0.39	0.81, 1.15
	Other ranks	585	640.53	0.91	0.03	648	680.56	0.95	0.21	0.96	0.24	0.87, 1.06
Other diseases	Officers	336	639.67	0.53	<0.001	359	711.24	0.50	<0.001	1.04	0.32	0.91, 1.19
	Other ranks	1,228	1,408.45	0.87	<0.001	1,303	1,506.90	0.86	<0.001	1.01	0.39	0.95, 1.08
Accidents and violence	Officers	71	44.21	1.61	<0.001	104	50.59	2.06	<0.001	0.82	0.11	0.62, 1.07
	Other ranks	301	261.08	1.15	0.02	255	252.13	1.01	0.85	1.14	0.07	0.99, 1.33
Unknown	Officers	15	–	–	–	18	–	–	–	–	–	–
	Other ranks	40	–	–	–	50	–	–	–	–	–	–
All causes	Officers	599	965.34	0.62	<0.001	683	1,073.33	0.64	<0.001	0.98	0.40	0.89, 1.08
	Other ranks	2,154	2,310.06	0.93	0.001	2,256	2,439.59	0.92	<0.001	1.01	0.40	0.96, 1.06

Notes

(a) Includes AWE employees in social class 1 with officers and other employees with other ranks.

(b) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(c) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(d) Confidence interval.

TABLE B.2a Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls by Service and broad cause of death

		Test participants				Controls			
Cause of death	Service	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]
Neoplasms	RN	282	278.14	1.01	0.81	320	312.03	1.03	0.65
	Army	140	185.45	0.75	<0.001	143	160.18	0.89	0.18
	RAF	297	382.58	0.78	<0.001	327	436.68	0.75	<0.001
	AWE	43	75.82	0.57	<0.001	60	83.18	0.72	0.01
Other diseases	RN	541	612.38	0.88	0.003	604	687.41	0.88	0.001
	Army	347	411.01	0.84	0.001	278	349.45	0.80	<0.001
	RAF	572	851.10	0.67	<0.001	662	979.18	0.68	<0.001
	AWE	104	173.62	0.60	<0.001	118	202.10	0.58	<0.001
Accidents and violence	RN	121	92.65	1.31	0.005	146	108.43	1.35	<0.001
	Army	98	81.73	1.20	0.01	59	55.30	1.07	0.64
	RAF	144	118.53	1.21	0.02	148	126.56	1.17	0.06
	AWE	9	12.37	0.73	0.40	6	12.42	0.48	0.07
Unknown	RN	16	–	–	–	29	–	–	–
	Army	18	–	–	–	9	–	–	–
	RAF	18	–	–	–	27	–	–	–
	AWE	3	–	–	–	3	–	–	–
All causes	RN	960	983.17	0.98	0.46	1,099	1,107.88	0.99	0.80
	Army	603	678.20	0.89	0.004	489	564.92	0.87	0.001
	RAF	1,031	1,352.22	0.76	<0.001	1,164	1,542.42	0.75	<0.001
	AWE	159	261.81	0.61	<0.001	187	297.70	0.63	<0.001

Note

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

TABLE B.2b Observed deaths (O), deaths expected from social class specific national rates (E_s), and standardised mortality ratios corrected for social class (SMR_s), together with relative risks (RR) of mortality in test participants compared with controls, by Service and broad cause of death

		Test participants[a]				Mortality rate in test participants relative to controls		
Cause of death	Service	O	E_s	SMR_s	Probability[b]	RR	Probability[c]	90% CI[d]
Neoplasms	RN	282	280.29	1.01	0.93	0.99	0.46	0.86, 1.14
	Army	140	176.10	0.79	0.01	0.85	0.10	0.69, 1.04
	RAF	297	360.18	0.82	<0.001	1.00	0.51	0.88, 1.15
	AWE	43	67.99	0.63	0.002	0.86	0.28	0.60, 1.24
Other diseases	RN	541	589.77	0.92	0.04	1.01	0.45	0.91, 1.11
	Army	347	372.82	0.93	0.19	1.07	0.21	0.93, 1.23
	RAF	572	768.29	0.74	<0.001	0.98	0.37	0.89, 1.08
	AWE	104	151.22	0.69	<0.001	1.16	0.17	0.91, 1.47
Accidents and violence	RN	121	82.49	1.47	<0.001	0.98	0.45	0.79, 1.20
	Army	98	72.88	1.34	0.005	1.19	0.20	0.87, 1.61
	RAF	144	104.27	1.38	<0.001	1.06	0.32	0.87, 1.30
	AWE	9	10.56	0.85	0.65	1.50	0.31	0.56, 4.12
Unknown	RN	16	–	–	–	–	–	–
	Army	18	–	–	–	–	–	–
	RAF	18	–	–	–	–	–	–
	AWE	3	–	–	–	–	–	–
All causes	RN	960	948.37	1.01	0.71	0.99	0.41	0.92, 1.06
	Army	603	619.58	0.97	0.51	1.03	0.31	0.93, 1.15
	RAF	1,031	1,229.21	0.84	<0.001	0.99	0.43	0.92, 1.06
	AWE	159	229.44	0.69	<0.001	1.08	0.28	0.89, 1.30

Notes

(a) E_s and SMR_s are based on national mortality rates among men in social class 1 for officers and for AWE employees with jobs in social class 1, and on national mortality rates among men in social class 3 (manual and non-manual combined) for other men.

(b) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(c) One-sided test that the RR is greater than unity (RR ≥ 1.00) or less than unity (RR < 1.00).

(d) Confidence interval.

TABLE B3 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls, and relative risks (RR) of mortality in test participants compared with controls, for 27 specific types of cancer

	Test participants				Controls				Mortality rate in test participants relative to controls		
Type of cancer	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
Cancer of the mouth, tongue, pharynx	11	14.94	0.74	0.37	22	15.97	1.38	0.17	0.56	0.07	0.28, 1.08
Cancer of the oesophagus	39	33.51	1.16	0.34	38	36.02	1.06	0.74	1.11	0.37	0.74, 1.65
Cancer of stomach	50	74.75	0.67	0.003	56	81.46	0.69	0.003	0.96	0.45	0.68, 1.34
Cancer of large intestine and rectum	85	99.43	0.85	0.15	91	107.31	0.85	0.11	1.00	0.52	0.77, 1.30
Cancer of liver	12	9.55	1.26	0.41	5	10.17	0.49	0.12	2.58	0.06	0.97, 7.22
Cancer of gallbladder	1	4.59	0.22	0.10	4	4.97	0.81	0.82	0.23	0.17	0.01, 1.77
Cancer of pancreas	39	39.84	0.98	0.94	38	42.99	0.88	0.49	1.07	0.43	0.72, 1.60
Cancer of larynx	8	8.88	0.90	0.87	14	9.58	1.46	0.19	0.60	0.17	0.26, 1.35
Cancer of trachea, bronchus, lung leura	242	329.42	0.73	<0.001	303	357.45	0.85	0.003	0.87	0.06	0.75, 1.01
Cancer of bone	1	3.71	0.27	0.20	1	3.76	0.27	0.20	1.07	0.73	0.04, 29.19
Cancer of connective and soft tissue	2	4.44	0.45	0.34	4	4.65	0.86	0.83	0.57	0.41	0.09, 2.90
Malignant melanoma	16	10.53	1.52	0.12	13	10.98	1.18	0.54	1.32	0.28	0.67, 2.61
Other skin cancer	0	2.35	0.00	0.19	0	2.54	0.00	0.12	–	–	–
Cancer of prostate	34	33.23	1.02	0.93	41	36.89	1.11	0.51	0.94	0.42	0.62, 1.41
Cancer of testis	9	8.29	1.09	0.86	9	8.00	1.12	0.72	1.02	0.58	0.41, 2.52
Cancer of bladder	29	27.32	1.06	0.77	11	29.90	0.37	<0.001	2.85	<0.001	1.51, 5.47
Cancer of kidney	21	21.58	0.97	0.92	36	23.10	1.56	0.01	0.61	0.04	0.37, 0.99
Tumours of central nervous system	46	45.70	1.01	1.00	43	47.84	0.90	0.52	1.12	0.34	0.77, 1.62
Cancer of thyroid	0	1.75	0.00	0.27	1	1.87	0.53	0.73	0.00	0.51	0.00, 13.14
Cancer of adrenals[d]	1	0.74	1.34	1.00	2	0.78	2.57	0.18	0.58	0.56	0.03, 6.31
Hodgkin's disease	7	13.28	0.53	0.08	11	13.21	0.83	0.59	0.61	0.22	0.24, 1.49
Non-Hodgkin's lymphoma	23	25.43	0.90	0.69	24	26.73	0.90	0.63	0.82	0.31	0.48, 1.41
Multiple myeloma	9	11.63	0.77	0.47	6	12.52	0.48	0.07	1.86	0.18	0.69, 5.12
Leukaemia	29	29.01	1.00	1.00	17	30.28	0.56	0.01	1.75	0.05	1.01, 3.06
Polycythaemia vera[e]	1	0.78	1.28	1.00	1	0.85	1.18	1.00	1.12	0.72	0.04, 30.71
Other specified neoplasms	13	20.99	0.62	0.08	17	22.35	0.76	0.29	0.84	0.40	0.43, 1.64
Unspecified neoplasms	24	46.48	0.73	0.07	42	50.05	0.84	0.26	0.91	0.39	0.60, 1.36
All neoplasms	762	921.99	0.83	<0.001	850	992.06	0.86	<0.001	0.96	0.22	0.88, 1.04

Notes

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(c) Confidence interval.

(d) Cancers of the adrenal glands are included only from 1958 in the comparison with national rates, no deaths in participants and none in controls occurred before this.

(e) Polycythaemia vera is included only from 1968 in the comparison with national rates, no deaths in participants and none in controls occurred before this.

TABLE B4 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants and controls, and relative risks (RR) of mortality in test participants compared with controls, for causes of death other than neoplasms

	Test participants				Controls				Mortality rate in test participants relative to controls		
Type of cancer	O	E	SMR	Probability[a]	O	E	SMR	Probability[a]	RR	Probability[b]	90% CI[c]
A Diseases related to smoking											
Coronary heart disease	872	1,095.80	0.80	<0.001	965	1,184.70	0.81	<0.001	0.97	0.29	0.90, 1.05
Bronchitis, emphysema and chronic obstructive lung disease[d]	68	126.18	0.54	<0.001	71	140.64	0.50	<0.001	1.03	0.46	0.77, 1.39
Aortic aneurysm	38	35.87	1.06	0.74	43	39.14	1.10	0.58	0.98	0.50	0.66, 1.45
B Diseases related to alcohol											
Cirrhosis of liver, alcoholism and alcoholic psychosis	50	34.25	1.46	0.01	54	36.23	1.49	0.01	1.01	0.51	0.72, 1.42
C Other diseases											
Infectious and parasitic diseases	18	26.70	0.67	0.10	21	28.53	0.74	0.16	0.93	0.47	0.52, 1.65
Diseases of nervous system	32	53.69	0.60	0.002	34	56.42	0.60	0.002	1.06	0.45	0.68, 1.63
Other diseases of circulatory system	293	372.23	0.79	<0.001	285	406.38	0.70	<0.001	1.11	0.12	0.96, 1.28
Other diseases of respiratory system	71	115.68	0.61	<0.001	71	126.37	0.56	<0.001	1.12	0.29	0.83, 1.50
Other diseases of digestive system	54	64.61	0.84	0.19	45	69.46	0.65	0.002	1.30	0.12	0.91, 1.85
Remaining diseases other than neoplasms	68	123.03	0.55	<0.001	73	130.18	0.56	<0.001	1.01	0.52	0.75, 1.35
D Accidents and violence											
Motor vehicle traffic accidents	99	99.75	0.99	0.96	97	94.96	1.02	0.84	0.96	0.41	0.74, 1.23
Drowning and water transport accidents	20	15.95	1.25	0.31	21	15.73	1.33	0.20	0.82	0.35	0.45, 1.50
Air and space transport accidents	40	3.42	11.71	<0.001	54	3.34	16.18	<0.001	0.86	0.28	0.59, 1.25
Suicide	82	84.49	0.97	0.83	80	85.80	0.93	0.55	1.09	0.32	0.83, 1.44
Other injury and poisoning	131	101.68	1.29	0.01	107	102.88	1.04	0.69	1.26	0.05	1.00, 1.59
All known causes, other than neoplasms	1,936	2,353.39	0.82	<0.001	2,021	2,520.82	0.80	<0.001	1.02	0.23	0.97, 1.08

Notes

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.

(b) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00).

(c) Confidence interval.

(d) ICD code 519 (other diseases of respiratory system) is included as it is impossible to separate deaths attributed to this cause from those attributed to ICD code 496 (chronic airways obstruction, not elsewhere classified) in calculating expected deaths prior to 1979.

TABLE B5 Numbers of incident cancers (I) among test participants and controls, and relative risks (RR) of incident cancer in test participants compared with controls, for all neoplasms and 27 types of cancer

	Test participants	Controls	Incidence rate in test participants relative to controls		
Type of cancer	I	I	RR	Probability[a]	90% CI[b]
Cancer of tongue, mouth, pharynx	23	29	0.88	0.37	0.53, 1.44
Cancer of oesophagus	44	44	1.07	0.42	0.74, 1.55
Cancer of stomach	59	68	0.93	0.37	0.68, 1.26
Cancer of large intestine and rectum	115	137	0.90	0.22	0.72, 1.12
Cancer of liver	14	5	3.02	0.02	1.17, 8.27
Cancer of gallbladder	2	4	0.45	0.30	0.07, 2.32
Cancer of pancreas	40	40	1.04	0.47	0.70, 1.55
Cancer of larynx	25	30	0.90	0.39	0.55, 1.45
Cancer of trachea, bronchus, lung and pleura	275	333	0.90	0.10	0.78, 1.03
Cancer of bone	4	2	2.32	0.28	0.45, 14.52
Cancer of connective and soft tissue	4	8	0.52	0.21	0.16, 1.60
Malignant melanoma	32	23	1.52	0.08	0.94, 2.48
Other skin cancer	124	171	0.76	0.01	0.62, 0.93
Cancer of prostate	62	63	1.12	0.29	0.82, 1.54
Cancer of testis	23	24	0.98	0.54	0.58, 1.67
Cancer of bladder	66	47	1.49	0.02	1.07, 2.08
Cancer of kidney	37	54	0.72	0.08	0.49, 1.05
Tumours of central nervous system	64	47	1.43	0.04	1.02, 2.00
Cancer of thyroid	3	3	0.98	0.65	0.20, 4.94
Cancer of adrenals	1	2	0.58	0.55	0.03, 6.30
Hodgkin's disease	13	18	0.70	0.22	0.36, 1.36
Non-Hodgkin's lymphoma	37	37	0.94	0.44	0.62, 1.43
Multiple myeloma	13	8	1.92	0.10	0.84, 4.50
Leukaemia	37	24	1.61	0.05	1.00, 2.57
Polycythaemia vera	4	5	0.84	0.52	0.23, 3.02
Other specified neoplasms	48	46	1.10	0.36	0.77, 1.58
Unspecified neoplasms	39	47	0.93	0.41	0.63, 1.36
All neoplasms	1,208	1,319	0.98	0.30	0.91, 1.05

Notes

(a) One-sided test that the RR is greater than unity (RR ≥ 1.00), or less than unity (RR < 1.00)

(b) Confidence interval.

APPENDIX C

Mortality from Leukaemia and Other Cancers Among Test Participants by Operation

TABLE C1 Observed deaths (O), deaths expected from national rates (E), and standardised mortality ratios (SMR) among test participants present at UK atmospheric nuclear weapons tests. For leukaemia the whole follow-up period and the period 2–25 years after start of first test participation are considered, and for other neoplasms the period more than 10 years after start of first test participation is considered

(a) Operation Hurricane

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	2	2.84	0.70	0.78
Leukaemia: 2–25 years	1	1.15	0.87	1.00
Other neoplasms: 10+ years	84	100.28	0.84	0.10

(b) Operation Totem

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	0	0.34	0.00	1.00
Leukaemia: 2–25 years	0	0.14	0.00	1.00
Other neoplasms: 10+ years	8	13.83	0.58	0.11

(c) Operation Mosaic

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	0	1.98	0.00	0.28
Leukaemia: 2–25 years	0	0.99	0.00	0.63
Other neoplasms: 10+ years	48	56.54	0.85	0.26

(d) Operation Buffalo

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	1	2.26	0.44	0.53
Leukaemia: 2–25 years	0	1.14	0.00	0.43
Other neoplasms: 10+ years	54	76.09	0.71	0.01

TABLE C1 (continued)

(e) Operation Antler

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	1	2.21	0.45	0.53
Leukaemia: 2–25 years	0	1.19	0.00	0.42
Other neoplasms: 10+ years	58	65.57	0.88	0.36

(f) Maralinga Experimental Programme

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	1	0.92	1.09	1.00
Leukaemia: 2–25 years	1	0.55	1.81	0.43
Other neoplasms: 10+ years	20	30.62	0.65	0.05

(g) Operation Grapple

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	6	4.90	1.22	0.65
Leukaemia: 2–25 years	4	2.61	1.53	0.53
Other neoplasms: 10+ years	112	138.85	0.81	0.02

(h) Operation Grapple X

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	4	3.23	1.24	0.78
Leukaemia: 2–25 years	2	1.75	1.14	1.00
Other neoplasms: 10+ years	80	91.22	0.88	0.25

(i) Operation Grapple Y

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	5	4.69	1.07	1.00
Leukaemia: 2–25 years	2	2.64	0.76	0.78
Other neoplasms: 10+ years	115	123.44	0.93	0.47

(j) Operation Grapple Z

Cause of death	O	E	SMR	Probability[a]
Leukaemia: whole follow-up period	6	5.63	1.07	0.83
Leukaemia: 2–25 years	4	3.20	1.25	0.78
Other neoplasms: 10+ years	125	150.85	0.83	0.03

Note

(a) Two-sided test that the difference between the number of deaths observed and that expected could have occurred by chance.