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National Radiological Protection Board

Chilton, Didcot, Oxon OX11 0RQ

January 1988

NRPB-R214

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| Quantity | New named unit and symbol | In other SI units | Old special unit and symbol | Conversion factor |
|---|---|---|---|---|
| Exposure | – | $C\ kg^{-1}$ | röntgen (R) | $1\ C\ kg^{-1} \sim 3876\ R$ |
| Absorbed dose | gray (Gy) | $J\ kg^{-1}$ | rad (rad) | 1 Gy = 100 rad |
| Dose equivalent | sievert (Sv) | $J\ kg^{-1}$ | rem (rem) | 1 Sv = 100 rem |
| Activity | becquerel (Bq) | $s^{-1}$ | curie (Ci) | $1\ Bq \sim 2.7 \times 10^{-11}\ Ci$ |

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# MORTALITY AND CANCER INCIDENCE IN UK PARTICIPANTS IN UK ATMOSPHERIC NUCLEAR WEAPON TESTS AND EXPERIMENTAL PROGRAMMES

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Approved for publication: January 1988

Publication date: January 1988

HMSO : Price £8.00 ISBN 0 85951 297 5

## ABSTRACT

A follow-up study has been carried out of the health of men who participated in the UK atmospheric nuclear weapon tests and experimental programmes that were carried out in Australia and the Pacific between 1952 and 1967. The names of participants were identified from archives of the Ministry of Defence (MOD) and a matched control group was selected from the same archives. The study groups defined totalled 22,347 participants and 22,326 controls, of which 99.6% were traced to 1 January 1984 and 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.

No comprehensive list of participants had been compiled at the time and it could not be assumed that all participants had been identified. Names of participants and identifying details were, therefore, also sought from many other sources. Reports were received of 2161 individuals who were apparently eligible for inclusion and who were adequately identified, and these 'independent respondents' were followed as a separate group. Of these, 1707 had been included in the main study group, 414 were accepted as participants but had not been included, and 7 could not be traced in MOD records.

Altogether 3198 deaths were recorded in the two main study groups and the certified cause of death was determined for 3134 (98.0%). Mortality rates in the two groups were closely similar, the relative risk (RR) in the participants compared with the controls being 0.96 for neoplasms, 1.00 for other known non-violent causes, 1.07 for accidents and violence, and 1.01 for all causes. In both groups the mortality was less than expected from national rates, the standardised mortality ratios (SMRs) being, respectively, 80 and 83 for neoplasms and 80 and 79 for all causes. In the main analyses, 38 causes of death were examined. In 6 cases the mortality rates in participants and controls differed significantly (by one-sided tests). Mortality from leukaemia ($p=0.004$), multiple myeloma ($p=0.009$) and 'other injury and poisoning' ($p=0.04$) was higher in the participants and mortality from cancer of the prostate ($p=0.01$), cancer of the kidney ($p=0.007$) and chronic bronchitis, emphysema, and chronic obstructive lung disease ($p=0.02$) was higher in the controls. Examination of cancer incidence rates showed similar differences for leukaemia ($p=0.009$), multiple myeloma ($p=0.0007$) and cancer of the kidney ($p=0.01$), but different results for cancer of the prostate, for which the rates were about equal in both groups, and for cancer of the lung, for which the rate was higher in the controls ($p=0.03$). Examination of the rates from cancer in different groups of participants, divided according to measured doses of external irradiation and different types of participation, failed to show any relationship between leukaemia, multiple myeloma, or all neoplasms and the recorded doses of external radiation, and it showed very little difference between the experience of different groups of participants. The highest RRs and SMRs for leukaemia and multiple myeloma were observed in men who were not present at a major test or involved in minor trials at Maralinga. A study of the 11 participants in this group who developed multiple myeloma or leukaemia (other than chronic lymphatic leukaemia) and 66 other participants in the same group matched for age failed to indicate any specific risk factor.

The difference between the two groups in the mortality from leukaemia and multiple myeloma (22 deaths from leukaemia and 6 from multiple myeloma in participants, against 6 from leukaemia and 0 from multiple myeloma in controls) was largely due to extraordinarily low rates from these diseases in the controls (SMRs, respectively, of 32 and 0), while the mortality in the participants was only slightly greater than expected from national rates (SMRs, respectively, of 113 and 111) and much of these differences seems likely to have been due to chance. The low relative risk in the participants from both chronic bronchitis and lung cancer suggests that participants may have smoked less than the controls

and this is supported by the finding that the mortality from the other principal diseases related to smoking, but not from other diseases, was also lower in the participants. The relatively high mortality in the participants from 'other injury and poisoning' and the relatively low mortality from cancer of the kidney seem likely to be the chance findings that must be expected when so many different causes of death are examined.

The low mortality in both study groups from neoplasms and other non-violent causes of death compared with that expected from national mortality rates is largely explained by the fact that both groups contained a high proportion of officers and men whose occupations would be classified in social class I by the Office of Population Censuses and Surveys, particularly in the older age groups in which most deaths occurred, and that both groups were selected for physical fitness.

Comparison of the mortality rates of the independent respondents who were, respectively, included in and omitted from the main study showed that the results were not substantially biased by the omission of some participants, but that the mortality rates observed might be slightly underestimated.

It is concluded that small hazards of leukaemia and multiple myeloma may well have been associated with participation in the nuclear weapons programme, but that such participation has not otherwise had a detectable effect on the participants' expectation of life or on their total risk of developing cancer.

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## TABLES

The tables associated with each section of the report are grouped at the end of that section for the convenience of the reader.

## 1. INTRODUCTION

Between 1952 and 1958, the United Kingdom Ministry of Supply (MOS) 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 also carried out by the MOS 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.

The Ministry of Defence (MOD) has always believed that only a small proportion of the UK participants could have been exposed specifically to ionising radiations by virtue of their participation and that those who were exposed received only a small radiation dose. Some participants, however, have expressed concern about the effects that their participation may have had on their health. No firm conclusion could be drawn from the studies of small groups of self-identified participants (Knox et al, 1983) nor from the increased incidence of leukaemia that had been reported in the participants in the US shot Smoky in the Plumbob series in Nevada (Caldwell et al, 1980; 1983) except that further research was desirable. MOD, therefore, commissioned the National Radiological Protection Board (NRPB) to undertake a study of the health of the participants, investigating whether it showed any correlation with radiation exposure (Reissland, 1983). The study now reported was designed and carried out by the authors, under the general direction of NRPB, and with the assistance of MOD and other NRPB and Imperial Cancer Research Fund (ICRF) staff, to provide the desired information.

The study was not easy to carry out as no complete list of participants was available for reference. A wide variety of sources were consulted and well over 100,000 records of various kinds had to be examined individually. Many of them, moreover, had to be examined two or three times to eliminate error, explain discrepancies, and make sure that no groups had been overlooked. The description of the methods used to make sure that the information had been accurately transcribed and was free of bias is necessarily long, but it has been included for the benefit of professional epidemiologists and statisticians who may wish to form independent opinions about the reliability of our results. The general reader, who is interested in the nature of our results rather than in the method by which they were obtained, may prefer to omit Section 3, apart from Sections 3.1 and 3.4, and Section 5 as they deal with these aspects, and perhaps also Section 6, which describes the mathematical techniques used to analyse the results.

## 2. METHOD OF INVESTIGATION

The authors sought first to identify as large a group as practicable of those UK servicemen and civilians who took part in the tests, including UK personnel who participated in the American tests at Christmas Island in 1962, and then to determine:

(i) whether they subsequently suffered a greater incidence of cancer, or mortality from cancer or other causes, than would normally be expected, and

(ii) if they did, whether the increase could be attributed to their participation and related to the level of exposure to ionising radiations that had been recorded.

The authors have chosen to rely primarily on the mortality from specific diseases and from all causes as indicators of the health of the participants for three reasons. Firstly, death is unequivocal, its recording is compulsory and unbiased, and information that it has occurred can be obtained efficiently and rapidly from national records. Secondly, mortality rates are believed to be the best available general indicators of the health of a community, even though they provide no information about the incidence of non-fatal diseases like cataract and eczema. Despite much thought, no better indicators have been suggested and the Department of Health and Social Security continues to use mortality rates for determining the health needs of different parts of the country in the allocation of funds (DHSS, 1976; 1986). Thirdly, any attempt to obtain reliable information about the incidence of a wide range of diseases would have required personal contact with each individual or his general practitioner and a subsequent approach to hospitals for access to many thousands of sets of hospital notes, many of which would prove to have been destroyed. Such an attempt was, in the authors' opinion, both impracticable and unnecessary. It was possible, however, to obtain incomplete but unbiased information about the incidence of cancer through the national cancer registration scheme and, as cancer is certainly the most serious, if not the only, likely effect of low doses of ionising radiations, this information was sought as well.

It could not, of course, be assumed that the mortality and incidence of cancer in the participants, in the absence of any effect of participation, would be identical with that of others in the UK population of the same sex and age. Firstly, participants were selected as fit and healthy for employment, either by the Services or by their civilian employers, and they were further selected as fit for deployment overseas to participate in the tests. Secondly, all participants experienced at least a short period of life in a tropical or desert environment and service personnel experienced a lifestyle that differed materially from that of the majority of the population for the period of their engagement. To overcome these difficulties, an approximately equal number of individuals who did not participate in the tests, but who otherwise had similar characteristics, was also identified from MOD archives to form a control group.

The test participants and controls were then followed up through service records or the records of their civilian employers, and national registers maintained by the Office of Population Censuses and Surveys (OPCS) and the Department of Health and Social Security (DHSS). The authors were thus able to compare cancer and other mortality rates in the test participants not only with the corresponding national rates, but also with those of a control group with a comparable service history.

For the study to be definitive, either all participants needed to be included or the authors needed to be able to show that those who were included were fully representative of all those who had participated. At the time of the test programme, no comprehensive list of participants was compiled, and this made it unlikely that after so many years the authors could be certain to identify every person eligible for the study. Therefore, names and identifying details of participants were sought from many sources other than MOD. People identified in this way include individuals who notified themselves as test participants, or who were notified by a third party. The identification may have been made by contacting a government department or some other public body (for example, NRPB, the BBC or the University of Birmingham), or through one of the organisations of test veterans who have assisted NRPB. A list of the sources from which this further information was obtained is given in Appendix C. The service or personnel records of those individuals who had not previously been identified by our searching of the MOD archives have been examined wherever possible and all for whom there is reason to think that they were eligible have been followed up as a separate group. These individuals are referred to subsequently as independent respondents, and are discussed further in Sections 5 and 7.

## 3. STUDY POPULATION AND DATA COLLECTION

### 3.1 Definition of a test participant

The 21 UK atmospheric nuclear weapon tests are listed in Table 3.1. The tests and associated experimental programme took place at the Monte Bello Islands in Western Australia, Emu Field and Maralinga Range in South Australia, and at Malden Island and Christmas Island in the Pacific Ocean. Visits to these five locations in connection with the testing programme were spread over 15 years, as is shown in Table 3.2. All UK servicemen and male employees of the Atomic Weapons Research Establishment, Aldermaston (AWRE) (now part of the Atomic Weapon Establishment (AWE)) and the Atomic Energy Research Establishment, Harwell (AERE), and of their preceding organisations, who were known to have visited any of these five locations during the periods indicated in Table 3.2 were included in the study population as test participants. Also included were UK personnel who worked at two other locations, RAAF Pearce in Western Australia and RAAF Edinburgh Field in South Australia, where the work included cloud sampling and dealing with contaminated aircraft. Men were not included if they had been involved only with peripheral activities associated with the test programme, such as weather forecasting or the handling of non-radioactive stores and supplies, at other locations.

With this definition, 22,347 individuals were identified as test participants, and these constitute the group of test participants in this study. Some individuals are included in it who are thought not to have been exposed to more radiation than the general public. These include, for example, individuals who left the test locations before the first detonation and those who worked at RAAF Edinburgh Field or RAAF Pearce but were not involved in cloud sampling or handling contaminated aircraft. To eliminate the dilution effect caused by their inclusion, the study group has been divided according to the dates when the locations were visited and the nature of the individual's participation in the programme (see Section 7.4).

A few civilians employed by organisations other than AWRE and AERE are also known to have participated in the tests. They have been excluded, however, because of the difficulty of compiling a list of those involved and of obtaining detailed information about them within the timescale of the present study. 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 AWRE or AERE, have also been excluded in order to simplify and expedite the analysis. Australian and Canadian nationals excluded from this investigation have been studied separately (Commonwealth Department of Health, 1983; Raman et al, 1984).

### 3.2 Listing of suspected test participants

Provisional lists of service and civilian personnel believed to have participated in the tests had been compiled by AWRE before NRPB was commissioned

to carry out the present study. These lists, collectively known as "the Blue Book", had been compiled by a search of archival material held by AWRE and the Services historical branches. When the Blue Book was examined, two or more entries were sometimes found for men with the same surname and service number. These were regarded as referring to the same individual and the later entries were eliminated. The resulting lists contained the names of approximately 13,000 potential participants. MOD advised, however, that the Blue Book did not provide a complete list, apart from employees of AWRE or AERE and men in the Services whose personal film badges showed exposures greater than the minimum recordable. MOD also advised that the information in the Blue Book had not been checked and might contain transcription errors especially as individuals named in planning documents had been included, some of whom did not, in the event, attend the tests. The Blue Book was, therefore, used only as the starting point for determining the list of participants and extensive searches of MOD archival material were made to identify additional service personnel who had taken part in the tests.

Identification of Royal Navy participants was simpler than for the other Services because most naval participants had been attached to ships for which ledgers, listing the crew, were kept. A number of HM ships had been identified as being involved in the tests by the Blue Book compilers but naval archives provided evidence that several additional ships had visited the test locations during the period covered by the study and the names of those on board at the time were extracted from the ships' ledgers. Extra names were also obtained by searching the ledgers of naval holding units for men on detached duties.

Army archives caused the greatest problem, as no special records had been kept which would have shown precisely who had participated. Personnel records of men who have been discharged from the Army are stored in groups, known as discharge collations, according to (a) the unit to which the man belonged (for example, corps or regiment), (b) whether or not he is currently receiving a pension, and, if not, (c) his year of discharge from Reserve liability. A complete search of all the collations would have taken at least 6 person-years of work and was, therefore, impracticable in the time available. Fortunately, however, the great majority of Army participants were Royal Engineers and the relevant collations for Royal Engineers could be, and were, searched systematically for evidence of test participation using the deployment information provided in each service record. Further names of Army personnel were identified from ships' ledgers, lists of Army honours awards, and security vetting records.

RAF archives contained squadron operational record books that related to test activities and several books were found that had not been examined when the original Blue Book lists were compiled. These yielded further names of RAF officers and some airmen.

Additional participants from all three Services were identified from day passes issued by the Australian authorities for the Maralinga range and from archival material discovered during the general search. A substantial number of soldier and airman participants were identified directly from service records when searching for the records of known test participants and in the search for controls. Altogether, these procedures identified approximately 17,000 men who might have been participants in addition to the 13,000 already included in the Blue Book.

3.3 Enumeration and characterisation of confirmed test participants

For each individual recorded in the Blue Book and for all other servicemen discovered from other sources, identifying data were recorded on NRPB's computerised data-base together with the relevant operation or test location, the dates present, and the man's ship, unit, squadron or other organisational group during the tests. For each individual on the data-base, NRPB produced a form, divided into two sections. (The form used is reproduced in Appendix A.) Section A was completed by NRPB and gave the details necessary for the man's identification and the information suggesting possible involvement in the tests, while Section B was for completion by the Service Record Offices.

There were altogether 28,580 forms for servicemen suspected of being test participants. This total is shown in Table 3.3 divided by service branch and the original source of information.

The forms for servicemen were then sent to Service Record Offices with detailed notes for guidance, and the record custodians of the three Services were asked to trace the record for each suspected participant and to find out whether the deployment information in the service record matched the information already recorded on the form and to complete Section B accordingly, including details of any additional test involvements mentioned in the service record. When the deployment and information on the form did not conflict but the deployment information was insufficient to confirm presence in the test area unequivocally, the source material that had suggested that the individual might have been involved in the tests was re-examined to see if it was clear enough to confirm test participation. In cases where the service record did not match the information given on the form, the source material was checked for transcription errors. When doubt persisted, all available information relating to the individual was examined by NRPB staff. If doubt still persisted, the individual was excluded.

When test participation was confirmed, service record custodians were asked to record in Section B of the form information showing characteristics of his service (National or Regular service, job in service, dates of first enlistment and last discharge, and reason for discharge) and information that would help in tracing the man (full forenames, any previous surnames, date and place of birth, nationality at birth, civilian addresses and dates, National Insurance Number,

and National Registration or Health Service Number). If the man was discharged dead, information was also requested about the date and place of death. Completed forms were then returned to NRPB and the additional information transferred to the NRPB data-base.

For AWRE and AERE test participants, forms were not produced but computer listings were made of the identification and test participation details that had been notified to NRPB. NRPB staff then examined the AWRE overseas travel registers and health physics records to confirm that each individual had actually visited a test location on the stated dates. Where neither of these two sources provided definite confirmation of participation, confirmation was sought from any other archival source. All employees of AERE and AWRE and their preceding organisations are included in follow-up studies of radiation-exposed workers being carried out by the Medical Research Council's (MRC) Epidemiological Monitoring Unit (Fraser et al, 1985; Beral et al, 1985) and the Unit's help was sought to obtain the necessary information about those who had been test participants.

The results of these checks are shown in Table 3.4. (Over 95% of the civilians in the study were employees of AWRE rather than AERE. For brevity they are all referred to as AWRE employees in the tables.) No relevant records could be traced for 897 (3.1%) of the servicemen and 5 (0.5%) of the civilians. The traced records confirmed that 22,347 individuals had participated in the tests (75.3% of the servicemen and 80.8% of the civilians), and showed that the remainder were ineligible for inclusion according to study criteria or were duplicate entries.

Of the suspected participants whose records were untraced, 640 (71%) were thought to have been in the RAF, some 217 (24%) were thought to have been in the Army, 40 (4%) in the Royal Navy, NAAFI, Royal Marines or RNVR, and 5 (0.6%) civilian employees of AWRE or AERE. The great majority of untraced individuals were associated with the tests on Christmas Island (47%) or Maralinga (40%) but some had been thought to be possibly associated with each operation and location except Pearce Field. The failure to trace records of suspected participants was often due to the lack of sufficient information for precise identification. It was possible that 243 (27%) were identical with men accepted as participants and 45 (5%) with men known to have been overseas visitors. There were 15 who were identified as probably being Canadians (and so ineligible), but regulations prevented the Canadian authorities from revealing their names. A further 3 individuals were identified as New Zealand citizens by the New Zealand authorities.

The reasons for which suspected test participants were regarded as ineligible are shown in Table 3.5. Out of a total of 2342, 954 (41%) were in the RAF, 905 (39%) in the RN and 296 (13%) in the Army. For 779 (33%), the man's name had been obtained from the ledger of HMS *Newfoundland* and so included in the

original Blue Book listings; but it was later established that HMS *Newfoundland* had not visited any of the test locations. For 459 (20%), the records revealed that the individuals were ineligible because they were not UK nationals (283) or because they were civilians not employed by AWRE or AERE (159) or female (17). For the remaining 1104 (47%) participation could neither be excluded nor confirmed. The majority of these men had visited Australia, but the records did not specify the task or the location.

For 10 test participants the service record was incomplete and information about date of birth, date of enlistment, date of discharge, or type of engagement was missing. One possible reason for the incompleteness of the record is that the man later developed a disease that he or his dependents attributed to his service, the consequent removal of the record for investigation causing the record to be mislaid. For this reason these men have been retained in the study population, with the value of the missing variable assumed to be equal to the average value of that variable for other men in the study with similar values for the remaining variables, and similar rank, service, and test participation details.

3.4 Radiation exposure of participants

The numbers of attendances at different operations and different locations that were made by the test participants are shown in Table 3.6. Men in the RM, the RNVR and the NAAFI have been grouped with those in the RN, under the heading RN, etc. Almost 60% of the attendances were at Christmas Island and just under a quarter were at the Maralinga Range. Overall more than 40% of visits were made by RAF personnel, but the distribution of visits between the three Services and AWRE varied from operation to operation. For Hurricane and Mosaic at the Monte Bello Islands, about 80% of visits were by men in the RN, etc, while for Totem at Emu Field, over 80% of visits were by AWRE personnel. Over half the attendances at the Maralinga Range and almost all at Edinburgh Field were by RAF personnel, and RAF personnel also contributed nearly 40% of the attendances at Christmas Island.

The distribution of the number of attendances made by each participant is shown in Table 3.7. In each of the three Services the majority of men were recorded as attending only once. In contrast, more than half the AWRE personnel were recorded as attending more often, and a few individuals were recorded as attending on 10 or more occasions.

At the start of the study NRPB were informed by MOD that only a small proportion of test participants were liable to have been exposed to radiation as a consequence of their test participation. The relevant groups of personnel were:

(i) the members of the crew of HMS *Diana* which sailed through the fallout plumes in Operation Mosaic;

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

(iii) RAF aircrews involved in radioactive sampling from the clouds of the explosions;

(iv) the RAF active handling flight, who decontaminated aircraft used in cloud sampling, and

(v) individuals not in groups (i)-(iv) but who had recorded radiation doses greater than zero.

The numbers of attendances at each operation by the members of these special groups, together with estimates of the total collective doses are shown in Table 3.8.

The numbers of individuals involved in the special groups are shown in Table 3.9 by Service. Of the 22,347 test participants included in the study, only 1804 (8%) are believed by MOD to have been liable to exposure to radiation. The proportion was very much higher for AWRE personnel, 409 (50%) of whom were included in a special group.

Explicit exposure data for 1373 men are recorded in the Blue Book listings. These were in the form of gamma exposure stated in millirem (mrem). In some cases surface exposures in the form of gamma plus beta aggregate or localised doses were also available. For operations listed in Table 3.1, exposures were given as totals for the operation, while for staff deployed for a period at the Maralinga range they were given as annual totals. The exposure data had been compiled by AWRE staff from original film badge records and summaries of radiation exposures recorded at the tests that had been prepared by the AWRE Health Physics Group in the early 1960s. Dosemeters at the tests had been calibrated in terms of roentgen but, in collating the data, AWRE staff made the conventional approximation that an exposure of 1 roentgen delivered a dose equivalent to the whole body of 10 mSv. In what follows the term "dose" will be used rather than "exposure". This both avoids confusion between the technical and general senses of the latter term and is more consistent with the units used (sieverts). NRPB were informed that the listings included doses from every personal film badge dosemeter issued that had registered a dose greater than the minimum recordable level. At the end of the test programme in the 1960s the minimum recordable level was 0.1 mSv but the normal figure in Australia was 0.2 mSv, though, on occasions, 0.3 mSv or 0.5 mSv were used. For the Buffalo Indoctrinee Force at Buffalo Round 1, the minimum recordable level was 4 mSv as low sensitivity emulsion film badges had been issued which did not record lower doses. Exposures to neutrons and from internal contamination by radioactive materials will not have been recorded on personal film badge dosemeters. This complication was recognised from the outset and its impact is considered later (see Section 8.2).

The total collective gamma dose recorded for test participants in the study was 16,641 man mSv (see Table 3.8). All the operations listed in Table 3.1 contributed, but the largest contribution was for operation Grapple Z for which a collective dose of 3814 man mSv was recorded. Table 3.10 shows the distribution of doses to individuals by Service or employer together with the collective dose in each dose category. Only 483 individuals received 5 mSv or more. Eighty test participants were recorded as having received 50 mSv or more, the current legal annual dose limit for radiation workers, though the doses referred to here are totals for the entire test programme and so may be spread over several years. A large majority (80%) of these 80 individuals were the crew of aircraft which sampled the radioactive cloud from the explosions. These aircrew received half the collective dose (8334 man mSv out of a total of 16,641 man mSv). AWRE employees received the next largest fraction of the collective dose (3723 man mSv).

In addition to the members of the special groups, there were 2928 more individuals mentioned in a series of Health Physics Documents held by AWRE. These were men who had had a dosemeter issued for which no detectable dose was recorded. Their distribution by Service or employer was RN, etc: 1253; Army:469; RAF:902; AWRE:304. NRPB were informed by MOD that the high proportion of naval personnel in this group reflected a greater propensity to monitor individuals at the first test, Hurricane, where there was a high proportion of naval personnel. It did not imply that men involved in Operation Hurricane were more likely to be exposed compared with men attending other tests.

A total of 1503 test participants were included in the study who are unlikely to have been exposed to more radiation than the general public. These were individuals whose only visits to test locations were in the following categories:

(i) Edinburgh Field or Pearce Field, with no evidence of any involvement in cloud sampling or the decontamination of aircraft;

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

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

(iv) 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 Mosaic.

Their distribution between the Services was RN, etc:396, Army:515, RAF:592. These individuals are considered as a separate subgroup in the analysis of the results.

3.5 Listing of possible controls

The criteria used for selecting controls varied between different categories of test participants, according to the differing information and record systems available.

For test participants in the Services, controls were chosen from servicemen who did not participate in the Weapon Test Programme, but who had served in tropical or sub-tropical areas other than the test locations while the tests were being carried out. Controls were selected by the service record custodians according to criteria laid down by NRPB. For the Royal Navy, the dates of visits made by each ship to the test locations were noted and the Naval Historical Branch was asked to identify a ship of similar size that was deployed on the same dates in tropical waters (including the Persian Gulf) away from the test locations. The names of those on board for the corresponding period were extracted from the ships' ledgers, excluding visitors and short stay personnel who were on board for less than 10 days.

For officers in the Army and in the RAF, control personnel were identified from the monthly Army strength returns and RAF operational record books for selected units and squadrons deployed in tropical or sub-tropical areas on dates at which test participants were deployed in test locations.

For airmen and soldiers no lists of individuals deployed in tropical areas were available and controls had to be selected directly from the service records using matching procedures. For airmen, the place in which an individual's service record was stored was not affected by premature death or ill-health. For each airman test participant, neighbouring service records were searched until an eligible control was found. For eligibility the control had to have the same type of service (National Service or Regular) as the test participant and a date of birth within 18 months, and he needed to have commenced a period of tropical service starting no earlier than 5 years before and ending no later than 5 years after the year of the test participant's first test participation. In a few instances these stringent criteria could not be met and National Servicemen were chosen as controls for regular airmen or vice versa (10% of cases) or the period of tropical service of the control lay slightly outside the specified limits (0.5% of cases).

For each soldier test participant, who had been discharged from the Army other than on medical grounds, who was not a current pensioner and had remained alive until the end of his period of Reserve liability, a control was selected from the same discharge collation (see Section 3.2), with the same type of service (National Service or Regular) as the test participant, whose year of birth and year of first enlistment were within 2 years of those of the test participant, who had commenced a period of tropical service within 2 years of the test participant's first participation in the test programme, who had been discharged from the Army on other than medical grounds, and who had remained alive until the end of his period of Reserve liability. In 27% of cases these stringent criteria could not be met and a slightly weaker set of criteria was used. It was still required that the year of discharge collation should be the same as that of the participant, that the control had been discharged from the

Army for reasons other than medical grounds, and that he had remained alive until the end of his period of liability for Reserve Service, but other corps or regiments could be used, the year of birth was matched as closely as possible, and the calendar requirement for the period of service in the tropics was relaxed. The service records for soldiers who died in service or during their period of liability for Reserve Service, or who were discharged from the Army on medical grounds, are stored in different discharge collations from the ones in which they would have appeared if the man had been discharged alive and well, and the records of serving soldiers, pensioners and others still liable for Reserve Service are stored separately. It was, therefore, impossible to use the collations of service records to select appropriate controls for test participants in these categories. Allowance for the lack of controls for these groups has been made in the analysis (see Section 6).

For employees of AWRE, AERE or their forerunners, controls were selected from AWRE employees who had not visited a test location or attended tests at a test site in the USA. Controls were selected from the data-base of AWRE employees compiled for the MRC's study of the health of nuclear energy workers. For each test participant, a control was selected who started work at AWRE in the same year as the test participant had started work at AWRE or AERE, and had the same social class (Office of Population Censuses and Surveys, 1970) and radiation worker status (defined as whether or not required to wear regularly for their work with AWRE a film badge that would measure the dose received). For 29 test participants, all of whom started work at AWRE in 1951 or earlier and who were radiation workers, no control could be found who satisfied these criteria exactly, and for these few, control radiation workers were selected using a slightly relaxed set of criteria, in which social classes 1 and 2 and the years 1946-49 for commencement of employment were each grouped together.

3.6 Enumeration and characterisation of selected controls

For each serviceman selected as a possible control, NRPB produced a form (see Appendix B) equivalent to the forms used for possible test participants. Altogether 22,186 forms were produced for servicemen. This total is shown in Table 3.11 divided by service branch. The forms were sent to the service record custodians, accompanied by detailed notes for guidance. The custodians were asked to provide corresponding personal data from the service record in Section B as they had been asked to do for test participants, and to make a careful study of the deployment information in the service record to ensure that there was no evidence that the man had participated in the test programme. For each individual identified via a ship's ledger, Army strength return, or RAF operational record book, the custodians were also asked to confirm that the individual was indeed deployed in the tropics as had been indicated in the original source material.

The results of these checks are shown in Table 3.12. No relevant records could be traced for 0.1% of the servicemen. The traced records confirmed that 97.0% of the servicemen and 98.7% of the civilians could appropriately serve as controls and showed that the remainder were ineligible or duplicate entries.

Of the 20 untraced controls, 8 were in the NAAFI, 6 in the RM, 3 in the RN, and 3 were officers in the Army. Controls for soldiers, airmen, and civilians were selected directly from the stored service records and the Harwell data-bases; consequently there were no untraced controls in these groups.

The reasons for which potential controls were excluded from the study are summarised in Table 3.13 by Service or employer. Out of a total of 302 exclusions, 124 (41%) were in the Royal Navy, 103 (34%) in the Army, and 54 (18%) in the RAF. The most common reason for exclusion, accounting for over half the exclusions, was that further investigation revealed that they were, in fact, test participants. Ten men identified from ships' ledgers were found to be short stay personnel or visitors to the ship and 98 men were found to have emigrated and 27 to have died before their nominal dates of entry to the study (see Section 6).

3.7 Comparability of test participants and controls

The distributions of test participants and of controls by Service or employer, rank or social class and, for servicemen, whether on National Service is given in Table 3.14. Of test participants, 39% were in the RAF, 30% in the group RN, etc, 28% in the Army, and only 4% employed by AWRE; the corresponding distribution among the controls was similar, except that there were relatively fewer controls in the Army (see Section 3.5). Overall, 14% of test participants and 15% of controls were either officers or in social class I; but the distribution varied between the Services. In the RN, etc, and the Army about one-tenth of personnel were officers, while in the RAF the proportion was about a quarter, and nearly half the AWRE personnel were in social class I. Some 12% of test participants and 13% of controls were on National Service, the majority being in the Army.

The distributions of test participants and of controls by year of birth, year of enlistment (servicemen) or commencement of employment (civilians), and year of discharge (servicemen) or termination of employment (civilians) are given in Tables 3.15-3.17. For all three variables the distribution is almost identical in the two groups, indicating that the control selection procedures had succeeded in identifying a group of individuals with closely similar characteristics to the test participants.

Table 3.1
UK atmospheric nuclear weapon tests in Australia and the Pacific, 1952-1958[1]

| Operation | Round | Location | Date of firing[2] | Yield | Explosion conditions |
|---|---|---|---|---|---|
| Hurricane | | off Trimouille Island, Monte Bello Islands, Western Australia | 3 Oct 1952 | 25 kt | Ocean surface burst |
| Totem | 1 | Emu Field, S. Australia | 14 Oct 1953 | 10 kt | Tower mounted |
| Totem | 2 | Emu Field, S. Australia | 26 Oct 1953 | 8 kt | Tower mounted |
| Mosaic | 1 | Trimouille Island, Monte Bello Islands, Western Australia | 16 May 1956 | 15 kt | Tower mounted |
| Mosaic | 2 | Alpha Island, Monte Bello Islands, Western Australia | 19 Jun 1956 | 60 kt | Tower mounted |
| Buffalo | 1 | One Tree, Maralinga Range, S. Australia | 27 Sep 1956 | 15 kt | Tower mounted |
| Buffalo | 2 | Marcoo, Maralinga Range, S. Australia | 4 Oct 1956 | 1.5 kt | Ground surface burst |
| Buffalo | 3 | Kite, Maralinga Range, S. Australia | 11 Oct 1956 | 3 kt | Air dropped - high air burst over land |
| Buffalo | 4 | Breakaway, Maralinga Range, S. Australia | 21 Oct 1956 | 10 kt | Tower mounted |
| Grapple | 1 | off Malden Island, Pacific Ocean | 15 May 1957 | megaton[3] | Air dropped - high air burst over ocean |
| Grapple | 2 | off Malden Island, Pacific Ocean | 31 May 1957 | megaton[3] | Air dropped - high air burst over ocean |
| Grapple | 3 | off Malden Island, Pacific Ocean | 19 Jun 1957 | megaton[3] | Air dropped - high air burst over ocean |
| Antler | 1 | Tadje, Maralinga Range, S. Australia | 14 Sep 1957 | 1 kt | Tower mounted |
| Antler | 2 | Biak, Maralinga Range, S. Australia | 25 Sep 1957 | 6 kt | Tower mounted |
| Antler | 3 | Taranaki, Maralinga Range, S. Australia | 9 Oct 1957 | 25 kt | Balloon suspended - high air burst over land |
| Grapple X | | off Christmas Island, Pacific Ocean | 8 Nov 1957 | megaton[3] | Air dropped - high air burst over ocean |
| Grapple Y | | off Christmas Island, Pacific Ocean | 28 Apr 1958 | megaton[3] | Air dropped - high air burst over ocean |
| Grapple Z | 1 | Christmas Island, Pacific Ocean | 22 Aug 1958 | kiloton[4] | Balloon suspended - high air burst over ocean |
| Grapple Z | 2 | off Christmas Island, Pacific Ocean | 2 Sep 1958 | megaton[3] | Air dropped - high air burst over ocean |
| Grapple Z | 3 | off Christmas Island, Pacific Ocean | 11 Sep 1958 | megaton[3] | Air dropped - high air burst over ocean |
| Grapple Z | 4 | Christmas Island, Pacific Ocean | 23 Sep 1958 | kiloton[4] | Balloon suspended - high air burst over land |

Notes:

1. A series of 25 US tests, part of US Operation Dominic and known as Operation Brigadoon, took place off Christmas Island between April and July 1962 (Carter and Moghissi, 1977). UK personnel known to have attended are also included in the present study.

2. Dates according to Greenwich Mean Time.

3. Megaton - yield range (few hundred kiloton to several megaton).

4. Kiloton - yield range (1-1000 kiloton).

Table 3.2

Locations and periods for the UK atmospheric nuclear weapon testing programme*

| Location | Period | Comment |
|---|---|---|
| Monte Bello Islands, Western Australia | Apr 1952-Jun 1956 | The first ships of the Royal Naval Task Force for Operation Hurricane arrived in April 1952. The last ships of the Royal Naval Task Force for Operation Mosaic left in June 1956. |
| Emu Field, South Australia | Aug 1953-Aug 1967 | The first members of the Radiological Hazards Group for trials at Emu Field arrived in August 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 | Jun 1956-Jun 1964 | The first UK personnel for Grapple arrived on Christmas Island in June 1956. The final clearing-up exercise finished in June 1964. |
| Malden Island, Pacific Ocean | Oct 1956-Jun 1964 | The first UK personnel for Grapple arrived on Malden Island in October 1956. 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-Nov 1960 | UK personnel involved with cloud sampling for Operation Buffalo were based at RAAF Edinburgh Field from August 1956. The RAF Holding Unit was withdrawn from RAAF Edinburgh Field in November 1960. |

* Only locations where there was a possibility of radiation exposure to UK personnel as a result of the weapon tests are included.