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ATOMIC WEAPONS ESTABLISHMENT

DIRECTOR SAFETY AWE

ES21/112

SAFETY DIVISION TECHNICAL NOTE 3/94

A SUMMARY OF THE EFFECTS OF NUCLEAR WEAPONS

A C WOODVILLE

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June 1994

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WITH REFERENCE TO THE UK ATMOSPHERIC NUCLEAR WEAPONS TEST PROGRAMMES

1952 - 1958

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WEFT/MHP AWE

The views and opinions expressed in this document are those of the author, and do not necessarily represent the official views of AWE.

Director Safety AWE
Aldermaston
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Berkshire RG7 4PR

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ILLUSTRATIONS

1. Aim

1.1 This is intended as an elementary introduction to the effects of nuclear weapons, with particular reference to the UK atmospheric nuclear weapon test programmes, from 1952 to 1958. Underground, underwater and exo-atmospheric explosions are thus not considered in detail.

1.2 For scientific and technical detail the general reader should consult Reference 1.

2. Characteristics of nuclear explosions

2.1 An explosive device is designed to liberate a large amount of energy on detonation in a small volume in a very short space of time. The energy liberated heats the device to a temperature at which it is converted into gas, radiating both infra-red (heat) and visible light. The hot gas, initially occupying the same volume as the original device and at high pressure, expands rapidly, initiating a shock wave in the surrounding air.

2.2 The foregoing applies equally to conventional (chemical) and nuclear explosions. Nuclear explosive devices differ in that they obtain their energy from nuclear rather than chemical reactions and can thus be made much more powerful for a given size.

2.3 Nuclear energy may be released in two ways. Heavy elements such as uranium and plutonium may be split (fission) to give a range of lighter elements (fission products) with a considerable release of energy. Alternatively, light elements such as deuterium and tritium may be combined (fusion) to give heavier elements, also with a considerable release of energy. Both these methods are exploited in nuclear weapons.

2.4 Nuclear reactions within the exploding device lead to the following additional effects:

(a) Ionising radiations, consisting principally of gamma rays and neutrons, are emitted by the device at the time of detonation. This is termed prompt radiation, and is by convention defined as that ionising radiation emitted up to one minute after the detonation.

(b) Additional gamma rays and beta particles are emitted by the residues of the nuclear reaction more than one minute after detonation.

(c) Further ionising radiation, principally alpha particles, are emitted by fissile materials present in the device and unconsumed by the fission process. Similarly, any tritium present in the device and unconsumed by the fusion process emits beta particles.

(d) Radioactivity may be induced in other materials by neutrons emitted at the instant of detonation. This is termed neutron activation. These activated materials subsequently emit ionising radiation, principally gamma rays.

2.5 The power of a nuclear explosive device is expressed as its approximate equivalent in kilotons or megatons of conventional high explosive. In practice it is impossible to measure the yield directly. Usually, various measurements are made on the effects of the explosion and radiochemical analyses are carried out on the residues. Each measurement can be used to derive an estimate of the yield. The various estimates are then put together to arrive at a 'best estimate' of the yield. Some uncertainty is, however, always involved; quoted yields should always be regarded as approximate. The yields given in this note are those believed by AWE at the time of writing to be the most reliable.

2.6 Approximately 50% of the total energy released by a nuclear explosive device appears as blast and shock, 35% as heat and light, 10% as residual radiation and 5% as prompt radiation (see 2.4 (a) and (b) for definitions).

2.7 Ionising radiations are potentially harmful to the human body and have the following characteristics.

(a) Alpha particles can only travel a few millimetres through air and cannot penetrate unbroken human skin. Alpha emitters are thus not hazardous unless taken into the body either by inhalation, ingestion or injection (eg through a contaminated break in the skin). Once inside the body they can irradiate cells and cause damage.

(b) Beta particles can travel up to a maximum of three metres in air but only a few millimetres in human tissue and can thus penetrate intact skin. Thus beta emitters may be hazardous if deposited on the skin or if taken into the body.

(c) Gamma rays and neutrons can travel considerable distances through the air and penetrate the human body. Thus they can be hazardous at long distances.

2.8 Radioactive materials decay with time, eventually becoming inert. Each radioactive species or nuclide has a characteristic half-life, the time taken to decay to half its original activity. This can vary from a fraction of a second to hundreds of thousands of years. The mixture of radionuclides likely to exist in the residues from a nuclear explosion decays at a rate which can be described by a rule of thumb known as the 7/10ths rule. According to this rule, increasing time by a factor of 7 will decrease activity by a factor of 10. Thus if fallout is giving a dose rate D one hour after burst, this will have decayed to D/10 7 hours after burst, D/100 2 days after burst, D/1000 2 weeks after burst etc. This is obviously approximate but helpfully illustrative.

3. Sequence of Events During Nuclear Explosions

3.1 On detonation within the atmosphere, the nuclear device incorporates some surrounding material, which may be air, soil or water and forms an incandescent gaseous mass, roughly spherical, termed the fireball. If the fireball touches the surface of the ground or sea it is termed a ground or surface burst respectively; if not it is termed an air burst. The point on the ground or sea surface vertically below the centre of the device is termed the ground or surface zero.

3.2 The temperature inside the fireball is initially many millions of degrees Centigrade and the pressure more than a million atmospheres. The fireball radiates heat, light and initial ionising radiation. At this stage neutrons emitted from the fireball may induce radioactivity in the surrounding medium.

3.3 Being at a higher pressure than its surroundings the fireball expands rapidly, to a maximum size which depends on the yield of the device. This is of the order of 100 metres for a 1 kiloton explosion and 1.1 kilometres for a 1 megaton explosion. To an observer the fireball will appear many times brighter than the sun. As the fireball expands it pushes the surrounding air away, forming a shock wave. As the expansion of the fireball slows, the shock wave separates and moves away from the fireball, initially travelling faster than sound.

3.4 If the explosion is at or near ground level, a crater will be formed. If the soil is sandy, the heat of the explosion may be sufficient to form a glazing of fused sand around ground zero.

3.5 While the fireball is still incandescent, all materials in it will be gaseous. As it expands, it engulfs the surrounding atmosphere and cools, at the same time rising like a hot-air balloon. As it cools further, the gaseous materials in it condense to form a cloud of solid and liquid particles. The amount of material in the cloud at this point depends on whether it was a surface, ground or air burst; air bursts contain the least amount of material.

3.6 Atmospheric drag and cooling of the outer layers as the hot cloud rises form it into a toroidal shape, with violent internal turbulence, whilst entrainment of air cools the cloud further. Depending on the height of burst and yield, a strong updraught may occur, lifting dust, spray and debris into the cloud. After about ten minutes the cloud cools to ambient temperature and ceases to rise further, the upper layers spreading to form the familiar mushroom shape. The cloud from a 1 kiloton explosion at, or near, the surface will reach a maximum altitude of about 3 kilometres. The height reached by the cloud from larger explosions is strongly affected by the tropopause, which in effect acts as a barrier through which only the most energetic rising clouds can penetrate. The height of the tropopause varies with season and latitude but is about 8 kilometres near the poles and about 18 kilometres at the equator. After the cloud has cooled to a temperature at which its constituents can condense to solid and liquid particles, the particles start to fall from the cloud at a rate determined by their size and density, the heaviest particles falling first and nearest to the surface zero.

3.7 In the case of a ground burst, significant amounts of material may be vapourised by the explosion and carried up into the cloud. Subsequent condensation will tend to form relatively large particles which fall to earth quickly and close to ground zero. This may produce a heavily contaminated area close to ground zero, which will be distributed according to wind direction. In the case of a sea surface burst, quantities of sea water may be taken up into the cloud but again these tend to condense to relatively small particles. The smallest particles may remain in suspension for periods of years and descend to earth thousands of miles from their origin, though atmospheric circulatory patterns usually retain them in the same hemisphere of the earth. Particulates carried up through the tropopause by high energy bursts fall back very slowly, typically remaining in the stratosphere for tens of years, though rates of fall are dependent on latitude, typically being less towards the equator.

3.8 In the case of an airburst, the only material to condense will be the residue of the device itself. This will be of relatively small mass and tend to form very small particles with a slow rate of fall to earth. Thus there will be no fallout close to surface zero, and the fallout that does occur at long range will be a limited hazard as it will be highly diluted, much of its radioactivity decaying before it reaches the ground.

3.9 It is possible for rain falling through the radioactive cloud to carry fallout particles down with it, forming areas of increased radioactivity ('hot spots') on the ground.

3.10 Depending on the yield of the explosion and the prevailing meteorological conditions, the cloud may remain visible for an hour or more. After this it will tend to disperse and become lost among the other clouds in the sky, though it may still be possible to track it for a period of days using aircraft equipped with sensitive radiation monitoring instruments.

3.11 If a nuclear device is detonated below ground, a cavity is formed. If the detonation is at a sufficient depth, the cavity does not break surface, there is no air blast or fallout, the prompt radiation is absorbed by the earth and the residual radioactive material remains trapped in molten rock in the cavity. The only effect detectable at a distance is the ground shock. Such a detonation is obviously least damaging to the environment. The technology for carrying out nuclear test detonations at a sufficient depth to achieve the above was developed by the US in the late 1950's. Underground emplacement later became standard for all US and UK nuclear tests.

4. Effects of atmospheric nuclear explosions on the human body

4.1 An atmospheric nuclear explosion may subject a human body to the effects of air blast, ground shock, thermal and visible radiation and ionising radiation.

4.2 There is some uncertainty surrounding the magnitude of these effects, as the only direct information available is derived from the surveys following the wartime bombings of Hiroshima and Nagasaki. In these cases, many deaths and injuries arose from secondary effects; individuals were struck by flying debris or were trapped in collapsed or burning buildings. As a further complication, most individuals were inadequately nourished prior to the bombing and received inadequate medical care subsequently.

4.3 Blast injuries are of two types. The strong wind associated with the passage of the blast wave can throw a person to the ground or against objects, causing contusions and fractures. The violent change of pressure associated with the passage of the blast wave can rupture air-containing organs such as the lung or ear drums and can damage the middle ear. These injuries are similar to those caused by conventional explosions, differing only in their degree of severity. Severe lung damage will occur at about 170 kiloPascals (kPa). Deaths will begin to occur at about 275 kPa. The threshold for overpressure damage, manifested by eardrum rupture, is about 16 kPa for blast approaching the ear at normal incidence. For the ear, the orientation of the head to the blast wave is important. The effect of blast wave rise time, duration and impulse together with ear geometry all play a part in determining probability of eardrum rupture. Assuming airbursts at heights calculated to maximise the blast overpressure footprint, a blast overpressure of 16 kPa would be experienced up to about three kilometres from a ten-kiloton burst and about six kilometres from a one-megaton burst. Protection can be assured simply by maintaining an appropriate distance from the burst.

4.4 Ground shock can also throw a person to the ground or against objects. The acceleration may also be sufficient to cause lower limb fractures.

4.5 In practice, blast and shock injuries are of small significance, as they are hazardous only within ranges at which thermal effects are lethal.

4.6 Thermal radiation can cause injuries either directly, by heating the skin, or indirectly, eg by igniting clothing. Burns are classified according to severity as first, second or third degree. The mildest, first-degree, is characterised by reddening of the skin accompanied by pain. Recovery, given basic medical care, is normally complete. Second-degree burns are characterised by deeper injury, though with adequate medical care complete recovery is usual with or without scarring. Third-degree burns are characterised by destruction of the skin. The only possible treatment is skin grafting. Scars usually result. The threshold for a skin burn is a skin temperature of about 43°C, corresponding to a fluence of about 2 cals/cm^2. The degree of burning is a function of the temperature to which the skin is raised, and the length of time for which the temperature is raised. For example, a skin temperature of 70°C for a fraction of a second will produce the same type of burn as a temperature of 48°C for a few minutes. The risk of skin burn is related to distance from the explosion by an inverse-square law; doubling the distance from the fireball will reduce the incident thermal radiation by a factor of four. A first-degree burn would be likely on unprotected skin exposed to a ten-kiloton explosion at a slant range of three kilometres, or a one-megaton explosion at a slant range of twenty-one kilometres. Protection against thermal effects can be assured by maintaining an appropriate distance from the burst and by covering the skin. Even light clothing provides considerable protection. Thick white material can absorb or reflect, without charring, about six times the incident thermal radiation that would be sufficient to cause a first-degree burn on bare skin.

4.7 The visible light from an exploding nuclear device is sufficiently intense to cause two effects on the human eye. Flash-blindness is a temporary condition caused by bleaching of the light-sensitive elements in the retina. No treatment is necessary and recovery is usually complete within a few minutes. More intense exposures may cause retinal burns. These are permanent impairments of sight caused by heating of the retina. They may occur in daylight at ranges of up to thirty kilometres from a ten-kiloton burst or fifty kilometres from a one-megaton burst, the values depending on burst height and the presence of cloud. Visible light is, however, readily absorbed by any solid material and protection may be assured by maintaining an appropriate distance, turning away from the burst, closing the eyes and covering them. Such injuries may also occur from, eg, observing the sun through binoculars.

4.8 Ionising radiation is potentially harmful to the human body. It acts by releasing energy inside the individual cells, damaging the genetic material in the nucleus. This may have two effects. If sufficient energy is deposited, the genetic material may be so damaged as to prevent the cell reproducing. This will give rise to tissue damage. Cells can often continue functioning for a time with a damaged nucleus, so this effect is seen first in those tissues where cells divide most frequently, such as the lining of the intestine and the blood-forming tissue. If less energy is deposited, the cell may still be able to reproduce, but with an altered genetic code so that the daughter cells differ from the parent. This may give rise to cancers, to leukaemia or to congenital disorders in the offspring of persons exposed.

4.9 The effects of ionising radiation are described as 'deterministic' or 'stochastic'. A deterministic effect is one where severity depends on dose, effects being visible within a short period (minutes to days). There is considerable uncertainty as to the lethality of acute doses, as so few people have ever been exposed to sufficient ionising radiation to cause early death. It is believed that there is an acute whole-body threshold dose of about one Sievert (Sv), which will have no detectable adverse effect on a healthy adult. An acute dose of 2-3 Sv will cause vomiting, diarrhoea and a reduction in the number of white blood cells. An acute dose of 3-4 Sv will be lethal in some cases, and 5-6 Sv lethal in most cases. Lethality is much lower if the doses are received over a extended period. Much also depends on general health prior to exposure and the standard of medical care thereafter.

4.10 Stochastic effects are those observed in populations exposed to low doses. The dose determines frequency of occurrence of symptoms, not their severity. The effects, which may include cancers, leukaemias and congenital disorders in the offspring of those exposed, may take decades to appear. Again, data is lacking because so few populations have ever been exposed to significant doses but recent estimates (eg Reference 2) suggest that the lifetime risks of fatal cancer in a population are 0.05 deaths/Sv. Thus, if 100 persons are exposed to 1 Sv, it may be expected that five will eventually die of cancer. It should be noted, however, that in the developed countries it would be expected that 20-25 of these persons would die from non-radiogenic cancers and leukaemias. The cancers and leukaemias induced by exposure to ionising radiation are not distinguishable from those induced by exposure to chemical carcinogens or occurring naturally. It is generally impossible to determine whether a particular condition was or was not radiogenic. The elevation in death rate of an exposed population may thus be difficult to demonstrate even with the use of sophisticated statistical techniques. There is argument as to whether or not a threshold exists for stochastic effects. For the purpose of radiation protection, it is conservatively assumed that no threshold exists and that any elevation of radiation dose above the inescapable natural background is potentially harmful.

4.11 The dose levels noted above may be compared with the current statutory dose limits for workers in the nuclear industry who are Classified Persons within the meaning of the Ionising Radiations Regulations 1985. For such persons, according to the latest recommendations of the ICRP (Reference 2) doses must be kept as low as reasonably practicable with a limit of 20 millisieverts (mSv) per year averaged over a working life and an overriding limit of 50 mSv in any year.

4.12 There are naturally occurring background ionising radiations to which all persons on earth are exposed. These come from the sun, from outer space and from naturally occurring radionuclides in the environment and in the human body. In the UK the natural background amounts to about 2 mSv per year per person, varying significantly with diet, lifestyle and place of residence. It is significantly higher for dwellers in areas of igneous rock such as Cornwall, Eastern Scotland, parts of Somerset, Northampton and some other areas.

4.13 The effects of ionising radiation on the human body are discussed in more detail in References 3 and 4.

4.14 When a nuclear device is detonated in the atmosphere, persons may be exposed to ionising radiation from three sources.

(a) The device will emit penetrating radiation as it explodes. Protection against this source may be assured by maintaining an appropriate distance. An inverse square law applies here, as noted for thermal effects in 4.6 above and there is also considerable attenuation by the atmosphere. Protection can thus be assured by maintaining a suitable distance from the point of detonation.

(b) The neutrons emitted by the exploding device may induce radioactivity in surrounding material. Thus if the device is detonated near the ground a crater may be formed, in which radioactive elements are formed in the soil. At the tests carried out in Australia, dose rates in the crater were sufficient to cause a significant short-term hazard to persons. Protection against this source was assured by not approaching the crater until an appropriate time had elapsed. After a few days the dose rates were down to tens of mSv per hour. A few years were sufficient for most activity to decay to levels which were difficult to distinguish from natural background. It was found that the soil in the crater, having been fused by the heat of the explosion, was not friable and was not resuspended by wind to any significant extent, so there was little spread of activity from the crater.

(c) The third source of exposure to persons is the residual material of the device plus any material taken up from the surface, ie fallout. Various measures were taken to minimise exposure. The device was exploded at such a height that virtually no surface material was incorporated. Devices of low yield were exploded on towers or suspended from balloons; higher yield devices were dropped from aircraft. The time of burst was selected to make use of favourable weather patterns, so that the fallout was carried away from inhabited areas and dispersed world wide. Thus dilution and decay reduced the dose to persons to levels indistinguishable from natural background.

5. Detection and measurement of ionising radiation

5.1 The design and operation of radiation detection instrumentation is highly specialised and complex. Instruments may be classified according to the nature of the radiation they are required to detect and the mode in which they are to be employed.

5.2 Personal dosemeters, designed to estimate the dose to an individual, are carried for long periods. They must be small, robust and convenient to wear. If dose rates are expected to be high the dosemeter must be capable of being read immediately by the wearer. Most personal dosemeters respond to beta particles, neutrons and gamma rays. They are unsuitable for measurement of dose from alpha emitters. However, alpha emitters can only be hazardous to humans if they enter the body. This internal contamination can be detected using radiochemical analysis of excreta in a specially equipped laboratory. During the period of the atmospheric nuclear weapon tests two forms of personal dosemeter were in use.

i) The film badge consisted of a piece of photographic film sealed in a light-tight package and contained in a cassette adapted for securing to the clothing. Exposure to ionising radiation caused blackening of the film. After conventional developing, the film could be compared with a standard and an estimate of dose obtained. The film-badge remains in common use in the nuclear industry.

ii) The quartz-fibre electroscope (QFE) was a direct-reading instrument consisting of an ionisation chamber with attached electroscope and scale. The instrument was set to zero by charging the electroscope. Exposure to ionising radiation allowed the charge to leak away and cause the electroscope to give a positive reading. While this instrument had the advantage that it could be read by the wearer, it tended to be over-sensitive. In particular, dropping the instrument could cause it to grossly over-indicate. Nevertheless, it was adequate as a warning device and similar systems are still in use today. It is important to note that the dose to the person for regulatory purposes was that indicated by the more reliable film-badge.

5.3 Survey instruments are designed to estimate the extent of contamination on surfaces, of the ground or objects. Typically, such instruments were used to plot fallout contours or monitor persons and vehicles for surface contamination. They must be robust, man-portable and capable of giving an instantaneous reading. They must be sensitive to alpha and beta particles, neutrons and gamma rays. During the period of the atmospheric trials such instruments were generally based on a tube filled with a gas such as argon or neon which, normally an insulator, when exposed to ionising radiation would become a conductor. The dose-rate could then be estimated using appropriate circuitry. Because of the low penetration of alpha particles, alpha monitors in particular are designed with very thin windows over the detector tube. They are thus very fragile. Beta monitors may be slightly more robust, and gamma and neutron monitors the most robust.

5.4 Laboratory instruments are designed to measure ionising radiations emitted from a variety of materials. They may be designed to cope with a wide variety of samples and conditions. They are often large, fragile and complex and may have to be designed specifically for a particular task. Long counting times may be necessary if the samples are of low activity.

5.5 During the UK atmospheric nuclear weapons test programmes, radiation protection was carried out in four consecutive phases.

(a) A theoretical analysis was performed to predict the radiation fields to which persons might be exposed. The experiment or trial was then designed in such a way as to bring these exposures into line with current statutory limits.

(b) Direct measurements of the radiation fields were carried out to confirm the theoretical analysis using monitoring instruments and, if necessary, laboratory analysis of samples.

(c) The results given by personal dosemeters were recorded as the external doses experienced by the individuals.

(d) In the very rare cases when there was reason to believe that individuals might have taken radioactive materials into the body, radiochemical analysis was carried out to estimate the extent of such contamination and the internal dose resulting from it. Current UK legislation requires the internal dose to be added to the external dose and kept on the dose record for the individual.

5.6 It should be noted that the policy regarding recording of doses has changed significantly over the years. In the 1950's there was no statutory requirement to record the doses to all persons involved in an operation. The emphasis was on keeping exposures of all personnel below pre-determined levels. In the early trials in Australia, a policy of issuing film badges to all participants was adopted. In later trials at Christmas Island, dosemeters were issued only to those individuals for whom it was believed that some risk of exposure existed; it was not considered necessary to issue dosemeters to those who could be kept at a sufficient distance from the detonation and who would not be required to enter radioactive areas. See Reference 5 for details of film-badge issues at specific tests.

5.7 Current UK legislation requires that dosemeters be issued to all workers likely to be exposed to significant doses and that records of all doses be kept in perpetuity. In the event, a considerable body of information on doses to individuals during the tests was kept by AWE Aldermaston even though there was, at the time, no statutory duty to do so.

6. Chronology of UK nuclear weapon tests

6.1 Dates and details of UK atmospheric nuclear tests are summarised in Tables 1 and 2.

6.2 The decision to develope nuclear weapons in the UK was taken by the Government in the summer of 1947. It soon became apparent that existing theory would be inadequate to guarantee the performance of service weapons. It therefore became necessary to mount a live test. A search was carried out for a suitable site which was under the control of the UK but remote from human habitation or trade routes. The site finally chosen was in the Monte Bello Islands off the north-west coast of Australia. The Operation, under the codename HURRICANE, was carried out by a Royal Naval task force with elements of other services and a party of civilian scientists, engineers and technicians. The prototype nuclear weapon was detonated in the target vessel, the frigate HMS Plym, moored off Main Beach, Trimouille Island on 3 October 1952. The yield was 25 kilotons.

6.3 Problems with the production programme led to the requirement for further tests in 1953. The difficulties involved in mounting a seaborne operation led to a search for a land site. A suitable site was eventually found near Emu Claypan in the outback of South Australia. Due to the remoteness of the area most supplies had to be flown in. There was thus a significant contribution by the RAF and RAAF. Under the codename Operation TOTEM, two test devices were detonated on 31-metre towers on 14 and 26 October 1953, with yields of 10 and 8 kilotons respectively.

6.4 By 1954 it had been realised that there would be a continuing demand for testing facilities and a search was made for a permanent proving ground. A suitable area was identified in Southern Australia and developed in cooperation with the Australian Government as the Maralinga Range. The site contained a village for the accommodation of trials personnel, an airfield and technical areas for scientific and engineering work. The firing sites were in open uninhabited country to the north of the village. Figures 1 and 2 show the location and general geography of the range.

6.5 In 1955 the requirement arose for weapons of greater yield than hitherto. It was necessary to carry out tests to study the problems involved, but not possible to do this at Maralinga, as the yields envisaged were greater than were permitted there. Also, tests would interfere with the Maralinga Range construction work. Accordingly, an Operation was mounted under the codename MOSAIC to carry out the tests at the Monte Bello Islands. Two devices were fired on 31-metre towers, the first on Trimouille Island on 16 May 1956 with a yield of 15 kilotons and the second on Alpha Island on 19 June 1956 with a yield of 60 kilotons.

6.6 In 1956 the Maralinga Range came into use for Operation BUFFALO, during which a series of four nuclear explosive devices were fired as part of a continuing experimental programme. In addition, the opportunity was taken to expose a variety of military equipment and structures to the explosions in order to gather data on nuclear weapon effects. A number of officers from the UK and certain foreign armed services were permitted to be present in the forward area at the time of some detonations and examine the exposed target response items. Devices were fired on 27 September 1956 (on a 31-metre tower, yield 15 kilotons), 4 October 1956 (surface emplacement, yield 1.5 kilotons), 11 October 1956 (dropped from a Valiant aircraft of No 49 Squadron, Royal Air Force to burst at 150 metres above ground level, yield 3 kilotons) and 21 October 1956 (on a 31-metre tower, yield 10 kilotons).

6.7 By 1957 the programme to develope high-yield weapons had progressed to the point where a major test series was necessary. The logistic difficulties in operating at the Monte Bello Islands stimulated a search for a more suitable base, which was found at Christmas Island in the Pacific. This was a small, isolated island with few inhabitants and off the main trade routes. Figure 3 shows the principle features. Facilities similar to those at Maralinga were constructed, with an airfield and a port. Operation GRAPPLE was mounted in the spring of 1957. Devices were dropped from RAF Valiant aircraft on a target area off the small, uninhabited Malden Island, 700 km to the SSE of Christmas Island. Round 1, SHORT GRANITE was dropped on 15 May 1957, detonating at an altitude of 2200 metres with a yield of 300 kilotons. Round 2, ORANGE HERALD, was dropped on 31 May, detonating at an altitude of 2400 metres with a yield of 0.7 megatons. Round 3, PURPLE GRANITE, was dropped on 19 June, detonating at an altitude of 2400 metres with a yield of 200 kilotons.

6.8 The experimental programme at Maralinga continued in 1957 with Operation ANTLER. Nuclear explosive devices were detonated on 14 September (on a 31-metre tower, yield 1 kiloton), on 25 September (on a 31-metre tower, yield 6 kilotons) and 9 October (suspended from an array of balloons at an altitude of 300 metres above ground level, yield 25 kilotons). These were the last nuclear explosions to take place in Australia.

6.9 The test programme continued on Christmas Island with Operation GRAPPLE X in which one device was dropped on 8 November 1957 from a Valiant aircraft over the sea off the south-east peninsular of Christmas Island. Detonation took place at an altitude of 2200 metres. Yield was 1.8 megatons.

6.10 Operation GRAPPLE Y, on 28 April 1958, was very similar to GRAPPLE X. A nuclear explosive device was dropped from a Valiant over the sea off the south-east peninsular of Christmas Island. Detonation took place at an altitude of 2500 metres. Yield was 3 megatons.

6.11 Operation GRAPPLE Z was conducted at Christmas Island in August-September 1958. Nuclear explosive devices were detonated suspended from arrays of balloons at an altitude of 450 metres above a remote area on the south-east part of the island on 22 August (PENNANT, with a yield of 24 kilotons) and 23 September (BURGEE, with a yield of 25 kilotons). Nuclear explosive devices were also dropped from RAF Valiant aircraft in a similar manner to Operations GRAPPLE X and Y. On 2 September the device FLAGPOLE was detonated at an altitude of 2800 metres with a yield of 1 megaton. On 11 September the device HALLIARD was detonated at an altitude of 2600 metres with a yield of 0.8 megatons.

6.12 This was the final UK atmospheric nuclear test. On 1 March 1962 an underground test (UGT) was fired at the Nevada Test Site, (NTS) USA in cooperation with the US authorities. All subsequent nuclear tests by the UK have been of this type.

6.13 Between April and July 1962 Operation DOMINIC was conducted at Christmas Island by the US government with the permission of the UK government, who appointed observers. The UK participation was codenamed Operation BRIGADOON. A number of UK servicemen were involved in support activities such as manning Christmas island airfield. A total of 25 nuclear devices were detonated, all as high airbursts over the sea.

6.14 A number of Minor Trials took place at Maralinga and Emu. These involved radioactive materials and explosives, but are not classified as nuclear explosions since no significant nuclear reactions occurred. Some radioactive contamination of the range environment did however result.

6.15 The Christmas Island base was closed down in 1964, all valuable items being recovered and waste dumped in the sea. The island was then surveyed and certified free of radioactive contamination. The island was in effect restored to its original state. A survey in 1981 by the New Zealand authorities on behalf of the Government of Kiribati confirmed that no radioactive contamination was present.

6.16 The Maralinga Range was closed down in 1967, all valuable items being recovered and waste buried. Efforts were made to remove remaining hazards and restore the area to its original state. Between February and March 1979 some plutonium-contaminated waste was exhumed and repatriated to the UK. In recent years further surveys have been carried out. Discussions have taken place between the UK and Australian Governments as to the state of the area and it is possible that further rehabilitation may be carried out.

7. Safety at atmospheric nuclear tests

7.1 Tests involved a large number of persons, civilian and military. From the earliest stages of planning for Operation HURRICANE it was apparent that it would not be easy to guarantee safety when testing a powerful device that was designed to kill people. Considerable resources were therefore devoted to safety assurance at all of the 21 UK atmospheric test detonations.

7.2 The first step towards safety assurance was to establish a disciplinary framework within which safety regulations could be made, issued and enforced. Details varied, but in all cases a set of regulations were issued, usually by the Task Force Commander, a civilian Scientific Superintendent, or the Director AWRE.

7.3 A considerable body of documentation on the UK atmospheric nuclear tests is held in the archives of AWE Aldermaston. A list of safety regulations and related documents is attached at Annex A. It is believed to contain all significant safety documentation.

7.4 Safety regulations took into account all the effects of nuclear explosions as set out above. It was apparent that, for the vast majority of those involved, the dominant immediate effect would be thermal radiation. The distance within which this could be tolerated was far greater than the hazards distance for ionising radiation. Figure 4 summarises the major hazards.

7.5 There were two areas where doses of ionising radiation could be expected to be significant. At several operations, it was necessary to obtain a sample of the radioactive cloud for analysis. At the time, the only satisfactory way of doing this was to fly an aircraft fitted with sampling equipment through the cloud. Doses of the order of hundreds of millisieverts were predictable and this task was assigned to specially trained volunteer officer aircrew. At some operations, there was a requirement to collect a sample from the crater area shortly after the burst and this task was assigned to volunteer civilian scientists. The general principle was to restrict potentially hazardous tasks as far as possible to well-informed volunteers.

7.6 In the event, exposures to ionising radiation during the tests were minimal. The vast majority of those involved received no dose sufficient to be measured by a personal dosemeter. Of those doses measured, most were within the statutory limits as set out in the Ionising Radiations Regulations 1985. The few individuals who did receive doses in excess of these limits were all volunteers from the civilian scientists and RAF officer aircrew.

7.7 The limits for exposure to ionising radiation evolved during the period of the atmospheric tests. The details are complex, as this was a period in which much research was carried out, leading to frequent changes in recommendations by international bodies and the introduction of new systems of measurement. A summary of the main features of dose regulation in this period is given in Annex B.

7.8 It should be made clear that all UK atmospheric nuclear test devices produced yields at, or very close to, the design figure. In no case did any hazard arise from an unanticipated yield. Similarly, in all cases where test devices were air-dropped, the detonation took place at, or very close to, the altitude intended. In no case did any hazard arise from a detonation taking place other than at the altitude allowed for in the safety planning process.

8. Conclusion

8.1 The phenomena associated with nuclear detonations and the chronology of the UK atmospheric nuclear weapon tests have been discussed. It is clear that these tests were conducted responsibly and with a proper regard to the safety of the participants. Retrospectively, evidence that safety standards were adequate has been provided by two independent studies.

8.2 Following public concern, the Ministry of Defence commissioned the National Radiological Protection Board to conduct an investigation into the health effects of the tests on participants. This was published in 1988 (Reference 6). The main conclusion was;

'It is concluded from this study that participation in the nuclear weapons test programme has not had a detectable effect on the participants' expectation of life nor on their total risk of developing cancer, apart from a possible effect on the risks of developing multiple myeloma and leukaemia (other than chronic lymphatic leukaemia). The evidence relating to multiple myeloma and leukaemia (other than chronic lymphatic leukaemia) is confusing.'

8.3 In 1993 the National Radiological Protection Board published a follow-up study (Reference 7) covering the five years subsequent to those covered by Reference 5. The main conclusion was;

'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 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 to have been a chance finding.'

8.4 It is concluded that the standards of safety at the UK atmospheric nuclear weapon tests were satisfactory. Evidence has been presented that no hurt or harm was caused to the participants.

9. References

1. The Effects of Nuclear Weapons
Eds S Glasstone and P J Dolan
Published by US Depts of Defence and Energy
3rd Ed 1977

2. The 1990 Recommendations of the International Commission on Radiological Protection
J Vennart
J Radiol. Prot. Vol 11 No 3 1991

3. Living with Radiation
Published by the National Radiological Protection Board
3rd Ed 1986

4. Sources, Effects and Risks of Ionising Radiation
United Nations Scientific Committee on the Effects of Atomic Radiation
1988 Report to the General Assembly
Published by the United Nations, New York
1988

5. Issue of Film Badges at UK Atmospheric Nuclear Weapons Tests and Minor Trials 1952-1967
A C Woodville
AWE Safety Division Technical Note 15/93
1994

6. Mortality and Cancer Incidence in UK Participants in UK Atmospheric Nuclear Weapon Tests and Experimental Programmes
S C Darby et al
Published by the National Radiological Protection Board
NRPB-R214 January 1988

7. Mortality and Cancer Incidence 1952-1990 in UK Participants in the UK Atmospheric Nuclear Weapon Tests and Experimental Programmes
S C Darby et al
Published by the National Radiological Protection Board
NRPB-R266 December 1993

ANNEX A

SAFETY REGULATIONS FOR ATMOSPHERIC NUCLEAR TESTS

This is a list of the regulations, orders and instructions relating to radiological and general safety that are known to have been current during the UK atmospheric nuclear weapons tests, experimental programmes and subsequent clean-up operations 1952-1967.

Documents are arranged in chronological order of issue, which is not necessarily the same order as the activities to which they refer. Undated documents are placed with other documents referring to the same operation.

Many other documents were produced in this period containing discussions and recommendations concerning Health Physics and radiological safety generally. In some cases these were sufficiently authoritative to have been regarded as instructions. Some such documents have been included here but the decision as to whether or not to include a specific document is often subjective.

It should be born in mind that these regulations were applied in addition to those regulations pertaining to safety and security that would have been current in the civil establishments and military units involved.

Copies of all these documents are held by the Safety Division, AWE Aldermaston.

1. HER Trials; Preliminary Notes on Radiation Measurement and Safety Organisation
   Issued by the Superintendent Radiological Research
   Undated (probably 1950)

2. Operation Epicure Radiological Group
   Issued by HER
   12 December 1950

3. Allowable Doses of Radiation
   Recommendations by the Medical Research Council
   July 1951

4. Operation Hurricane - Radiation Dosage
   Note by Dr W G Penney
   22 October 1951

5. Maximum Permissible Dosages to be taken by Participating Teams in Operation HURRICANE
   Minute by Dr W G Penney
   Undated

6. Letter F C Wickson MoS - Rear Admiral A D Torlesse
   giving instructions as to permissible doses to civil servants
   14 January 1952

7. Letter Rear Admiral A D Torlesse - Dr W G Penney
   re responsibilities
   29 May 1952

8. Operation Hurricane - Radiation Dosage
   Note by Dr W G Penney
   30 July 1952

9. HURRICANE Trial Orders

   No. 160 Exposure to radiation

   No. 161 Safety distances

   No. 255 Radiation safety

   No. 257 Precautions to be taken against light flash

   No. 259 Sequence of events

   No. 262 Sea and air patrols in prohibited and danger areas

   No. 265 Meteorological procedure around D-day

   No. 270 Phase iii outline plan

No. 271 Control of re-entry

No. 272 Contamination survey

No. 273 Recovery of records

No. 274 Salvage of equipment

No. 275 Movements and safety of ships in Phase iii

No. 276 Protection of personnel

No. 277 Evacuation of personnel from H1 after the event

No. 278 Clean areas

No. 279 Boats and landing craft

No. 280 Control of operations in Phase iii

No. 281 Employment of helicopters

No. 282 Radiological safety instructions for HMS Zeebrugge

No. 723 Crater survey

No. 1101 Medical arrangements for dealing with radiological hazards

No. 1210 Organisation of Ministry of Supply personnel

Appendix A Division of responsibilities

Appendix J Training in radiological safety

Issued by Rear Admiral A D Torlesse, Naval Commander
Undated

10. Radioactive Contamination of Ships of the Special Squadron
Instructions as to Decontamination
Signals Rear Admiral A D Torlesse - Admiralty
24 November 1952 and 14 January 1953

11. Radiation Dosage - Operation Totem
Letter Dr W G Penney - D E H Peirson with reply
11 February 1953

12. Monte Bello Ships to be Decontaminated
Handout No. 55/53
Issued by the Admiralty
6 March 1953

13. X200 Project Force Standing Orders
Issued by Brigadier L C Lucas
Undated

14. Operation TOTEM Radiological Safety Orders
Issued by C A Adams, Scientific Superintendent
14 August 1953

15. Safety Levels for Contamination from Fall-out from Atomic Weapons Trials
Health Physics Memo 6/55
Recommendations by G C Dale
Undated

16. Radiological Safety Regulations Maralinga Range
First Edition
Issued by R Pilgrim, Senior Superintendent Trials Division
1 January 1955

17 Radiological Safety Regulations Maralinga Range (Provisional)
Second (Provisional) Edition
Issued by R Pilgrim, Senior Superintendent Trials Division
1 March 1955

18. KITTENS 55 Radiological Safety Orders
Issued by R Pilgrim, Senior Superintendent Trials Division
8 March 1955

19. On Commencing a Radiological Survey over Weapon Debris
Issued by Captain W N Saxby
9 March 1955

20. KITTENS 1955 Instructions to Escorts Travelling with Consignments of Radioactive and Explosive Stores
Issued by R Pilgrim, Senior Superintendent Trials Division
23 March 1955

21. Maximum Permissible Doses for Weapons Trials
Recommendations by D E Barnes, Superintendent Health Physics
April 1955

22. Radiological Safety Regulations Maralinga RSRM 55(4)
Fourth (Provisional) Edition
Issued by the Director AWRE
November 1955

23. Safety on Weapon Trials
Health Physics Branch Memo 1/56
Issued by G C Dale
1956

24. KITTENS Third Series Radiological Safety Instructions
Issued by R Pilgrim, Senior Superintendent Trials Division
17 January 1956

25. Operation MOSAIC Joint Operational Plan
Section E Radiological Safety Regulations
Issued by the Director AWRE
17 January 1956

26. Radiological Safety Regulations Maralinga RSRM/56(5)
Fifth Edition
with Amendment No. 1 2 June 1960
Issued by the Director AWRE
March 1956

27. Radiological Safety Regulations for Trimouille Island
MOSAIC Joint Trial Order No. 12
Issued by Commodore H C Martell, Commodore Special Squadron
26 March 1956

28. Radiation Safety in Operation MOSAIC
Special Squadron Memorandum No. 1
Issued by Commodore H C Martell, Commodore Special Squadron
24 April 1956

29. Health Physics Regulations for HMS Diana
Issued by Commodore H C Martell, Commodore Special Squadron
June 1956

30. Range Standing Orders (Provisional) Maralinga
No issuing authority given
Undated

31. Operation Buffalo
Radiation Safety Regulations
Issued by Major W G McDougall, Group Leader Health Physics
Undated

32. Air Task Group Buffalo Operational Standing Orders
and Instructions
Issued by Group Captain S W B Menaul,
OC Air Task Group Buffalo
31 August 1956

33. Instructions to Escorts with Consignments of Radioactive
Stores
Appendix B to RAF/AWRE/TS.1272
Issued by RAF/AWRE
26 June 1956

34. Health Physics Services Group
Duties of Check Point Attendants
Issued by Lt Colonel S J Dagg, Health Physics
4 September 1956

35\. Buffalo Trials Indoctrinee Instruction No. 3
Issued by Brigadier R B W Bethell
4 September 1956

36\. Australian Services Task Force
Administrative Instruction No. 43/56
Operation BUFFALO Round 2
Issued by the Adjutant
4 October 1956

37\. Operation BUFFALO
Contaminated Clothing Trials Summary of Instructions
Issued by Major D B B Janisch
November 1956

38\. Radiological Safety Regulations for Operation GRAPPLE
First (Provisional) Edition
Issued by the Director AWRE
Undated

39\. Admiralty Notice to Mariners
33(T) Pacific Ocean - Line Islands - Danger Area
Issued by the Admiralty
3 January 1957

40\. SSTD Working Instruction No. 11
Operation GRAPPLE - Procedure for Reporting Casualties
Issued by G R Summers, AO Trials
3 January 1957

41\. Operation GRAPPLE
Warrior Atomic Precautions Instructions and Memoranda
Issued by the ABCD Officer, HMS Warrior
February 1957

42\. Operation Order No. 5/57
Sea Search
Issued by HQ Task Force GRAPPLE
1 February 1957

43\. Operation GRAPPLE - the Operational Phase
The Joint Operational Plan
Part 7
The Radiological Safety Plan
Issued by HQ Task Force GRAPPLE
1 March 1957

44. Operation GRAPPLE - the Operational Phase
The Joint Operational Plan
Part 10
The Evacuation Plan
Issued by HQ Task Force GRAPPLE
1 April 1957

45. Operation Order No. 1
Issued by Colonel J C Woollett, Garrison Commander
May 1957

46. No. 160 Wing Standard Operating Instructions

No. 1 Terminology

No. 2 Cloud sampling

No. 7 Procedure for entering and leaving the active area

No. 8 Procedure for refuelling contaminated aircraft

No. 10 Procedure for leaving and re-entering active aircraft

Issued by Air Commodore C T Weir, Air Officer Commanding
No. 160 Wing RAF
May 1957

47. Operation GRAPPLE - the Operational Phase
The Joint Operational Plan
Part 5
Precautions against the Effects of the Weapon
Fish Sampling
Issued by HQ Task Force GRAPPLE
4 May 1957

48. Maralinga Atomic Weapons Proving Ground
Range Standing Orders
Issued by the Range Commander
I July 1957

49. Operation GRAPPLE X
Personnel Safety Plan
Issued by HQ Task Force GRAPPLE
20 October 1957

50. Operation GRAPPLE X
AWRE Instruction No. 1
Personnel Safety Plan
Issued by K D Bomford, Scientific Superintendent
23 October 1957

51. Operation GRAPPLE X
Scientific Schedule for Re-entry
Issued by K D Bomford, Scientific Superintendent

52. UK Personnel for duty at Maralinga
Issued by the War Office
19 November 1957

53. Health Physics Instructions

No. 1/58
Second Line Servicing of Contaminated Aircraft of 76 Sqdn

No. 2/58
First Line Servicing of Contaminated Aircraft of 76 Sqdn

Issued by Flg Off J A K Edwards, Health Physics Officer
RAF Detachment, RAAF Edinburgh Field
Undated

54. The Naval Plan for Operation GRAPPLE

Appendix B
Instructions for the prevention of surface intruders

Appendix D
Search and rescue

Appendix E
Action in the event of a surface burst

Appendix F
Fish sampling

Issued by HQ Task Force GRAPPLE
22 January 1958

55. Radiological Safety Regulations Christmas Island RSRC/58(1)
Issued by the Director AWRE
March 1958

56. Shipment of Radioactive Stores
Issued by A C Draycott, SAO AWRE Liason Office,
Maralinga Project Office, Adelaide, Australia
4 March 1958

57. Operation GRAPPLE Y
Personnel Safety Plan
Issued by HQ Task Force GRAPPLE
5 April 1958

58. HQ GRAPPLE Directive on the Control and Operation of Remedial Action as Required from X-60 minutes to Stand-down
Issued by HQ Task Force GRAPPLE
16 April 1958

59. Instructions on Precautionary Action to be Taken by Units prior to D-Day
Issued by HQ Task Force GRAPPLE
21 April 1958

60. Monitoring Orders for the Port Area on D-Day
Issued by the ABCD Officer, HMS Resolution
23 April 1958

61. Health Control of Workers exposed to X-Rays and Radioactive Materials
AM Order A.129
Issued by the Air Ministry
23 April 1958

62. Personnel Safety Plan
Issued by W E Miller, Senior Admin Officer
21 April 1958

63. Personnel Safety Plan - Forward Area
Issued by P G E F Jones, Forward Area Commander
24 April 1958

64. Standard Operating Procedure for Cloud Sampling Operations

Instruction No. 1
Terminology

Instruction No. 2
Cloud sampling

Instruction No. 4
Particle sampling equipment

Instruction No. 5
Gas sampling

Instruction No. 6
Procedure for entering and leaving the aircraft decontamination area

Instruction No. 7
Procedure for refuelling contaminated aircraft

Instruction No. 8
Crash procedure for contaminated sampling aircraft

Instruction No. 9
Procedure for leaving contaminated Canberra aircraft

Instruction No. 10
Procedure for leaving contaminated Shackleton aircraft

Issued by Air Commodore J F Roulston, Air Task Group Commander
30 April 1958

65. Return to the United Kingdom of Contaminated Aero Engines
Issued by Flt Lt L Wild, RAF Detachment, RAAF Edinburgh Field
May 1958

66. Radiological Safety Regulations Christmas Island RSRC/58(2)
Issued by the Director AWRE
July 1958

67. Operation GRAPPLE Z
Provision of Protective Equipment and Radiac Instruments to HM Ships and RFA's
Issued by Captain G Western, Captain GRAPPLE Squadron
26 July 1958

68. Grapple Squadron Orders
Chapter II General Instructions
Issued by Captain G Western, Captain GRAPPLE Squadron
30 July 1958

69. Nuclear Weapons Trials Parties - Blood Examinations
Extract from CAFO Issue 17/58
1 August 1958

70. Operation GRAPPLE Z
The Air Plan
Annex 5
Search and Rescue Standing Orders
Issued by HQ Task Force GRAPPLE
Undated

71. Personnel Safety Plan - Air Drop
Issued by HQ Task Force GRAPPLE
18 August 1958

72. Operation GRAPPLE Z
Flagpole Air Drop
Forward Area Re-entry Schedule
Issued by W E Jones, Deputy Trials Planning Officer
26 August 1958

73. Personnel Safety Plan - FLAGPOLE
Issued by HQ Task Force GRAPPLE
28 August 1958

74. Operation GRAPPLE Z
Personnel Safety Plan
HALLIARD
Issued by HQ Task Force GRAPPLE
3 September 1958

75. Operation GRAPPLE Z
Personnel Safety Plan
BURGEE
Issued by HQ Task Force GRAPPLE
12 September 1958

76. AWRE Explosive Safety Regulations for Maralinga Range
Issued by the Head of Safety Co-ordination for the Director AWRE
Undated

77. Assessment Tests 1959 Safety Instructions
Issued by N Pearce, Superintendent Planning Trials
5 March 1959

78. Admiralty Fleet Orders
Issue 10/60

No. 227 ABCD - Nuclear explosions - shelter from radiation effects

No. 228 ABCD - Radiological monitoring organisation and techniques

No. 229 ABCD - Radiation hazards - protection afforded in ships from residual radiation

No. 230 ABCD - Radiation hazards - guidance on the institution of radiological countermeasures

No. 231 ABCD - Nuclear explosions - radiation problems in machinery spaces

Issued by the Admiralty
22 January 1960

79. Maralinga Experimental Programme 1960 Safety Instructions
Issued by R Pilgrim, Head of Safety Co-ordination
For the Director AWRE
8 April 1960

80. Maralinga Experimental Programme 1961 Safety Instructions
Issued by R. Pilgrim, Head of Safety Co-ordination
For the Director AWRE
7 February 1961

81. Maralinga Experimental Programme 1963 Safety Instructions
    Issued by R. Pilgrim, Head of Safety Co-ordination
    For the Director AWRE
    January 1963

82. Amendment No. 2 to Radiological Safety Regulations Maralinga
    RSRM/56(5)
    9 January 1963

83. Maralinga Range Security Instructions
    Issued by the Range Commander
    30 January 1963

84. Radiological Safety Provisions in Australia
    for Air Transport between AWRE and Maralinga
    of Specified Shipments of Radioactive Materials
    Issued by the Commonwealth of Australia Department of Supply
    March 1963

85. Radioactive Contamination of Aircraft
    Code of Practice for the Protection of Persons Exposed
    to Ionising Radiations Arising from the Radioactive
    Contamination of Aircraft
    Issued by the Ministry of Aviation
    1966

ANNEX B

SCHEMES OF DOSE LIMITATION

1. Aim

1.1 The aim of this annex is to provide information on the background to the development of schemes limiting the exposure of test participants to ionising radiation.

2. History

2.1 Rontgen discovered X-Rays in 1895. Before the end of 1896, the first casualties had occurred. Thus one of the first facts to be realised about ionising radiation was that it was potentially dangerous. However, the potential uses were sufficiently apparent to spur research.

2.2 It was deduced that damage to the human body was some function of dose, but at this time there was no coherent theory of dosimetry. An early standard was the exposure required to radiograph a human hand. Early attempts to design dosemeters made use of the brightness induced in fluorescent compounds.

2.3 The first practical device capable of giving reproducible results was an ionisation chamber designed by Szilard in about 1913. About this time it was also deduced that damage to tissue is some function of the energy deposited in it by the radiation.

2.4 By the twenties, there was sufficient interest in medical radiology and the commercial use of radium-based luminising compounds for the first International Congress of Radiology to be organised in 1925. This led among other things to the setting up of the International Commission on Radiological Units and Measurements (ICRU) and the International Committee on X-Ray and Radium Protection. The second International Congress in 1928 adopted the first unit of ionising radiation, the Rontgen (abbreviated r). It is defined as the quantity of radiation which, under standard conditions, produces in 1 cm^3 of air such a degree of conductivity that 1 e.s.u. of charge is measured.

2.5 The discovery of fission and the consequent expansion in military and civil nuclear programmes led to increased interest in dosimetry and schemes of protection. The International Committee on X-Ray and Radium Protection, which had suspended its activities during the second World War, re-convened in 1950 under the title of the International Commission on Radiological Protection (ICRP), which it holds today. Recommendations of the

ICRP are widely accepted and incorporated into EEC directives and national legislation. Members are elected to the ICRP solely on the basis of their internationally recognised expertise in appropriate branches of science and technology.

2.6 Other international bodies were set up under the auspices of the United Nations. The United Nations Scientific Committee on the effects of Atomic Radiation (UNSCEAR) reviews current scientific knowledge and provides a significant amount of data for ICRP. The International Atomic Energy Agency (IAEA) is the main UN agency for the promotion of the peaceful uses of nuclear power and much of its effort is devoted to standards and safety recommendations.

2.7 While the Rontgen was an adequate unit in the early years of medical radiology, with the emergence of a nuclear industry a requirement arose for a unit that could be used for neutrons, alpha and beta particles. In 1953 the ICRU recommended the adoption of the rad as a unit of exposure.

2.8 For the same amount of absorbed energy different types of radiation produce differing degrees of biological damage. To allow for this the rem was adopted in 1954. In 1975 the current SI unit of absorbed dose, the gray (1 joule per kilogram) was adopted. The becquerel (1 disintegration per second) was adopted as the SI unit of activity to replace the curie.

2.9 In 1962 the ICRU recommended the adoption of the term 'dose equivalent' for a quantity expressing for all ionising radiations the energy deposited in tissue. Consequently in 1977 ICRP recommended the adoption of the sievert as the unit of dose equivalent. The sievert is numerically equal to the gray multiplied by appropriate modifying factors.

2.10 AWE adopted the SI units on 1st January 1986, at the same time as the Ionising Radiations Regulations 1985 came into force. Historical dose records at AWE will still however be found in the older units.

3. Rationale for Dose Limitation

3.1 Currently, the Health and Safety Executive is the statutory authority in the UK for the control of the exposure of persons to ionising radiation. Current ICRP recommendations are incorporated in the Ionising Radiations Regulations 1985. Medical and dental exposures are not covered by legislation but are the subject of codes of practice issued by the relevant medical organisations to practitioners. The National Radiological Protection Board acts as an impartial advisor to the Government, other bodies and the general public on matters of radiation safety.

3.2 Only in a few cases (e.g. the exposure of miners to radon) has there been any serious attempt to control exposure to natural background radiation, though research to determine levels of exposure of the general public has increased in recent years.

3.3 In the early days, the concept of a maximum permissible dose was employed. It was considered, by analogy with chemical toxicity, that the relationship between dose and biological damage was of the threshold type, i.e. that there was a dose below which no injury would occur. It would therefore suffice to set a maximum dose some way below this threshold.

3.4 In 1953 the ICRP suggested that there might exist a significant risk below the recommended permissible level. The latest ICRP recommendations distinguish between stochastic and non-stochastic effects. The former comprise effects such as neoplasms and genetic defects whose probability of occurrence is a function of the dose received. The latter comprise acute effects, whose severity is dependent on the dose received. The threshold concept applies only to the latter.

4. Regulatory Standards during the UK Nuclear Tests

4.1 Standards of radiation protection for both workers in the nuclear industry and members of the general public continued to evolve during the 1950's. The process was complicated by the introduction of new units during the period. Standards of protection for members of the various task forces were based on those in force at AWE (then AWRE) Aldermaston. These were in turn based on those current in the UK nuclear industry.

4.2 However, at the time of Operation HURRICANE in 1952, no statutory regulations had been promulgated. Consequently, some form of limitation had to be devised by the Ministry of Supply and the Admiralty. The ICRP had recommended in 1950 a maximum dose for workers in the nuclear industry of 0.5 rontgens per (5-day) week to whole body and 1.5 rontgens per week to skin. Exposures in the nuclear industry would be expected to be fairly uniform over time, while exposures at a nuclear weapon test would be expected to be high at first, declining rapidly with time. It was expected that the vast majority of the test participants would not be exposed at rates higher than the ICRP weekly limit. However, it could be anticipated that some essential tasks might entail exposure to higher rates. Thus the concept was proposed of 'integrated doses' which it would be permissible to receive provided that the exposure was followed by a sufficient period of non-exposure. The test was expected to take ten weeks. The ICRP limit would be 5 rontgens to whole body and 15 rontgens to skin over this period. The following limits were thus set;

(a) The Normal Working Rate of not more than 0.3 Roentgens Effective Physical (rep) per day of which the gamma component was not to exceed 0.1 rontgens.

(b) A Lower Integrated Dose of up to 15 rep in the ten-week period in one or more exposures, of which the gamma component was not to exceed 3 roentgens. Persons receiving this dose were not to be exposed further for a period of at least six weeks.

(c) A Higher Integrated Dose of 50 rep in one or more exposures of which the gamma component was not to exceed 10 rontgens. This was expressly for key personnel who might be required to respond to an accident or emergency. Persons so exposed were not to be exposed further for a period of at least one year. This limit was set after discussions with the Medical Research Council had indicated that no short-term effects would be detectable following such a dose.

4.3 Protection against inhalation of radioactive materials which might give rise to internal dose was assured by the issue of respirators. In the event, the hazard from airborne radioactive particulates was minimal during all the UK atmospheric tests.

4.4 For Operation TOTEM the same dose limits were used as for Operation HURRICANE. It was formally stated that the maximum permissible levels for inhalation, ingestion and skin contamination would be the same as those in force at AWE. A formal code of practice was drawn up encompassing these limits.

4.5 New recommendations as to maximum permissible doses were made by the ICRP in 1955. These were followed by AWE in all subsequent tests and experimental programmes.

4.6 The new Normal Working Rate was changed to 1.5 rep per week of which the gamma component was not to exceed 0.3 rontgens. In the case of the Lower and Higher Integrated Doses, the period of non-exposure following was changed to that required to bring the mean weekly dose down to the same as the Normal Working Rate. In addition, a new Special Higher Integrated Dose of 75 rep was proposed, the gamma component of which was not to exceed 25 rontgens. Application of this limit could be authorised only by the commander of the operation, after consultation with the relevant medical and health physics authorities. Exposure to the Special Higher Integrated Dose would debar the individual from exposure for a period of at least three years.

4.7 It was explicitly stated that the number of persons exposed should be strictly limited and that all doses should be as low as practical.

4.8 In 1958 the ICRP recommended new limits which were in effect one-third of the previous levels. In addition, it was explicitly stated that both stochastic and non-stochastic effects should be taken into account in radiation protection. The new limit for whole body, blood-forming organs, gonads and lens of the eye was 5 rem per year mean after age 18 (i.e maximum total dose to be 5(N-18) rem, where N was the age of the individual) or 3 rem per

13 weeks. The limit for skin and thyroid was 30 rem per year and 8 rem per 13 weeks. The limit for any other single organ was 15 rem per year and 4 rem per 13 weeks.

4.9 The 1958 limits were not published until the GRAPPLE series of tests had finished, but they remained in force during the Minor Trials at Maralinga and the clean-up operations at Maralinga and Christmas Island.

4.10 There were minor modifications to the 1958 limits in 1962, 1965, 1977 and 1980 but the next major revision was not until 1st January 1986 when the Ionising Radiations Regulations 1985 came into effect. The limit for whole-body dose was unchanged at 50 mSv (5 rem) per year but there were detailed changes, the most important of which was the introduction of the requirement to estimate effective dose equivalent arising from radionuclides taken into the body. In addition, the onus of protection was transferred from the occupier of a premises to the employer of the individual and the detailed arrangements for advice and record-keeping were formalised. New recommendations were published in 1990. Briefly, the dose limit for workers was reduced to 20 mSv per year averaged over a working life with an overriding limit of 50 mSv in any year, and that for members of the public to 1 mSv per year averaged over 5 consecutive years, with an overriding limit of 5mSv in any year.

5. Conclusion

5.1 It will be seen from the above that assertions to the effect that the recommended maximum doses of ionising radiation have changed out of all recognition over the years are without foundation. It should also be borne in mind that many of the reductions in limits have been made to allay public anxiety, not in response to evidence that workers in the nuclear industry were suffering harm under the previous limits. In the event, the nuclear industry is among the safest in the world, with regard to both its workers and the general public.

TABLE 1

UK ATMOSPHERIC NUCLEAR WEAPONS TESTS IN AUSTRALIA

Operation and **Location**	**Date** and **Time** (GMT)	**Site**	**Emplacement**	**Altitude** (m)	Best Estimate of **Yield** (kt)
HURRICANE Monte Bello, WA	03 10 52 0000Z	Lagoon (12m deep)	Aboard HMS Plym	-3	25
TOTEM Emu Field, SA	14 10 53 2130Z	T1	Tower	31	10
	26 10 53 2130Z	T2	Tower	31	8
MOSAIC Monte Bello, WA	16 05 56 0350Z	G1 Trimouille	Tower	31	15
	19 06 56 0214Z	G2 Alpha	Tower	31	60

TABLE 1 Continued

Operation and Location	Date and Time (GMT)	Site	Emplacement	Altitude (m)	Best Estimate of Yield (kt)
BUFFALO	27 09 56 0730Z	One Tree	Tower	31	15
Maralinga, SA	04 10 56 0700Z	Marcoo	Ground Surface	0	1.5
	11 10 56 0557Z	Kite	Airburst	150	3
	21 10 56 1435Z	Breakaway	Tower	31	10
ANTLER	14 09 57 0505Z	Tadje	Tower	31	1
Maralinga, SA	25 09 57 0030Z	Biak	Tower	31	6
	09 10 57 0645Z	Taranaki	Balloon suspended	300	25

TABLE 2

UK ATMOSPHERIC NUCLEAR WEAPON TESTS IN THE SOUTH PACIFIC

Operation and **Location**	**Date** and **Time** (GMT)	**Site**	**Emplacement**	**Altitude** (m)	Best Estimate of **Yield**
GRAPPLE	15 05 57 1937Z	Off Malden Island	Airburst	2200	0.3 Mt
Christmas Island	31 05 57 1941Z	Off Malden Island	Airburst	2400	0.7 Mt
	19 06 57 1940Z	Off Malden Island	Airburst	2400	0.2 Mt
GRAPPLE X Christmas Island	08 11 57 1747Z	Off SE point of Christmas Island	Airburst	2200	1.8 Mt
GRAPPLE Y Christmas Island	28 04 58 1905Z	Off SE point of Christmas Island	Airburst	2500	3.0 Mt
GRAPPLE Z	22 08 58 1800Z	Over SE point of Christmas Island	Balloon suspended	450	24 Kt
Christmas Island	02 09 58 1724Z	Off SE point of Christmas Island	Airburst	2800	1.0 Mt
	11 09 58 1748Z	Off SE point of Christmas Island	Airburst	2600	0.8 Mt
	23 09 58 1759Z	Over SE point of Christmas Island	Balloon suspended	450	25 Kt

TABLE 2

UK ATMOSPHERIC NUCLEAR WEAPON TESTS IN THE SOUTH PACIFIC

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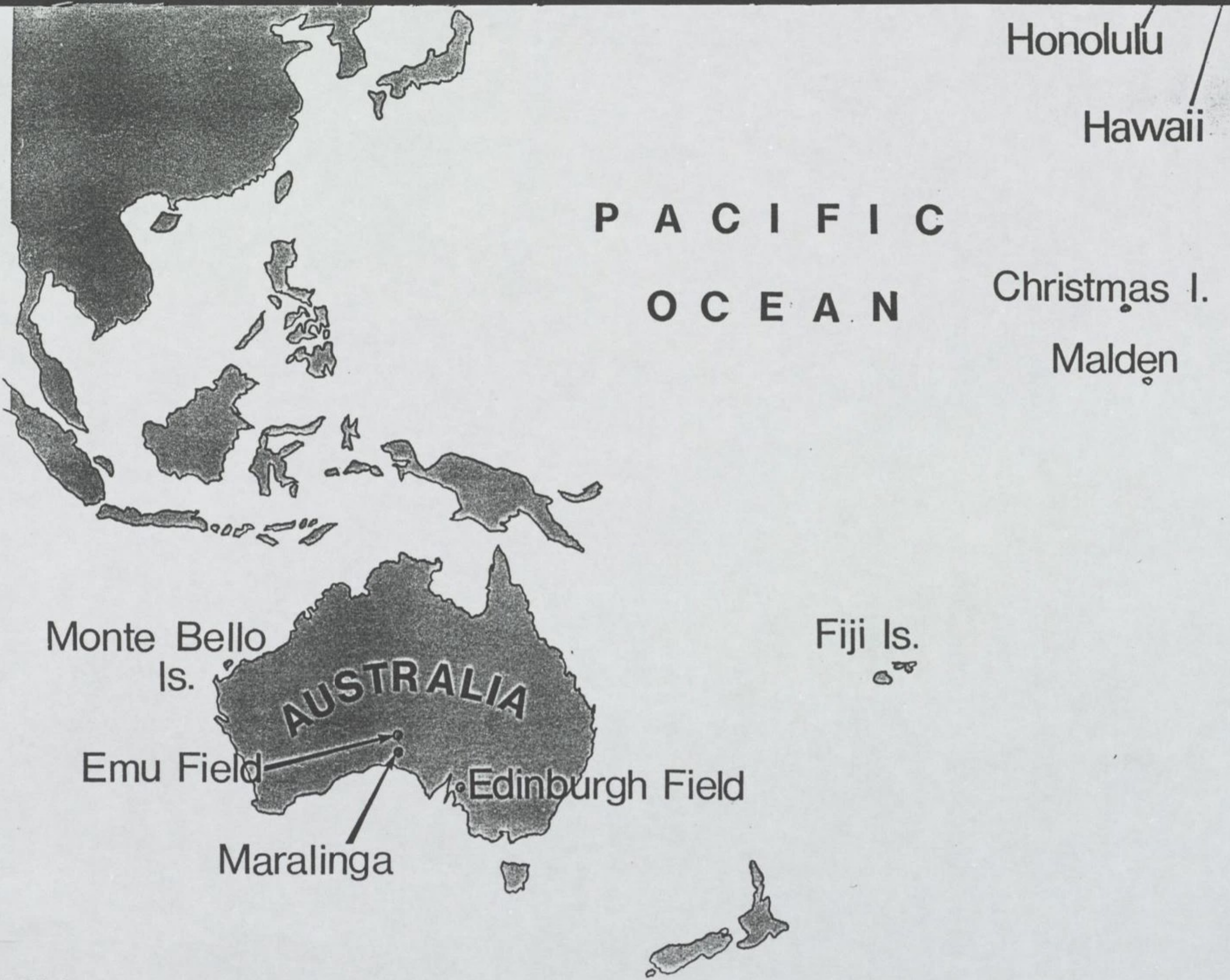
Honolulu
Hawaii
P A C I F I C
O C E A N
Christmas I.
Malden
Monte Bello Is.
AUSTRALIA
Emu Field
Maralinga
Edinburgh Field
Fiji Is.

FIGURE 1

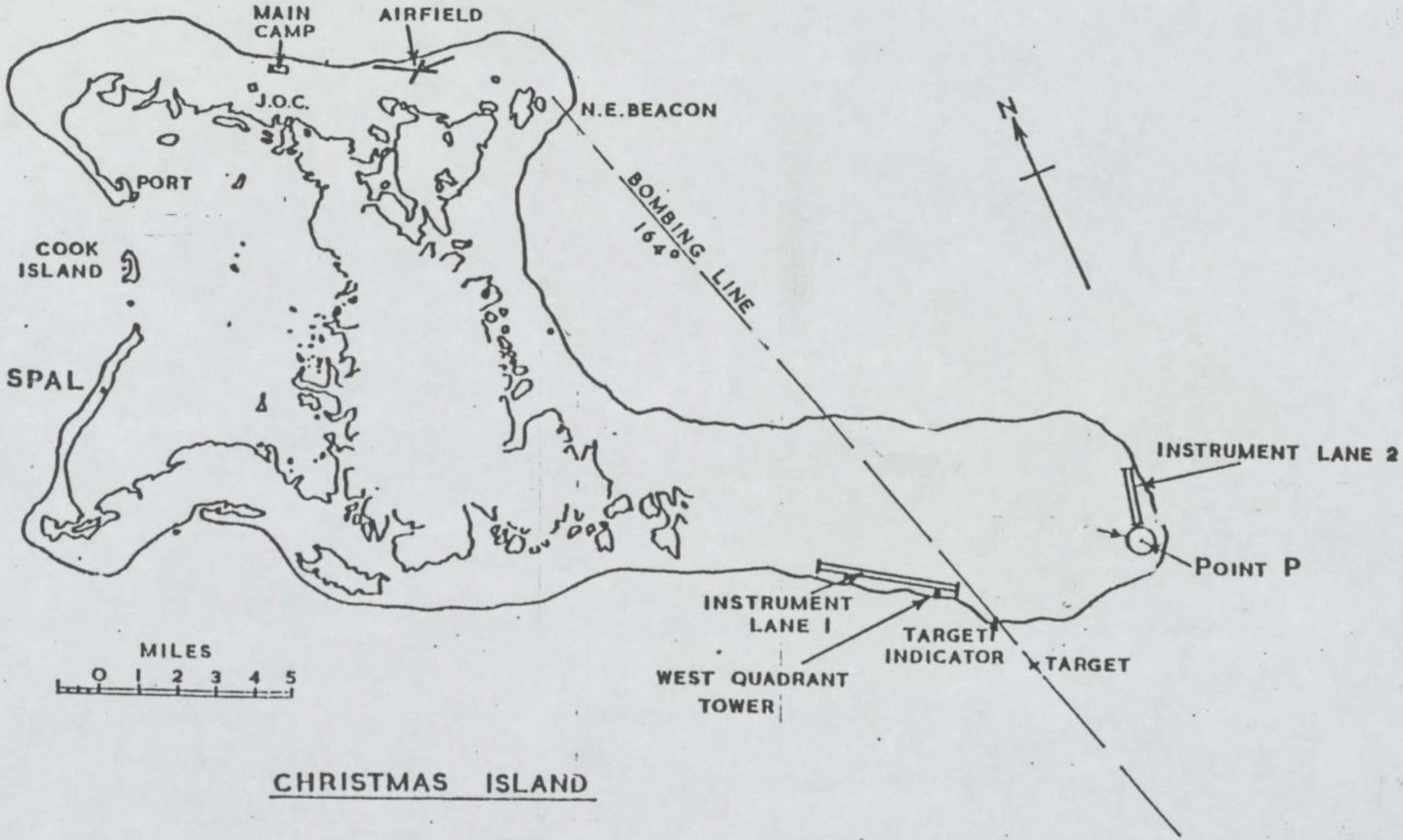
MAIN CAMP
AIRFIELD
J.O.C.
N.E. BEACON
PORT
BOMBING LINE
164°
COOK ISLAND
SPAL
INSTRUMENT LANE 2
POINT P
INSTRUMENT LANE I
TARGET INDICATOR
TARGET
WEST QUADRANT TOWER
MILES
0 1 2 3 4 5
N
CHRISTMAS ISLAND

FIGURE 3

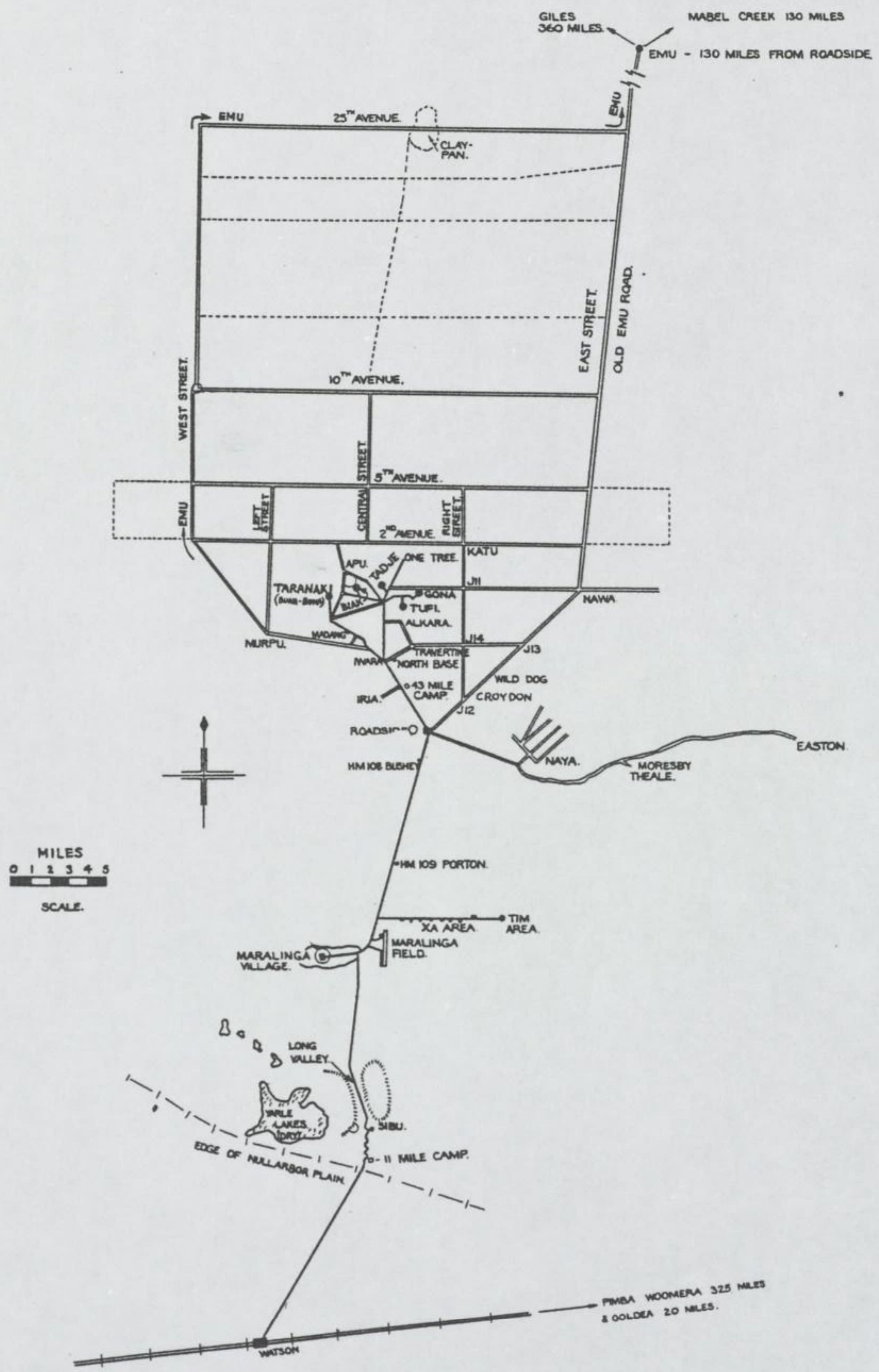
GILES
360 MILES
MABEL CREEK 130 MILES
EMU - 130 MILES FROM ROADSIDE
EMU
EMU
25TH AVENUE
CLAY-PAN.
OLD EMU ROAD.
EAST STREET.
WEST STREET.
10TH AVENUE.
5TH AVENUE.
CENTRAL STREET
EMU
LEFT STREET
2ND AVENUE.
RIGHT STREET.
KATU
APU.
TADJE
ONE TREE.
J11
TARANAKI
(Buma-Bomb)
BIAK
GONA
TUFI.
NAWA
ALKARA.
WADANG
MURPU.
J14
J13
TRAVERTINE
NWARA
NORTH BASE
WILD DOG
IRIA.
43 MILE CAMP.
CROYDON
J12
ROADSIDE
NAYA.
EASTON.
MORESBY
THEALE.
HM 108 BUSHEY
MILES
0 1 2 3 4 5
SCALE.
HM 109 PORTON.
XA AREA
TIM AREA.
MARALINGA VILLAGE.
MARALINGA FIELD.
LONG VALLEY.
YARLE LAKES (DRY)
SIBU.
11 MILE CAMP.
EDGE OF NULLARBOR PLAIN.
PIMBA WOOMERA 325 MILES
& OOLDEA 20 MILES.
WATSON

FIGURE 2

Initial distribution:

Internal

Dr G Ballard	D Safety A85.1
G C R Sallit	MHP A85.1
T P Maish	PDS(C&DE) A6.1
Dr N P Tancock	PDS(C&DE) A6.1
Mrs P M Clare	WEFT A72.1b
S J Woods	WEFT A72.1b
A C Woodville	WEFT A72.1b

External

R Mansell	Head PL(LS) Metropole Building
W B McCormick	Sc(Nuc)2a MoD Main Building
J M Richards	DRPS INM Alverstoke
A Williams	WPD DSS Norcross
K. JOHNSON	D2

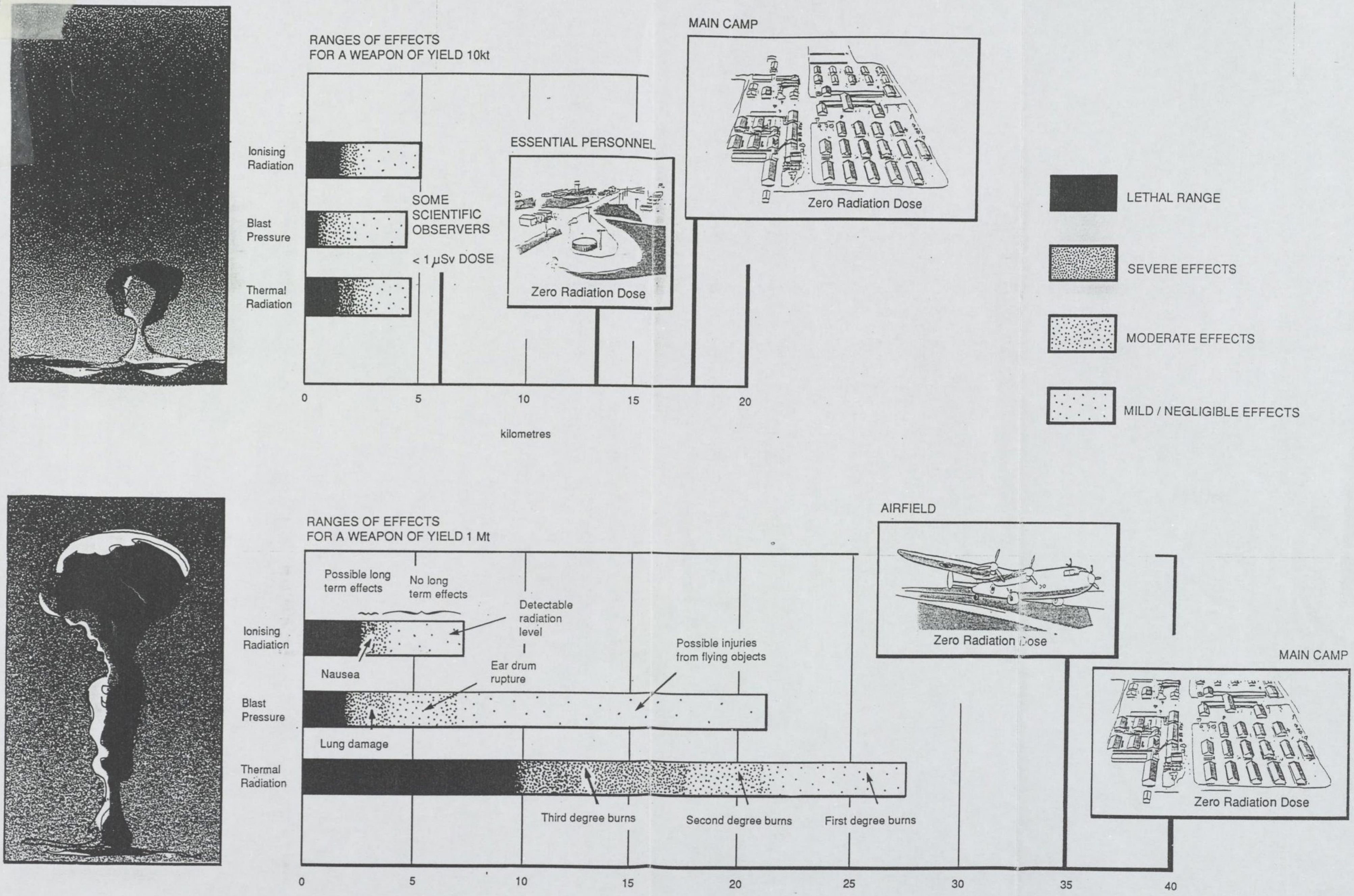

FIGURE 4

Effects of Nuclear Weapons on Unprotected Personnel

Initial distribution:

Internal

Dr G Ballard	D Safety A85.1
G C R Sallit	MHP A85.1
T P Maish	PDS(C&DE) A6.1
Dr N P Tancock	PDS(C&DE) A6.1
Mrs P M Clare	WEFT A72.1b
S J Woods	WEFT A72.1b
A C Woodville	WEFT A72.1b

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R Mansell	Head PL(LS) Metropole Building
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K. JOHNSON	D2