7 Results

Summary

This chapter takes the information and procedures discussed in previous chapters and applies them to actual Australian work groups and their tasks at the tests, in order to estimate the radiation doses that they could have received. Calculations have been done for each of the five major test series, the minor trials and other activities carried out after the major trials finished. The RAAF involvement in cloud sampling and aircraft decontamination is assessed in a separate section.

Radiation doses were assigned in five categories, A to E, with A receiving very low or no dose, and E the highest. Where there was not enough information to decide on a dose category, F was assigned; see Table 6.1(a). A table determined by the Exposure Panel that sets out exposure categories by work group for study participants is in Appendix 1.

For Operation Hurricane (Monte Bello Islands), most Australians received doses in the lowest categories A or B. The major groups receiving higher doses were members of the Joint Services Training Unit (JSTU) who entered contaminated areas (categories C to E) and crews from HMAS Koala and HMAS Hawkesbury (category C).

For operation Totem (Emu), the most exposed group was the Radiation Hazards Group (category D). Others, including Peace Officers, who entered contaminated areas or traveled extensively in contaminated vehicles over contaminated ground, may have received doses that placed them in category C.

For the Mosaic tests (Monte Bello Islands), all doses received by Australians were considered to be in the A or B categories.

With the exception of a small number of RAAF aircrew, the most highly exposed groups at Buffalo (Maralinga) included elements of the Maralinga Range Support Unit (MARSU) and the Indoctrinee Force at One Tree (category C). Australian Indoctrinee Force members at Marcoo received lower doses (category A).

Peace Officers who worked on the Maralinga Range from Operation Buffalo through to the shut-down of the range could have received radiation exposures in category D.

For the final major trial series, Antler (Maralinga), the most highly exposed ground-based groups were members of MARSU engineering and recovery teams with doses in the C category.

For the minor trials and other activities after Antler, a number of groups involved in radiation monitoring and decontamination and some members of MARSU received doses in categories C and D.

Some RAAF aircrews that flew through the radioactive clouds in RAF Canberra aircraft could have received doses in the D and E categories. Ground crews involved in decontaminating those aircraft are estimated to have received doses in category B.

In all cases, where individuals were present for several series, or were exposed doing several tasks at one series, the doses were combined to give a total exposure category; see Table 6.1(b).

Overall, the doses received by participants were small. Seventy-nine per cent of participants received exposures in the lowest dose category. Only 4% of participants received more than the current Australian annual dose limit for occupationally exposed persons (20 mSv).

These results were compared with those from an independent study of doses to British participants in the tests in Australia (Muirhead et al 2003). There is good general agreement in the doses received, although some British participants appear to have received somewhat higher doses than the most highly exposed Australians (UK 210 mSv vs Australia 133 mSv).

7.1 Introduction

This chapter addresses the tasks carried out by Australian participants and assesses those activities that could possibly have led to radiation exposures in category B and above. The tasks varied with each test series, and the potentially exposed participants also changed from series to series.

The tasks performed at each test series are reviewed, and the radiation doses received by the participants performing those tasks are estimated. The doses are derived from contemporary monitoring results where available, and, particularly for internal exposures, on the results of the modelling described in Chapter 6. This review included an assignment of estimated radiation exposures into the six exposure categories listed in Table 6.1(a).

As experience was gained in the conduct of the atomic tests up to and including Operation Buffalo, the management of the tests and the control of radiation exposures improved. However, there is some evidence that for Operation Antler the implementation of safety procedures was less effective, as, by 1957, UK attention was increasingly focused on Operation Grapple, the thermonuclear weapons tests carried out on Malden and Christmas Islands in the Pacific Ocean.

The sampling of radioactive clouds by aircraft and the subsequent decontamination of those aircraft resulted in exposure situations, to both air and ground crews, that were markedly different from the other exposure situations in the various test series. For this reason, they are considered separately in Section 7.8.

This chapter considers exposures during each of the major test series followed by an assessment of the impact of the minor trials. In each section, the groups likely to be of interest are discussed, followed by consideration of the tasks performed by those different groups. This analysis provided indications of situations where significant radiation exposures could have occurred.

Finally, the dosimetric aspects of the tasks were examined to provide guidance on the estimated radiation doses received. The exposure categories are discussed in Chapter 6. More than four decades have elapsed since the completion of the major tests and minor trials. This has meant that in some cases insufficient information could be found to enable any dose estimates. Those tasks have been designated as category F (exposure unknown).

Wherever possible, the number of missing exposure estimates was reduced by drawing on historical records of exposures for individuals or groups known to have performed similar tasks and assessing doses by analogy.

7.2 Operation Hurricane

7.2.1 Groups potentially exposed

As Hurricane was primarily a military operation, the Australian participants were drawn from the Royal Australian Navy, the Australian Army and Royal Australian Air Force.

Some civilians were present, but with the exception of Professor EW Titterton,[29] they were either associated with meteorological forecasting or acted as observers and were not exposed to either an internal or external radiation hazard.

Operation Hurricane time line

A time line to assist the understanding of where Australian groups were at Operation Hurricane is given in Table 7.1.

[29]Professor of Physics at the Australian National University and also later chairman of the Atomic Weapons Tests Safety Committee.

Table 7.1 General time line for Operation Hurricane

Date	Days post-test	Event
Pre-test		Ships were anchored beyond the imposed 16 km limit or taking up position on the perimeter of the 160 km exclusion zone
3 Oct 1952 at 0800h[a]	0	25 kT submarine atomic weapons test at a point off the west coast of Trimouille Island
Pre- and post-test		Patrols by HMAS Culgoa, HMAS Macquarie, HMAS Sydney, HMAS Shoalhaven, HMAS Tobruk, HMAS Warreen, HMAS Reserve and HMAS Murchison
3 Oct 1952	0	HMAS Koala entered lagoon
3 Oct 1952	H + 16.5 h	Five aircraft begin searching for the cloud; the cloud was sampled, at 3000 m at 0100h on 4 Oct; landed at Broome 4 Oct at approx 0700h
5 Oct 1952	H + 43 h	Three Lincoln aircraft sampling at 1500 m; two aircraft obtained active samples
5-6 Oct 1952	H + 55 h	Townsville group — aircraft sampling at 3000 m
11-17 Oct 1952	8–14	HMAS Hawkesbury; records recovery
12 Oct 1952	9	Bad weather; landing craft (LCA) sunk at Daisy Island
23 Oct 1952	20	Completion of UK re-entry activities; two Australians involved
27 Oct 1952	24	Joint Services Training Unit (JSTU) in residence on South East Island
30 Oct 1952	27	LCA salvage by HMAS Koala — taken out to sea and dumped; HMAS Koala's cables and interior contaminated
31 Oct 1952	28	Contamination survey of HMAS Koala by RAAF Officer who had had training in radiation safety
31 Oct 1952	28	HMS Campania escorts UK naval squadron from Monte Bello Islands; HMAS Hawkesbury remained for security duties
2 Nov 1952	30	Completion of decontamination of HMAS Koala
Nov 1952	30+	HMAS Hawkesbury patrolled prohibited areas
6 Nov 1952 to 16 Dec 1952	34–74	JSTU begins training exercises, monitoring of sea moorings for radioactive contamination and collect samples on Trimouille Island[b]
18-20 Nov 1952	46–48	11 crew from HMAS Hawkesbury land on SE Island and later visit Trimouille Island; decontamination exercise on return to ship
15 Jan 1953	90	Termination of security duties of HMAS Hawkesbury
Nov 1953	Approx.400	Contamination of HMAS Karangi following the recovery of Jeep
9-15 Nov 1953	405–411	HMAS Fremantle, HMAS Junee and HMAS Karangi arrive with scientific party; HMAS Karangi monitored radiation levels and recovered mooring gear
Oct 1954	700	Visit by HMAS Karangi

a All times listed are Western Standard Time (WST).
b See Table 7.5 for probable dates.

7.2.2 Operations and major tasks

Potential sources of exposure

Table 7.2 lists the potential exposure sources and pathways that were considered relevant for assessing the data.

Table 7.2 Potential irradiation pathways considered for Operation Hurricane

Source	External hazard	Internal hazard
Gamma flash	Initial γ/neutron burst	
Island re-entry	Fallout material	Resuspension of fallout
Cloud sampling	Immersion in cloud	Inhalation of active particles
	Contaminated aircraft surfaces	
Surface contamination	Ship surfaces	Decontaminating ships
	Aircraft surface	Contamination from Landing Craft (LCA) salvage
	Contaminated clothing	Recovery of contaminated buoys
		Decontaminating aircraft
		Contaminated clothing
Contaminated seawater	Sailing over	Divers swallowing contaminated water
	Divers recovering material	Swimmers ingesting splashed water or spray
	Swimming	
Ship-borne water	Ships boilers	Contaminated water from distillers
	Salt-water circulation systems and desalinators	Consumption of contaminated water
Contaminated food		Eating contaminated fish

7.2.3 Dosimetry outcomes

Outcomes

The radiation dose estimates derived for Operation Hurricane are provided in Tables 7.3 and 7.4. Those estimates were used by the Exposure Panel to assign the exposure categories defined in Chapter 6.

Major Australian re-entry exercise

The dates of visits to the island and recorded doses for the Exercise Director of the JSTU are given in Table 7.5.

Table 7.3 Operation Hurricane: estimated external exposures

Task/exposure	Work group	Evidence/data[a]	Exposure category
External gamma/neutron flash	All Australians	Too far away	A
External beta/gamma ($\beta\gamma$) from sea water	All ships prior to D+ 4	Measurements in the Parting Pool and Lagoon at D + 4 gave approx 40 and 10 μSv/h, respectively. For possible exposure times for RAN ships of 25 to 100 h, maximum accumulated dose would have been 4 mSv. (By D + 14, radioactivity in the Parting Pool was $<$1 μSv/h.) No data have been seen for the Bunsen Channel.	B
External from γ contaminated sea water taken into boilers and evaporators	All ships operating within the Monte Bello Archipelago up to D+ 16[b]	HMS Tracker at withdrawal position; maximum reading 2.5 μSv/h at the Evaporators and 2.0 μSv/h in the Main Circulators at D + 8[c] HMS Campania at D + 11, max reading 6 μSv/h at Evaporators and 10 μSv/h in Main Circulators HMS Zeebrugge at North Sandy Island: sea reading not recorded, at D + 16 max reading recorded of 6 μSv/h in Main Evaporator; assume worst case of continuous exposure at 10 μSv/h = 4 mSv.	B
External $\beta\gamma$ from sea water	Small boats providing a ferry service for UK scientists	As row 2 above	B
Re-entry to Trimouille Island	Joint Services Training Unit	Highest recorded accumulated gamma dose: 52 mSv over a period of 36 d. Film badge records available for 11 of 13 participants and these indicated categories E (2), D (1) and C (10).	C–E
Recovery of landing craft (LCA), Oct 1952	Divers from HMAS Koala	No readings sighted; however, mooring gear recovered in Nov 1953 gave readings of up to 80 μSv/h (RC 137/004) corresponding to approx 2 mSv/h. At Oct 1952, no data on length of time the operation took.	D
Recovery of mooring buoys, Nov 1953	Divers and crew from HMAS Karangi	Mooring buoy in the lagoon read 20 μSv/h, another up to 80 μSv/h. No data on exposure time. Assume 20 h, radiation dose max 1.6 mSv.	B
Swimming	All personnel	Given sea readings of 10 μSv/h (see above) or less, a swimmer would have to have spent up to 10 h in contaminated water to reach exposure level B.	A
Working parties on the island including recovery of body of deceased soldier	Personnel from HMAS Junee and HMAS Fremantle, Nov 1953	One film badge reading of 0.2 mSv	B
Practical decontamination on Trimouille Island	11 Ratings from HMAS Hawkesbury	Three days training 17–19 Nov with visit to Trimouille on last day. On 21 Nov, a JSTU member received 300 μSv (see Table 7.5).	B

Task/exposure	Work group	Evidence/data[a]	Exposure category
Transport of contaminated Jeep to Fremantle	Crew of HMAS Karangi	Reported levels of contamination were low. Highest level recorded 2000 cps (full scale deflection on 1021, approx equal to 200 μSv/h) on left front brake drum. General levels in accessible areas, 25 to 150 cps, approx equal to 10 μSv/h. For, say, a total transport time of 100 h = 1 mSv.	B
Driving contaminated jeep	Western Command Workshops	Jeep decontaminated at Western Command workshop and HMAS Leeuwin	A
Observation	Meteorological Officers and Observers	No participants exposed in the explosion aftermath (other than a scientist from the Australian National University)	A

a The original measurements were in roentgen per hour (R/h) or counts per second (cps) or counts per minute (cpm); they have been changed to SI units using the following relationships: 1 R/h is approx equal to 10 mSv/h, thus a reading quoted above of 1 μSv/h was originally measured as 0.1 mR/ h; 1000 cps γ on a model 1021 contamination monitor very approximately equals 10 mR/ h or100 μSv/ h.
bOn 13 Oct, all ships were ordered to close down distillers for 8.5 h; HMAS Hawkesbury evaporators closed down for 3 d during 11–17 Oct.
c At 1600h on day D + 10, the Health Physicist on HMS Tracker measured 2.5 μSv/h (0.25 mR/h), which was the maximum recorded at the 'Anchorage position' between days D + 8 and D + 12; the fresh water reading was 25 cpm and the seawater count 979 cpm; the fresh water count rates measured between days D + 8 and D + 12 ranged from 15 to 71 cpm (tinned beer read 80 cpm).

Table 7.4 Operation Hurricane: estimated internal exposures

Task/exposure	Work group	Evidence/data	Exposure category
Swimming in contaminated water	All personnel	Levels of radioactive contamination away from the lagoon not excessive: 'It was evident that the bulk of the activity deposited in the lagoon was rapidly dispersed…so that the water-borne activity soon degenerated into a negligible hazard' (Operation Directors Report); D + 4 approx. 150 Bq/cm (β); swallowing, say, 25 cc of water is approx equal to 3.75 kBq is equivalent to a dose of 5.6 μSv (No α measurements).	A
Water spray/splashing	All personnel	Low levels of contamination	A
Eating contaminated food, particularly fish	All personnel	Food stored on deck could possibly have been exposed to fallout. Contamination would have been completely removed by washing and peeling vegetables. Fallout would not penetrate tinned foods and meats would have been stored in refrigerated containers. Some fish were caught and monitored. Most activity could be washed off.	A
Contamination of deck and cabins following recovery of the landing craft (LCA)	Crew of HMAS Koala	No data on the levels of contamination transferred to the deck and cabins; however, experience suggests that both inhalation and ingestion from such contamination would be relatively low.	A
Recovering the LCA	Divers and crew from HMAS Koala	The method of diving to attach the lifting cables not sighted. Protective diving gear would have limited the intake of contaminated water. However, no special contamination control precautions appear to have been taken in undressing or in checking levels of contamination. Comparison with swimming in contaminated waters (row 1 above) indicates any radiation dose would have been low.	A
Recovering mooring buoys in Oct 1953	Divers and others, from HMAS Karangi	Lower levels of contamination 12 months after the detonation.	A
Assisting in recovery of mooring buoys in Oct 1953	Crew from HMAS Karangi	See above	A
Transporting contaminated Jeep	Crew of HMAS Karangi	The contamination was mainly in the dirt, grease and rust covered components. Therefore, little risk of accidental inhalation or ingestion.	A
Decontaminating Jeep	HMAS Leeuwin and Western Command Workshops	Primarily wet methods of decontamination, hosing and use of detergents minimised the risk of ingestion and inhalation. There is a reference to scrubbing with a 'wire brush'.	A
Re-entry to Trimouille Island	Joint Services Training Unit	This was primarily a Health Physics training exercise and it appears that good contamination control was maintained throughout. Some anecdotal evidence that respirators were not worn at all times, but exact work locations and contamination levels not sighted.	A
Practical decontamination on Trimouille Island	11 crew from HMAS Hawkesbury	Practical exercise in sampling and decontamination.	A

Table 7.5 Film badge readings for the JSTU during exercises and sample collections associated with Operation Hurricane

Date (in 1952)	Days post test	Event	Dose[a] (mSv)
9 Nov	37	Team exercise	1.8
10 Nov	38	Plotting exercise	0.5
12 Nov	40	Plotting exercise	2.5
21 Nov	49	Monitoring exercise	0.3
4 Dec	62	Sample collection	0.1
5 Dec	63	Stores recovery	4.0
7 Dec	65	Sample collection	1.0
8 Dec	66	Sample collection	20.0
9 Dec	67	Sample collection	20.0
11 Dec	69	Sample collection	2.0
12 Dec	70	Sample collection	10.4
15 Dec	73	Placing of signs	2.2
13–15 Dec	71–73	Decontamination	14.0

a From the dose records of the Exercise Director, originally quoted in roentgens

7.3 Operation Totem

7.3.1 Groups potentially exposed

The Totem series was mainly a scientific operation under the control of the UK Department of Supply. The operation appears to have been hurriedly organised, and owing to limited road transport and water, conducted in a very difficult environment. It would appear that the operation lacked the same level of radiological control exercised during the Hurricane series, and the rather better integrated management of the later series conducted at Maralinga.

The main groups of potentially exposed Australian personnel were:

- individuals forming part of the Radiation Hazards Group, who carried out surveys of surface contamination around each ground zero (GZ) following both tests (T1 and T2), and entered Forward Areas to collect target response items
- aircrew involved in cloud sampling, and ground crew involved in aircraft decontamination (see Section 7.8.3)
- Peace Officers employed during and after the Totem series to guard the test sites
- senior officials and officers inspecting the Totem 1 site at T_1 + 5 days
- Aircraft Research and Development Unit personnel.

Smaller groups that were considered included a team of three RAAF plant operators constructing a road for the Woomera missile range after T1.

7.3.2 Operations and major tasks

Ground surveys

Four Australian personnel were involved in carrying out ground surveys of dose rates near GZ soon after each explosion. These personnel were part of a team of five full-time and five part-time Health Physics Surveyors. The full-time surveyors made between 10 and 15 surveys each; the part-time surveyers made three to five surveys. Permission was obtained from the Trials Director for all full-time surveyors to receive the Higher Integrated Dose (100 mSv gamma dose, total 500 mSv beta/gamma).

Gaskell and Saxby (1956) estimated that the mean gamma doses to the full-time and part-time Health Physics Surveyors were 49 mSv and 22.5 mSv, respectively, with beta doses of 60 mSv and 18 mSv, respectively. An approximate guide to the dose per person per survey at entry times ranging up to D + 3 days is, therefore, approximately 4 mSv gamma with a beta dose of approximately 5 mSv.

Surveys of the T1 and T2 craters were undertaken at D + 5 days and D + 630 days. It is not known if Australian personnel were involved in these surveys; however, two scientific advisers participated in target response studies.

Potential sources of exposure

Table 7.6 lists the potential exposure sources and pathways used for assessing the data.

Table 7.6 Potential irradiation pathways for Operation Totem

Source	External hazard	Internal hazard
Gamma flash	Initial γ/neutron burst	
Entry into Forward Areas and fallout zones	Induced activity near GZ Fallout material	Inhalation/ingestion/injection of resuspended activity or personal contamination
Cloud sampling	Immersion in the cloud Contaminated aircraft surfaces	Inhalation of active particles
Surface contamination	Contaminated aircraft surfaces Contaminated clothing Contaminated vehicles	Contaminated equipment and records Contaminated vehicles Contaminated aircraft Contaminated clothing

7.3.3 Dosimetry outcomes

Table 7.7 lists the estimated radiation dose assignment categories for participants in Operation Totem.

Table 7.7 Operation Totem: estimated combined internal and external exposures

Task/exposure	Work group	Evidence/data	Exposure category
Radiological surveys near GZ	Radiation Hazards Group	Gaskell and Saxby (1956)	D
Inspection of Totem 1 site at D + 5 d	Officers and senior officials	Assume 4 mSv for entry at D + 3 d; then at D + 5 d, estimated dose using standard decay law is $4 (3/5)^{1.3}$ = 2 mSv	B
Decontamination of records and equipment recovered from Forward Area	Australian decontamination unit	Low levels of activity not generating significant inhalation or ingestion hazards	A
Security for test sites	Peace Officers	See note for radiation doses estimated for travel in vehicles used during Operation Buffalo (Table 7.13)	C
Transport in contaminated vehicles moving through contaminated areas	Various personnel	Doses derived by comparison with Operation Buffalo, using contamination levels from Atomic Weapons Research Establishment (AWRE) T22/57 (Stevenson 1957) and based on 400 h exposure, are 2 mSv external and 8 mSv from driving over contaminated ground; see Table 6.7 and Section 6.6.3 for further explanation. The Land Rovers were the most highly contaminated vehicles with levels above 1000 cps detected in up to 35% of vehicles.	C
Recover Target Response tanks and move overland to Puckapunyal	Various personnel (see Commonwealth of Australia 1985, pp 226–228)	Average level of activity as measured by the Commonwealth X-Ray and Radium Laboratory (CXRL) was 300 cpm or 5 cps. If the conversion 100 cps is equivalent to 10 μSv/h (1 mR/h) is used and the exposure was for 10 h/day over 20 d, the estimated unshielded dose is 0.1 mSv.	A

7.4 Operation Mosaic

7.4.1 Groups potentially exposed

The Mosaic series of two tests, G1 and G2, was mainly a scientific operation under the control of the **United Kingdom Atomic Energy Authority (UKAEA)** and the Ministry of Supply and was the second of the two series at the Monte Bello Islands.

Because of the setting, the operation was largely controlled by the Royal Navy and the RAF, with support from both the RAN and the RAAF.

The complement of personnel during Mosaic was mainly UK scientists and the military. The scientific work for the Mosaic trials was under the control of AWRE and, apart from members of the Atomic Weapons Tests Safety Committee (AWTSC) who were on HMS Narvik (the Control Ship), there appears to have been no involvement of Australians in the scientific programs conducted on the islands. Re-entry operations were done under strict Health Physics control, which limited the number of men in contaminated areas.

The evidence indicates that very few Australians were involved close to the test zone. The exceptions include the Australians involved in cloud sampling and, away from the test zone, ground crew decontaminating aircraft at RAAF Pearce in Western Australia. In addition, at least one naval officer assisted with recovery of equipment to HMAS Karangi, and support staff at Onslow may have been exposed when the radioactive cloud crossed the Australian coast.

7.4.2 Operations and major tasks

Naval operations

Royal Navy and RAN ships, their function and their approximate location at the time of the G1 and G2 explosions are summarised in Table 7.8. One RN ship, HMS Narvik, was used as the control vessel for the two nuclear explosions. One Australian naval officer was present on HMS Diana when it was placed in the path of the fallout for decontamination trials at both tests.

Cloud sampling

As in the earlier Hurricane trials, RAF Canberra aircraft were used to sample the radioactive cloud shortly after detonation. Australian support included additional RAN ships for patrol and servicing duties and RAAF aircraft, principally Neptunes, for site patrols and transport. RAAF facilities at Pearce were used for RAF and RAAF aircraft, while a search and rescue base was established at Onslow. An RAAF Wing Commander and crew were provided to fly an RAF Canberra that sampled radioactive clouds from both tests. Some meteorological data were collected by an RAF Shackleton aircraft based in Darwin. Partial decontamination of aircraft was performed at Pearce (see Section 7.8.4).

Table 7.8 Naval vessels used for the Mosaic series

Task Group	Ship	Function	Location at test[a]	
			G1	G2
308.1	HMS Narvik[b]	Control	13 km S	19 km S
	HMS Alert[b]		15 km S	19 km S
308.2	HMAS Fremantle	Support	19 km S	Fremantle
	HMAS Karangi	Support	Fremantle	Onslow
	HMAS Junee	Support	19 km S	Fremantle
	MRL 252	Lighter	25 km S	19 km S
	MWL 251	Lighter	25 km S	19 km S
308.4	HMS Diana[b]	Contamination Trials	19 km N	160 km N

a Approximate position; estimated from the Royal Commission report maps and recorded naval proceedings
b The numbers of Australian personnel on UK vessels were: four on HMS Narvik, nine on HMS Alert and one on HMS Diana; the weather ship was located at 20 deg S, 105 deg E from 9 Apr 1956; when not on duty ship would be located at Fremantle or, on at least one occasion, visiting the Monte Bello Islands.

Long-range fallout from the tests

Wise and Moroney (1992) calculated possible long-range fallout levels in Australia, including corrections for sampling inefficiencies.

Ground contamination was measured at Australian population centres both by radiation surveys and passive sticky paper samplers. High-volume air samplers were used to measure airborne contamination.

Potential sources of exposure

Table 7.9 lists the potential exposure sources and pathways used for assessing the data.

Table 7.9 Potential irradiation pathways considered for Operation Mosaic

Source	External hazard	Internal hazard
Gamma flash	Initial γ/neutron burst	
Re-entry to Forward Areas and to fallout zones	Induced activity near GZ Fallout material	Inhalation/ingestion/absorption through wounds of radioactive contamination
Entry into fallout plume	Fallout cloud shine Contaminated equipment	Inhalation of active particles
Cloud sampling	Immersion in the cloud Contaminated aircraft surfaces	Inhalation of active particles
Surface contamination	Aircraft surfaces Contaminated clothing	Recovery of contaminated equipment and records Contaminated vehicles Decontaminating aircraft
Buoys and moorings	Contaminated surface	
Contaminated food		Eating contaminated fish
Contaminated salt water systems	External from γ contaminated sea water taken into boilers and evaporators	Drinking contaminated water

7.4.3 Dosimetry outcomes

Table 7.10 lists the estimated radiation dose assignment categories for participants in Operation Mosaic. The larger yields for both G1 and G2 (Table 1.1) have been considered in estimating these dose assignments.

Table 7.10 Operation Mosaic: estimated combined internal and external exposures

Task/exposure	Work group	Evidence/data	Exposure category
Initial flash	RAN ships and HMS Narvik and HMS Alert	Nil dose as ships too far away; film badge records indicate <0.2 mSv	A
Fallout contamination and decontamination	RAN members on HMS Diana	Possible exposure to contaminated salt water systems; see Table 7.3 (Operation Hurricane)	B
Hermite Island Work Group	Re-entry tasks	The Royal Commission report (Vol. 1, paragraph 7.6.15) reports a sortie to the northern tip of Hermite Island and that this area was free of contamination.	A
Logistical support for G1	HMAS Fremantle and HMAS Junee	Possible exposure to contaminated salt water systems; see Table 7.3 (Operation Hurricane)	B
Logistical support and equipment recovery for G2	HMAS Karangi	Maximum dose on UK film badge records of 1.7 mSv	B
Supply duties	MRL252 and MWL251	Maximum dose on UK film badge records of 0.4 mSv	A
Fallout deposit	Staff based at Onslow	External dose was of order 0.1 mSv; see Section 6.6.6.	A

7.5 Operation Buffalo

7.5.1 Groups potentially exposed

The Buffalo series was principally a scientific operation undertaken in conjunction with an assessment of the effects of a nuclear explosion on military personnel, equipment and biological specimens, as well as seismic studies, all carried out under the control of the UK. Buffalo was the first of two major series of trials at the newly constructed permanent site at Maralinga.

This series of tests provided an opportunity for military personnel to experience at first hand the effects of an atomic test at close range, observe the effects of the blast on equipment and structures and, thus, become a nucleus of knowledge on nuclear warfare for dissemination among the Services. Approximately 250 observers, known as the Indoctrinee Force (I-Force), were officers drawn from the armed services of the UK, Australia and New Zealand. The I-Force was intended to be self-sufficient. It had its own administrative organisation, built its own accommodation and had a separate field decontamination facility.

There was greater Australian involvement in Health Physics operations during Buffalo than in earlier series. Six Australians were selected to provide Health Physics support and three of these participants were given training in the UK. Before the operation, one of these, the Deputy Director of CXRL, trained a further 20 Australian service personnel who formed the nucleus of the Australian Radiation Detection Unit (ARDU). ARDU personnel were rotated between Maralinga and Emu, 190 km north of the Maralinga test site. A group known as the Australian Health Physics Team arrived at Maralinga in August 1956 where they were attached to the British Radiation Measurement, Health

Physics and Decontamination Groups (Australian Archives AG11 and Royal Commission 7.5.4/5).

Sundry engineering telemetry and target response infrastructure tasks were also undertaken, which involved potential radiation exposures of Australians during and after each test. One example is the sandbagging of instrument bunkers to limit the entry of neutrons. Radiation exposures of Engineer Troop personnel could have resulted from neutron activation products in soil, or fallout, when they removed the bags after each test to allow access to the instruments.

Vehicle and plant recovery, decontamination and repair groups operated in the Decontamination Centre (DC) Area adjacent to the Maralinga Village, along the 'dirty track' and in the YELLOW area.[30] A mobile vehicle decontamination unit operated inside the YELLOW boundary. Because of a lack of drainage facilities, it was necessary to move this unit as the ground beneath became both contaminated and muddy.

The Target Response Programme was divided into seven groups, each with its own team. Australia contributed representatives to each of these teams: Ordnance, Electronics, Aircraft, Materials, Explosives, Structures and Biological (Symonds 1985, p 304).

The highest level of induced contamination (neutron activation of various components) recorded for Target Response equipment was 70 to 80 μSv/h from a 25-pound gun and a Scout Car on day $D_1 + 2$. At early times, post-test, copper alloys were found to be the most radioactive, with radiator cores and ammunition also moderately radioactive. Lead acid accumulators were especially radioactive. Steel work was initially less radioactive, but after a few days became the principal activated material contributing to radiation doses (Stevenson 1957).

The Biological Group contained six Australians who assisted with experiments using live animals to investigate the ingestion and retention of radioactive fallout (Royal Commission report 7.0.10).

7.5.2 Operations and major tasks

Initial surveys near ground zero

The measurements of radioactivity on the ground are described in an AWRE report (Rae 1957). Prior to the tests, a grid for the local survey program was established based on the main roads and secondary tracks, with all tracks and roads sign posted. The initial survey used teams dressed in full protective clothing to confirm that the site chosen for the mobile Health Control centre was free of fallout and to place warning signs at the 20 mSv/h contour. Hard-topped Land Rovers were used in this preliminary survey. Entry into the survey areas was within 10 minutes of firing.

These early surveys were carried out by UK personnel, but radiation surveys after the Breakaway test (round 4) were made by a Canadian Radiation Detection Unit, working under military conditions, using their own Victoreen No. 592 γ survey meters.

For the Kite test (round 3), a rapid reconnaissance, made within 2 hours of firing, was carried out to check contamination levels at the Health Control site, and in the instrument lanes and the camera towers.

[30]See extract from RSRM/56(5) in Section 4.2.3.

For all except the Kite round, four teams of three Health Physics Surveyors were used to survey the roads and tracks from days D + 1 to D + 5. The survey of all except the central area containing the craters was completed by day D + 5. The crater surveys were made on foot at 10 days after the One Tree and Breakaway firings by three teams of two Surveyors drawn from the British Army and ARDU, respectively.

The Indoctrinee Force

The scientific program included extensive Target Response (TR) studies at the One Tree test. As part of their training, the I-Force observed these during a 3-day period starting 1 day after the One Tree explosion. Approximately half the group toured the target response sites on $D_1 + 1$ and the remainder on $D_1 + 2$. The involvement of I-Force at One Tree was regarded as being very successful and steps were taken for part of the original I-Force to observe the Marcoo test at close range from a Centurion tank, from slit trenches and from the ground surface. The placement of members of I-Force during the One Tree and Marcoo tests is summarised in Table 7.11. There were no post-detonation tours after the Marcoo test.

Table 7.11 The Indoctrinee Force at Operation Buffalo

Test and site	Location	Personnel[a]	Radiation dose[b]	Internal exposure[c]
Prompt radiation doses[b]				
One Tree				
North Base	7.2 km S of GZ and upwind	177 UK, 100 Australian, 5 New Zealand	Nil	Nil
Marcoo Centurion tank	1800 m S of GZ	4 UK	2.5 mSv	Nil
Marcoo Field shelters (0.9 m cover)	1800 m S of GZ	20 UK 3 Australian 1 New Zealand	0.3 mSv	Nil
Marcoo Mina Stand in open	3000 m S of GZ	53 UK 27 Australian 2 New Zealand	0.03 mSv	Nil
Total radiation doses[d]				
One Tree				
Vicinity of GZ	Examined Target Response	100 Australian	<4 – 7.6 mSv	0.01 mSv[e]
	for 2.5 h over next 4 d	177 UK 5 New Zealand	mean <5 mSv	
Forward Area	Marching as trial of service clothing	24 volunteers	3 mSv[f]	0.16 mSv[f]

a These numbers include civilian as well as military personnel.
b It is not known if these estimates of prompt radiation doses were calculated or recorded by film badge (quoted in letter to Hon Barry Cohen from Emeritus Prof A M Clark AM, dated 2 August 1984); alternative estimates are to be found in Section 6.6.1.
c Indoctrinees were fitted out with the appropriate levels of protective clothing, and entered and exited Forward Areas through a Health Physics control point.
d Total radiation doses quoted in letter to Hon Barry Cohen from Emeritus Prof A M Clark AM, dated 2 August 1984; see also dose list in Australian Archives from Australian Military Forces (IFA/44/1/2, dated 12 October 1956).
e Estimated internal dose for I-force members based on average external exposure over 2.5 h Target Response inspection of 5 mSv at D + 1 d; the calculation assumes resuspension of fission products from the surface (in practice, the external radiation was from induced activity in the soil and only a very small fraction of this would be resuspended).
f See Table 6.6

One of the I-Force tasks was an investigation of the contamination of service clothing. This involved 18 volunteers from I-Force and six members of the TR team on day $D_1 + 3$. The personnel were divided into three groups and moved into a fallout area, where the dose rate ranged from 1 to 10 mSv/h. Some wore respirators of the AWRE pattern and the remainder wore a standard service respirator. Group One drove to and fro over a 1-mile course in an open truck, dragging sacks to create as much dust as possible, and the second group marched over the same course for 3 km whilst the truck passed at frequent intervals. The third group marched across the country for 2 km, brushing against trees, while stirring up as much dust as possible and also crawling through the undergrowth for 100 m. After the trial, the men returned to a separate field decontamination centre where they were monitored by members of the Decontamination Group using contamination Monitor Type 1320, with the β-window open (Janisch et al 1957).

External radiation doses, estimated from film badge readings, are available for participants in I-Force. Several participants from I-Force at Mina Stand recorded doses in the region of 6 mSv. As the radiation doses from the initial flash for these participants were negligible, because they were too far from GZ, the bulk of the dose would have been obtained during examination of target response items at One Tree. Thus, 6 mSv is suggested as an estimate of those I-Force members for whom no dose records were found.

Indoctrinee decontamination

This was carried out in a field facility set up and operated by Indoctrinees under Health Physics supervision.

The Australian Radiation Detection Unit and its functions

Subgroups of the Australian Radiation Detection Unit (not to be confused with the Aircraft Research and Development Unit) were rotated through the former Emu test site where they performed ground radiological surveys out to 200 miles (300 km) from GZ. Their work also included air sampling (including some cascade impactor sampling), water sampling and collection of animal thyroids and bones. During the passage of the fallout cloud, sticky paper collectors and cascade impactors were set up at locations across the predicted path of the cloud. After the cloud had passed, five teams of two men each carried out surveys using 1390 beta/gamma contamination monitors. Four teams operated along radial tracks from Emu and one team along the North-South Road.

For One Tree, test fallout was measured at approximately 320 km from GZ using AWRE predictions to guide the placement of samplers. The ARDU established sampling sites along the North–South road from Tarcoola to Coober Pedy and Welbourn Hill and northwest to Ernabella. At Coober Pedy, a total of 33 MBq/m^2 of fallout (corrected to H + 1 hour) was collected over a 5-hour period from H + 3 hours. From Table 6.3, the conversion factor from the activity of ground deposit to dose rate at H + 5.5 hours is approximately 0.2 μSv/h for 1 MBq/m^2 at H + 1 hour. The measured radioactivity at Cooper Pedy, therefore, corresponds to a dose-rate of 7 μSv/h at the middle of the collection period, giving a total dose for the operation of 35 μSv.

Given that Marcoo was a relatively small ground burst, it is unsurprising that fallout from this test was restricted mainly near the Maralinga Range. At distances of more than 80 km from GZ, the dose rate from the plume was less than 19 μSv/h.

The third test, Kite, was an **airburst** and as such generated only small quantities of intermediate fallout. However, some fallout fell on Maralinga village approximately

10 hours after the explosion. This amounted to 3.3 MBq/m^2 (corrected to H + 1 hour) which, using a conversion factor from Table 6.3, corresponds to an integrated dose from H + 10 hours of approximately 16 µSv. The Royal Commission concluded (RC 8.3.29(c)) that this round '…should not have been fired under the conditions prevailing at the time'.

The final test in the Buffalo series, Breakaway, was similar to One Tree in yield and type of burst and could have been expected, therefore, to give similar fallout levels. The ground survey was carried out by the Canadian RDU to a distance of approximately 24 km from GZ using a helicopter to survey much of this area. This showed that the fallout cloud had moved east of GZ with the maximum dose-rate from fallout corresponding to approximately 2.5 mSv/h corrected to H + 24 hours.

Maralinga Range Support Unit (MARSU)

The MARSU was the generic name for a variety of groups responsible for the logistical, engineering and administrative support of the range. During the major trials periods, the Australian Range Commander was responsible to the Trials Superintendent through the UK Services Commander. The groups who were potentially exposed to external and internal radiation hazards were principally scientific and engineering teams. The majority of MARSU members who performed service functions in and near Maralinga Village would have received minimal radiation exposures.

A number of important records of day-to-day activities could not be located — for example, Permit to Work in Active Areas Certificates (paragraph 3.3 RSRM/56(5)), Countdown Schedules, Re-entry and Recovery Schedules, Health Physics Entry to Active Area and Dosage Records, Construction Schedules and Hospital Treatment Records.

Vehicle decontamination

Vehicle decontamination was carried out by Decontamination Group DC2, in both the DC area near the Village and inside the YELLOW area using a mobile decontamination plant. Measured β and γ contamination levels for the MARSU YELLOW fleet (38 vehicles) at specific times after detonation are contained in Table 4 of AWRE T22/57 (Stevenson 1957).

Later work

Between the Buffalo and Antler series, the 'Inter-Trial' period, responsibility for Radiation Health Control on the Maralinga Range was passed to the Australian Health Physics Representative (AHPR). This occurred in stages from 30 October to 8 November 1956. The rapid exodus of UK personnel left the AHPR with several problems that became apparent only slowly.

At the end of the Buffalo series, the YELLOW area was described in the AHPR's report of November 1956 as the boundary:

> …along the north side of the Pom Pom–Kite–Nawa Road, east side of East street, north side of 5th Avenue until 1.7 miles west of central Street, due south to 0.5 miles west of Breakaway, then curving to the south of Breakaway until 0.2 miles from Breakaway on the Tanka road, and finally across to Pom Pom.

Turner, the AHPR, also described the Control Area boundary and stated that every access road to the YELLOW area (this may have been one or two roads, depending on the distance from Roadside) had a barrier at either the controlled boundary or at the junction of West Street. In his March 1957 Report, the AHPR reported the discovery of an 'active area' extending south of the marked YELLOW boundary into the proposed Antler work sites.

Turner's report also stated that Breakaway fallout had swamped the whole of the One Tree area and inundated the area around Marcoo. These factors added to the difficulties of the crater surveys.

Potential sources of exposure

Table 7.12 lists the potential exposure sources and pathways considered relevant for assessing the data.

Table 7.12 Potential irradiation pathways for Operation Buffalo

Source	External hazard	Internal hazard
Gamma flash	Initial γ/neutron burst	
Re-entry to Forward Areas and to fallout zones	Induced activity near GZ Fallout material	Inhalation/ingestion/injection of resuspended activity or personal contamination
Entry into fallout plume (e.g. by the Australian Radiation Detection Unit during ground surveys)	Immersion in the cloud Driving vehicles Handling contaminated equipment	Inhalation of active particles
Cloud sampling	Immersion in the cloud Contaminated aircraft surfaces	Inhalation of active particles
Surface contamination	Aircraft surfaces Contaminated clothing Contaminated vehicles	Contaminated equipment and records Contaminated vehicles Decontaminating aircraft Contaminated clothing
Work in Forward Areas/fallout zones	γ and β radiation from contaminated surfaces	Dust-producing activities, e.g. sandbagging of bunkers, cable laying, fencing
Patrolling the Maralinga Range	γ and β radiation from contaminated surfaces	Driving contaminated vehicles, walking through contaminated areas

7.5.3 Dosimetry outcomes

Table 7.13 lists the estimated radiation dose assignment categories for participants in Operation Buffalo.

Table 7.13 Operation Buffalo: estimated combined internal and external exposures

Task/exposure	Work group	Evidence/data	Exposure category
General engineering support[a]	Maralinga Range Support Unit (MARSU) Engineer Troop	Assume 10 h/d for 50 d in region with dose-rate 0.01 mSv/h; adopting the example in Section 6.6.2 gives external dose of 5 mSv, ingestion dose of 0.1 mSv and inhalation dose of 0.4 mSv for total of 5.5 mSv.	C
Hoisting of weapon to tower	Engineer Tower Party	Low external dose-rate for short time.	A
Install and recover camera, radar and British Insulated Callenders Cables Plc (BICC) towers	MARSU Engineer Troop	Some data (see, for example, Table 7.5 and Section 7.3.2) indicate dose per entry is of the order of 4 mSv. If several entries are involved, then dose is of the order of 10–20 mSv.	C
Sandbag parties (post test)	MARSU Engineer Troop	Assume 5 h for each task, two tasks per countdown and three countdowns for total of 30 h. Corresponds to three 10-h days. See Table 6.7; external dose per day of 0.1 mSv and internal dose per 10-h day (assume 100-day-old fallout) of 0.06 mSv. Total for three days of 0.5 mSv.	A
Immediate re-entry and recovery tasks that could not be delayed including target response items	MARSU Scientific and Engineering recovery teams	Some data (see, for example, Table 7.5 and Section 7.3.2) indicate dose per entry is of the order of 4 mSv. If several entries are involved, then dose is of the order of 10–20 mSv.	C
Examine target response items	Indoctrinee Force	See Table 7.11	C
Indoctrinee decontamination	Health Physics	Carried out in controlled environment by men trained in decontamination procedures. Appropriate monitoring equipment available at the control point.	A
Vehicle and plant recovery	MARSU Engineer Troop	Some data (see, for example, Table 7.5 and Section 7.3.2) indicate dose per entry is of the order of 4 mSv. If several entries are involved, then dose is of the order of 10–20 mSv.	C
Define fallout boundary	Australian Radiation Detection Unit (ARDU) (>H + 8 h)	See Table 6.7	B
Vehicle decontamination	DC2 team (Decontamination)	See Table 6.7; derived vehicle contamination was 5 μSv/h. Assume 10 h/day for 20 d for dose of 1 mSv.	B
Radiation surveys	ARDU (inter-trial period)	Estimated from similar exposures recorded in Australian Health Physics Representative (AHPR) post-Antler reports.	B

Task/exposure	Work group	Evidence/data	Exposure category
Transport in contaminated vehicles moving through contaminated areas[b]	Various personnel	Doses derived for Operation Buffalo using contamination levels from Atomic Weapons Research Establishment (AWRE) T22/57 (Stevenson 1957) and based on 400 h exposure are 2 mSv external, 0.5 mSv internal and 8 mSv from driving over contaminated ground; see Table 6.9 and Section 6.6.3 for further explanation. Land Rovers were the most highly contaminated, with levels above 1000 cps detected in up to 35% of vehicles.	C
Security for test sites	Peace Officers	See radiation doses estimated above for travel in vehicles.	C

a These tasks included: construction of instrument and rocket lanes and associated fencing, provision and removal of heat, blast and neutron protection, laying of cables prior to test, construction of instrument bunkers, preparation of lanes for Health Physics Surveyors, construction of BICC masts.
b The estimated hours for driving YELLOW vehicles includes a period between Operations Buffalo and Antler.

7.6 Operation Antler

7.6.1 Groups potentially exposed

Antler was primarily a scientific operation executed mainly under the control of the UK. Six tests were originally planned for this series, but only three were carried out. The Australian participants were drawn almost exclusively from the armed services, with civilians being needed for the meteorological services and as support staff at the Maralinga facilities.

The airborne activities of the RAAF were similar to those in earlier tests. Australian personnel included a Wing Commander, an RAAF Canberra aircrew that flew several missions in an RAF Canberra and a variety of support staff. There was substantial RAAF involvement in ground-based roles. Some aircraft decontamination was carried out by RAAF ground crew under controlled conditions.

A large number of personnel were required for the Antler test series. As well as the many UK scientific teams, Australian support included the 28 Australians forming the ARDU, 11 Australians in the meteorological unit and as part of the 450 in the MARSU.

7.6.2 Operations and major tasks

Initial surveys near ground zero

The RAF Regiment Land Survey Team carried out the initial surveys near GZ. They used three Land Rovers with two men fully dressed in protective clothing for each of the three survey teams. Each team carried 1390 and 1301 beta-gamma contamination monitors and a 1324 dose-rate meter. Five minutes after each test, one team left Roadside to survey along the instrument lane up to a 20 mSv/h line. Concurrently, the second and third teams cleared sites to the east and west of the instrument lanes and then worked round to Second and Fifth Avenues to find the edges of the fallout. The maximum external dose received by any team on one survey was 10 mSv. In general, the teams had returned to the Health Physics control site by 90 min post-firing. Table 7.14 summarises the distances at which the 20 mSv/h (2 R/h) level was detected during the initial surveys.

Table 7.14 Distances from GZ to 20 mSv/h line for each test

	Approximate distance from GZ (m)	Approximate time after firing (min)
Tadje	460	33
Biak	690	51
Taranaki	530	50

Source: McDougall et al 1958.

The Australian Radiation Detection Unit (ARDU) and its functions

The ARDU performed ground radiological surveys in the Alice Road (Stuart Highway) area. The ARDU used four specially equipped Land Rovers to sample and measure fallout on the road to Alice Springs. The Land Rovers were based at Mt Clarence and were directed by radio to the fallout area predicted by the Theoretical Predictions group. Sticky paper collectors and cascade impactors were set up at each of seven locations across the expected path of the cloud. The sticky papers and the filters were changed five times during the expected transit of the cloud. After the expected passage of the cloud, a ground survey was carried out using type 1390 gamma survey meters and type 1320 beta-gamma contamination monitors.

Fallout delineation for each test

The following is a summary of the work by ARDU during the Antler series (Commonwealth of Australia 1985).

For the Tadje test, the AWRE Theoretical Predictions group predicted the direction of the fallout incorrectly, which meant that the sticky paper collectors and the cascade impactors were in the wrong location. Hence, no measurements were possible using these devices. Instead, ground deposition was measured using 1390 meters and 1320 monitors. The maximum contamination along the Emu–Mabel Creek Road was 444 MBq/m^2, corrected to H + 1 hour at 5 km east of Emu. An aerial survey showed the distance from GZ to the peak value of the fallout was approximately 13 km and the dose-rate, corrected to H + 24 hours and a height of 1 m, was less than 20 μGy/h.

For the Biak test, the predicted path for the fallout was between Mabel Creek and 48 km north of Ingomar. This was sufficiently close for fallout samples to be collected. The maximum fallout from the gamma dose survey occurred at approximately 8 hours, 16 km north of Ingomar. The level was approximately 174 MBq/m^2, corrected to H + 1 hour. The aerial survey showed the fallout had an easterly path to the south of Coober Pedy. The distance from GZ to the peak value of the contamination was less than 1.5 km.

Taranaki was a balloon-supported airburst, and the theoretical prediction was that there would be no measurable medium or long-range fallout. Therefore, no air sampling was carried out. The ground survey showed the maximum fallout along the North–South road was 255 MBq/m^2, corrected to H + 1 hour, at Ealbara, 35 km north of Tarcoola. The close-in fallout was much smaller than expected.

Maralinga Range Support Unit

As with Operation Buffalo, MARSU was responsible for the logistical, engineering and administrative support of the range. During the major trial periods, the Australian Range Commander acted under the command of the UK Services Commander.

Clean up of the Taranaki test site

One unfortunate aspect of the Biak test was the contamination of the Taranaki site by weapon debris. This required decontamination of the site before the Taranaki test could proceed.

The cleanup was done by the UK Range Facilities (RF), Decontamination (DC) and Health Physics (HP) Groups starting on the first day after the Biak test (i.e. D_2 + 1 day) with the assistance of two Australians who were involved in the decontamination. An assessment of their possible radiation doses has been given in Section 6.6.5.

Later work

After the completion of the Antler series, responsibility for Radiological Control was transferred to the AHPR, with effect from 22 October 1957. At handover, the YELLOW area was the same as at the end of the Buffalo series with additional areas around Tadje, Biak and east of Taranaki (MacDougall et al 1958).

^{60}Co pellets at Tadje

About nine months after the handover to the AHPR and his team, one of the Australian Health Physics Surveyors discovered unexpectedly high radiation levels from small pellets near the Tadje GZ. Later analysis showed the pellets to be ^{60}Co, with a single pellet having an activity of the order of 400 MBq. The concerns this contaminant caused are described fully in the Royal Commission report (Commonwealth of Australia 1985, Section 9.5). It is clear that the Australians in charge of the radiological management of the range had not been advised of the presence of ^{60}Co prior to its discovery. The last report by the AHPR to AWRE in December 1958 noted that 180 pellets totalling 166 GBq had been recovered from an area of approximately 10 000 m^2 north of the Tadje GZ and that the pellets were prone to fragmenting when pressure was applied to them.

Thus, it can be calculated that the pellets had an average activity of 0.9 GBq and a surface density of 0.018 m^2, corresponding to approximately 17 MBq/m^2 of ^{60}Co averaged over the contaminated area. Given the relatively low pellet density, it is to be expected that the dose-rate at different locations would have varied considerably. Calculations show the mean dose rate in air was approximately 0.14 mGy/h, with a standard deviation of 0.13 mGy/h.

^{239}Pu contamination at Tadje

Enhanced levels of ^{239}Pu had been found in this area during the rehabilitation of the Maralinga lands. A major rehabilitation program, Operation Brumby, had been undertaken in 1967, which concentrated on the surroundings of each GZ and gave special attention to the area north of Tadje GZ (Cooper et al 1978). This special treatment included the removal of pellets, enriched in ^{60}Co, for secure disposal. Whilst the area near each GZ was graded and ploughed to a diameter of several hundred metres, it is not clear whether this was done in the area where the pellets were found. Measurements of 12 soil samples from this area (Cooper et al 1978) showed that the ^{239}Pu concentration in the soil ranged from 63 to 670 kBq/kg, with a median value of 170 kBq/kg. For those participating in activities raising 'normal' levels of dust, the median activity concentration corresponds to a dose-rate of around 0.03 mSv/h from inhalation of ^{239}Pu. If, prior to Operation Brumby, work in this area raised dust to beyond 'nuisance' levels for exposure times in excess of 10 h, then the possible internal doses from the inhalation of ^{239}Pu would have been significant.

Potential sources of exposure

Table 7.15 lists the potential exposure sources and pathways that were considered relevant for assessing the data.

Table 7.15 Potential irradiation pathways for Operation Antler

Source	External hazard	Internal hazard
Gamma flash	Initial γ/neutron burst	
Re-entry to Forward Areas and to fallout zones	Induced activity near ground zero Fallout material	Inhalation/ingestion/injection of resuspended activity or personal contamination
Entry into fallout plume (e.g. by the Australian Radiation Detection Unit during ground surveys)	Immersion in the fallout cloud Ground deposit	Inhalation of active particles
Cloud sampling	Immersion in the cloud Contaminated aircraft surfaces	Inhalation of active particles
Mechanically enhanced resuspension during cleanup of Biak sourced fallout at Taranaki	Fallout material	Inhalation and/or ingestion
Surface contamination	Aircraft surfaces Contaminated clothing	Contaminated equipment and records Contaminated vehicles Decontaminating aircraft
Work in Forward Areas/fallout zones	γ radiation from contaminated surfaces	Dust producing activities (e.g. sandbagging of bunkers, cable laying, fencing)

7.6.3 Dosimetry outcomes

Table 7.16 lists the estimated radiation dose assignment categories for participants in Operation Antler.

Table 7.16 Operation Antler: estimated combined external and internal exposures

Task/exposure	Work group	Evidence/data	Exposure category
General engineering support[a]	Maralinga Range Support Unit (MARSU) Engineer Troop[b]	Assume work 11 d after Tadje, 14 d after Biak and 90 d after Taranaki at 10 h/d in the region with a dose-rate of 0.01 mSv/h. Total of 115 d. External dose of 11.5 mSv, ingestion dose of 0.24 mSv. Inhalation dose components are 16 µSv (Tadje), 28 µSv (Biak) and 2.0 mSv (Taranaki) for an inhalation dose of 0.6 mSv. Total dose = 13.5 mSv.	C
Hoisting of weapon to tower	Engineer Tower Party	The Tadje test involved use of ^{60}Co sources and dose contribution cannot be evaluated as distances and exposure times are not known.	F
Sandbag parties	MARSU Engineer Troop (pre- and post-test)	Assume 5 h for each task, two tasks per countdown and five countdowns for a total of 50 h. Corresponds to five 10-h days. See Table 6.7; external dose per day of 0.1 mSv and internal dose per day of 0.06 mSv (assume 100-day-old fallout). Total = 0.8 mSv.	B
Immediate re-entry and recovery tasks that could not be delayed	MARSU Scientific and Engineering recovery teams	Some data indicate dose per entry is of the order of 4 mSv. If several entries are involved, then the dose is of the order of 10–20 mSv.	C
Collect rocket pods in Buffalo YELLOW area[c]	MARSU recovery teams	Assume these are collected over 10 h/test for a total of 30 h. From Section 6.6.2, dose estimate is 0.3 mSv.	A
Recovery of equipment for next test	MARSU recovery teams	Assume recovery was a week after test. The dose received would be approx 10 times smaller than for immediate re-entry (see above), say 0.4 mSv.	A
Define fallout boundary	Australian Radiation Detection Unit (ARDU) (>H + 8 h for each test)	For Tadje: maximum fallout 444 MBq/m^2; from Table 6.13, dose estimate is 0.27 mSv. Similarly, for Biak: 255 MBq/m^2 and 0.15 mSv and for Taranaki: 174 MBq/m^2 and 0.1 mSv for total of 0.5 mSv.	A
Decontamination of Taranaki site	Engineer troop: two men per day, changed daily (D_2 + 1 to D_2 + 3 d)	Dose estimated as shown in Section 6.6.5, Table 6.11. The internal dose was <0.1 mSv and dominated by the external dose, which was up to 1.8 mSv.	B
Vehicle decontamination	DC2 team (Decontamination)	See Table 6.7; derived vehicle contamination was 5 µSv/h. Assume 10 h/d for 20 d for a dose of 1 mSv.	B
Transport in contaminated vehicles moving through contaminated areas	Various personnel	Assume 2 h/day for 75 d for a total of 150 h. Use a similar approach to Section 6.6.3 based on 400 h exposure, giving a total dose of 10.5 mSv from driving over contaminated ground to get an estimate of 10.5 × 150/400 = 4 mSv.	B
Security for test sites including long-term post-Antler period	Peace Officers	See note for radiation doses received by Peace Officers during Operation Buffalo (Table 7.13).	C

a These tasks included: fence construction south of Buffalo YELLOW boundary from January to March 1957, laying of up to 50 miles of cable prior to Tadje, construction of rocket lanes, construction of instrument bunkers, preparation of lanes for Health Physics Surveyors, construction of BICC masts and dismantling of towers in the YELLOW area, road and track maintenance.

b The MARSU Engineer doses may appear low in comparison with those for members of the Joint Services Training Unit (JSTU) at Hurricane (Tables 7.3 and 7.5) who similarly spent time in close-in fallout areas; the measured fallout levels and gamma dose rates from Hurricane fallout were much higher due to the nature of the Hurricane test, and JSTU deliberately sought out higher contamination areas for training purposes.
c There were other entries of shorter duration by members of MARSU into YELLOW areas (e.g. indoctrination sorties of approx ½ day) and these personnel would have received correspondingly smaller doses

7.7 Minor trials and post-Antler activities

7.7.1 Groups potentially exposed

No Australians can be identified as participating directly in the minor trials. However, other activities continued after the Antler series and these are included in this section along with the background to the trials.

The minor trials, later known as the **Maralinga Experimental Programme (MEP)**, were conducted in parallel with the major trials and extended into 1963. Their initial purpose was to support the development of components of the nuclear weapons, whereas later trials examined safety issues. The UK authorities planned, controlled and executed these trials with little Australian input beyond logistical and administrative support. Intense secrecy meant that the Australian Government had only sketchy details on the nature of the trials. The AWTSC had only an advisory role, with no power of veto over any proposed experiment. Table 7.17 outlines some features of these trials. The trials used conventional explosives, an assortment of hazardous materials such as beryllium, polonium and natural uranium and, importantly, in the Vixen series, plutonium. Some of the radioactive materials involved also had toxic properties; for example, uranium, while slightly radioactive, is a toxic heavy metal, and a few non-radioactive toxic materials were also used, such as beryllium. (Note: this study considers only radiological and not toxicological hazards.) A detailed list of the amounts of the hazardous materials used is given in Table 7.18 (Commonwealth of Australia 1985).

The Radiation Safety Regulations in use for the minor trials were those in force for the major tests. Additional Radiation Safety Orders were often written for the minor trials. During the trials, a senior British scientist assumed responsibility for radiological safety at the sites. On the completion of each series, the team leaders for the trials were required to take reasonable steps to make the experimental areas safe and to give the Scientific Superintendent of Operations a map showing contaminated areas.

In turn, the superintendent made checks and passed to the Range Commander a map showing any contaminated areas and buildings. A signed statement about levels of residual radioactivity and any precautions necessary was also provided. However, there is evidence that information on the radiological aspects of these minor trials was not readily supplied to the AHPR.

Summary values given for the residual contamination at the beginning of 1961 are shown in Table 7.18.

As there was minimal Australian involvement in the conduct of the minor trials, but significant contamination remained on some of the sites, potential exposures to Australians would mainly have occurred during management of the range both during the inter-trial periods and after the trials were completed.

The following Australian groups have been identified as being likely to have been exposed.

- Members of the Australian Health Physics team. Film badge results for members of Australian Health Physics Team were included in the monthly reports to CXRL. Few data are available for possible internal doses.
- Attendees at the Radiation Detection courses, whose dosimetry records are also available.
- Members of the Australian Health Physics team and the attendees at the 1958 Radiation Detection Course collecting ^{60}Co pellets resulting from the Tadje test (see Section 7.6.2).
- Those assisting with the decontamination of the DC12 facility, which took place during March 1961. The exposures recorded are given in the Australian Health Physics report of March 1961.
- Peace Officers who regularly checked sites including Taranaki, which was heavily contaminated by the minor trials.
- Personnel involved in later cleanup operations at Maralinga.

Some areas of plutonium contamination presented a significant hazard. In very dusty conditions, surface plutonium contamination of the order of 40 kBq/m^2 could have resulted in inhalation doses of up to 45 µSv/h of exposure. According to the Statement of Residual Radioactive and Toxic Contamination of 17 January 1961, prepared by R Pilgrim of AWRE, the contaminated area around Taranaki had been fenced.

Table 7.17 Program for the minor trials

Series name	Location[a]	Radiological hazard	Period	No. trials	Purpose
Kittens	Emu Field and Naya	U_{nat}, ^{210}Po	1953–1961	99	Tests of weapons components: neutron initiator development (^{210}P, beryllium and uranium)
Tims	Naya and Kuli	U_{nat}, ^{239}Pu	1955–1963	321	Tests of weapons components: tamper development (uranium and beryllium at Kuli) and studies of plutonium compression under explosive force (at TM100/101 at Naya)
Rats	Naya and Dobo	^{228}Th, U_{nat}	1956–1960	125	Tests of weapons components: developmental experiments involving internal radiography and explosive dispersal of uranium
Vixen A	Wewak	U_{nat}, ^{239}Pu	1959–1961	31	Dispersal of various radioactive materials by fire and explosion (including uranium and plutonium)
Vixen B	Taranaki	U_{nat}, ^{235}U, ^{239}Pu	1960–1963	12	Effect of accidental detonation and ongoing weapons development (explosive dispersal of uranium and plutonium)

a All sites were at Maralinga, with the exception of some trials conducted at Emu Field, 190 km north of Maralinga.

Table 7.18 Radiological and non-radiological hazards at the Minor Trials

Location	Hazard	Trial	Dates	Amount[a] (kg)	Residual contamination[b]
Emu	Be[c]	Kittens	1953	0.036	
Kuli	Be	Tims	1957–61	65.2	Areas >1 mg/m^2
	U_{nat}	Tims	1957–61	7500	<40 kBq/m^2
Naya	Be	Kittens	1955–57	0.75	
	Be	Tims	1957	1.6	
	^{239}Pu	Tims	1960–61	1.2	Areas of the order of 100 MBq/m^2
	U_{nat}	Rats	1955	151	Areas >4 kBq/m^2
	U_{nat}	Kittens	1955–57	120	
	U_{nat}	Kittens	1957–62	60.4	
Wewak	Be	Vixen A	1959–61	6	Areas >1 mg/m^2
	^{239}Pu	Vixen A	1959	0.98	Areas >4 kBq/m^2
	U_{nat}	Vixen A	1959	67.8	Areas >4 kBq/m^2
Taranaki	Be	Vixen B	1960–63	17.6	
	^{239}Pu	Vixen B	1961–63	22.2	Areas of the order of 100 MBq/m^2
	U_{nat}	Vixen B	1961–63	24.9	
	^{235}U	Vixen B	1961–63	22.4	
Dobo	^{228}Th	Rats	1959–60		Areas >4 kBq/m^2
	U_{nat}	Rats	1959–60	28	

a This refers to the amount of material used and is not necessarily the amount of material released.
b From Statement of Residual Radioactive and Toxic Contamination, 17 Jan 1961
c Not a radiological hazard

7.7.2 Dosimetry outcomes

Table 7.19 lists the estimated radiation dose assignment categories for participants in activities during the period following the Antler tests and in any of the minor trials.

Table 7.19 Post-Antler activities and minor trials: estimated combined internal and external exposures

Task/exposure	Work group	Evidence/data	Exposure category
Radiation surveys	Australian Health Physics Group	The median cumulative dose to January 1962 was 14.7 mSv (Australian Health Physics Representative [AHPR] reports).	C
Collect ^{60}Co pellets	Radiation Detection Course (21 Aug 1958 to 19 Sept 1958)	Approx 110 pellets collected by 19 people. The total dose from film badges was 62.4 mSv (i.e. approx 3 mSv per person or approx 0.5 mSv per pellet (AHPR report Sep 1958).	B
Collect ^{60}Co pellets	Australian Health Physics Group (July to August 1958)	70 pellets were collected by seven people (i.e. an average of 10 pellets per person). At 0.5 mSv per pellet, the average dose is approx 5 mSv (AHPR reports July & Aug 1958).	C
Practical monitoring exercises	Radiation Detection course attendees Sep 1959 and Jun 1960	Recorded doses (AHPR reports): Sep 1959 course 0.2–0.6 mSv; Jun 1960 course 0 mSv.	A
Initial decontamination of DC12	Training Unit (TU)	AHPR report (Feb 1960) gives details. Recorded doses ranged from 0.7 to 7 mSv.	C
Removed 1 TBq of waste activity from DC12 in five large crates, including two hotboxes. Operation monitored to ensure no inhalation hazard	Training Unit, Technical Services (TS), Health Physics (HP), Decontamination (DC) Groups and engineers	AHPR report (Mar 1961) gives details for personnel: summary range (mSv): 10–40, 0.7–4.3, 11–22, 3–18, <0.2–7.	TU group: D TS group: B HP group: D DC group: C Engineers: A-C
Range support	Maralinga Range Support Unit (MARSU) Engineers	AHPR reports give details. Members recorded film badge readings of 0.2 to 1 mSv. The inhalation dose, calculated for 90 to 200 d post-fission, is almost the same as the external dose. The total dose is estimated to be 0.4 to 2 mSv.	B
Fencing contaminated areas where areas of ^{239}Pu contamination may have existed	MARSU Engineers	Assume 1 MBq/m^2 of ^{239}Pu, 60 h work at breathing rate of 3 m^3/h = 7 mSv.	C

a TBq = Terabecquerel (i.e. 10^{12}Bq)

7.8 RAAF

7.8.1 Introduction

A large number of RAAF personnel were involved at various stages of the test series. However, it was only air and ground crews participating in the sampling of radioactive clouds and subsequent decontamination of aircraft that faced potentially high exposures. Cloud sampling tasks were usually carried out within a few hours of the explosion. Initially ground crews were given little advice on the precautions necessary during the decontamination of aircraft that had flown through the clouds.

A study of the hazards to personnel from contaminated aircraft made the following general observations (Kulp and Dick 1960):

- for aircrew participating in cloud penetration flights, the exposure to external radiation is much higher than to internal radiation from ingestion or inhalation
- for those servicing aircraft, the external radiation hazard is more important than the ingestion hazard even with fresh debris; three days after the nuclear explosion, the hazard from gamma radiation was 10 to 100 times more significant than the ingestion hazard
- the level of external hazard from a contaminated aircraft can be measured with a calibrated gamma-survey meter
- an indication of the inhalation/ingestion hazard can be obtained from a close (2.5 cm) beta survey meter; smear sampling is not particularly useful without suitably calibrated counting equipment.

In this section, the various hazards to RAAF personnel resulting from cloud sampling are considered. The changes in knowledge and therefore management of the radiological hazard to RAAF personnel are reviewed for each test series.

7.8.2 Hurricane

Both Symonds (1985) and the Royal Commission (1985) discuss in some detail the sampling of the radioactive cloud from the Hurricane test. This was appropriate given that film badges, dosimeters (QFEs) or gamma-ray detection equipment were not provided for the first sampling flights. The lack of equipment to assess radiation exposures of aircrew probably resulted from the views of Marley, the Head of Health Physics Division at the UK **Atomic Energy Research Establishment (AERE)**, who considered that under defined circumstances flying through a cloud of nuclear weapons debris would give a negligible dose to the aircrew. Marley also indicated that avoiding flying through the visible cloud following an atomic bomb explosion was sufficient to guard against radiation injury. At later times, when the visible cloud had dispersed, Marley considered that there would be no danger to aircrews (Symonds 1985, p 43). Marley's views would have been based on UK experience in flights over the Atlantic whilst sampling clouds from US nuclear tests. Cloud sampling in Australia was much closer to the explosion site. Ironically, the initial sampling of the radioactive cloud was somewhat delayed because of communication problems between HMS Campania and the Broome base. This, by default, implemented Marley's criteria for the initial flights.

Doses to the aircrew were estimated to be no more than 10–20 μSv. The dose to the ground crew servicing the aircraft was stated in the Royal Commission report (Commonwealth of Australia 1985, paragraph 5.5.47) as being well within the approved lowest radiation dosage level. These estimates were based in part by comparing the Hurricane data to data gained later during the Totem series held in 1953. Doses to aircrew of the Dakota flight from Broome to Onslow were estimated to be small, given the gamma dose rate of 0.01 μSv/h measured in the aircraft on landing.

7.8.3 Totem

Overview

One striking aspect of air operations during Totem is the apparent breakdown in communication when AWRE and the RAF failed to inform the RAAF of the radiation hazards. Both Symonds (1985) and the Royal Commission (1985) report that the RAAF were led to believe there was minimal hazard to RAAF personnel and aircraft associated with sampling radioactive clouds. The RAAF responded well to the unexpected hazard. With the support of AWRE, RAF and USAF experts, the RAAF learnt the basis of the control of aircraft contamination after sampling the T1 cloud and how to manage exposures for the smaller sampling program after the T2 test. The experience gained from control and decontamination procedures developed at Emu, Woomera and Amberley contributed to the success of control procedures used during the later test series.

Operation Hotbox

One potentially hazardous exercise, which had peripheral Australian involvement, was a research program, separate from the air sampling and survey programs, designed to assess the performance and safety of an aircraft flying near and in radioactive clouds. The need for this arose from a controversy over whether and when aircraft could be safely used in such an environment. An RAF Canberra was modified by sealing the aircraft against entry of contaminants, and it carried external filters to sample the radioactive cloud. The aircraft entered the cloud at 9 minutes after T1 exploded and took just over 9 seconds to transit the cloud. Further passages were made 100 ft (30 m) above and below the cloud. The aircraft was surveyed with a 1021 contamination monitor, isolated for 4 hours and then decontaminated by six trained RAAF officers wearing protective clothing, including masks (Commonwealth of Australia 1985 p 207). Sir William Penney vetoed a similar flight for T2 because of unnecessary risk.

Cloud sampling

Unpressurised Lincoln bombers were used to track and sample the radioactive clouds produced by the T1 and T2 tests. Table 7.20 summarises some features of these investigations (Gale 1954). The USAF also participated using a B29 based at Richmond. Their contribution is not discussed here, although two Australians may have joined the flights.

For T1, sampling was carried out at 600, 1200 and 2000 km from GZ using, respectively, the Woomera, Townsville and Richmond bases. The intercept distances correspond to times after fission of 11 hours, 25 hours and 44–51 hours, respectively. The RAAF were led to believe that cloud sampling at these ranges would not pose a hazard (see Section 7.8.2) and the crews flew with no means of determining their radiation doses or for limiting the personal radiation hazard; neither protective clothing nor film badges were issued. Contamination was evident in aircraft sampling at the 400 mile (644 km) point, and on their return to Woomera procedures were put in place to isolate and decontaminate the aircraft. Extensive discussions of this incident are to be found in Symonds (1985) history and the Royal Commission report (paragraphs 6.5.32 to 6.5.92).

For T2, only four Lincoln aircraft were flown from Woomera base, with two of the aircraft acting as couriers. The crew were provided with dosimeters, film badges and protective clothing. The two aircraft that flew through the cloud were heavily contaminated. Curiously, the aircrew in the cloud-intercepting flights were later shown to have received only small gamma doses. Inhalation of radioactive particles was limited by breathing a mixture of cabin air and oxygen through masks. The added oxygen increased from nil as the height above 3000 m increased.

Aircraft decontamination

It was not realised until two days after T1 that the air sampling aircraft were contaminated and it was not until five days after T1 that radiological control measures were instituted. Nine Lincoln aircraft operating from Woomera had various levels of contamination: three were highly contaminated, three were slightly contaminated and two had some areas just above the 'tolerance level' as it was then described. The remaining aircraft had contamination below the tolerance level. Two men known to have serviced the aircraft before control measures were put in place received estimated gamma doses of up to 5 mSv and beta doses of 53 to 58 mSv (Austin 1954; Commonwealth of Australia 1985, p 220). They were not permitted to do further work on contaminated aircraft. Austin's narrative suggests that the men servicing the Lincoln aircraft were not issued with film badges.

The radiation control measures at Woomera, not established until five days after T1, were (Austin 1955):

- restricting access to aircraft
- issuing protective clothing to personnel working outside the aircraft, including head covering, and contamination monitoring; personnel were not permitted to eat, drink or smoke until declared free of any contamination; if clothing was contaminated above a pre-determined level, 15 cps on a 1021 monitor, it was left for laundering
- disallowing personnel working inside the aircraft to eat, drink or smoke until monitored on leaving the aircraft; these personnel were not issued with protective clothing
- segregating the equipment from the aircraft until checked and, if necessary, decontaminating this equipment.

Similar measures were also put in place at RAAF Richmond.

Table 7.20 Summary information on Totem air sampling flights by Lincoln aircraft (adapted from Gale 1954)

Test	Aircraft	Base [a]	Time in cloud (min)	Intercept time (h)	Max concentration[b] (KBq/m^3)	Filter β activity (Bq)	Corrected to day	Gamma dose[c] (MSv)	Residual dose-rate[d] (μSv/h)
Sampling at 600 km from ground zero (GZ)									
T1	A73-47	W	10	H + 11	1100	10^8	D + 1	0.5	120
	A73-52	W	45	H + 11	1100	3×10^8	D + 1	1.2	250
	A73-53	W	55	H + 11	400	4×10^7	D + 1	0.1	2
	A73-54	W	30	H + 11	400	10^8	D + 1	0.06	2
	A73-56	W	10	H + 11	1100	10^8	D + 1	0.45	100
T2	A73-41	W	Aircraft withdrawn to avoid unnecessary cloud contact						
	A73-47	W	45	H + 10.5	400	3×10^7	D + 1	na	na
	A73-52	W	60	H + 10.5	1100	6×10^7	D + 1	na	na
Sampling at 1200 km from GZ									
T1	A73-25	T	~150	H + 25	~40	$\sim 3 \times 10^7$	D + 4	~0.5	~20
Sampling at 1800 km from GZ									
T1	A73-21	R	na	H + 44	na	10^4	D + 4	<1	<1
	A73-26	R	na	|	na	2×10^5	D + 4	<1	<1
	A73-27	R	On descent	to	na	10^3	D + 4	<1	<1
	A73-37	R	On ascent	|	na	10^5	D + 4	<1	<1
	A73-40	R	On ascent	H + 51	na	3×10^5	D + 4	<1	<1

a W = Woomera, T = Townsville, R = Richmond
b Maximum concentration encountered in cloud during flight
c Integrated gamma dose to crew members
d Residual dose-rate on landing
na = not available

Radiological surveys using aircraft

UK scientists equipped three Dakota aircraft to carry out radiation surveys of ground contamination. These aircraft operated from Woomera using a flight plan that included flying in arcs at nominated distances from GZ and also along the line of maximum fallout. Air or ground crews working with these aircraft would have received little, if any, additional radiation doses from the Dakota operations, as cloud interceptions were not involved.

7.8.4 Mosaic

Aircraft survey

RAF aircraft were used to assess ground deposits out to a distance of 600 km. The aerial surveys were carried out using type 1398 aerial survey equipment fitted to Vickers Varsity aircraft and Westland Whirlwind helicopters. A background survey was made over the length of Trimouille Island prior to G1 and over the crater area after G1. An aerial survey from Onslow to Broome using Varsity aircraft was undertaken on D_1 + 1 day. Before and after G2, aerial surveys were carried out over a course from Onslow to Darwin via Port Hedland, Broome, Derby, Wyndham and return. Small areas of fallout of less than 2 μSv/h were located.

Cloud sampling

Sampling was undertaken by an RAAF crew flying an RAF Canberra for both G1 and G2. The RAF crews were engaged in re-entry operations from RAAF Pearce. They were issued with a sortie badge and a QFE. Table 4 of Hole (1957) summarises doses in excess of 0.5 mSv for staff based at RAAF Pearce. The table indicates that the external radiation doses to RAF personnel fall into two groups:

- for flight crews, 23 to 58 mSv
- for ground crews, 0.7 to 3.5 mSv with one extreme reading of 8 mSv.

The larger values have been adopted for RAAF personnel, although it is not clear whether Australian aircrew flew similar sorties or were monitored in the same way as RAF and AWRE personnel.

Aircraft decontamination

The limited decontamination of aircraft carried out at Pearce Field involved only partial cleansing of the aeroplanes. Before the aircraft were moved to the Buffalo trials at Maralinga, a barrier paint was used to seal any remaining contamination.

7.8.5 Buffalo

Overview

As in earlier series, aircraft were used to sample the radioactive clouds shortly after a test, to track the clouds and to survey the ground surface at some distance from the test site. Aircraft were also used to search for people, mainly Aborigines, who may have lived in or moved through the test areas. By the Buffalo series, methods were in place to minimise the radiation hazard to the service personnel from contaminated aircraft. The Decontamination Group carried out aircraft decontamination principally at the Maralinga airfield. The decontamination centre was staffed by both RAF and RAAF personnel. Aircraft contaminated to a lesser degree were decontaminated at RAAF Edinburgh, South Australia, using personnel trained and supervised by a member of the British Decontamination Group.

Aircraft surveys

Mainly RAF aircraft were used to assess ground fallout deposits out to a distance of 600 km. The aerial surveys were carried out using plastic scintillator detectors fitted to Vickers Varsity aircraft and Westland Whirlwind helicopters. The Varsity aircraft were used to obtain background measurements of the firing area and out to approximately 600 km prior to each test. Type 1398A aerial survey equipment was used in these surveys. After each test, radiation contour measurements were made out to approximately 80 km from GZ and later out to approximately 600 km to establish the fallout pattern. The aircraft also carried type 1324 and 1392A dose rate meters. The helicopters were fitted with type 1398 aerial survey dose rate meters for the crater surveys.

Cloud sampling

During cloud sampling, the radiation dose rate in the aircraft cabin was monitored using a type 1324 survey meter, which used three scales ranging up to 3 mr/h (30 μSv/h) and a type 1392A survey meter that read logarithmically up to 100 mr/h (1 mSv/h).

Measurements were also made of the total activity on filter samples taken from air entering the cabin of Canberra aircraft. Table 7.21 summarises estimates of the inhalation of fission products for four cloud-sampling operations (Holmes 1958), together with estimates of the internal doses based on present-day ICRP dose conversion factors.[31] It is known that an Australian aircrew flew one of ten RAF Canberras[32] that were involved in cloud sampling during Operation Buffalo, but it is not known which particular aircraft was used. There would have also been exposures to RAAF personnel involved in decontamination operations. A document dated 12 November 1956 from the Director-General Medical Services (Australian Army) shows that the radiation doses to RAAF personnel following the One Tree test were below 6 mSv and most were recorded as 'less than 0.4 R' (<4 mSv). These, however, are not consistent with the results in the first two rows of Table 7.21.

The program included two primary sampling aircraft for each explosion plus other samplers and trackers for penetrating the cloud at later times. Four Canberra aircraft were each contaminated on at least one major sampling sortie, and two Varsities were also contaminated to a moderate degree. The inter-round period was cut from ten to seven days, thus reducing the time available for dealing with the aircraft between shots. Because the aircraft had to be left for two to three days in order for the radioactivity to decay to a level at which prolonged working was possible, this meant that the decontamination treatments between explosions were perfunctory (Stevenson 1957).

Table 7.21 Mean external γ doses and estimated internal doses from cloud sampling during Operation Buffalo (adapted from Holmes 1958)

Round	RAF Aircraft number	Time of cloud penetration	Duration of sample	Estimated intake (MBq)	Estimated internal dose[a] (mSv)	Mean γ dose[b] (mSv)
1	WH 978	F + 22 min	30 s	79	3	30
1	WH 979	F + 2.75 h	75 min	14	3	7
2	WH 978	F + 33 min	41 min	na	na	3
3	WH 976	F + 1 h	2 min	21–79	2–7	30
4	WJ 754	F + 20 min	36 s	166	7	38

a Estimated effective dose from inhalation of fission products based on the intake and International Commission on Radiological Protection dose conversion factors (ICRP 2001)
b Mean γ dose to whole body during operation

Aircraft decontamination

All decontamination was carried out by Decontamination Group DC3 at Maralinga and Edinburgh fields using 1320, 1324, 1349A and NIS44 instruments to determine contamination levels. The RAF Task Force was transferred *en bloc* from Operation Mosaic to Operation Buffalo with aircraft that were still partially radioactive. At Operation Mosaic, all aircraft were painted with AWRE barrier paint prior to operational use. Contaminated aircraft were resprayed with this paint to seal in contamination after participation on active missions and, because of limited facilities, no final decontamination work could be attempted. Because of this continuing lack of facilities, these aircraft continued to fly with the 'old and weathered barrier paint coating dating from 4 months earlier' (Stevenson 1957).

[31] A caveat is that it is not clear in the original report how Holmes derived the intakes to the lungs for crew in unmodified aircraft by using air filter measurements made in modified aircraft.
[32] The RAF Canberra aircraft were involved in cloud sampling, cloud tracking and meteorological operations.

Stevenson also noted that the decontamination facilities were designed to accommodate one or two aircraft only and were inadequate for the number involved in Operation Buffalo.

7.8.6 Antler

Aircraft surveys

Mainly RAF aircraft were used to assess ground deposit. After the cloud had passed, an aerial survey was done using improved type 1398A equipment fitted in Vickers Varsity aircraft and Westland Whirlwind helicopters. The radiation detectors were calibrated by comparing dose rates determined by the aircraft with the dose rates measured by a ground survey (see Section 7.6.2). Both surveys were made along a length of road that crossed the fallout pattern. As soon as the distant fallout had been deposited, the aircraft measured the fallout by flying across the pattern at various distances from GZ.

Cloud sampling

An RAAF crew was made available for air operations in one of ten RAF Canberra aircraft.[33] These personnel may have flown on one or more of the sampling flights made during the three Antler firings. The sampling programs were designed to limit aircrew radiation doses to less than 30 mSv. Integrated doses of 47 mSv for Round 1, 12.5 to 34 mSv for Round 2 and 100 mSv for Round 3 were recorded for RAF crews (Eyre 1958).

Aircraft decontamination

This was now a British responsibility and no RAAF personnel were involved (RC800).

7.8.7 Potential sources of exposure for RAAF personnel

Table 7.22 lists the potential exposure sources and pathways that were considered relevant when assessing the data for all RAAF operations.

Table 7.22 Potential irradiation pathways for RAAF operations

Source	External hazard	Internal hazard
Cloud sampling	Immersion in the cloud	Inhalation of active particles
	Contaminated aircraft surfaces	
Surface contamination	Aircraft surfaces	Decontaminating aircraft
	Contaminated clothing	

7.8.8 Dosimetry outcomes

Tables 7.23 and 7.24 list the assigned exposure categories derived from estimated external and internal doses, respectively, resulting from RAAF operations during all major test series.

[33] RAF Canberras were used for cloud sampling, cloud tracking and meteorological operations.

Table 7.23 RAAF operations: estimated external exposures

Task/exposure	Work group	Evidence/data	Exposure category
Operation Hurricane			
Flying through contaminated cloud	Air crew in RAAF Lincolns	No badges or dosimeters were provided; doses could be estimated from activity on filters external to aircraft; Symonds' report suggests a dose of no more than 20 μSv.	A
Servicing and decontaminating aircraft	Ground crew	Doses estimated from exposure to contaminated aircraft surfaces are small — external dose rates from the surfaces of aircraft were of the order of 10 μSv/h from sampling at H + 24 h and 0.1 μSv/h from sampling at H + 55 h.	A
Operation Totem			
Flying through contaminated cloud	Air crew in RAAF Lincolns	Gale (1954) — see Table 7.20	B
Servicing and decontaminating aircraft	Ground crew	Austin (1954); Commonwealth of Australia (1985), p. 220	B
Operation Mosaic			
Flying through contaminated cloud	RAAF air crew in an RAF Canberra	Table 4 of Hole (1957) quotes RAF exposures of up to 58 mSv; see Section 7.8.4	E
Aerial survey	Air crew	No contact with radioactive cloud	A
Servicing and decontaminating aircraft	RAAF ground crew servicing and decontaminating RAF aircraft	See Section 7.8.4. Contamination control procedures were only instituted after Totem 1; see Section 4.2.2 and Section 7.8.3.	B
Operation Buffalo			
Flying through contaminated cloud	RAAF air crew in an RAF Canberra	See Table 7.21	D
Aerial survey	Air crew	No contact with radioactive cloud	A
Servicing and decontaminating aircraft	RAAF ground crew servicing and decontaminating RAF aircraft	By analogy with Totem and Mosaic	B
Operation Antler			
Flying through contaminated cloud	RAAF air crew in an RAF Canberra	For RAF aircrew the reported integrated doses were 47 mSv for Round 1, 12.5 to 34 mSv for Round 2 and 100 mSv for Round 3 (Eyre 1958). Thus, external dose could be as high as 180 mSv if an RAAF aircrew participated in all three flights and received similar doses.	E
Servicing and decontaminating aircraft	RAAF ground crew servicing and decontaminating RAF aircraft	By analogy with Totem and Mosaic	B

Table 7.24 RAAF operations: estimated internal exposures

Task/exposure	Work group	Evidence/data	Exposure category
Operation Hurricane			
Flying through contaminated cloud	Air crew in RAAF Lincolns	Atomic Weapons Research Establishment (AWRE) theoretical physics note indicates fission product particulates could give lung dose comparable to external dose (i.e. no more than 20 μSv).	A
Servicing and decontaminating aircraft	Ground crew	Doses estimated from ingestion of all activity on hands are small — of the order of 1 μSv or less.	A
Operation Totem			
Flying through contaminated cloud	Air crew in RAAF Lincolns	Table 7.21, for Operation Buffalo, indicates internal dose is approx one-quarter of external dose. Max external dose for B category is 5 mSv, which suggests internal dose is approx 1.3 mSv.	B
Servicing and decontaminating aircraft	Ground crew	There would have been little inhalation hazard as the contamination was generally 'well held' by oil and grease (Austin 1954).	A
Operation Mosaic			
Flying through contaminated cloud	RAAF air crew in an RAF Canberra	Table 7.21 indicates internal dose is approx one-quarter of external dose. Max external dose for D category is 50 mSv, which suggests internal dose is approx 12 mSv.	C
Servicing and decontaminating aircraft	RAAF ground crew servicing and decontaminating RAF aircraft	External dose for ground crew from Hole (1957) is less than 5 mSv and one-quarter of this suggests an internal dose of approx 1.2 mSv.	B
Operation Buffalo			
Flying through contaminated cloud	RAAF air crew in an RAF Canberra	See Table 7.21	C
Aerial survey	Air crew	No contact with radioactive cloud	A
Servicing and decontaminating aircraft	RAAF ground crew servicing and decontaminating RAF aircraft	External dose for ground crew from Hole (1957) is less than 5 mSv and one-quarter of this suggests an internal dose of approx 1.2 mSv.	B
Operation Antler			
Flying through contaminated cloud	RAAF air crew in an RAF Canberra	Table 7.21 indicates internal dose is approx one-quarter of external dose. External doses, assuming air crew participated in three rounds, is approx 180 mSv, suggesting internal dose is approx 45 mSv for participants in all three rounds.	D
Servicing and decontaminating aircraft	RAAF ground crew servicing and decontaminating RAF aircraft	External dose for ground crew from Hole (1957) is less than 5 mSv and one-quarter of this indicates an internal dose of approx 1.2 mSv.	B

7.9 Overall exposures

7.9.1 Work groups

The tasks performed by individuals or groups were examined for each of the major tests. A summary of the principal findings is shown in Table 7.25.

Groups with exposures in category A (i.e. the lowest exposures) included:

- most Australians at Operation Hurricane
- most Australians at Operation Mosaic
- most Australians at Operation Totem
- the large number of military and civilian participants who were involved in infrastructure and support duties, including transport, supply of services, equipment maintenance, camp staff and others, who did not enter contaminated areas.

Those participants exposed in category B included:

- crews and divers from ships operating in the Monte Bello Archipelago after Operations Hurricane and Mosaic
- scientific and survey teams
- engineering support teams
- some RAAF air and ground crews.

The following main groups were exposed at the level of category C or higher.

- The Australian aircrews who flew RAF Canberra aircraft through contaminated clouds during operations Mosaic, Buffalo and Antler. The external doses were either in category D (Buffalo) or in category E (Mosaic and Antler); the internal doses are estimated to have been in category C or D. The combination of estimated external with internal doses results in an overall category E assignment for these groups.
- During the Hurricane test program, crews from HMAS Hawkesbury and HMAS Koala crew were category C and divers from HMAS Koala who recovered a landing craft were category D. Most members of the Joint Services Training Unit were category C; three individuals in JSTU received doses in the D or E category.
- During the Totem series, those with category C exposures included the Peace Officers and those travelling extensively in contaminated vehicles over contaminated ground. Members of the Radiation Hazards Group who performed surveys near GZ probably incurred category D exposures.
- During the Buffalo series, category C exposures were received by members of the Indoctrinee Force and by those engineers or scientists in the MARSU who recovered instruments, equipment containers and target response items. MARSU personnel who made several entries could have had category D exposures. MARSU continued to operate during the inter-trial period.
- During the Antler series, personnel with exposures in category C were the MARSU Engineer Troop and the MARSU recovery teams. Those members of MARSU who

worked at more than one round of this series or were involved in more than one task giving a dose of category C could have had category D exposures.

- Peace Officers who continued to work in the post-Antler period and drove for lengthy periods in contaminated areas could have had category D exposures. Peace Officers/Commonwealth Police/Australian Protective Service (APS) continued to patrol the range until 1987. Williams (1990, p 135) estimated the inhalation dose for Australian Protective Service patrols at 0.55 mSv per 6-week period of duty per mg/m^3 of inhalable dust. Williams derived the dose from the levels of inhalable plutonium and other radionuclides present in 1987. No allowance was made for either external or ingestion doses. Williams noted that the Peace Officer/APS patrols were unsupervised and members of the service were not adequately briefed on the risks and actions to be taken to minimise radiation doses.
- Following the cessation of the major tests, the AHPG had radiation safety responsibilities for the range. Members of the AHPG group incurred category C or D doses conducting radiation surveys. Some AHPG members also received category C doses whilst collecting ^{60}Co pellets scattered in the first Antler round (Tadje).
- Following completion of the minor trials, Building DC12, the high-level radionuclide handling facility, was decontaminated. This required the removal of a highly contaminated 'hotbox' and five crates of radioactive waste. Participants received exposures in categories C or D.

The exposure groups are summarised in Table 7.26.

Table 7.26 Summary of main exposure outcomes

Test period	Dose category for task A	B	C	D	E	F
Hurricane	Most participants RAAF air crew RAAF ground crew	Crews of ships operating in the Archipelago up to day D + 16 Crews of small ferry boats Divers recovering mooring buoys Working parties on Trimouille island	Joint Services Training Unit[a] Crews from HMAS Hawkesbury and HMAS Koala	Divers from HMAS Koala		
Totem	Most participants	Members of Totem 1 site inspection team RAAF and ground and aircrew	Peace Officers Drivers and participants transported in contaminated vehicles[d] RAAF air crew	Radiation Hazards Group		RAAF ground crew[b,c]
Mosaic	Most participants RAAF ground crew	Crews of HMS Diana, HMAS Fremantle, Junee, Karangi RAAF ground crew			RAAF air crew flying RAF Canberras	
Buffalo	Most participants RAAF ground crew	ARDU, DC 2 team	Indoctrinee Force Drivers and participants transported in contaminated vehicles[d,e] Maralinga Range Support Unit (MARSU) Engineering and Scientific teams[f]	Peace Officers[g]	RAAF air crew flying RAF Canberras	
Inter-trial	Most participants	Australian Radiation Detection Unit (ARDU) RAAF ground crew	MARSU Engineering and Scientific teams[f]			
Antler	Most participants	Vehicle decontaminatio n Transport in contaminated vehicles		MARSU Engineering and Scientific teams[f] Peace Officers[g]	RAAF air crew flying RAF Canberras	

Test period	Dose category for task A	B	C	D	E	F
		RAAF ground crew				
Post-Antler/Minor Trials	Most participants	Radiation Detection Course (collection of ^{60}Co) MARSU range support	Australian Health Physics Group (AHPG) radiation surveyors AHPG ^{60}Co pellet collection	DC12 Decontamination Team including AHPG Peace Officers[g]		

a Three individuals received doses in D or E category.
b Except for those known to service the aircraft before control procedures were put in place
c 92% of all participants in category F (unknown) are from the RAAF (see Table 7.26).
d This includes drivers and passengers in vehicles travelling over contaminated ground.
e Includes the inter-trial period between Operations Buffalo and Antler
f Those members of MARSU Engineer and Scientific teams who worked at more than one round or were involved in more than one task giving a dose in category C could have had exposures in category D.
g From the end of Operation Buffalo to the closure of the range and beyond

7.9.2 Exposure statistics

The overall distribution of radiation exposures amongst the study cohort of Australian test participants is set out in this section.

Table 7.27 Numbers exposed in each category

Exposure category		RAN	Army	RAAF	Civilian	Total	%
<1 mSv	A	2274	747	2028	3616	8665	78.9
1 to 4.9 mSv	B	622	45	19	12	698	6.4
5 to 19.9 mSv	C	194	201	71	40	506	4.6
20 to 50 mSv	D	2	232	3	163	400	3.6
>50 mSv	E	0	4	14	1	19	<0.2
Unknown	F	5	16	639	35	695	6.3
Total		3097	1245	2774	3867	10983	
Film badge		169	196	61	44		4.3

RAN = Royal Australian Navy; RAAF = Royal Australian Air Force

Overall, 79% of the study cohort received doses less than 1 mSv. This dose level is equivalent to the current recommended annual dose limit for members of the Australian public and about half the dose received annually from natural **background radiation**. Approximately 4% received greater than 20 mSv, the current recommended annual dose limit for workers in Australia. The average dose to the participants was approximately 2.8 mSv.

The Army was the most heavily exposed group, with 35% being in category C or above.

The table also includes the numbers of participants for whom a film badge record is available. Overall, only 4% of the participants have some recorded monitoring, and this could be seen as of some concern for the study. However, as noted above there were a number of major work groups for which significant exposure was highly unlikely.

The Dosimetry Panel formed the view that the lack of comprehensive monitoring data has not affected the broad outcome of this study.

- Most RAN personnel were at Hurricane or Mosaic where they spent most of the trial period(s) on their ship, and the whereabouts and likely resulting exposures of these are well known.
- Many of the unmonitored RAAF personnel were on bases where contaminated aircraft were serviced, but they had no involvement with them. Large numbers of the civilians were employed in service functions in and around the camps, and so were not monitored.
- For the Army, the number with monitoring records is 16%. This group includes many of the most exposed Engineers and Infantry who regularly entered contaminated areas.

As discussed earlier in Section 5.3, the Dosimetry Subcommittee is of the opinion that there was sufficient information available, in reports, official papers and sundry other documents, to overcome the relatively small number of film badge records.

The following comparison with a major UK study supports the Dosimetry Subcommittee's view.

7.9.3 Comparison with a United Kingdom study

An independent study, similar to the one reported here, has been undertaken for the British participants in nuclear weapons testing (Muirhead et al 2003). Table 7.28 summarises their results for the Australian tests. Only external doses were assessed in the British study (this Australian study includes internal and external radiation exposures); thus, the tabulated doses will be an underestimate of the total dose. Based on our results, the underestimation will be small, with the possible exception of those involved in some of the minor trials.

Table 7.28 Summary of doses estimated for British participants in weapons tests in Australia

Series	No. participants	No. monitored	No. >1 mSv	Max. individual dose (mSv)
Hurricane	1398	1340	179	48
Totem	106	78	54	145
Mosaic	1383	599	56	210
Buffalo	1285	786	194	53
Antler	1548	737	172	160
Maralinga Experimental Program (Minor Trials)	555	510	61	54
Maralinga other	2555	253	10	36
All series	8830	4303	726	210

Overall, the results are similar to those derived in this study for the Australian participants:

- 83% of the British would be placed in category A (compared with 79% of the all Australian participants)
- the mean dose of the 'non-zero' categories was 7.1 mSv, which is lower than the mean dose for Australian 'non-zero dose' participants of approximately 15 mSv.

However, there are some differences in the higher dose categories. The highest known dose for the Australians was 133 mSv from film badge records. For the British participants, the highest dose during the Australian tests was 210 mSv, and RAF personnel received almost all of the doses above 100 mSv, presumably during cloud sampling. It is also reasonable to assume that British scientists were closely involved in some of the high dose-rate tasks, such as early recovery of instruments and samples after an explosion.

There is a significant difference between the numbers of British and Australians for whom monitoring records have been found. There are personal monitoring records for only 4 % of the Australians, compared with 49% for the British. To some extent, this is to be expected because, as noted above, British participants were more likely to have been closely involved in the actual tests, whilst many Australians were employed in support roles that did not bring them into significant contact with radiation. Nevertheless, the difference is striking, and may reflect different policies having been applied to the two groups. However, it is also noteworthy that of all the British participants monitored, 68% had external doses that were too low to be detected by the film badges used.

7.10 Case control study

Following the estimation of doses to work group categories, a total of 270 individual doses were estimated for the 'case control' study, and 32 individuals were re-assessed for quality control purposes.

For these assessments, all available information on the individuals was considered. This included the information gathered for the work group assessment, individual service records, Nominal Roll data, and information available from questionnaires submitted to the Donovan Study.

Some differences between the individual dose estimates and those assigned to the relevant work group were found. Some of these arose from better information on the actual duties performed, others from consideration of the actual times at which the individual was at the test site. However, there was reasonable agreement between the results. The major change was the re-assignment of all but one of the 25 subjects originally assigned to the unknown exposure category (Category F) to a known category, because of the better information available. Three subjects were re-categorised into Category F for the case-control study. Of the other 242 subjects in the case-control study, 212 received the same exposure category as in the cohort study, and a further 20 were re-categorised in the next category up or down. Only in 10 subjects did the exposure change by more than one category.

Further details are described in Section 11.3 of the Mortality and Cancer Incidence Report.

7.11 Conclusions

Overall, the doses received by Australian participants were small. Seventy-nine per cent of participants received exposures in the lowest dose category. Only 2% of participants received more than the current Australian annual dose limit for occupationally exposed persons (20 mSv).

These results were compared with those from an independent study of doses to British participants in the tests in Australia (Muirhead et al 2003). There is good general agreement in the doses received, although some of the British participants appear to have received somewhat higher doses than the most highly exposed Australians (UK 210 mSv vs Australia 133 mSv) and the mean of British non-zero doses was about half the Australian figure.

While there are some significant gaps, it is believed that there is enough information available to make reasonable estimates of the radiation doses received by Australian participants, and that our methods have achieved this. It has also been noted that the estimates derived here are generally consistent with the estimates made for British participants.

The main function of this report is to support the epidemiological study of the mortality and cancer incidence amongst the Australian participants in the British nuclear tests in Australia. While it is obviously highly desirable that the doses derived are accurate, the most important requirement is that the ranking of participants according to dose should be valid. Even if there were substantial underestimations (or overestimations) of doses, provided that the more highly exposed participants have been correctly distinguished from those with smaller or zero doses, this would not invalidate the epidemiological study. We are confident that this requirement has been achieved.

7.12 References

Austin J (1955). *The Prevention and Removal of Radio-active Contamination, Part 6: Decontamination of aircraft and health control at Woomera and Amberley, AWRE Report T106/54*, Atomic Weapons Research Establishment, Aldermaston.

AWRE (Atomic Weapons Research Establishment) (1956). *Radiological safety regulations Maralinga, 5th edn, AWRE Report RSRM/56 (5)*, Atomic Weapons Research Establishment, Aldermaston.

Commonwealth of Australia (1985). *The report of the Royal Commission to British Nuclear Tests in Australia Vol 1 and 2*, Australian Government Publishing Service, Canberra.

Cooper MB, Duggleby JC, Kotler LH and Wise KN (1978). *Residual radioactive contamination of the Maralinga Range from nuclear weapons tests conducted in 1956 and 1957, Australian Radiation Laboratory Report ARL/TR005*, Australian Radiation Laboratory, Melbourne.

Dale GC (1955). *Safety levels for contamination from fallout from atomic weapon trials, AWRE Report O-41/55*, Atomic Weapons Research Establishment, Aldermaston.

Eyre AW (1958). *Airborne sampling of radioactivity, AWRE Report T24/58,* Atomic Weapons Research Establishment, Aldermaston.

Gale HJ (1954). *Radioactive sampling and analysis report, AWRE Report T6/54*, Atomic Weapons Research Establishment, Aldermaston.

Gaskell WTM and Saxby WN (1956). *The survey of residual contamination from Operation Totem, AWRE Report T4/55*, Atomic Weapons Research Establishment, Aldermaston.

Hole JA (1957). *OPERATION MOSAIC: Radiological Group report, AWRE Report T21/57*, Atomic Weapons Research Establishment, Aldermaston.

Holmes RE (1958). *The hazards to aircrew flying through atomic cloud, AWRE report T54/57*, Atomic Weapons Research Establishment, Aldermaston.

ICRP (1990). *Recommendations of International Commission on Radiological Protection*, Pergamon Press, Oxford.

Janisch Maj DBB et al (1957). *Target response tests: Field trials of radiac instruments in a radioactively contaminated area, AWRE report T2/57*, Atomic Weapons Research Establishment, Aldermaston.

Kulp JL and Dick JL (1960). The radiation hazard from contaminated aircraft. *Health Physics* 4:133–156.

McDougall WG, Rexford-Welch SC and Douglas K (1958). *Operation Antler: Health Physics Services, UKAEA Report T45/58*, Atomic Weapons Research Establishment, Aldermaston.

Muirhead CR et al (2003). *Mortality and Cancer Incidence 1952–1998 in UK participants in the UK Atmospheric Nuclear Weapons Tests and Experimental Programmes, National Radiation Protection Board Report NRPB–W27*, National Radiation Protection Board, Chilton (ISBN 0-85951-499-4).

Rae JJ (1957). *The radiation survey of ground deposited radioactivity, AWRE report T49/57*, Atomic Weapons Research Establishment, Aldermaston.

Stevenson DG (1957). *Decontamination group report, Parts 1–4, AWRE report T22/57*, Atomic Weapons Research Establishment, Aldermaston.

Symonds JL (1985). *A History of British Atomic Tests in Australia*, Australian Government Publishing Service, Canberra.

Williams GA (1990). *Inhalation Hazard Assessment at Maralinga and Emu, Australian Radiation Laboratory Report ARL/TR078*, Australian Radiation Laboratory, Melbourne.

Wise KN and Moroney JR (1992). *Public health impact of fallout from British nuclear weapons tests in Australia, 1952–1957, Australian Radiation Laboratory Report ARL/TR105*, Australian Radiation Laboratory, Melbourne.