CHARACTERIZATION OF PLUTONIUM CONTAMINATION AT MARALINGA — DOSIMETRY AND CLEANUP CRITERIA

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ABSTRACT

An area of South Australia remained contaminated following British atomic tests at Maralinga during 1955–1963. Of importance is the long lived ^{239}Pu of which some 24 kg was explosively dispersed in several 'minor trials'. The extent, quantities and physical characteristics of the plutonium have been assessed and estimates of dose, dominated by the inhalation pathway in the critical group of Aborigines living a semi-traditional lifestyle, have been made for potential occupants. Dosimetry, together with social and economic factors, underpins the setting of cleanup criteria in terms of activity concentrations averaged over large areas and permissible concentrations of contaminated particles. The possibility of intentional behaviour such as fragment scavenging has also influenced limits on particulate contamination. Rehabilitation of the most contaminated areas is underway, with scraping of surface soil and burial on site completed. Vehicular-mounted radiation detector systems for widearea and particle monitoring have been developed, and procedures established for determining cleanup boundaries and for the verification monitoring to ensure that the cleanup process has met the specified criteria. Data are being obtained for a final dose and health risk assessment of the cleaned up site.

1. INTRODUCTION

1.1. Major trials

The United Kingdom conducted a programme of nuclear weapons development trials at Maralinga in South Australia between 1955 and 1963, including seven atomic explosions. The smallest was about one kiloton yield, and the largest was of 27 kiloton. All were atmospheric tests, generally exploded on 31 m high towers. The sites of these major trials no longer present any significant health risk, because all the radioactivity released in the explosions was either widely dispersed (i.e. worldwide) at the time, or has decayed sufficiently [9].

1.2. Minor trials

The UK also conducted several hundred 'minor trials' at Maralinga over the years 1955 to 1963. These minor trials were essentially developmental experiments designed to investigate the performances of various components of a nuclear device, separately and in combination. Almost all involved radioactive materials with conventional high explosives, and resulted in radioactivity being dispersed to the local environment.

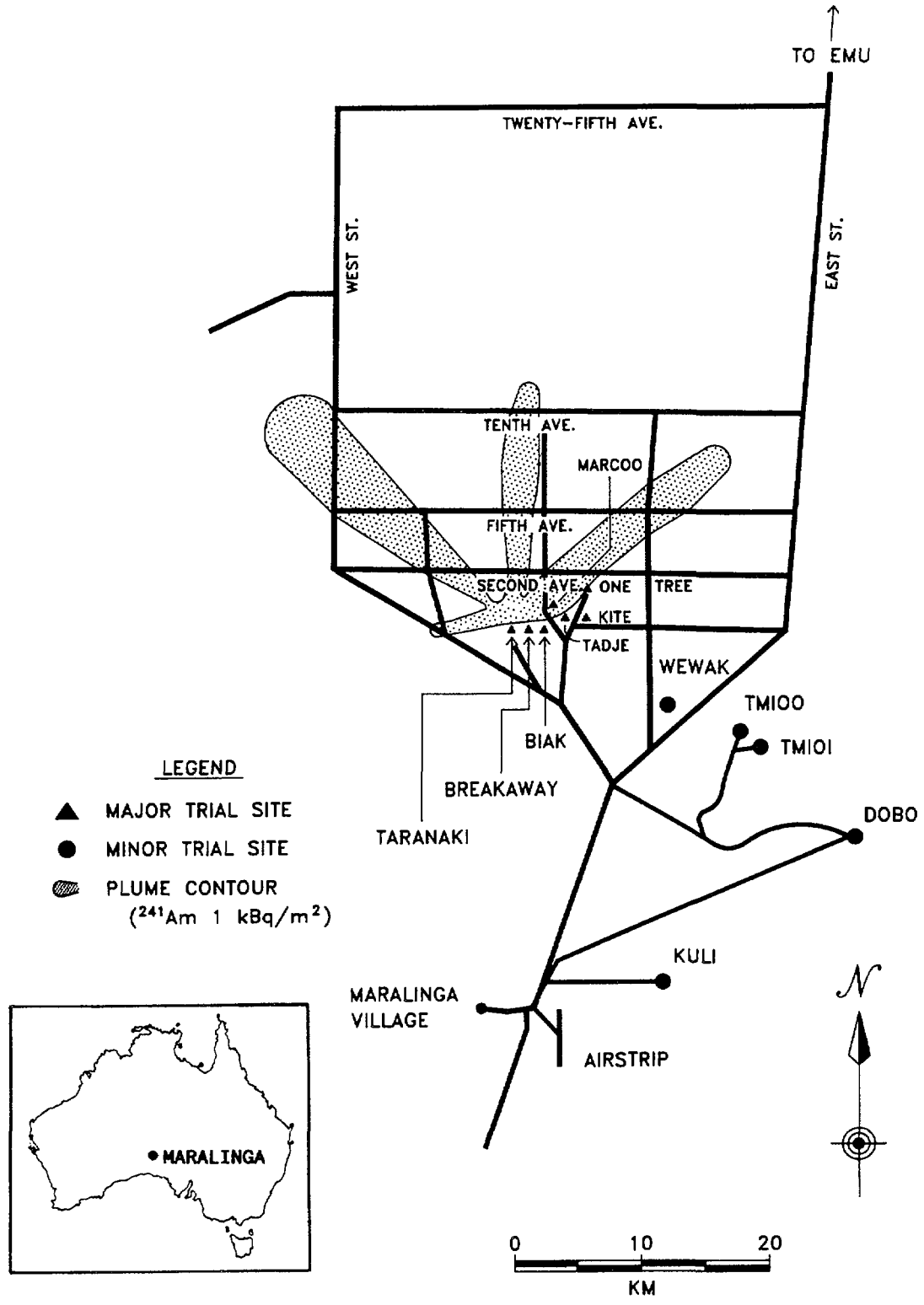

FIG. 1. The Maralinga area showing major and minor test sites and main features.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) has surveyed the minor trial sites at Maralinga, and a report was presented to the Royal Commission into British Nuclear Tests in Australia [9]. In many cases the sites had already been adequately cleaned up, or the radioactive materials used were of sufficiently short half lives that they

were no longer detectable. The major and minor trial sites are shown in Fig. 1 and those which were significantly contaminated with plutonium are detailed below.

Wewak — Burnings and explosive dispersals of beryllium, uranium and plutonium occurred at Wewak in trials code-named 'Vixen A'. Two plutonium burnings (involving a total of 405 g plutonium, of which 395 g was returned to the UK in 1959) and four explosive dispersals of a total of about 570 g of plutonium took place at the site. Surrounding the site are fragments of metal contaminated with plutonium.

TM100 and TM101 — Explosive dispersals of plutonium (about 600 g at each site) took place at both of these locations. Some 500 g of plutonium from TM101 was returned to the UK in 1979. There was a high concentration of plutonium-contaminated fragments and smaller friable particles close to the firing sites.

Taranaki — Taranaki is the site at Maralinga which was most extensively contaminated with plutonium, and which therefore represented the greatest remaining potential hazard to health. It was the site of the final major atomic detonation at Maralinga in October 1957. This was a balloon-borne test of 27 kiloton yield at 300 m, which left very little contamination nearby. Between 1960 and 1963, the area to the north of the ground zero was used for 12 'one point safety trials' (code-named 'Vixen B') in which about 22 kg of plutonium was explosively dispersed in a sector extending from the west, through north, to northeast of the site. As well as plutonium, uranium-235 and beryllium were also dispersed in these trials.

In these one point safety trials, jets of molten plutonium were projected up to 1000 m into the air, and the contamination was dispersed by wind in narrow 'plumes'. The main plumes extend to the west, northwest, north and northeast of Taranaki. The most extensive of these is the northwest plume which can be detected up to 100 km from the firing pads at Taranaki. These trials were very similar in nature to those conducted in 1963 as a joint project between the UK and the USA in 'Operation Roller Coaster' at the Nevada Test Site. The purpose of Roller Coaster was to study the effects of transportation and storage accidents involving nuclear weapons, and in particular to investigate the nature and fate of the plutonium aerosol.

The plutonium contamination close to Taranaki occurred mainly in three forms [2] — as a fine dust, as small sub-millimetre particles, and as surface contamination on larger fragments (where a fragment is defined as visually identifiable foreign matter). It is likely, however, that most of the plutonium was dispersed as an aerosol over very wide areas at low levels of contamination.

1.3. Radionuclide composition

The plutonium contamination contains isotopes ^{238}Pu (88 y), ^{239}Pu (24,110 y), ^{240}Pu (6,600 y) and ^{241}Pu (14 y). The minor trials involved negligible fission yield so the isotopic composition of the source material was unaffected by the explosion but radioactive decay has substantially removed the ^{241}Pu and replaced it with ^{241}Am (433 y). The 59.5 keV γ-ray from ^{241}Am serves as the most useful indicator, in the field, of plutonium in soil once the ratio of plutonium to americium has been determined experimentally. This ratio and the isotopic composition of the plutonium vary from site to site, and even from one trial to another at the same site [3]. At Taranaki, ^{239}Pu/^{241}Am activity ratios vary between 6 and 22 (1988 values), with the most common value 6.8. At sites TM100, TM101, and Wewak the ^{239}Pu/^{241}Am ratios are 20, 7.6 and 20 respectively (1988 values).

At present, the americium content is slowly increasing as the remaining ^{241}Pu decays. The ^{241}Am levels referred to above for determining cleanup boundaries based on the agreed inhalation dose limit, and as criteria to be met following clearance, are based on Pu/Am activity ratios pertaining in 1988. Levels measured in the field today are some 10% higher.

1.4. Previous cleanups

During the period that the Maralinga Range was in use, various radiation surveys and cleanup operations were performed [10]. Once the decision was taken to close the Maralinga Range, a cleanup of all sites was undertaken by the UK in Operation Brumby in 1967.

In Operation Brumby, the surface soil in the central area at Taranaki was treated by mixing to reduce average contamination levels, and plume areas were ploughed. Beyond the ploughed area the plutonium contamination tends still, some 30 years later, to be on the surface. Within 500 m of the firing pads there were still many thousands of contaminated fragments large enough to attract attention as potential souvenirs. The range of types of fragments included wire, rusty steel plate, lead, pieces of a grey metal alloy of low density, bitumen and yellow bakelite.

1.5. Maralinga Aborigines

The traditional occupants of the Maralinga lands are the Maralinga Tjarutja (Pitjantjatjara) Aboriginal people. Currently the Maralinga Tjarutja lands cover some 80,000 km^2, with a pool of about 2000 Aborigines who have traditional obligations to parts of these lands. The area that is currently denied to the Aborigines due to the former atomic weapons tests comprises 3,200 km^2. In recent times, between 60 and 200 of the Maralinga people have established a semi-traditional lifestyle at Oak Valley, some 100 km northwest of the Maralinga range.

2. THE HEALTH RISKS

2.1. The inhalation pathway

The inhalation of plutonium dust presents the most significant potential health hazard arising from residual contamination of the Maralinga area, due to the very low solubility of the plutonium oxide at Maralinga and the dusty, dry conditions. ARPANSA has performed a study to determine the input data for dose and health risk assessments for the inhalation pathway [11] [8] [4]. The study included a survey of ambient concentrations of radionuclides and dust in air, artificial resuspension studies, the characterisation of the contamination in the Maralinga soil, particularly particle size, and a dose assessment for the inhalation pathway. Ambient levels of airborne radionuclides are very low except during dust storms, and risk is dominated by possible exposure to isolated events such as a severe dust storm or from dust resuspended by human or mechanical activity.

Anthropological examination of the Aboriginal lifestyle showed that resuspension of dust by everyday actions of adults, children, and their dogs was much more important than natural resuspension. Aboriginal children, being closer to the ground and playing at activities which raise a lot of dust, living a semi-traditional lifestyle were shown to be the critical group for radiation protection purposes [8].

Given the relatively low importance of natural resuspension, the dust was taken to be produced from soil in the top 10 mm. This is appropriate for dust raised by vehicle tyres and human feet, whereas a much thinner layer might be resuspended by wind. Thus the average radionuclide concentration in this layer, scaled by an empirically determined enhancement factor and average dust loadings, was used to calculate the activity concentration of the inhalable fraction of each radionuclide in air.

2.2. Other exposure pathways

Other exposure pathways include ingestion, either directly of individual particles or of contaminated soil, or through eating contaminated foodstuffs, and incorporation of plutonium into open cuts and wounds. In determining cleanup criteria, dosimetry for these other pathways has only been considered in detail for ingestion of individual particles (or soil containing the same activity). However, a general allowance has been made for dose from pathways other than inhalation. For example, at sites contaminated with plutonium, for adults and children, all dose pathways other than inhalation contribute approximately an extra 10% of dose [6] [7].

2.3. Aboriginal health and lifestyle

There are several lifestyle aspects and related health issues, which might alter doses received by residents of an Aboriginal community living in contaminated areas. It is noted that the Aborigines at Oak Valley are commonly mouth breathers, many are heavy smokers, and upper respiratory tract infections are endemic. Mouth breathers tend to have lower deposition in the naso-pharyngeal region of the respiratory tract, which can affect dose intake conversion factors. Smoking further complicates the matter, but generally seems to have a small effect on regional deposition while substantially altering mechanical clearance capability. Endemic respiratory tract infections also complicate the situation, probably causing changes in regional deposition and clearance capability. These infections may also be related to high dust exposures and possibly are a cause for the high incidence of mouth breathing.

Other factors, which may affect dose intake conversion factors, are the general health and dietary habits of the population. The dose conversion factors used in our assessment have been computed from a model designed for essentially healthy workers, a scenario which is not directly applicable to many of the Oak Valley residents. Unfortunately, while these factors are obviously important in assessing doses that might be received by an Aboriginal resident in a contaminated area, little or no data exist to quantify their importance.

2.4. Short term visitors

A casual visitor to Maralinga is unlikely to remain in contaminated areas for very long and almost certainly would be exposed to lower dust concentrations than a member of an Aboriginal community. If it is assumed that the visitor is only exposed to ambient sources of resuspended dust, the greatest hazard would arise if that person were present during a dust storm (and unable to shelter in a vehicle or move out of the area while conditions were unpleasant). Calculations for this scenario, pre cleanup, indicate that there was no significant inhalation hazard for casual visitors to even the most contaminated sites at Maralinga, so long as dust raising activities were avoided [11].

2.5. Intervention philosophy

Calculation showed that doses well in excess of 100 mSv per year were possible (albeit unlikely) if continuous occupancy was to occur in some localised regions before the cleanup. While very few areas presented a significant hazard to the casual visitor even when dust raising activities were considered, doses in excess of 1 mSv per year were possible over a large area for continuous Aboriginal occupancy; this would be the case wherever the levels of ^{239}Pu exceed about 5 kBq/m^2. Because of the narrow plume structure of the contamination, 100% occupancy of contaminated areas by the very mobile Aboriginal people is most unlikely. However, the presence of plutonium in visually identifiable pieces of debris in megabecquerel quantities meant that deliberate collection by a visitor was possible and malicious misuse must be considered.

In circumstances like this, where the contamination is already in place and not subject to the normal controls of radiation protection, international principles of radiological protection state that dose limits are not directly applicable. Rather, a strategy aimed at minimising the overall harm should be formulated based on what is reasonable, having regard to economic, social and environmental factors. The cleanup strategy adopted involves a judgement based on weighing the benefits of a cleanup (e.g. doses averted by the public, ability to reuse land) against the detriment in cleanup (e.g. doses to workers, ecological cost, financial cost). The contamination level used to determine the soil removal areas was based upon knowledge of the present lifestyle of the semi-traditional Aborigines and their life expectancy, and took into account their values. Occupational exposures, however, are treated as for any ongoing radiation activity with full protection and personal monitoring being given to workers.

The Maralinga Aboriginal people have indicated a general acceptance of this approach. They were well aware that, pre cleanup, some of the contaminated areas were considered dangerous for continuous traditional occupation by them. The dilemma faced by the Maralinga people was what form of cleanup could adequately deal with this situation, and they have been very concerned about the gross environmental damage that the removal of too much top soil from large areas would cause — as it would involve the removal of every tree and blade of grass from an area of verdant bush land, with potential for subsequent erosion problems. The decision of the traditional Aboriginal owners has been that they are not prepared to solve one environmental problem by creating another [1]. They have thus reluctantly accepted the 'fencing off' of several hundred square kilometres of their traditional lands as being unsuitable for permanent occupation.

3. THE CLEANUP PROGRAMME

A Technical Assessment Group (TAG), set up by the Government of Australia following the report of the Royal Commission into British Nuclear Tests in Australia, identified a range of options for rehabilitation of the Maralinga lands based on a series of scientific studies. After consultation with the South Australian Government and Maralinga Tjarutja, a preferred programme of remediation was decided. This involves removing surface soil from the worst contaminated areas, and restricting Aborigines living a semi-traditional lifestyle from permanently occupying a further area of about 400 km^2 of land. The Maralinga Tjarutja has been compensated for denial of full access to this area.

The standard for this intervention is that the annual committed dose, for any scenario involving permanent occupancy by semi-traditional Aborigines, will be less than 5 mSv. In

fact, following the cleanup, annual doses are not expected to exceed 1 mSv for any realistic scenario. The possibility of intentional behaviour, such as fragment scavenging, has led to limits on particulate contamination.

3.1. The 'non-residential area'

A non-residential area will be established comprising those areas in which the expected annual dose by inhalation for 100% occupancy to the critical group (Aboriginal children living a semi-traditional lifestyle) exceeds 5 mSv per year. At Taranaki, this corresponds to approximately 3 kBq/m^2 of ^{241}Am and, because campsites are moved frequently, averaging over 3 km^2 is appropriate. An annual committed dose of 5 mSv and its associated risk of fatal disease of approximately 10^{-4} per year at age 50 have been accepted by the TAG and the potential Aboriginal inhabitants as a reasonable limit. The boundary of this non-residential area has been marked at close intervals with signs to indicate that the area is suitable for hunting but not for camping. In practice, the boundary follows existing roads and tracks and includes a larger area than is strictly necessary.

Within the non-residential area, transitory activities such as hunting and travel will be perfectly acceptable. However, routine use will be discouraged by the removal of some defined tracks and by re-vegetation of some areas. Alternative routes, passing around the area, will be improved to encourage their use.

3.2. Soil removal boundaries

Taranaki — Within the non-residential area, close to the Taranaki test site, short duration visits prior to the cleanup, particularly if they involved dust raising and large respiratory volumes, could still have given rise to unacceptably high doses. Moreover, the presence of highly active fragments and particles made the contamination of wounds and the deliberate collection of plutonium possible. Such hazards are difficult to quantify. Therefore, it was decided to remove, entirely, the contaminated soil along with contaminated debris from areas in which:

— the average level of ^{241}Am over a hectare exceeds 40 kBq/m^2; and/or,
— particles and fragments exceeding 100 kBq ^{241}Am are present; and/or,
— particles of >20 kBq ^{241}Am exceed a surface density of 1 per 10 m^2.

By limiting the activity of the remaining soil to below 40 kBq/m^2 of ^{241}Am, and by limiting occupancy factors to those typical of hunting activities in a particular location (0.8%), worst-case annual doses of less than 5 mSv can be anticipated. An area of about 1.5 km^2 has been treated by removal of surface soil at Taranaki. The need to satisfy the second and third criteria relating to particles and fragments has meant that the worst-case dose will be, in fact, lower than expected.

TM100, TM101 and Wewak — As these three sites are to remain outside the area of restricted occupancy ('fenceline'), cleanup levels are required to be more stringent than for Taranaki; essentially, the areas that would otherwise have been enclosed within the fenceline have been cleared of surface soil to levels acceptable outside the fenceline. The appropriate average americium levels for TM100 and TM101 are 1.8 and 4.0 kBq/m^2 respectively, and for the plumes at Wewak the appropriate average level is 1.8 kBq/m^2. The criteria for particle/ fragment densities are the same as at Taranaki.

Areas of about 0.46 and 0.31 km^2 have recently been treated by removal of surface soil at the TM sites and at Wewak, respectively.

3.3. Clearance criteria

The criteria to be met following soil clearance for particles and fragments were the same at all sites as the criteria used to set the soil removal boundaries. With regard to dispersed activity, at Taranaki contaminated soil was removed to achieve levels less than 3 kBq/m^2 (averaged over one hectare). This has the virtue that should a future reassessment dictate lower levels for the cleanup boundary, then it is unlikely that further removal of soil would be required from the area already treated. In circumstances where the achievement of the 3 kBq/m^2 clearance criterion was practically very difficult, ARPANSA was able to authorise an upper limit of 10 kBq/m^2. In fact, the highest value approved was 3.8 kBq/m^2.

At the sites TM100, TM101 and Wewak, contaminated soil was removed to achieve levels of americium at or below the levels used to define the soil removal boundary, with averaging over one hectare.

3.4. Soil removal

After trials to assess the suitability of various types of plant for removing the sandy Maralinga soil in thin layers, the standard scraper was identified as the most efficient for soil removal, transport and effective deposition of soil in burial trenches. All plant involved in the dusty soil removal operations had modified cabins to protect the operators, who worked within a sealed and pressurised cabin, with filtered air intakes and extracts, without the need to wear special personal protection equipment.

The soil removal areas were divided into individual Lots of 3–4 ha area. In the soil removal process, cuts of about 100 mm depth were taken except where windrows were present from earlier 'ploughing' operations. In this case, the total windrow plus a further 100 mm depth was removed as the windrows contained much of the contamination. After such treatment, there was a need for 'operational monitoring' to be conducted (by someone other than the regulator responsible for the signing off of Lots) over the cleared area, to give a first estimate of whether further treatment was needed to meet the clearance criteria. Based on the results of the operational monitoring, the Lot was either thoroughly monitored to check for compliance with the clearance criteria, subject to a further general cut of 100 mm depth, or given spot treatment such as the removal of individual particles or fragments or small scale soil removal.

The contaminated soil and debris has been buried well above groundwater levels in trenches excavated close to each of the sites and covered with a minimum of 5 m of clean fill. Currently, contaminated debris in 21 pits is being rendered practicably inaccessible by exhumation of the pit contents and burial at depth.

3.5. Field monitoring

3.5.1. Detector systems

In order to define the boundaries of the soil removal areas, or to demonstrate that a site conforms to certain clearance criteria following the removal of contaminated soil ('verification monitoring'), the quantity of ^{241}Am per unit area in the surface soil had to be

measured and the number and activity of particles and fragments estimated. These tasks required that two sets of measurements be made.

The first, derived from the risks associated with the inhalation pathway, measures the average level of americium, and hence plutonium, contamination in the surface layer of soil. The photon emissions from ^{239}Pu itself are too low in energy and intensity to be of much practical use in surveying large areas of soil. The 59.5 keV γ-ray from ^{241}Am, almost universally associated with ^{239}Pu, penetrates several centimetres of soil and metres of air and allows large areas to be surveyed, even from altitudes of tens of metres in aircraft.

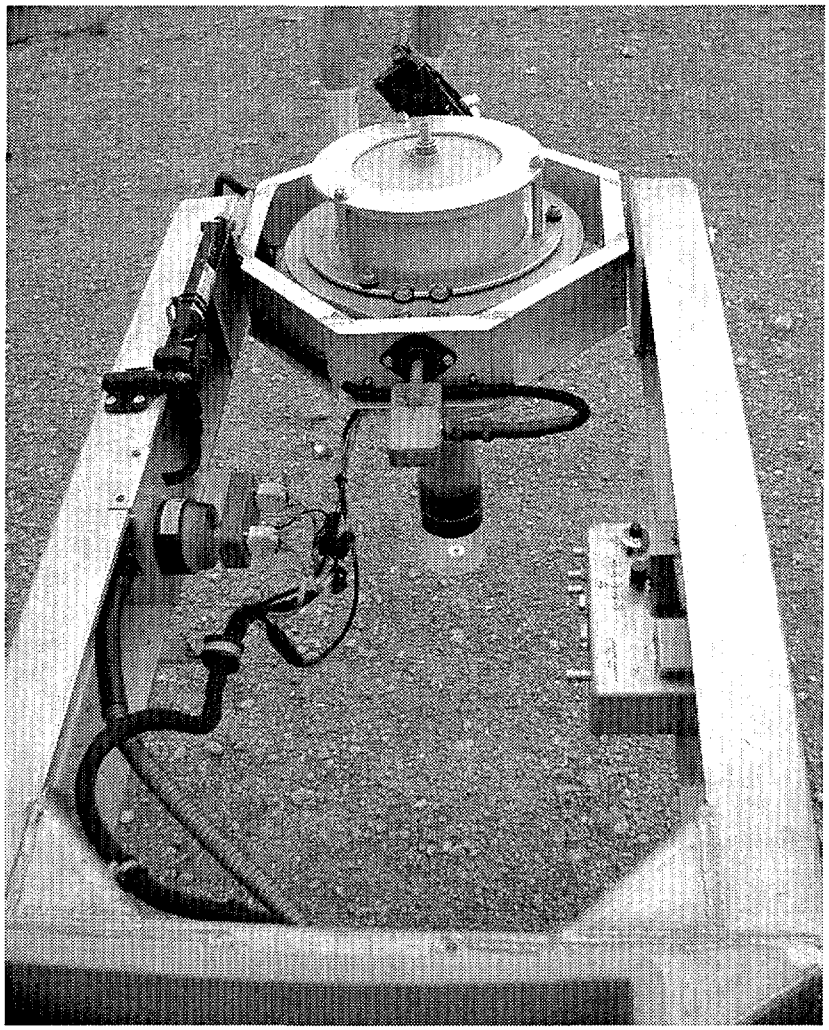

FIG. 2. Germanium detector mounted on gimbal assembly at end of boom, showing calibration source being measured, and test electronics.

The average level of contamination is measured with a closed-end coaxial instrinsic γ-ray detector (Fig. 2), held at 4 m above ground level on a boom mounted on a light truck (Figs. 3 and 4). Both the front face and cylindrical sides of the detector intercept the γ-ray flux emanating from the ground, and a single measurement effectively averages over an area of thousands of square metres. The good resolution (approximately 0.8 keV FWHM at 60 keV) allows easy separation of the ^{241}Am γ-ray from the background contributions of natural radionuclides (^{40}K, U- and Th-series), the Compton continuum from these radiations, and the contributions from fission products and neutron-activation products remaining from the major trials.

A full spectrum to at least 900 keV is acquired and stored by use of a portable MCA system and notebook PC. All the electronics is powered from a stabilised DC supply derived from the 12 volt vehicle supply. The vehicle provides an air-conditioned environment for the operator and electronics but the detector itself remains exposed to the outside temperatures which can approach 50°C in summer. Some reflective protection from direct sunlight has been found useful but generally the 5 or 7 litre portable dewar has proved adequate for a full day of operation in the field. The detectors used are ORTEC POP-TOP detectors of nominally 25% efficiency. The electronics comprises a CANBERRA INDUSTRIES INSPECTOR together with an IBM THINKPAD computer. A custom-built hydraulically operated boom allows the detector to be positioned at 4 m height at about 4 m in front of the vehicle, or to be brought right down to ground level for close measurements or access during calibration and setting up. For transport, the boom pivots back over the vehicle where the detector can be reached from the rear tray of the truck. The boom may be raised or stored in about 30 seconds. The vehicle is a diesel-powered, four-wheel drive 5 tonne OKA truck built in Australia. Measurement times of 600 – 1000 seconds are normal allowing a minium detectable ^{241}Am activity of approximately 0.3 to 0.5 kBq/m^2 depending on the background at the location.

FIG. 3. OKA γ-ray spectroscopy vehicle with boom and detector in retracted position for movement between sites.

FIG. 4. OKA γ-ray spectroscopy vehicle with boom extended in measuring position (detector not fitted).

In assessing the contamination level from the high-resolution γ-ray measurements, it is usually assumed that the americium (and plutonium) is distributed uniformly over the surface and is distributed exponentially with depth in the soil. In particular, a depth distribution with a characteristic depth of 0.5 cm is taken as standard. This agrees with measurements of the soil depth profile from undisturbed areas but is, of course, very different from that found in areas where soil mixing or other disturbance has occurred. However, because the inhalation pathway involves primarily dust raised by mechanical action on only the top 1 cm of soil, this assumed depth distribution provides a realistic and conservative calibration. Where the contamination is distributed to much greater depth,, the measurement will underestimate the total inventory of americium in the soil but will lead to a slight overestimate of the inhalation dose. Where the contamination is much shallower, the measurement will overestimate the amount of contamination but, again, overestimate the inhalation dose.

The calibration is derived from a mathematical calculation and from the measured response of the detector in the laboratory. It takes into account the variation with angle of the detector response, the inverse-square behaviour of the count-rate from a distant source, attenuation in soil and in air. A numerical integration provides a calibration which, for the situation at

Maralinga, is approximately 0.4 counts per second in the 60 keV peak per kBq/m^2 of ^{241}Am on the ground. This semi-empirical value has been confirmed by measurements made in the field at a site where numerous soil samples have been taken and analysed. Unfortunately, due to the particulate nature of much of the contamination, there is very wide variation between one soil sample and the next and this intercomparison only allows verification of the calibration to, perhaps, ±30%. This is, however, adequate for assessment of dose for risk assessment purposes.

The second measurement technique is required to determine the presence of particulate contamination. While the results of the high-resolution spectrometry set an upper limit on the numbers and activities of particles, the clearance criteria require that particles and fragments be surveyed in a separate operation. For most of the survey work to define the soil removal boundary, this was done by use of handheld 5 cm diameter by 3 mm thick sodium-iodide detectors incorporating a single channel analyser tuned to the 60 keV γ-ray. By scanning the ground with the detector held only a few centimetres above the soil, particles down to few Kilo–Bequerels of americium may be detected. Once located, the activity of the particle is estimated by comparison of the count-rate with that from standards. This method is, however, labour intensive and tedious. Automated methods were examined, but replacing the ability of a human operator to detect and then confirm slight increases in an audible count-rate proved difficult. However, the exhaustive particle searching required for the verification monitoring has necessitated the design and construction of an automated system.

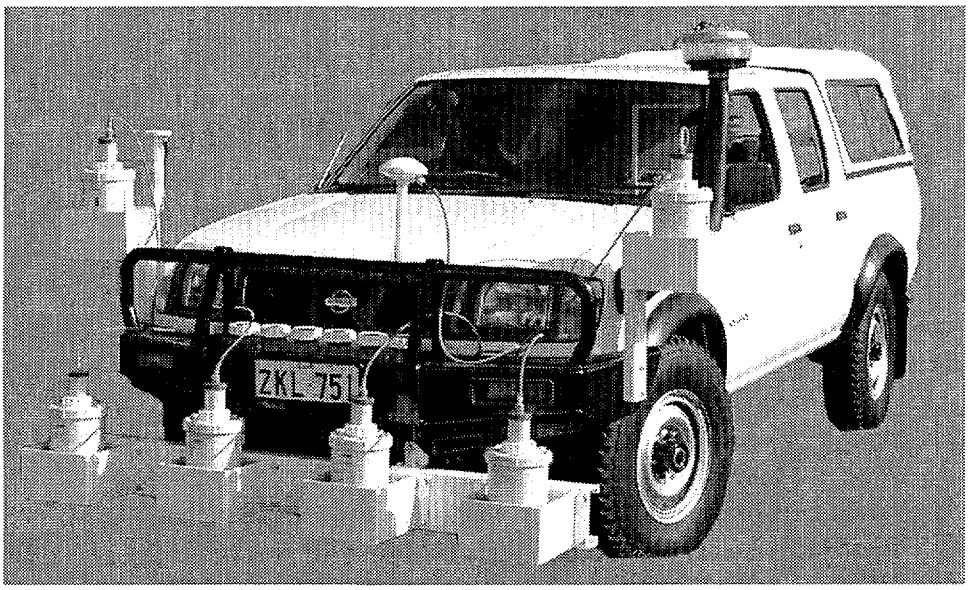

FIG. 5. Nissan particulate contamination detection system.

Four detectors, 12.5 cm diameter and approximately 2 mm thick, have been placed at 0.5 m centres at about 28 cm above ground level on the front of a four-wheel drive Nissan utility vehicle (Figs. 5 and 6). In this case thin-crystal sodium iodide detectors (BICRON FIDLER G5) are used. The thin crystal provides significant rejection of the high energy background and is still fully efficient at 60 keV. When driving at a nominal 1.7 m/s the system can reliably detect every 100 kBq particle in its 2 m wide track and cover a hectare in 1–2 hours. The detection of 20 kBq particles is essentially statistical with a significant background rate (several hundred per hectare) and only approximately a 50% detection efficiency. This is somewhat increased by the multiple coverage provided by adjacent detectors, overlapping passes, and successive counting intervals.

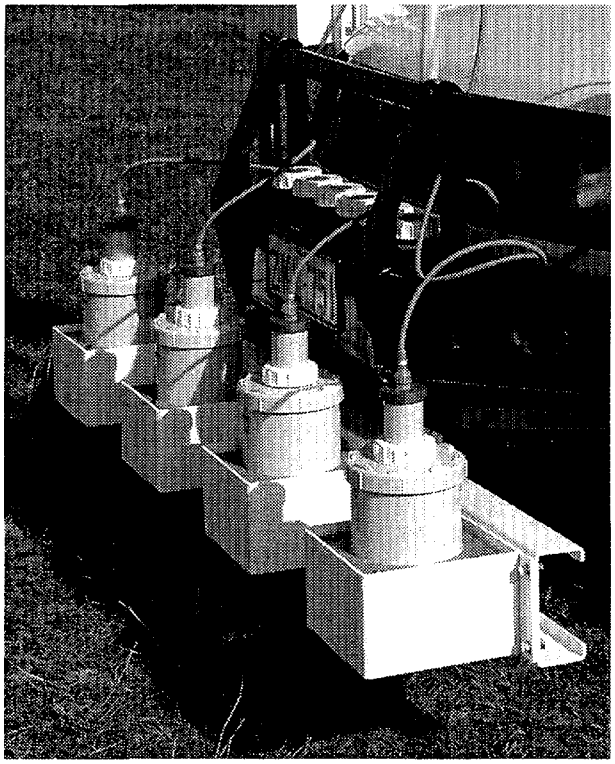

FIG. 6. Four large area NaI detectors mounted in protective canisters on the Nissan vehicle.

A differential GPS system provides accurate position information. The front end electronics used with the FIDLER detectors comprises modified commercial portable scaler/ratemeters made by LUDLUM. This equipment runs from 3 volts DC and provides the high-voltage photomultiplier supply, the pre-amplifier, and pulse–height discrimination. The rate-meter gives useful information for diagnostic purposes. Pulses are derived from a single channel analyser window set around the 60 keV peak, approximately from 40–80 keV. The threshold and window voltages are set either by multiturn trim potentiometers built in to the LUDLUM ratemeters or by external voltages controlled by the computer interface. Under computer control, the threshold and window can be wept from zero to about 100 keV and a 50 channel spectrum obtained. This provides the necessary information to adjust the high-voltage and to set the built-in threshold and window. The threshold, window and high-voltage supply voltages, as well as the battery supply voltage, are all monitored continually by the computer to ensure correct operation. A later version provides full computer control of the threshold, window and HV and eliminates the need for screwdriver adjustments.

In normal operation the pulses from each of the four counting channels are counted continuously together with a 1000 Hz clock as a timing reference. Every time the vehicle advances by a nominal 20 cm all five counters (four detectors plus timing reference) are read and stored. The data in three successive counting intervals are summed and examined to determine whether or not a high-activity particle has been observed. In this way a 60 cm path over the particles and roughly centred on it is used to measure its activity. The alternative of using fixed duration counting intervals can include unnecessary amounts of background when the particle is not under the detector. Background rates of 10–20 counts per second are observed in the field and the sensitivity is approximately one count per second per kBq of ^{241}Am. The actual efficiency depends on the lateral displacement of the particle relative to the detector. At the nominal forward speed of 1.7 m/s, the effective counting time is 0.35 s giving background counts of about 5 and counts for a 100 kBq particle of 35. The 100 kBq particle

will be usually detected several times as it approaches and leaves the detector. The efficiency for detection of 100 kBq particles is effectively 100% and the false positive rate only a few per hectare. Variations between one detector and another, changes in detector height due to vehicle movement and other factors mean that particles in the range 50 to 100 kBq may need to be investigated by handheld equipment to show whether or not they actually exceed the 100 kBq limit. The large detectors at 30 cm from the ground will also sum the effect of several smaller activity particles producing false signals in some areas.

3.5.2. Field survey methods

3.5.1.1. Determining cleanup boundaries

There are two main requirements for defining the soil removal area. The quantity of ^{241}Am per unit area in the surface soil must be measured and the number and activity of particles and fragments must be estimated. In-situ γ-ray spectroscopy is the main tool for measuring the overall level of contamination. As explained above, the inhalation hazard may be estimated from the apparent concentration of ^{241}Am as determined by the γ-ray that escapes the surface.

Previous surveys of contamination by soil sampling, by ground based high-resolution γ-ray spectroscopy, and by helicopter based aerial survey making use of a large array of sodium-iodide detectors [5], gave guidance as to the approximate locations of the soil removal boundaries at the appropriate ^{241}Am activity concentrations for each site. These boundaries were defined in detail by systematic measurements using the vehicle-mounted germanium detector at 4 m height. Boundaries thus determined were checked, largely by the handheld thin-crystal NaI detectors, for compliance with the particle criteria, and where these criteria were breached, extensive statistical surveys were require to define the new location of the soil removal boundary.

The vehicle-mounted detector system for particle searching was not available early in the boundary-marking phase of the work, and it is doubtful of its advantage due to difficulties of the generally rough terrain (Unlike the relatively smooth surface available after soil removal treatment). A prototype trolley-mounted system suffered due to both difficulties with the terrain and also its weight which made pushing it around in a hot environment difficult.

The lower levels of americium (approximately 3 kBq/m^2) at the boundary of the non-residential area (outer 'fenceline') will require longer counts but do not require high spatial resolution. As this boundary will follow existing roads and tracks, most field monitoring will be for verification purposes. The germanium detector and truck will again be used with satellite GPS navigation for determining locations.

3.5.1.2. Verification monitoring

For surveying treated areas of land, high-resolution gamma ray measurements are made on a roughly square grid of approximately 35 m spacing. Measurements are made as close as 15 m to a boundary where it is recognised that some contribution to count-rate will come from outside the measured area. This can be estimated, when it is important, by making a second measurement at 1 m from the ground. Where the activity is distributed uniformly over the ground the expected count-rate would then be approximately double that obtained at 4 m. If a lower or similar value is found, it may be deduced that significant input from far afield is occurring. Nine adjacent points on the grid cover an area of approximately one hectare and the clearance criteria at Taranaki, for example, specify that the contamination be less than 3.0

kBq/m^2 averaged over one hectare. In assessing an area, all sets of nine such points are taken and the measurements averaged. The worst-case location of the square of nine points is considered but contrived shapes are not. No account of uncertainties is made in calculating the average. Where no 60 keV peak is detected, the net peak area, be it positive or negative, is included to give an unbiased average.

Where the average for an area exceeds the clearance limit, some remedial action is usually required. Normally any active particles will already have been removed so the only course of action is further removal of contaminated soil from the most active regions. Detailed information from the particle searching scan described below can assist in locating the areas from which soil can most beneficially be removed. In cases where further removal of soil is impossible or the effort required is disproportionate, ARPANSA (as the 'regulator') is able to authorise levels of up to about three times the clearance limit.

The second set of measurements, usually performed first, is to search for, and remove if necessary, any highly localised pieces of contamination. Where the contamination is found on a visible piece of debris (a 'fragment') the activity is not usually taken into account although a value of a few kBq is a practical lower limit. For vehicle-borne equipment covering large areas, 20 kBq of ^{241}Am is about the lowest that can be detected with better than 50% reliability. Where the contamination is not visible (a 'particle') two levels of activity are considered under the clearance criteria. No particles exceeding 100 kBq are permitted to remain, and an average of less than one particle exceeding 20 kBq per 10 square metres is permitted. In order to detect such particles in the presence of background, it is necessary to place an appropriate detector close to, at least briefly, every part of the area to be surveyed.

All the count data, together with differential GPS position information, are displayed and stored on the notebook computer. Analysis of the computer records allows re-visiting the position of a potential 100 kBq particle for verification. Using handheld NaI equipment the activity can be measured more reliably and a decision made on what action is required. If the offending activity arises from a fragment, or a particle exceeding 100 kBq, it will usually be removed using hand equipment and the area rescanned to ensure it is now free of contamination. The GPS equipment provides coordinates accurate to about 1 m which ensures that only a small area around each potential particle must be scanned by hand.

Examination of the computer files produced by the particle scan allows checks for total coverage of the area. In practise, small drifts in the GPS coordinates can mean that a few gaps may occur in the coverage but generally better than 99% coverage is expected. A computer display shows the operator where areas require re-scanning.

The computer files also can show the average contamination levels throughout the area being scanned. Some uncertainty in the absolute level of contamination will exist due to the very variable background observed in the field. However, localised hot-spots of perhaps 10 – 20 kBq/m^2 are easily observed. Where the germanium detector results show the need for further remediation, the NaI results can produce useful spatial information.

4. CONCLUSIONS

The cleanup criteria were guided by conservative principles and by estimated doses for realistic scenarios. These included the possibility of an Aboriginal group living for a whole year on the edge of the non-residential area in regions of the highest activity permitted outside it (~20–35 kBq/m^2 of ^{239}Pu depending on the site). This could lead to an annual dose of 5 mSv. If, more realistically, the group spent its time randomly over the Maralinga lands outside the restricted area, or even randomly around its perimeter, average activity levels and hence doses may be confidently expected to fall by at least an order of magnitude.

Similarly, the criterion for soil removal at Taranaki was based on 0.8% occupancy of the most contaminated remaining land within the non-residential area. This was consistent with a tenth of the typical hunting time being spent in this one region. Most of this land will contain levels of plutonium far below the maximum residual level and randomly distributed hunting would incur much lower intakes of radionuclides.

While arguments about occupancy levels and consequent doses are subject to a certain amount of arbitrariness, the rehabilitation, when complete, will have removed three of the present possibilities for very high doses:

— Soil will have been removed from areas where the production of large amounts of dust in locations of high plutonium concentration could lead to doses exceeding acceptable limits.
— Areas containing highly active particles or large numbers of particles will have been cleaned to prevent the deliberate collection of contaminated fragments and particles.
— Burial pits containing debris contaminated with plutonium will be rendered practicably inaccessible by the process of exhumation and burial at depth.

In the case of short term visitors making intermittent forays to the cleanedup site, for example tourists, geological prospectors and surveyors, inhalation doses of very much less than the 1 mSv annual public exposure level can be confidently assured.

During the field monitoring work being conducted in support of the actual cleanup process, data are also being obtained from remediated areas to allow a final dose and health risk assessment to be performed for various scenarios and potential occupants once the cleanup is complete and the area is released from institutional control. These data include remaining levels of contamination, both within and outside of the treated areas, and a study of resuspension parameters (including plutonium concentrations and particle size characteristics in resuspended material) from the remediated areas. However, one can confidently predict that not only will the cleanup have achieved all its objectives, but it will have actually done better in that predicted annual doses for all realistic scenarios are expected to be very considerably lower than the required value of 5 mSv.

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