MARALINGA

HISTORY OF THE MARALINGA SITE

Between 1955 and 1963, the United Kingdom conducted a program of nuclear weapons development tests at Maralinga in the remote outback of South Australia (Figure 1). This testing led to widespread dispersal of radioactive contamination to the local environment.

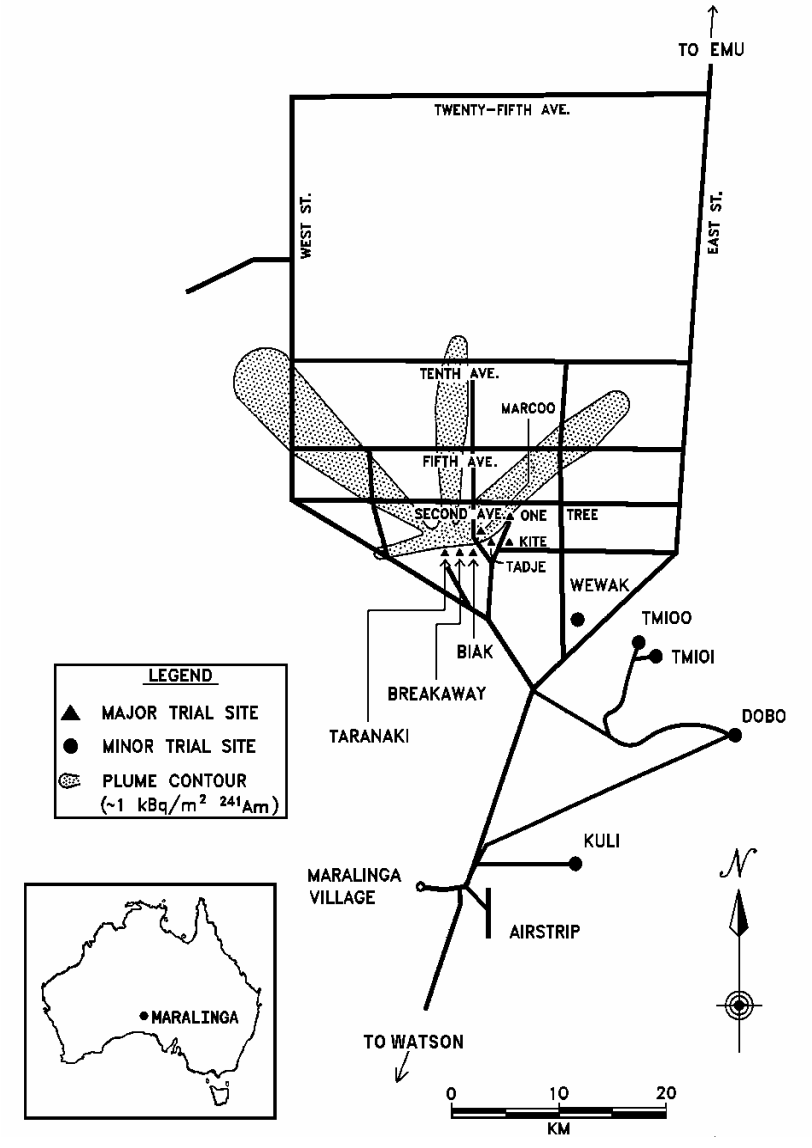

Figure 1. Maralinga, South Australia

Seven atomic explosions took place at Maralinga in 1956 and 1957. The contamination from these "major trials" has largely decayed and no longer presents a significant health risk. Many "minor trials" were also conducted on the site. These were safety tests and other experiments designed to develop the components of a nuclear device. These tests involved the burning and explosive dispersal of

plutonium, uranium, and other radionuclides. Much of the contamination from these minor trials remained on or close to the ground surface following the decommissioning of the site by the British. In many cases the radionuclides were short-lived and have long disappeared, but three sites, Taranaki, TM100/101 (TMs), and Wewak remained highly contaminated with plutonium 40 years later. This plutonium has been assessed as representing a significant health risk to potential occupants of the land [TAG, 1990].

Taranaki

Taranaki was the site of the highest-yield nuclear explosion conducted at Maralinga. The device was detonated on October 9th 1957 with a yield of 27 kilotons. The device was exploded from a balloon at a height of 300 m and left the area relatively uncontaminated. The Taranaki site was subsequently used for a series of minor trials during the Vixen B series [Symonds, 1985].

These Vixen B minor trials, conducted in 1960, 1961 and 1963, left Taranaki the most severely contaminated site at Maralinga. Approximately 22 kg of ^{239}Pu and the same quantity of ^{235}U were dispersed at the site during 12 single-point safety trial [Symonds, 1985].

These trials involved negligible fission yield but produced jets of molten, burning plutonium extending hundreds of feet into the air [Symonds, 1985]. Following each trial this plutonium was carried by the wind and deposited in long plumes extending large distances in the direction of the wind at the time of the trial.

Contamination remaining at the Taranaki site on the completion of the UK weapons testing program and subsequent partial clean-up was in three basic forms:

Fragments - plutonium-contaminated debris that is visibly identifiable when lying on the surface. This included contaminated metal, plastic, wire, lead etc.

Particles - sub-millimetre pieces of soil or other material incorporating plutonium oxide. These are indistinguishable from soil on casual inspection but have much higher activity than the average for surrounding soil.

Dust - very finely divided, and potentially inhalable, grains of plutonium oxide or contaminated soil.

SITE REHABILITATION

In a rehabilitation operation carried out by the UK Ministry of Defence in 1967 (Operation Brumby), an attempt was made to dilute the surface concentration of plutonium in the more highly contaminated areas, particularly in central Taranaki. This was done by turning over and mixing the surface soil. In future rehabilitation programs this area was known as the “ploughed area”.

At the same time the remains from the firings, including numerous contaminated fragments and most of the remaining infrastructure, were buried in a series of 22 pits,

each approximately 2-3 m deep. These pits were each sealed with a 12 inch cap of concrete, reinforced with three-quarter inch mild steel bars every four feet. The plutonium content of each of these pits was unknown [Symonds, 1985], but the range of credible values included kg quantities.

At this time a series of high-cyclone-mesh (HCM) fences was erected to enclose the burial pits containing significant quantities of plutonium at Taranaki and the TM sites.

Since the closure of the site in 1967, numerous studies have been carried out to map and characterise the contamination at Maralinga. Detailed studies were carried out in 1984-85 by the Australian Radiation Laboratory (ARL, which became ARPANSA in February 1999). These studies revealed that contamination levels at the site were greater than earlier acknowledged [Lokan, 1985]. At the completion of this study, additional three-strand fences, which became known as the "ARL fences", were erected at each of the three sites outside the HCM fences erected at the completion of Operation Brumby. These fences were intended to enclose all significant particulate contamination, but more extensive examination showed areas where particles could be found outside the fences.

In 1986 a Technical Assessment Group (TAG) was set up by the Australian Government to oversee and report on further technical studies of the site, and to advise on rehabilitation options. Information gathered in the TAG studies, including a comprehensive aerial survey of the Maralinga range conducted by EG&G [EG&G, 1988], led to a recommendation being made regarding rehabilitation of the area. The three sites which were severely contaminated with plutonium, viz. Taranaki, TMs and Wewak, were recommended for remediation by removal and burying of surface soil.

Planning of the Maralinga rehabilitation project began in 1993 with the establishment of the Maralinga Rehabilitation Technical Advisory Committee (MARTAC) whose purpose was to provide advice to the Department of Primary Industries and Energy (later the Department of Industry, Science and Resources, DISR), the project managers responsible for the site. MARTAC was given the responsibility for establishment of the clean-up criteria for remediation of the site. These clean-up criteria are presented and discussed below.

The Consultative Group that had functioned during the TAG era was reconvened for the rehabilitation project in 1993. This Group was established to serve as a forum to discuss all matters of the site rehabilitation. The Consultative Group comprised representatives from the Commonwealth, South Australia, Western Australia and the UK, together with members of the Maralinga Tjarutja Aborigine people (the traditional land-owners) and their legal representatives [Lokan, 1999].

The first stage of the rehabilitation project consisted of defining the clean-up boundaries at the sites contaminated with plutonium, followed by bulk removal of contaminated soil from the three sites and burial within purpose-built burial trenches under at least 5 m of clean rock and soil. At Taranaki the 22 pits in which the British disposed of unknown quantities of plutonium associated with the 12 Vixen B firings also required rehabilitation. Eleven of these were treated by means of in-situ vitrification (ISV) while the remaining pits were exhumed and their contents reburied in another custom-built burial trench.

To facilitate control of the process, the soil removal area was divided into so-called Lots of between 2 and 5 hectares in area. Each Lot then underwent a sequence of soil-removal, checking by the health physics provider, re-treatment if necessary and then monitoring by ARPANSA. In a small number of cases, measurements by ARPANSA revealed the need for further treatment in order to meet MARTAC clearance criteria.

PLUTONIUM

Of the long-lived radionuclide contaminants at the Maralinga site, plutonium-239 presents the most significant radiological hazard. Other isotopes of plutonium contribute ~15% additional dose but are not subject to chemical or physical separation and need not be separately measured. The most important pathway for exposure is by inhalation. The aim of the rehabilitation of the Maralinga range was therefore to reduce the risk arising from exposure to radiation of individual Aborigines, living an outstation lifestyle, to a level that was acceptable to the Aboriginal community and the Australian Government [TAG, 1990].

Plutonium, being an alpha emitter, presents a health risk only if it enters the body. Of the three pathways for entry into the body (viz. inhalation, ingestion, or through cuts and wounds), inhalation of plutonium and subsequent retention in the lungs gives rise to a risk of lung cancer. However, if the plutonium enters the body through one of the other pathways the greater risk is of bone cancer (osteosarcoma) or cancer of the liver [Stover & Jee, 1972]. The degree to which each of these exposure pathways contributes to potential dose depends on the type of lifestyle practised by occupants of the land [TAG, 1990].

The plutonium at Maralinga is largely in the form of insoluble plutonium oxides [Williams, 1990, Ch.4; Stradling *et al*., 1992]. Due to this insolubility, the ingestion pathway is of much less importance to potential dose. Wound contamination is less likely to occur but does have the potential to deliver large single doses [Harrison *et al.*, 1993]. This may occur through contaminated dust or particles entering existing wounds, or the simultaneous injury and wound contamination caused by a contaminated fragment [Lokan & Williams, 1995]. For nomadic Aborigines such as the Maralinga Tjarutja, living an outstation lifestyle, the inhalation dose pathway is by far the most significant for both adults and children [Haywood & Smith, 1992]. For this reason, in assessing the requirements for land rehabilitation with regards to dispersed contamination, it was necessary to quantify the risk to the Maralinga Tjarutja people of inhalation of contaminated soil [Johnston *et al*., 1992; Williams 1990; 1994].

None of the plutonium isotopes present in the contamination at Maralinga emits any gamma-ray with sufficient intensity to permit practical measurements in the field. Measurement of alpha-particles is possible only for freshly deposited contamination lying on smooth, clean surfaces and even then, the reliability of such measurements has been questioned. The isotopes of plutonium do emit low-energy X-rays with considerable intensity but these are heavily attenuated in only a few millimetres of soil and do not provide reliable information about weathered contamination which has migrated downwards into the soil.

Fortunately, a minor constituent of the plutonium, ^{241}Pu, is short-lived ($T_{1/2}$ = 14 years) and decays to ^{241}Am, which is an alpha-particle emitter but also emits a 59.5

keV gamma-ray with a probability of 36%. This gamma-ray can travel through several centimetres of soil, or many metres of air, and permits reliable and practical measurement of the ^{241}Am concentration in the surface layers of soil. The quantitative detection of this gamma-ray has been the basis of the aerial survey and ground-based measurements at Maralinga.

THE CLEAN-UP CRITERIA

The aim of the Maralinga rehabilitation was to ensure that the risk to potential inhabitants from exposure to radioactive contamination would be acceptable. The dividing line between acceptability and unacceptability of risk [TAG, 1990] was determined to be an annual committed dose of 5 mSv, assuming full time occupancy by Aborigines living an outstation lifestyle. This corresponds to an annual risk of fatal cancer following the inhalation or ingestion of contaminated soil of not more than 1 in 10,000 by the fiftieth year of life [TAG, 1990]. The value of 5 mSv is broadly consistent with the intervention level of 10 mSv that has recently been proposed by the International Commission on Radiological Protection [§6.1 in ICRP, 1999] and which is under consideration by the International Atomic Energy Agency [IAEA, 2002]. Both of these international bodies are proposing that, in future, a generic reference level of around 10 mSv be set, under which intervention is generally not justified.

Two actions were undertaken to achieve this limitation of possible radiation dose. First, where levels of radioactivity were so high that a dose of 5 mSv could be received in a short time, the contamination would be removed and safely buried in disposal trenches. In areas where there was no acute hazard but permanent occupation could result in doses exceeding 5 mSv, restrictions on land-use would be imposed.

When determining the soil removal criteria, MARTAC took into account three dose pathways, inhalation of resuspended dust, ingestion of soil or contaminated food, and wound contamination. There were thus two main requirements for defining the criteria for soil removal. The first was the concentration of plutonium in the surface soil, which would be available for resuspension and inhalation. This criterion was stated as the maximum quantity of ^{241}Am per unit surface area, taking account of the Pu/Am activity ratios and the enhancement factors. The second was a limit on the number and activity of contaminated particles and fragments near the surface. These had the potential to be accidentally eaten or to cause or contaminate a break in the skin of a potential inhabitant.

The Maralinga Technical Advisory Committee (MARTAC) established three sets of criteria for levels of contamination that were to be permitted to remain following rehabilitation [Cooper *et al*., 1997; Williams *et al*., 1998].

- Soil-Removal Criteria: At Taranaki, contaminated soil (or the offending contamination itself) was to be removed where the levels of dispersed ^{241}Am exceeded 40 kBq/m^2 averaged over 1 hectare (10,000 m^2) or where contaminated particles exceeding 100 kBq were found, or where the density of particles exceeding 20 kBq was greater than 1 in 10 m^2.

- Clearance Criteria: Where soil was removed, the residual levels of dispersed contamination in the cleared area was not to exceed 3 kBq/m^2 ^{241}Am averaged

over 1 hectare and particulate contamination was to meet the Soil-Removal Criteria.

- Unrestricted Land-Use Criteria: Permanent occupancy and unrestricted land-use was only to occur where levels of dispersed contamination were less than 3 kBq/m^2 ^{241}Am averaged over 3 km^2, and the particulate contamination met the Soil-Removal Criteria.

For the dose conversion factors accepted for general use at the time, and the site-specific factors applying at Taranaki, the concentration of ^{241}Am in the surface levels of soil of 3 kBq/m^2 was expected to lead to an annual dose of 5 mSv through inhalation of contaminated dust, under conditions of continuous occupancy [Lokan & Williams, 1995]. Realistic scenarios for other exposure pathways showed the doses involved to be no more than 10% of this.

MARTAC criteria for the removal of contaminated particles and fragments states that no particles of ^{241}Am activity greater than 100 kBq and no observable contaminated fragments should remain outside the soil-removal contour or within the rehabilitated area at the conclusion of the operation. There should also be no more than an average of one discrete particle of activity greater than 20 kBq per 10 m^2.

MARTAC did not specify any averaging criterion for particles of 20 kBq or below, but 0.1 per square metre or 1 per 10 square metres was not very practical. ARPANSA interpreted this criterion as requiring that there be fewer than 1000 particles exceeding 20 kBq ^{241}Am per hectare.

EQUIPMENT AND METHODOLOGY

During each phase of the rehabilitation project, ARPANSA was required to make measurements of the levels of contamination to determine compliance with the criteria set by MARTAC for dispersed and particulate contamination. This required two different kinds of measurements:

- *in-situ* high-resolution gamma-ray spectrometry to measure the dispersed contamination by means of a germanium detector and associated electronic equipment mounted on and in a light truck (OKA); and

- low-resolution detectors with associated electronics to be used for scanning areas of ground for radioactive particles and for determining their activities when found. Initially small, hand-held, scintillation detectors were used for both scanning and activity measurement, but later an array of four large detectors mounted on a Nissan utility vehicle was available for rapid and thorough scanning of large areas.

Dispersed Contamination - Germanium Detector System

For the measurement of the large-scale average level of americium, and hence plutonium, in the surface layer of soil, a closed-end coaxial intrinsic gamma-ray detector suspended at a height of 4 m was used. These measurements are related to the risks associated with the inhalation of contaminated dust.

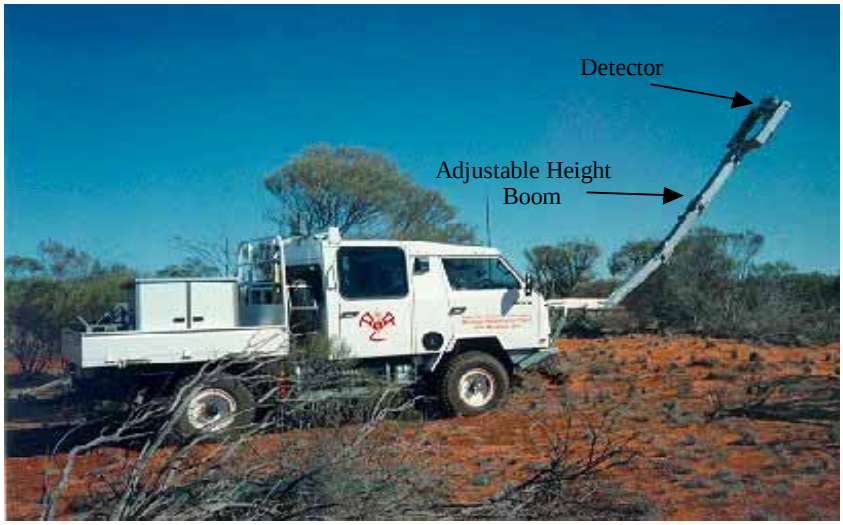

Figure 2. OKA vehicle with area-averaging gamma-ray system

A four-wheel drive light truck (OKA) was modified to incorporate an adjustable-height boom to which the gamma-ray detector is fitted (Figure 2). The custom-built boom was hydraulically operated and allowed the detector to be positioned at varying heights in front of the truck. For most routine monitoring, the detector was held at 4 m above the ground, and for calibrations and testing at about 1 m. For transport, the boom pivoted back to lie along the roof of the truck. The detector could be left on the boom for transport over relatively short distances, but was removed and placed in a specially fitted cabinet for travel to and from the monitoring site.

Particulate Contamination - Nissan Particle-Detection System

The other criteria set by MARTAC were for particulate contamination. Detection of point-source contamination requires a separate monitoring operation, in which the detector array passes over as close to 100% of the entire ground surface as possible.

For the determination of discrete particulate contamination, or contaminated fragments, an array of four 12.5 cm diam by 1.6 mm thick sodium-iodide detectors was mounted on the bull-bar of a four-wheel drive Nissan Navara (Figure 3). These detectors were each connected to a single-channel analyser set to count gamma rays of ~59.5 keV. The thin-crystal detectors provide significant rejection of the high-energy background but are still fully efficient at 59.5 keV.

The detectors were mounted at a height of 25-30 cm above the ground with their centres 0.5 m apart. This allowed the system to effectively scan a 2 m wide track, and by driving at a speed of 5-6 km/h, individual particles and fragments of 20 kBq could be detected with approximately 50% efficiency. All particles and fragments with an activity of 100 kBq or greater are reliably detected within the 2 m track of such a system. By this procedure, the vehicle was able to thoroughly scan a hectare in 1 - 2 hours.

Figure 3. Nissan vehicle-mounted particle detection system

The vehicle was fitted with a differential GPS system that was also interfaced with the computer so that the entire area covered by the searching process was accurately recorded. The position of all positive signals from any of the four detectors was also recorded to an accuracy of 1 m.

POST- REMEDIATION ASSESSMENT

Radiation doses (committed effective dose values for the inhalation pathway) have been calculated for a range of sites at Maralinga following the latest clean-up [Williams *et al*., 2002]. Other pathways have been considered in the past, but it is clear that inhalation is by far the dominant contributor to overall dose given realistic exposure scenarios. For all sites considered, the dose due to inhalation was dominated by ^{239}Pu (*ca*. 75% of total) with minor contributions from other isotopes of plutonium and from ^{241}Am.

While many of the input parameters in the dose calculations are subject to considerable uncertainty, one of the most uncertain is the occupancy factor. As it is impossible to predict with confidence future occupancy factors for the Maralinga areas by Aboriginal communities, a value of 100% (permanent occupancy) has been generally assumed in the calculations. In practice such estimated doses must be scaled down by whatever is assumed to be a reasonable occupancy factor for the actual contaminated areas within the restricted area.

The essential purpose of this assessment has been to ensure that the whole Maralinga area has been rendered safe following work undertaken during the 1994-2000 Maralinga Rehabilitation Project. To this end, at many stages during the calculations *conservative* assumptions have been made in order to confidently attain this goal. These will in general lead to estimated doses being *over*estimates.

From pre-remediation dose estimates, certain areas were found to have inhalation dose rates that were too high to be acceptable under all but the most rigorously controlled circumstances. These included central areas at Taranaki, Wewak, TM100 and TM101. Now, following the rehabilitation by removal and burial at depth of contaminated surface soil, all areas at Maralinga are shown by the dose assessments to be well within acceptable limits for all envisaged land uses.

The restriction on permanent occupancy within the 'restricted land-use' (non-residential) boundary surrounding Taranaki can be seen as a purely precautionary measure as doses due to inhalation for permanent occupancy of all but a few areas (essentially within the untreated plumes) are well below the 1 mSv/y limit for members of the public. For a semi-traditional Aboriginal lifestyle, with camp sites occupying considerable area and moving regularly, it is difficult to envisage circumstances which would lead to inhalation doses, even within most of the restricted zone, above acceptable limits. The argument for maintaining restrictions on land-use at central Taranaki should perhaps be seen as restricting access to the sites of the new burial trenches (and thus discouraging intrusion). The restricted access also reduces the highly unpredictable (stochastic) and essentially non-assessable hazard from possible contact with any undiscovered active particles remaining in the plumes *adjacent to the soil-removal areas*. Thus, at some time in the future (*eg.* when the current 'boundary' signs decay) consideration could be given to contracting the restricted area to only include the burial trenches and inner plume areas (where any remaining particles will be) at Taranaki, together with the small area of plutonium contamination at Tadje.

In making this recommendation, we are cognisant of the fact that the new dosimetry, based as it is on a revised kinetic and dosimetric model of the human respiratory tract, has resulted in decreases of the doses due to inhalation of plutonium and americium of the order of 75%. Thus the TAG requirement that restrictions be placed on permanent occupancy of areas with the potential to give annual doses of 5 mSv has resulted in the 'restricted land-use' (non-residential) boundary being placed considerably beyond what is actually required with the new dosimetry.

MARTAC criteria for the 'restricted land-use' (non-residential) boundary were based on a requirement that permanent occupancy of any area of 3 km^2 should result in doses of less that 5 mSv/y by inhalation or ingestion. As a consequence of the combined effects of the revised dosimetry and better-than-expected level of clean-up of residual contamination, the estimated inhalation dose for the worst-case 3 km^2 within the 'restricted land-use' zone is 3.6 mSv/y and a restricted area is not strictly required to meet MARTAC's objective for the inhalation pathway.

Some representative dose calculations have been performed for specific scenarios including digging, driving in a vehicle following another along a dusty track, and repairing a puncture. In all these situations, estimated doses for the activity are acceptably low, especially considering envisaged land uses (*ie*. probability of multiple exposures is low).

It is now impossible for casual visitors making intermittent forays to the area, for example tourists, geological prospectors and surveyors, who do not engage in abnormal dust raising or large-scale soil-disturbance activities, to receive a committed effective dose by inhalation of anything approaching 1 mSv. The estimated doses received during ambient (calm) conditions are very low, and exposure to the substantial dust loadings observed during times of severe dust storms also results in doses which are essentially insignificant. The conclusion of Shinn [Shinn, 2002] is that under ambient conditions, concentrations of plutonium in air and plutonium resuspension factors are not markedly different from world-wide background values.

Looking to the future, there are a number of effects which will alter the potential doses and health risks with time. One effect is obviously radioactive decay, although this is only significant over time-scales of millennia. Over hundreds of years, assuming the contamination stays in its present location, the dose will remain approximately the same (due to the long half-life of ^{239}Pu). However, the readily detectable ^{241}Am with its half-life of 432.2 y will diminish. Over this time span of hundreds of years, the activity due to ^{238}Pu will also decrease, ^{241}Pu is virtually all gone already (decayed into ^{241}Am), and activities of ^{240}Pu will also remain essentially unchanged.

Another effect which will alter potential doses is weathering. CSIRO have recently performed a climate-modelling study of the Maralinga area, and concluded that dust resuspension is not expected to change as a result of greenhouse climate change [Hunt & Elliott, 2001]. It should be noted that all recent measurements and comparisons with 1987 data suggest a reduction in ^{241}Am values (and hence plutonium concentrations) with time, despite a predicted increase due to radioactive ingrowth. It seems likely that the plutonium is moving deeper into the soil, and not migrating off-site, but in either case the result is to give less inhalation dose to a potential inhabitant. Shinn's estimates of resuspension rates [Shinn, 2002] suggest that time-scales for loss of plutonium through continued resuspension due to wind erosion are of the order of many thousands of years.

Lifestyle changes could also markedly affect dose estimates. If in time the Maralinga Tjarutja were to move towards a more European lifestyle, with extensive areas being covered by concrete, tarmac, buildings and lawns, and living in western-style houses in suburban settings, then the dust levels and hence doses are expected to be much lower.

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