TRN AU7904146

AAEC/E476

AAEC/E476

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

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June 1979

ISBN 0 642 59668 9

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Abstract

Residual plutonium levels in soil, flora, fauna and the air of the Maralinga (South Australia) Atomic Weapons Testing Range are presented and discussed.

It is shown that only on rare occasions (and possibly never) would the plutonium concentration in air from wind resuspended dust exceed the maximum allowable concentration for continuous exposure of the general public. In the case of artificially resuspended dust, this maximum concentration could be exceeded for short periods, but the accompanying dust level would be such that working conditions would be uncomfortable, if not intolerable.

Potential hazards from other possible exposure routes are so low that they are of no consequence.

This report was published as Annexe 4 in *Radiological Safety and Future Land Use at the Maralinga Atomic Weapons Test Range*. The Australian Ionising Radiation Advisory Council, Canberra, AIRAC Report No.4 [January 1979]

National Library of Australia card number and ISBN 0 642 59668 9

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PLUTONIUM; PLUTONIUM DIOXIDE; CONTAMINATION; ENVIRONMENT; SOILS; PLANTS; WILD ANIMALS; DUSTS; AIR; NUCLEAR EXPLOSIONS; RADIOACTIVITY; SOUTH AUSTRALIA; RADIATION MONITORING

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1. INTRODUCTION

In 1956 and 1957 the United Kingdom Atomic Weapons Research Establishment (UKAWRE Aldermaston) exploded seven nuclear devices at Maralinga, some 50 miles (80 kilometres) north of Watson, on the South Australian section of the Trans-continental Railway. In addition to the seven nuclear explosions, experiments other than nuclear explosions but which involved plutonium (and other materials) were performed in the Maralinga area for a few months each year, from 1959 to 1963. These experiments included measurement of the behaviour of plutonium when subjected to non-nuclear explosions and also the study of petrol fires involving nuclear material. The experiments resulted in extensive plutonium contamination (as PuO_2) on the surface of the surrounding area.

Figure 1 shows the location of these experiments in areas designated Taranaki, TM100, TM101 and Wewak. The sites of the nuclear explosions and other activities are also shown in this figure.

In 1964, the area was partially cleaned up by UK personnel and, in 1967, a team of Royal Engineers and staff from the UKAWRE carried out 'Operation Brumby', which, *inter alia*, reduced the residual plutonium contamination in some areas.

At the request of the Australian Ionising Radiation Advisory Council (AIRAC), a survey was made of the Maralinga Range by an Australian team in August 1977. This report deals with the residual plutonium contamination found in the experimental areas as determined by that survey while other aspects of the survey were concerned with other radiation and contamination hazards.

In Operation Brumby, partial decontamination of some of the areas had been achieved by mixing the top 10 cm of soil by 'scraping', grading and covering more heavily contaminated areas with about 8 cm of clean top soil.

The average residual levels of plutonium contamination in the various areas at the conclusion of Operation Brumby were:

Taranaki

Processed area inside the high cyclone mesh (HCM) fence.	500 pCi g^{-1} (19 Bq g^{-1}) in the top few cm of soil.
Other processed areas outside HCM fence.	100-400 pCi g^{-1} (4-15 Bq g^{-1}) in the top few cm of soil.
Unprocessed areas outside fence where plutonium is essentially on the ground surface.	$\sim$ 1 µCi m^{-2} (37 kBq m^{-2}).

TM100 and TM101

Processed area	300 pCi g^{-1} (11 Bq g^{-1}) in the top few cm of soil.

Wewak

Unprocessed area	$\sim$ 1 µCi m^{-2} (37 kBq m^{-2}) over small areas.

It should be emphasised that these are average values only and that some readings were several times higher.

2. AIM OF SURVEY

The aim of this section of the survey was to ascertain the levels of plutonium in soils and selected flora and fauna within the various areas and to obtain information on particle size and activity distribution within the soils. This would enable an assessment to be made of the hazards to persons who might inhabit or traverse the Maralinga Range and would thus facilitate a decision concerning the future of the area.

3. FIELD PROCEDURE

3.1 Measurement Techniques

Radiation measurements were taken at individual points in the field by means of a scintillation detector, with a 3 cm diameter x 6 mm thick sodium iodide crystal, connected to an AAEC type 500 ratemeter/scaler. Readings were taken with the scintillation detector held about 8 cm above the ground level; this detected the 60 keV gamma radiation from americium-241, formed from the decay of plutonium-241, which is always associated with plutonium-239 and 240.

3.2 Soil Sampling Procedure

Immediately after a field reading was taken, the soil was sampled from the same position in one of two ways:

(a) In the areas which had been ploughed and graded, *i.e.* those areas where the plutonium had been distributed throughout the top 10 cm of soil, a sample was taken by scooping up a few hundred grams of soil to a depth of 4-5 cm over an area of 50-100 cm^2. The results for these samples were subsequently expressed in pCi g^{-1} (Bq g^{-1}).

(b) In the areas which had not been disturbed, *i.e.* where the plutonium remained distributed on the surface, a Petri dish of diameter 11 cm was pressed into the soil to a depth of about 1 cm, a flat aluminium plate slipped underneath and the entire sample placed in a plastic sample jar. The results for these 'surface' samples were subsequently expressed as μCi m^{-2} (kBq m^{-2}).

Either before or after the sample was taken, the position of the sampling point was determined by surveyors using appropriate previously surveyed reference points in the area.

About 250 samples were taken by either of the above methods at Taranaki (both inside and outside the existing HCM fence) and at TM100 and TM101 (see Figures 2-5). A few samples were also taken at Wewak.

A few samples were also taken from the path of the fall-out plume from the Marcoo nuclear explosion to determine whether unfissioned plutonium could be detected in this area. This low yield device was detonated at ground level. Note that any plutonium in this area would have been deposited by a different method from that in the other areas.

Attempts were made to take core samples in order to study the distribution of plutonium to a soil depth of about 25 cm. In the event, the coring device proved difficult and time consuming for one person to use in the field. With the limited time available, it was considered preferable to concentrate on obtaining more general soil samples.

Other depth samples were obtained by sampling with a scoop at one point, then by excavating deeper in the same hole, scooping another sample, and repeating the process. However, this procedure almost certainly results in cross contamination of samples from different levels, a problem which is difficult to avoid even with conventional coring equipment. The plutonium levels in these samples are, therefore, probably high.

Within the fenced area at Taranaki there are several pits (Figure 2) where plutonium-containing debris is buried. As a check on whether any buried plutonium has migrated downwards from the pits, bore holes were drilled at an angle of 45^{o} beneath two of the pits (Nos. 6 and 9) and samples

were collected from these cores. The geometry of these holes (and the plutonium content of the core samples) are shown in Figure 6.

A 'cemetery' for radioactive debris had been established alongside the airfield. About 30 Ci (1.1×10^6 MBq, $\sim$ 500 g) of plutonium particles, dispersed in about one tonne of salt, had been buried there in six steel drums in a concrete-lined pit (I 1/18). Angle drilling was also carried out beneath this pit to check on any plutonium migration. The geometry of this bore hole (and plutonium levels) are shown in Figure 6(a).

All samples were contained in plastic screw-top jars, numbered, and sent to the Australian Atomic Energy Commission (AAEC) Research Establishment at Lucas Heights for plutonium analysis.

3.3 Plant and Animal Sampling

Plant samples were taken from alongside some of the soil sampling points by the survey team's botanist. Animal (rabbit and dingo) samples were taken from appropriate areas and dissected by the team's ecologist. A few millilitres of preserving alcohol was added to each plant and animal sample in a plastic bag, which was then sealed. These plant and animal samples were then despatched to the AAEC Research Establishment for plutonium analysis.

3.4 Dust Sampling

Cascade impactors were used in an attempt to obtain various size samples from dust normally present in air and from dust artificially created by turning the soil with a shovel or by dragging a slab of concrete across the ground behind a truck (see Commonwealth Bureau of Meteorology report to AIRAC, January 1979 (Soil Suspension and Migration at Maralinga); henceforth referred to as the B. Met. report).

3.5 Water Age Determination

Two samples of water for tritium dating were taken from a bore at Roadside and one from a bore at Freshbore, near Iwara (Figure 1). Before sampling, each bore was pumped to ensure that only 'new' water was sampled. Attempts to obtain suitable water samples from Freshbore for ^{14}C dating were prevented by the unsuitability of the samples and other logistic problems.

4. SAMPLE TREATMENT

4.1 Soils

The soil sample (usually about 200-500 g) was dried, ground and thoroughly mixed by blending and passing through a sample splitter. A 20 g aliquot was used to determine the ^{241}Am (the decay product of ^{241}Pu) by counting its 60 keV gamma radiation on a gamma spectrometer with a Ge(Li) detector.

The plutonium content of selected soil samples was found by a chemical method which involved complete dissolution of the sample, separation and purification of plutonium on an anion exchange resin column and electroplating the plutonium onto a metal disc, followed by alpha spectrometry. Because ^{239}Pu and ^{240}Pu have very similar alpha energies (5.15 and 5.16 MeV), they cannot be resolved and are usually quoted together as $^{239}Pu/^{240}Pu$; ^{238}Pu is also determined by this procedure. The results from the alpha spectrometer were used to calibrate the ^{241}Am results from the gamma spectrometer in terms of $^{239}Pu/^{240}Pu$. A standard uranium source was also used to check the efficiency of the Ge(Li) detector for gamma rays of energy less than 100 keV.

The size distribution of dust on each cascade impactor stage was found by counting the number of particles in each size range (see B. Met. report). Selected stages were then examined for plutonium content by either α-particle counting or fission track detection after thermal neutron irradiation in the AAEC 100 kW research reactor, Moata.

Two soil samples from Taranaki were sieved to determine the distribution of soil sizes. Each size fraction was weighed, then counted on a gamma spectrometer to determine its inherent plutonium content. It was hoped to obtain further information on particle size, shape, type and association of plutonium with sand particles, *etc.* by examining soil samples with an optical microscope and a scanning electron microscope, but samples examined were too low in plutonium.

4.2 Plants

Plant samples were compounded, dried and ashed and the ^{238}Pu and $^{239}Pu/^{240}Pu$ contents were determined by the chemical method described in Section 4.1.

Each sample was washed with 3 x 10 mℓ of water; these washings were added to the alcohol in which the sample had been transported. The plutonium content of the combined washings was then determined by the same chemical method. Of the plant samples taken, Table 1 shows those selected for plutonium

analysis on the basis of the plant's significance as an edible species and/or the high plutonium content of the soil from which the plant was taken, as indicated by the field readings.

4.3 Animals

Dissected samples, sealed in plastic bags containing a few millilitres of alcohol were transported frozen, and held in cold storage until analysed. The whole sample (including the alcohol) was ashed and analysed for plutonium by the method described above.

The animals chosen for analysis were four lactating female rabbits, numbered R1 (pregnant), R13, R16, and R17, taken from outside the Taranaki fenced area, and one male dingo (D) taken between Taranaki and Marcoo.

Rabbit R1 was taken near Pit No. 2, R13 near T46 and T47, R16 near T100, and R17 towards Breakaway (see Figure 2). No soil samples were taken from the R1 and R17 locations. As dingoes (in contrast to rabbits) cover large areas of territory, it was not feasible to take a soil sample that was representative of the dingo's habitat.

The dissected animal organs were classified as follows: A, skin; B, gut; C, lung; D, bone and muscle; E, foetus. Samples from all four rabbits were compounded before analysis; thus sample RA consisted of four rabbit skins, *etc.*

5. RESULTS

5.1 Soils

The results of the analyses of soils from Taranaki and adjacent areas are given in Table 2, those from TM100 and TM101 in Tables 3 and 4, and those from Wewak and Marcoo in Table 5.

The size analysis of the two soil samples from Taranaki, plus the distribution of activity in the various size fractions of these samples, are shown in Table 6.

Table 7 and Figures 6 and 6(a) show the results of plutonium analyses of the cores from bore holes drilled at 45° beneath pits 6 and 9 at Taranaki and pit I at the airfield cemetery.

During the time of the survey, the wind was almost calm except on the last day, when a moderate wind prevailed. This was thus the only day on which the ambient airborne dust concentration was measured with a cascade impactor. The results were:

Suspended dust at 1.5 metre height	~ 0.03 mg m^{-3}
" " at 0.15 " "	~ 0.15 mg m^{-3}

(See B. Met. report, p.21). This test was carried out 3 km south of Taranaki and thus the samples were not assayed for plutonium.

Pieces of adhesive paper were placed at a height of 2 m on the Taranaki fence for nine days to measure the suspended dust during that period. Only very few particles which could have been due to local resuspension were observed (B. Met. report, p.22). In the event, these samples were unavailable for plutonium analysis.

During the experiments with artificially raised dust, the cascade impactors became overloaded and there was thus considerable 'overlapping' between one slide and the next.

Experiments 1, 5 and 6 in the B. Met. report show the relative particle sizes and masses of the dust fractions collected for the artificially raised dust work. By adding the total activity of plutonium found on all slides (4) from one particular experiment, the total amount of Pu retained by the impactor was found. Knowing the sampling time and the air flow rate, and thus the total volume of air sampled during the experiment, the average concentration of Pu in the air was found. As some of these particles are bigger than the respirable limit of $\sim$ 50 μm (see B. Met. report for particle sizes), this procedure gives a value higher than the respirable 'concentration'. However, this figure may be considered as the upper limit of the respirable plutonium concentration thus introducing a considerable safety factor. These results are listed in Table 8.

5.2 Plants

Table 9 lists the plutonium content of the plant samples and of the soil from which these samples were taken.

5.3 Animals

The results for the animal samples are given in Table 10.

5.4 Tritium

The results of the tritium analyses of bore water samples were:

Roadside 1	-	0.1 ± 0.4 tritium units
Roadside 2	-	0.3 ± 0.4 " "
Freshbore	-	0.5 ± 0.4 " "

All three samples are essentially 'dead' to tritium hence the probable 'age' of the water was at least 50 years.

6. DISCUSSION

6.1 Plants

The results of the plant assays (and of analyses of the soils from which they were taken) listed in Table 9 indicate higher soil-plant concentration ratios than have been reported elsewhere. Soil-plant concentration ratios between 10^{-2} and 10^{-7} have been reported for transuranic elements [ERDA 1975] whereas the values obtained in the present analysis are 8.2×10^{-3}, 8.0×10^{-2} and 2.6×10^{-1} respectively.

The probable explanation is that the washing procedure used on the plants before analysis, *i.e.* washing with alcohol (during transport) and then with 3 x 100 mℓ of water, may not have completely removed plutonium adhering to the plants. Any residual surface plutonium would then have been analysed along with that genuinely absorbed by the plant, thus leading to a high result.

Another possibility is that the plutonium dioxide may have become partially soluble during its 20-year exposure on the ground, thus making it more available to plants; this again would lead to a higher result than expected.

In any event, exposure by the ingestion of plutonium in food is likely to be of little consequence, and is certainly of less potential significance than the inhalation route. This is because plutonium has one of the lowest known absorption factors from the human gastro-intestinal (G.I.) tract to the blood stream, *viz* 10^{-6} (insoluble), of which about 45% lodges in the bone (the critical organ) and is characterised by very low transfer through food chains to man (see Figure 8).

The maximum permissible body burden for plutonium-239 for a member of the public is 0.004 μCi (148 Bq); if we take the average plutonium content of plants to be 100 pCi g^{-1} (3.7 Bq g^{-1}) - the highest value observed was 72 pCi g^{-1} (2.7 Bq g^{-1}) - a plant consumption of about 8×10^{4} kg would be necessary for an individual to reach the allowed limit. The risk from ingestion is therefore trivial.

6.2 Animal Samples

The specific activity in the ashed animal specimens decreased in the order skin, gut, lung and bone, and muscle; this was to be expected. The high plutonium content in the rabbit skin was almost certainly from dust adsorbed onto the rabbits' fur. The gut content could be the result of ingestion of plants and possibly of soil (on the plants) as well. The comparatively low lung content of about 2 pCi g^{-1} (74 mBq g^{-1}) - total 0.75 pCi (28 mBq) - can be taken as an indication of the low plutonium content of the

ambient air under average conditions.

The above discussion applies mainly to rabbits as they are territorial animals, *i.e.* they remain within a small area which, in the case of the four rabbits used here, is an area contaminated with plutonium either on the surface or distributed through the top few centimetres of soil.

This argument does not apply to the dingo as this species roams over a large area. The dingo was taken outside the main plutonium area of Taranaki and it is impossible to tell how long it had spent in a plutonium contaminated area. The results for the dingo samples are thus of little quantitative significance.

6.3 Soils

Tables 2-4 show that there is a wide variation in soil concentrations of plutonium at the three major sites, with levels ranging from almost zero to a maximum of 30,250 pCi g^{-1} (1120 Bq g^{-1}) at Taranaki, 71,000 pCi g^{-1} (2630 Bq g^{-1}) at TM100 and 209,500 pCi g^{-1} (7750 Bq g^{-1}) at TM101. A more detailed survey would probably have indicated an even wider variation. This very heterogeneous distribution of plutonium in the soil poses a problem in the interpretation of the results. The plutonium levels can and do change dramatically over a very small distance, in some cases only a few centimetres. The plutonium is undoubtedly in a particulate form, so the analytical figure obtained in some cases depends on the amount of soil taken in the sample. As an indication of the problem, a spherical particle of plutonium dioxide, 100 μm in diameter (a feasible dimension, from Table 6) would have an activity of about 370,000 pCi (∿ 13,700 Bq).

6.4 Downward Movement of Plutonium

Because the main potential hazard at Maralinga is the inhalation of airborne plutonium emanating from the soil's surface, the limited time available was used to take as many surface samples as possible, at the expense of depth samples. Depth sampling is also far more time consuming than surface sampling; thus only a few depth samples were taken and this precluded a complete picture of the distribution of plutonium with depth. The few that were taken indicate that, in the previously processed areas, there is a marked decrease in the plutonium concentration below the top 4-10 cm of soil (Tables 2 and 3). This is to be expected as the soil had been processed to a depth of about 10 cm during Operation Brumby . However, these meagre results do not allow firm conclusions to be drawn concerning further downward migration of plutonium in the soil.

For some time it was believed that plutonium deposited on the soil surface did not move downward to any significant extent. However, with the development of more sensitive techniques for detecting plutonium, this material has been found at unexpected depths. Thus, Harley [1971] reported world wide plutonium fallout to a depth of 15 cm in soil, whereas Lynch & Gudiksen [1973] found plutonium to a depth of at least 30 cm in many profiles from the Eniwetok Proving Ground. Essington *et al.* [1975], in a study of Nevada test site soil profiles, found that although in many cases over 95% of the plutonium occurred in the top 5 cm of soil, some plutonium could be detected to a depth of 25 cm and possibly beyond. These authors also discussed abnormal profiles including those in which the plutonium concentration varies irregularly with depth with, in some cases, large quantities of plutonium depositing in bands at various depths in the soil profile.

It is possible that plutonium could become partially soluble by microbial action, thus contributing to its downward migration. Micro-organisms, in intimate association with soil particles, are known to play an important role in effecting solubilisation of elements considered insoluble in soils strictly on the basis of their inorganic chemistry [Wildung & Garland 1977].

This aspect of the environmental behaviour of plutonium could be important, particularly in the very long term (hundreds of years) at Maralinga. It could have a significant long-term effect on the uptake from the soil of 'insoluble' plutonium by plants and animals.

Much more work in this field is required to elucidate this problem and several programs are currently under way in the USA to provide a realistic evaluation of the role of microbial processes in influencing the long-term behaviour of transuranic elements in soil [Wildung & Garland 1977].

6.5 Resuspension and Dust

The most hazardous exposure route for plutonium is that of inhalation. Table 8 shows the plutonium concentration in air during three experiments carried out at Taranaki, the maximum value being 2.8×10^{-10} µCi cm^{-3} (1.04×10^{-2} mBq cm^{-3}) while the dust concentration in air was 1200 mg m^{-3} as measured in Expt. 5 (10 m) and assumed in Expt. 1 (2 m) of the B. Met. report.

If the plutonium level in the soil is taken to be 100-500 pCi g^{-1} (3.7-18.5 Bq g^{-1}) then the plutonium level in the air should be between 1.2 and 6.0×10^{-10} µCi cm^{-3} (4.4×10^{-3}-2.2×10^{-2} mBq g^{-1}). The actual values as shown in Table 8 are 2.8, 1.7 and 1.9×10^{-10} µCi cm^{-3} (1.04×10^{-2}, 6.3×10^{-3} and 7.0×10^{-3} mBq g^{-1}) which are within the above limits.

Note that the figures in Table 8 for the plutonium values determined by the 'fission track' method are probably high owing to low levels of naturally occurring uranium in the soil; the fission track method does not distinguish between plutonium and uranium. Note also that Table 6 and Figure 7 show that only a small percentage of particles lie within the respirable size range, thus introducing an added safety factor.

The above evaluation is reasonable confirmation that, for dust originating in the Taranaki area, a dust loading in air of 1200 mg m^{-3} will give a plutonium level in air no higher (and probably appreciably less) than about 2.8×10^{-10} µCi cm^{-3} (1.04×10^{-2} mBq cm^{-3}) which is some 280 times the International Commission on Radiological Protection (ICRP) recommendation of 10^{-12} µCi cm^{-3} (3.7×10^{-5} mBq cm^{-3}) for the maximum permissible concentration of plutonium in air for continuous exposure of non-radiation workers, *i.e.* members of the public (ICRP 1959). Assuming that the relationship between dust loading in air and plutonium concentration in air is linear, it is apparent that the limiting dust loading in air which will produce the limiting plutonium concentration is about 4 mg m^{-3}.

From the B. Met. report it is apparent that this figure of 4 mg m^{-3} of dust air will occur only very rarely owing to wind resuspension of soil. In the B. Met. experiments 2 and 3, when the wind speed was 6.9 m s^{-1} at a height of 2.1 m, the dust loading was only 0.03 mg m^{-3} at 1.6 m above soil level and only 0.15 mg m^{-3} at 15 cm above soil level. Two of the conclusions of the B. Met. report are that for the greater part of the time there is very little suspended dust which has the local soil as its origin, and that 'significant' soil suspension occurs on average only two or three times per year.

When it is realised that dust resuspended by wind will contain some material from outside the Taranaki area, thus giving a dilution effect, it is apparent that this dust will very rarely (probably never) contain the limiting concentration of plutonium and hence there would be no need to limit the exposure time of members of the public to these conditions.

6.6 Artificial Resuspension

However, when artificially raised dust is considered it can be seen that high levels in air can arise; as all this dust originates in the Taranaki area, the plutonium levels will be as discussed in Section 6.5. The B. Met. experiment 5 showed that concentrations of 1200 and 440 mg m^{-3} were obtained 10 and 30 m respectively downwind of the disturbance, whereas experiment 6 showed a dust level of 2700 mg m^{-3} and experiment 7 an estimated value 10 times this figure.

The average concentration of solid matter in a heavy dust cloud is about 10 mg m^{-3} of air, whereas a loading of 100 mg m^{-3} is barely tolerable to man. Considerable discomfort would be experienced in working in a loading of 4 mg m^{-3}, particularly for extended periods.

The ICRP recommended maximum level for plutonium in air, quoted earlier as 10^{-12} µCi cm^{-3} (3.7×10^{-8} Bq cm^{-3}) for the general public, applies to continuous exposure (168 hours/week) for a lifetime. Considering this, and the fact that most of the airborne plutonium is outside the respirable range (see Table 6 and Figure 7), the general statement can be made that if artificially raised dust within the Taranaki area is not sufficient to cause discomfort, there will be an insignificant hazard from the plutonium content, even for long exposure times. Also, as is shown in Section 6.5, the plutonium hazard from dust suspended by wind action is negligible.

As the TM sites are smaller than the fenced area at Taranaki and the average plutonium levels are of the same order of magnitude, a similar argument would apply to those sites.

6.7 Estimate of Cancer Risk

Let us assume that a person is exposed to a plutonium-in-air concentration of 10^{-10} µCi cm^{-3} (3.7×10^{-6} Bq cm^{-3}) - 100 times the ICRP maximum allowable lifetime figure - continuously for 24 hours. (This situation would be virtually impossible at Taranaki because the concentration of artificially raised dust corresponding to this figure would be about 400 mg m^{-3}, which is four times the amount considered barely tolerable to man.)

The total amount of air inhaled per day is 2×10^{7} cm^{3}, which represents 2×10^{-3} µCi (74 Bq) of plutonium. Although there is no detailed information on the particle size distribution of the dust at the exposure point, it can be seen from Table 6 that there is almost no plutonium with particle sizes less than 15 µm present in the soil. Also, from Figure 7 it can be seen that plutonium particles larger than 90-100 µm will not deposit in the lung. From Table 6 and Figure 7 it can be estimated conservatively that a maximum of about 5% (10^{-4} µCi (3.7 Bq)) of the plutonium inhaled will lodge in the pulmonary region.

The total cancer risk from plutonium is about 5% per µCi (37 kBq) lodged in the lung [Cohen 1977], *i.e.* only about 1 in 200,000 per 10^{-4} µCi (3.7 Bq) deposited. Thus it can be seen that, even for a very large over-exposure which could be incurred only under intolerable working conditions, the risk of contracting cancer (the main risk associated with plutonium inhalation) is extremely small.

6.8 Discussion of Resuspension

The limited sampling program at Maralinga did not produce information on the wind dispersal of plutonium, although the wind dispersal of soil was discussed in the B. Met. report.

Because of the potential hazards associated with the inhalation of plutonium, an important aspect of its presence in soils is the resuspension factor (R_f), defined as the ratio of air concentration of plutonium (μCi m^{-3} or Bq m^{-3}) to the surface deposition (μCi m^{-2} or Bq m^{-2}) below the air mass [Hanson 1974].

Variations in R_f between 10^{-2} and 10^{-11} m^{-1} have been reported. Healy [1971] discussed the limitations of the resuspension factor, pointing out that plutonium can be present in soils under a variety of conditions, from freshly deposited material on the surface of the ground, readily available for resuspension, to a weathered deposit that has become distributed through the soil and thus is only partially available. Resuspension is of great importance in the movement of plutonium, as is shown in the 11 km movement of this material from waste disposal sites at Rocky Flats [Volchok 1971]. Stewart [1964] recommended a value of 10^{-5} m^{-1} for moderate activity in an area of fresh deposition, and Anspaugh *et al.* [1975] have developed an expression wherein the resuspension factor is a function of time to account for the observed decrease in air concentration without a significant net loss of the deposited contaminant. This decrease could be due to a slight downward movement of plutonium away from the actual soil surface and/or firmer incorporation of plutonium in the soil.

The expression of Anspaugh *et al.* indicates that the R_f value of a deposit aged about 17 years (about the 'mean' age for Maralinga as of 1978) would be about 10^{-9} m^{-1} given an initial value of 10^{-4}-10^{-5} m^{-1}.

Taking the conservative value of $R_f = 10^{-8}$ m^{-1} for a task performed at T59 (Figure 3) and considering a surface concentration of 0.70 μCi m^{-2} (26 kBq m^{-2} (T59 - Table 2)), the concentration of plutonium in air would be 7×10^{-15} μCi cm^{-3} (2.6×10^{-10} Bq cm^{-3}) which is very much less than the maximum allowable air concentration for continuous exposure for members of the public.

Numerous studies have demonstrated that soil movement occurs by three processes, *viz.* surface creep, saltation and suspension. Particles moving by surface creep , although fairly large, are less than 2 mm and merely roll along the surface. Particles moving by saltation are between 50-500 μm diameter, *i.e.* small enough to move by direct wind action but large enough to

have settling velocities higher than the upward eddy velocity of the wind. They rise almost vertically into the air stream, are carried along, then, on falling back to the soil due to gravity, they may bounce up again or may cause other particles to move by any of the three above methods. Particles moving in suspension are less than 100 μm diameter and have settling velocities less than the turbulent eddy velocities of the wind [Anspaugh *et al.* 1975].

The suspended particles are of most interest because they are transported the greatest distance even though by far the greatest mass of eroding soil moves by saltation or surface creep. Suspended particles are also the only ones which can be deposited in the pulmonary region of the respiratory system.

Table 6 indicates that about half to two thirds of the plutonium at Taranaki is either directly or indirectly (through attachment to soil particles) over 90 μm diameter and that only 20 to 30% is associated with particles under 50 μm. Because of the high density of the PuO_2 ($\sim$ 13 g cm^{-3}), the wind speed required to shift a particle is almost 2½ times as great as that required to shift a sand grain (density $\sim$ 2.5 g cm^{-3}; see B. Met. report). Thus, despite their small size, the PuO_2 particles would be resistant to movement by wind. The B. Met. report states that the suspension and migration of PuO_2 particles are likely to be minimal, but may happen with those strong wind episodes which occur after little rain and high temperatures; these episodes are rare.

6.9 Spot Concentrations

There has been some discussion in the literature concerning the fact that sand mounds built up beneath bushes contain more plutonium than sand found elsewhere, because of the accumulation of migrating surface grains. However, within the area of high plutonium concentration at Maralinga, *i.e.* within the HCM fence at Taranaki, the vegetation is still fairly sparse - there has been little regeneration since the vegetation was destroyed in the explosion - and there appeared to be very few mounds which could be examined.

Outside this area, average plutonium levels were lower (TM 100 and 101) and it was deemed more worthwhile to concentrate on collecting conventional soil samples.

6.10 $^{238}Pu/^{239}Pu$ Ratios

Although the small amount of plutonium-238 in Maralinga samples is of little consequence compared with the plutonium-239 content, it is of some interest to note the $^{238}Pu/^{239}Pu$ ratio in various samples.

Hakonson & Johnson [1973] discuss the changing availability of ^{238}Pu, listing the $^{238}Pu/^{239}Pu$ ratio in soils, vegetation and animal samples of the

Trinity Site ecosystem (USA) as 0.05 (soils), 0.10 (plants) and 1.0 (mammals), respectively. These compare with approximate values obtained for Maralinga of 0.02-0.03 (soils and plants) and 0.07 (animals). Various possibilities have been put forward to account for the greater uptake of ^{238}Pu, from chelation to the big difference in specific activities of the two isotopes.

6.11 Anomaly at Pit 6 - Taranaki

Table 7 and Figure 6 show high plutonium readings (*e.g.* 478 pCi g^{-1} (17.7 Bq g^{-1}) at P6-8) for the bore hole drilled at 45° beneath pit 6 at Taranaki. The question that arises is: Has this plutonium been leached in some way from the plutonium-contaminated debris within the pit, or has it arrived at that location through some other mechanism?

The plutonium in the core samples is in the form of the oxide (PuO_2) which is highly insoluble in water. Plutonium is strongly adsorbed by soil and very high adsorption coefficients have been measured. Any plutonium which dissolved from the debris would be readsorbed by the soil over a very short distance - probably a few centimetres at most. The material at P6-8 obviously would have had to travel at least 1.6 metres and that at P6-24 some 3.7 metres. It is extremely unlikely that this plutonium has been leached from within the pit.

The exact method of construction of the pit is unknown but it is thought to have been excavated by a bulldozer, possibly with some blasting of solid limestone encountered during the excavation. This technique could have resulted in surface material being buried at various depths below ground level. Pit 6 is in an area of relatively high surface plutonium contamination, the closest four samples containing 2100 pCi g^{-1} (78 Bq g^{-1}) (T15), 8500 pCi g^{-1} (315 Bq g^{-1}) (T75), 5000 pCi g^{-1} (185 Bq g^{-1}) (T76) and a high of 30,250 pCi g^{-1} (1120 Bq g^{-1}) (T77). Only a small amount of this high activity surface material needs to be incorporated into the soil below ground level to lead to these high readings. This is supported by the fact that the core samples are very heterogeneous with respect to plutonium, *i.e.* the material is present in the particulate form as it is on the surface, as illustrated by the difficulty experienced in homogenising the samples. If the plutonium had been derived by leaching, the core samples would have been much more homogeneous.

The core samples may also have been contaminated with plutonium by the action of the drill itself and/or the water used in drilling, thus carrying small quantities of highly active material from near the surface down to the

deeper levels. Another possibility is that the core samples could have become contaminated with plutonium while they were left in the open core box in a high plutonium area, pending completion of coring. Attempts to 'peel' these samples to remove the outer layer before analysis, and thus remove any contamination, proved impractical. A further possible explanation of the anomaly is that the concrete cap could be slightly offset with respect to the pit. This would have allowed the drill to intercept the pit at its lower margin and become contaminated directly from pit contents.

Another significant piece of evidence is that europium-152/154 has been identified in at least one of the core samples (P6-8) containing a high plutonium level. Radioactive europium (^{152}Eu, half-life 13 years, and ^{154}Eu, half-life 16 years) was formed in or near the surface of the soil by neutrons emitted in the explosion of the nuclear device at Taranaki. Neutrons would not have penetrated to the vertical depth from which P6-8 was taken (about 3.2 m) and it is most unlikely, because of its high specific activity and its adsorption onto soil, that europium would have migrated to the depth at which it was found.

Pit 6 is above the water table and little or no rainwater would penetrate there because of the generally low rainfall in the area and the presence of the concrete slab. Thus the pit contents would probably be dry for most of the time - a condition which is not conducive to leaching.

There are thus several possible explanations for the presence of unexpectedly high concentrations of plutonium in some of the drill core samples taken from beneath pit 6 which do not involve migration of plutonium from the pit, and many reasons for thinking that such transfer, by leaching, is most unlikely. It is virtually certain that there has been no leakage of plutonium from the pit, whatever may be the correct explanation of the anomalous findings.

7. BUILD-UP OF AMERICIUM-241 FROM PLUTONIUM-241

The plutonium used at Maralinga contains some plutonium-241 (a beta emitter, half-life 14.3 years) which decays primarily to americium-241 (an alpha emitter, half-life 433 years), leading to a gradual increase in the activity of the latter nuclide. This build-up may increase the effective dose from a given exposure, so the problem should be examined.

The increase will be according to the expression:

$$dA/dt = (1 - e^{-\lambda t}) e^{-\lambda' t}$$

where A is the activity of ^{241}Am, and λ and λ' are the decay constants for ^{241}Pu and ^{241}Am respectively.

Equating the first derivative of the above expression to zero, it is clear that the ^{241}Am will reach a maximum value in about 71 years from the time of fuel processing to separate the plutonium.

The support experiments with plutonium were made at Maralinga from 1959 to 1963, the 'mean' time being 1961. Let us assume that the plutonium was separated in 1958; the present 'age' of the plutonium and americium in 1978 is thus about 20 years and the ^{241}Am will reach its maximum value in 51 years' time, *i.e.* about the year 2030.

It may also be shown that the activity of ^{241}Am at present (1978) is $\sim$ 60% of the initial activity of ^{241}Pu and that the maximum activity of the ^{241}Am will be $\sim$ 86% of the figure for ^{241}Pu. Thus, there will be an increase of about 45% in the ^{241}Am activity over the next 50 years, although the rate of change on either side of the maximum value will be very slow (only a few per cent over a period of 40-50 years).

At present (1978) the ratio of $^{239}Pu/^{240}Pu$ activity to that of ^{241}Am is about 2.7:1 (ratio assumed constant for plutonium used in all experiments) and in 50 years' time the ratio will be 2.7:1.45. The existing conditions, where ^{241}Am is present as a minor component of an insoluble matrix (PuO_2), resemble those in which Bair [1970] was unable to detect dissociation of ^{241}Am from inhaled PuO_2, and it may be assumed that ^{241}Am behaves similarly to $^{239}Pu/^{240}Pu$ in the lung. As their alpha energies are similar, we may simply add the ^{241}Am contribution in calculating dose and dose rate. Thus, in 50 years' time (2030) the total effect (or dose) will have increased from 3.7 (2.7 + 1) to 4.15 (2.7 + 1.45), *i.e.* a percentage increase of (0.45/3.7) x 100 = 12%. The ^{241}Am activity will then start to decrease very slowly and will eventually decrease with its own half-life of 433 years.

The increase in dose due to build-up of ^{241}Am can thus be a maximum of only about 12% which, in view of the accuracy available, is insignificant.

8. CONCLUSIONS

In a brief survey such as this, it is not possible to draw rigid conclusions. A much more extensive survey, involving much more time and manpower, followed (and preceded) by extensive laboratory work, would be needed to fully evaluate the Maralinga situation.

However, from the available data, the main conclusions are:

(i) The uptake of plutonium by plants appears to be a little higher than was expected, but this may have been due to the difficulty of washing the

samples. In any event, these levels do not present a hazard to animals or man eating the plants.

(ii) There is only very minor uptake of plutonium by small animals. This is in agreement with other findings and is of no consequence.

(iii) Plutonium is distributed very unevenly with a wide concentration variation occurring at the three main sites.

(iv) The prevailing meteorological conditions are such that only on very rare occasions (if ever) would the plutonium concentration in air from naturally resuspended dust in the processed areas exceed the maximum allowable figure for members of the public.

(v) Dust raised artificially in the processed areas, *e.g.* by movement of vehicles, cattle or perhaps large numbers of people could result in an airborne concentration of plutonium greater than the maximum lifetime recommendation for non-radiation workers. However, the concentration of the dust itself would be so high that it would make working conditions uncomfortable, particularly for extended periods.

(vi) Because of the very low resuspension factors extant in the unprocessed areas, the concentration of plutonium in the air resulting from tasks performed in these areas would be well below the allowable limit for members of the public.

(vii) The chance of a person contracting cancer from exposure to plutonium at Maralinga is extremely remote, even when the dust concentration in the air is such that it makes working conditions intolerable.

(viii) Because of the high density of PuO_2 and the small fraction of fine particles, this material would be resistant to movement by wind. Its suspension and migration would occur only during the rare occasions when high winds followed a period of little rain and high temperature.

9. ACKNOWLEDGEMENTS

Helpful comments on this report, offered by Mr. D.R. Davy, Dr. J.L. Symonds and Dr. G.M. Watson are gratefully acknowledged. The efforts of the AAEC Analytical Chemistry Section in making many difficult and time-consuming plutonium determinations and the assistance of Physics Division with the track-etch determinations are much appreciated.

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NOTES

TABLE 1

PLANT SAMPLES SELECTED FOR PLUTONIUM ANALYSIS

Sample No.	Botanist's Ident. No.	Location	Plant Species
PL1 (Composite sample)+	9519 9521 9606 9607 9608	T37 T44 T75 T76 T77	Salsola kali
PL2 (Composite sample)+	9520 9528	T38 T56	Maireana turbinata Maireana integra
PL3	9525	T53	Enneapogon avenaceus
PL4 (Composite sample)+	9597 9598	'Hot spot' near 07 (no soil sample)	Bassia eriocantha* Bassia uniflora*

* Roots included

\+ Each composite sample contained roughly equal amounts of its constituents.

TABLE 2

PLUTONIUM CONTENT OF MARALINGA SOILS(1)

Taranaki

Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})	
T1	2.6	0.10	T21	1437	53	T42	150	5.6
T2	3.4	0.13	T22	56	2.1	T43	3.6	0.13
T3	34.4	1.3	T23	919	34	T44	56.8	2.1
T4	357	13.2	T24	1020	38	T45	30	1.1
T5	688	25.5	T25	891	33	T46	10	0.37
T6	216	8.0	T26+	513	19	T47	14	0.52
T7	25	0.93	T27+	23	0.85	T48	237	8.8
T8	115	4.3	T28+	0	0	T49	26	0.96
T9	196	7.3	T29x	6552	242	T50	7	0.26
T10	104	3.8	T30x	226	8.4	T51	13	0.48
T11	167	6.2	T31x	225	8.3	T52	5	0.19
T12	37	1.4	T33	162	6.0	T53	8.1	0.30
T13	90	3.3	T34	328	12	T54	43	1.6
T14	4262	158	T35	1369	51	T55	1	0.04
T15	2102	78	T36	440	16	T56	27.8	1.0
T16	127	4.7	T37	259	9.6	T57	7.5	0.28
T17	1899	70	T38	4.6	0.17	T58	42.0	1.6
T18	243	9.0	T39	595	22	T59*	0.70	25.9
T19	46	1.7	T40	1030	38	T60*	0.041	1.52
T20	2566	95	T41	325	12	T61*	0.45	16.7

\+ Depth sample taken alongside T23.
T26 0-4 cm, T27 4-8 cm, T28 8-11 cm.

x Depth sample taken 40 m NW of T22.
T29 0-4 cm, T30 4-8 cm, T31 8-10 cm.

* Surface sample (concentration in $\mu Ci\ m^{-2}$ and $kBq\ m^{-2}$).

(1) Note. Some of the results in Tables 2, 3, 4 and 5 may be altered slightly when more detailed analytical results become available. These changes (if any) should not affect the substance of the report.

TABLE 2 (contd.)

Taranaki (contd.)

Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})	
T62*	0.009	0.33	T76	5010	185	T108	1.7	0.06
T63*	0.045	1.67	T77	30254	1119	T109	11.4	0.42
T64*			T90	8200	303	T111	26.1	0.97
T65*	1.5	56	T92	630	23.3	T112	NS	
T66*	Nil		T100	509	19	T113	NS	
T67*	Nil		T101	7.3	0.27	T114	NS	
T68*	0.015	0.56	T102	4.1	0.15	T115	NS	
T69*	0.008	0.30	T103	9.6	0.36	T116+	3.5	0.13
T70*	0.009	0.33	T104	Nil		T117+	Nil	
T71*	0.052	1.92	T105	3.8	0.14	T118x	877	32
T72*	0.025	0.93	T106	20.0	0.74	T119x	297	11
T75	8460	313	T107	36.1	1.3			

* Surface sample (concentration in $\mu Ci\ m^{-2}$ and $kBq\ m^{-2}$)

NS No sample

\+ Depth sample taken at T101. T116 5-10 cm, T117 10-20 cm

x Depth sample taken at T100. T118 5-10 cm, T119 10-20 cm

TABLE 3

PLUTONIUM CONTENT OF MARALINGA SOILS

TM100

Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})	
0-1	100	3.7	0-26	78	2.9	0-50	10436	386
0-2	3	0.11	0-27	182	6.7	0-60	3	0.11
0-3	4	0.15	0-28	83	3.1	0-61	4	0.15
0-4	95	3.5	0-29	6	0.22	0-62	6	0.22
0-5	2	0.07	0-30	37	1.4	0-63	NS	
0-6	13	0.48	0-31	38	1.4	0-64	5	0.19
0-7	28	1.0	0-31A	114	4.2	0-65	174	6.4
0-8	25	0.93	0-32	58	2.1	0-66	NS	
0-9	8	0.30	0-33	44	1.6	0-67	91	3.4
0-10	19	0.70	0-34	4	0.15	0-68	NS	
0-11	7	0.26	0-35	109	4.0	0-69	266	9.8
0-12	66	2.4	0-36	9	0.33	0-70	210	7.8
0-13	447	17	0-37	7	0.26	0-71	1517	56
0-14	190	7.0	0-38	24	0.89	0-72	252	9.3
0-15	815	30	0-39	61	2.3	0-73	1957	72
0-16	310	11	0-40	12	0.44	0-74+	2650	98
0-17	655	24	0-41	23	0.85	0-75+	335	12
0-18	277	10	0-42	9	0.33	0-76	NS	
0-19	81	3.0	0-43	6	0.22	0-77	71060	2629
0-20	12	0.44	0-44	29	1.1	0-78	1520	56
0-21	90	3.3	0-45	122	4.5	0-79†	1693	63
0-22	117	4.3	0-46	56	2.1	0-80†	52	1.9
0-23	79	2.9	0-47	68	2.5			
0-24	19	0.70	0-48	32	1.2			
0-25	99	3.7	0-49	21100	781			

\+ Depth sample taken at 0-73

0-74 5-10 cm
0-75 10-15 cm

† Depth sample taken at 0-78

0-79 5-10 cm
0-80 10-15 cm

NS No sample

TABLE 4

PLUTONIUM CONTENT OF MARALINGA SOILS

TM101

Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})		Sample No.	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})	
1-1	6	0.22	1-26	785	29
1-2	10	0.37	1-27	5420	201
1-3	39	1.4	1-28	537	20
1-4	10	0.37	1-29	318	12
1-5	44	1.6	1-30	889	33
1-6	104	3.8	1-31	285	11
1-7	1226	45	1-32	513	19
1-8	4160	154	1-33		
			1-34	6	0.22
1-10	209505	7752	1-35	2329	86
1-11	147	5.4	1-36	267	10
1-12	36	1.3	1-37	792	29
1-13	14	0.52	1-38	1426	53
1-14	7	0.26	1-39	811	30
1-15	47	1.7	1-40	674	25
1-16	28	1.0	1-41	963	36
1-17	66	2.4	1-42	27	1.0
1-18	278	10	1-43	67	2.5
1-19	2629	97	1-44	16	0.59
1-20	154875	5730	1-45	150	5.6
1-21	583	21	1-46	1049	39
1-22	279	10	1-47	101	3.7
1-23	317	12	1-48	316	12
1-24	722	27	1-49	79356	2936
1-25	46	1.7	1-50	99409	3678

TABLE 5

PLUTONIUM CONTENT OF MARALINGA SOILS

Wewak (W) and Marcoo (M)

Sample No.	$^{239}Pu/^{240}Pu$ ($pCi\ g^{-1}$; $Bq\ g^{-1}$)	
W-1	213	7.9
W-2	1140	42
M1*	Results not yet available	
M2*		
M6*		
M7*		
M9*		
M12*		
M13*		
M14*		

* Surface samples (concentration in $\mu Ci\ m^{-2}$ and $kBq\ m^{-2}$)

TABLE 6

SIZE DISTRIBUTION AND PLUTONIUM ACTIVITY

IN TWO SOILS FROM TARANAKI

Soil Sample T15

Range (μm)	Wt. (g)	Abundance (%)	Activity in Fraction (counts/100s)	Activity in Fraction (counts/100s g^{-1})	Activity per gram of Soil (counts/100s g^{-1})	% Contribution
> 90	249.7	86.8	5593	22.4	19.4	48.9
90-63	18.95	6.6	1120	59.1	3.9	9.8
63-50	10.57	3.7	958	90.6	3.4	8.6
50-30	4.59	1.6	842	183.4	2.9	7.3
30-25	3.48	1.2	1726	496.0	6.0	15.1
25-15	0.48	0.17	403	2371	4.0	10.1
15-10	0.0016	0.00056	9	16071	0.1	0.3
				Total	39.7	100.1

TABLE 6 (contd.)

Soil Sample T25

Range (μm)	Wt. (g)	Abundance (%)	Activity in Fraction (counts/100s)	Activity in Fraction (counts/100s g^{-1})	Activity per gram of Soil (counts/100s g^{-1})	% Contribution
> 90	237.4	84.0	5863	24.7	20.7	65.1
90-63	21.14	7.5	407	19.3	1.4	4.4
63-50	12.36	4.4	967	78.2	3.4	10.7
50-30	5.94	2.1	781	131.5	2.8	8.8
30-25	4.82	1.7	732	151.9	2.6	8.2
25-15	0.90	0.32	236	262.2	0.84	2.6
15-10	0.0050	0.0018			-	-
				Total	31.8	99.8

TABLE 7

CONCENTRATION OF $^{239}Pu/^{240}Pu$ IN CORES

FROM HOLES DRILLED AT 45° UNDER PITS 6 & 9 (TARANAKI)

& PIT I (AIRFIELD CEMETERY)

Angle Depth (m) (Sample No.)	Pit 6 (Taranaki) (pCi g^{-1}; Bq g^{-1})		Pit 9 (Taranaki) (pCi g^{-1}; Bq g^{-1})		Pit I (Airfield Cem.) (pCi g^{-1}; Bq g^{-1})	
0.95 (P6-1)	1484	55				
1.55 (A2)					0.08	0.003
2.95 (P6-2)	1.8	0.07				
3.55 (A4)					0.05	0.002
3.95 (P6-3,P9-4)	4.3	0.16	0.2	0.007		
4.45 (P6-4)	123	4.6				
4.55 (P6-5,P9-5)	104	3.8	0.1	0.004		
4.65 (P6-6)	140	5.2				
4.75 (P6-7)	163	6.0				
4.85 (P6-8)	478	18				
4.95 (P6-9)	112	4.1				
5.10 (P6-10)	61	2.3				
5.15 (P9-6)			0.5	0.02		
5.30 (P6-11)	12	0.44				
5.50 (P6-12)	2.2	0.08				
5.55 (P9-7,A6)			0.1	0.004	0.06	0.002
5.70 (P6-13)	10.8	0.40				
5.85 (P9-8)			0.2	0.007		
5.90 (P6-14)	22	0.81				
6.10 (P6-15)	5.0	0.19				
6.30 (P6-16)	19	0.70				
6.50 (P6-17)	27	1.0				
6.55 (P9-9)			0.1	0.004		
6.65 (P9-10)			0.1	0.004		
6.70 (P6-18)	3.0	0.11				
6.90 (P6-19)	0	0				
7.10 (P6-20)	1.8	0.07				
7.30 (P6-21)	8.9	0.33				
7.50 (P6-22)	24	0.89				
7.55 (A8)					0.06	0.002
7.70 (P6-23)	32	1.2				
7.85 (P9-11)			0.06	0.002		
7.90 (P6-24)	22	0.81				
8.10 (P6-25)	0	0				
8.30 (P6-26)	26	0.96				
8.40 (P9-12)			0.09	0.003		
8.50 (P6-27)	2.4	0.09				
8.55 (A9)					0.06	0.002
8.70 (P6-28)	2.7	0.10				
8.90 (P6-29)	9.1	0.34				
9.10 (P6-30)	0	0				
9.30 (P6-31)	0	0				
9.55 (A10)	2.7	0.10			0.02	0.001

TABLE 8

PLUTONIUM CONTENT OF CASCADE IMPACTOR SLIDES AND OF SAMPLED AIR

Experiment No. and Details*	Slide No.	Pu on Slide (pCi; Bq)				Vol. of Air Sampled (m^3)	Pu Conc. in Air ($\mu Ci\ cm^{-3}$; $Bq\ cm^{-3}$)	
		α Counting		Fission Track++				
1 (at 2 metres)	1	2.8	0.10	1.3-6.7+	0.05-0.25			
	2	0.5	0.02					
	3	1.1	0.04					
	4	∿ 0.6**	0.02					
Assume dust conc. in air same as expt. 5 (1200 mg m^{-3})	Total	∿ 5.0	0.18			0.018	2.8×10^{-10}	1.04×10^{-5}
1 (at 3.5 metres)	1	1.9	0.07					
	2	1.0**	0.04					
	3	0.1	0.004					
	4	0.07	0.003					
	Total	∿ 3.0	0.12			0.018	1.7×10^{-10}	6.3×10^{-6}
5 (at 10 metres)	1 }			1.3	0.05			
	2 }			0.09	0.003			
	3			0.13	0.005			
	4							
Dust conc. in air = 1200 mg m^{-3}	Total			∿ 1.5	0.06	0.008	1.9×10^{-10}	7.0×10^{-6}

* As in B. Met. report

** Estimate

\+ Uncertainty due to some stars containing too many tracks to count

++ Results probably high due to presence of 1-2 $\mu g\ g^{-1}$ natural uranium in the soil.

TABLE 9

PLUTONIUM CONTENT OF (a) PLANT SAMPLES (AND WASHINGS) AND (b) SOIL FROM WHICH THEY WERE TAKEN

(a) Plants

Sample No.	Fresh Wt. (g)	Dry Wt. (g)	Wt. Ash (g)	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1} ash)		Total $^{239}Pu/^{240}Pu$ (pCi; Bq)		$^{239}Pu/^{240}Pu$* (pCi g^{-1}; Bq g^{-1} fresh wt.)		^{238}Pu (pCi g^{-1}; Bq g^{-1} ash)	
PL1 (Washings)	822	216	49	1200	44	58800 4700	218 174	72	2.7	21 94 (3.5)	0.78 (total)
PL2 (Washings)	223	89	15.5	19	0.70	295 5	11 0.19	1.3	0.05	0.3 0.1(0.004)	0.01 (total)
PL3 (Washings)	48	35	5.3	19	0.70	101 78	3.7 2.9	2.1	0.08	0.5 1.4(0.05)	0.02 (total)
PL4 (Washings)	150	110	20	460	17	9200 990	340 37	61	2.3	5.6 8.4(0.31)	0.21 (total)

* Washings excluded

N.B. The ashed samples were not homogeneous; the above figures are means of several determinations. The above figures probably represent an upper limit, as some soil (and plutonium) may not have been removed by the washing procedure.

TABLE 9 (contd.)

(b) Soils

Plant Sample ($^{239}Pu/^{240}Pu$ Content)	Soil Sample	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1})	Mean (pCi g^{-1}; Bq g^{-1})	Pu Conc. in plant / Pu Conc. in soil
PL1 (72 pCi g^{-1}; 2.7 Bq g^{-1})	T37	259 9.6	8808 326	8.2×10^{-3}
	T44	56.8 2.1		
	T75	8460 313		
	T76	5010 185		
	T77	30254 1119		
PL2 (1.3 pCi g^{-1}; 0.05 Bq g^{-1})	T38	4.6 0.17	16.2 0.60	8.0×10^{-2}
	T56	27.8 1.0		
PL3 (2.1 pCi g^{-1}; 0.08 Bq g^{-1})	T53	8.1 0.30	8.1 0.30	2.6×10^{-1}
PL4 (61 pCi g^{-1}; 2.3 Bq g^{-1})	Near 07	No soil sample available		-

TABLE 10

PLUTONIUM CONTENT OF ANIMAL SAMPLES

Sample No.*	Fresh Wt. (g)	Dry Wt. (g) (1)	Wt. Ash (g) (2)	$^{239}Pu/^{240}Pu$ (pCi g^{-1}; Bq g^{-1} ash)		Total $^{239}Pu/^{240}Pu$ (pCi; Bq)		^{238}Pu (pCi g^{-1}; Bq g^{-1} ash)	
RA	823	175	7	55	2.0	385	14	0.8	0.03
RB	805	179	24	6.7	0.25	161	6.0	0.1	0.004
RC	43	8	0.34	2.2	0.08	0.75	0.03	0.2	0.007
RD	612	209	34	0.1	0.004	3.4	0.13	0.02	0.0007
RE	60	8	0.83	11	0.41	9.1	0.04	0.3	0.01
DB	150	37	4	14	0.52	56	2.1	0.2	0.007
DC	67	10	0.99	1.8	0.07	1.8	0.07	0.1	0.004
DD	321	158	50	< 0.02	< 0.0007	< 1.0	< 0.04	0.03	0.001

* Prefix R - Rabbit
" D - Dingo
Suffix A - skin
" B - gut
" C - lung
" D - bone and muscle
" E - foetus

(1) Dried at 110°C for 24 h.
(2) Ashed at 450°C for 24 h.

NOTES

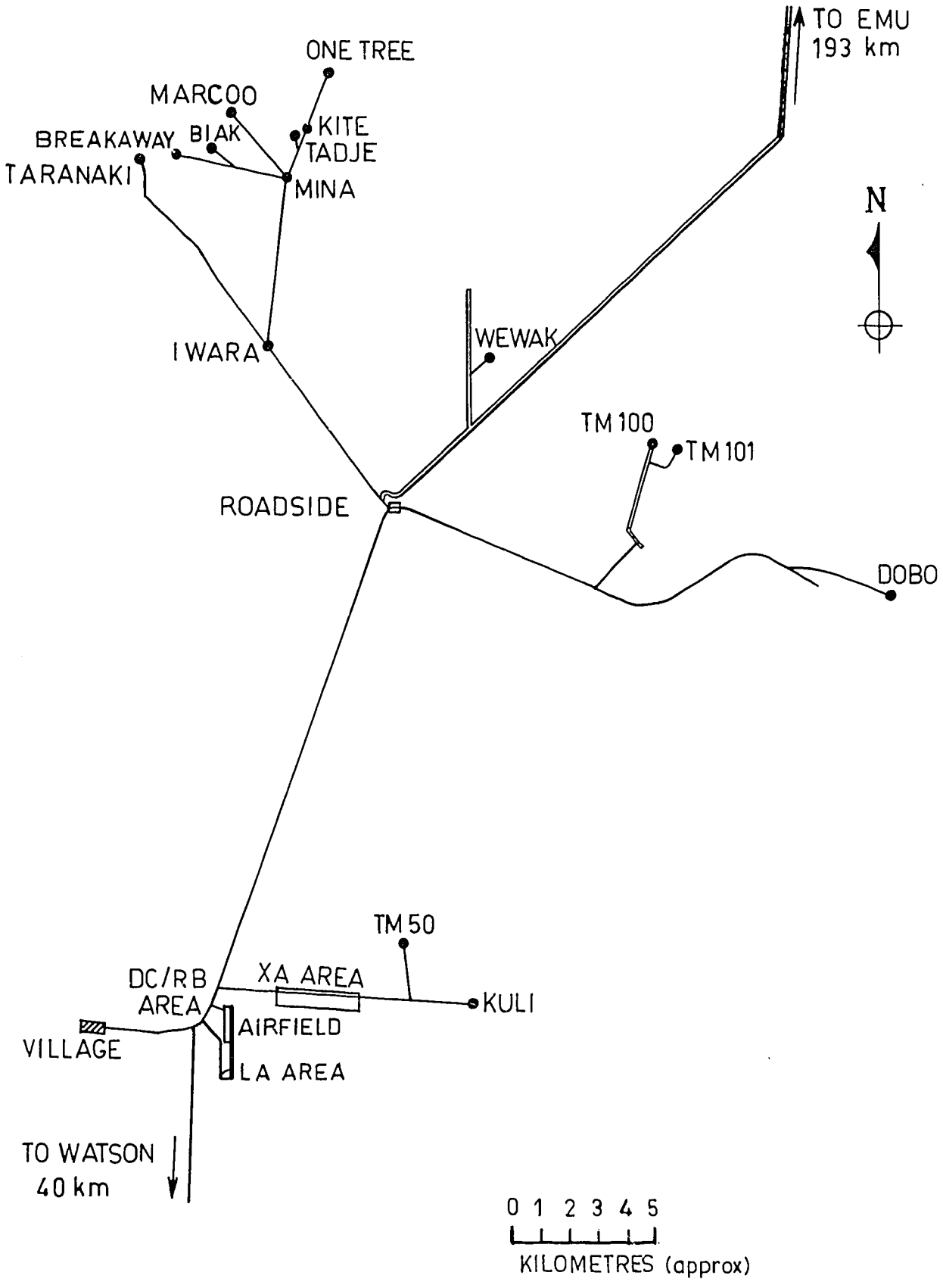


FIGURE 1. MARALINGA RANGE - SITE MAP

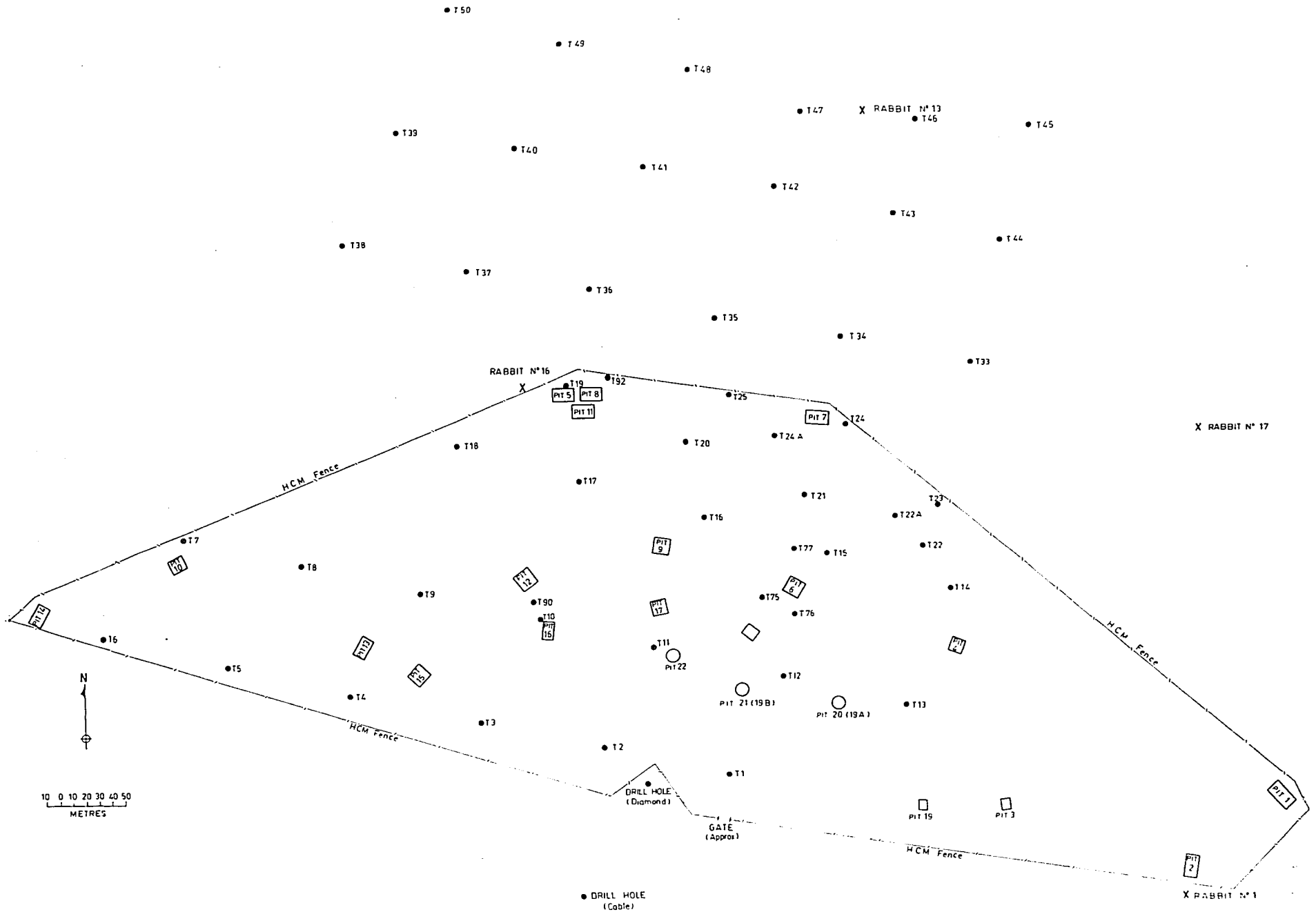


FIGURE 2. SOIL SAMPLES - TARANAKI (ALSO BURIAL PITS AND RABBIT SAMPLES)

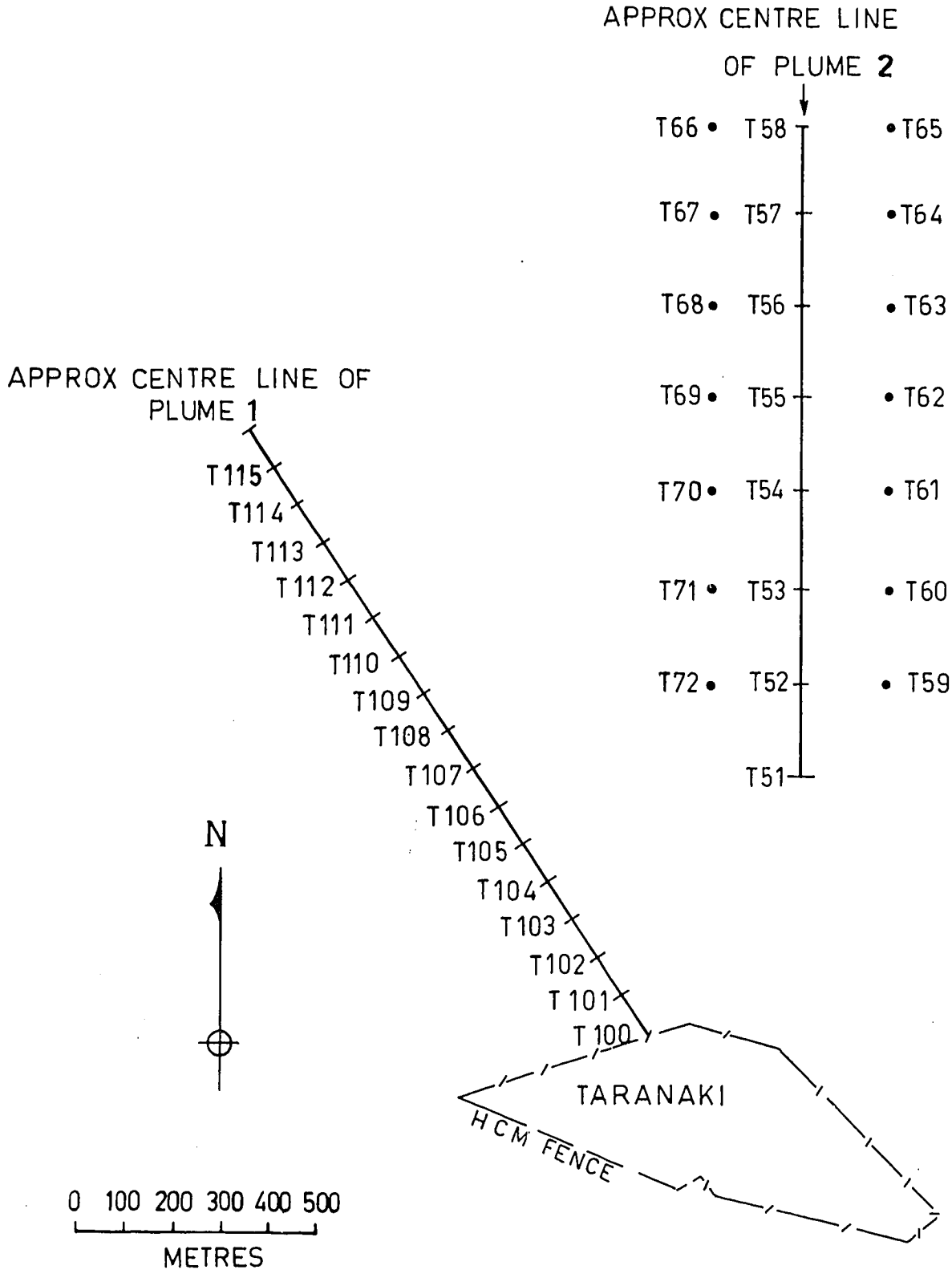


FIGURE 3. SOIL SAMPLES - NORTH OF TARANAKI

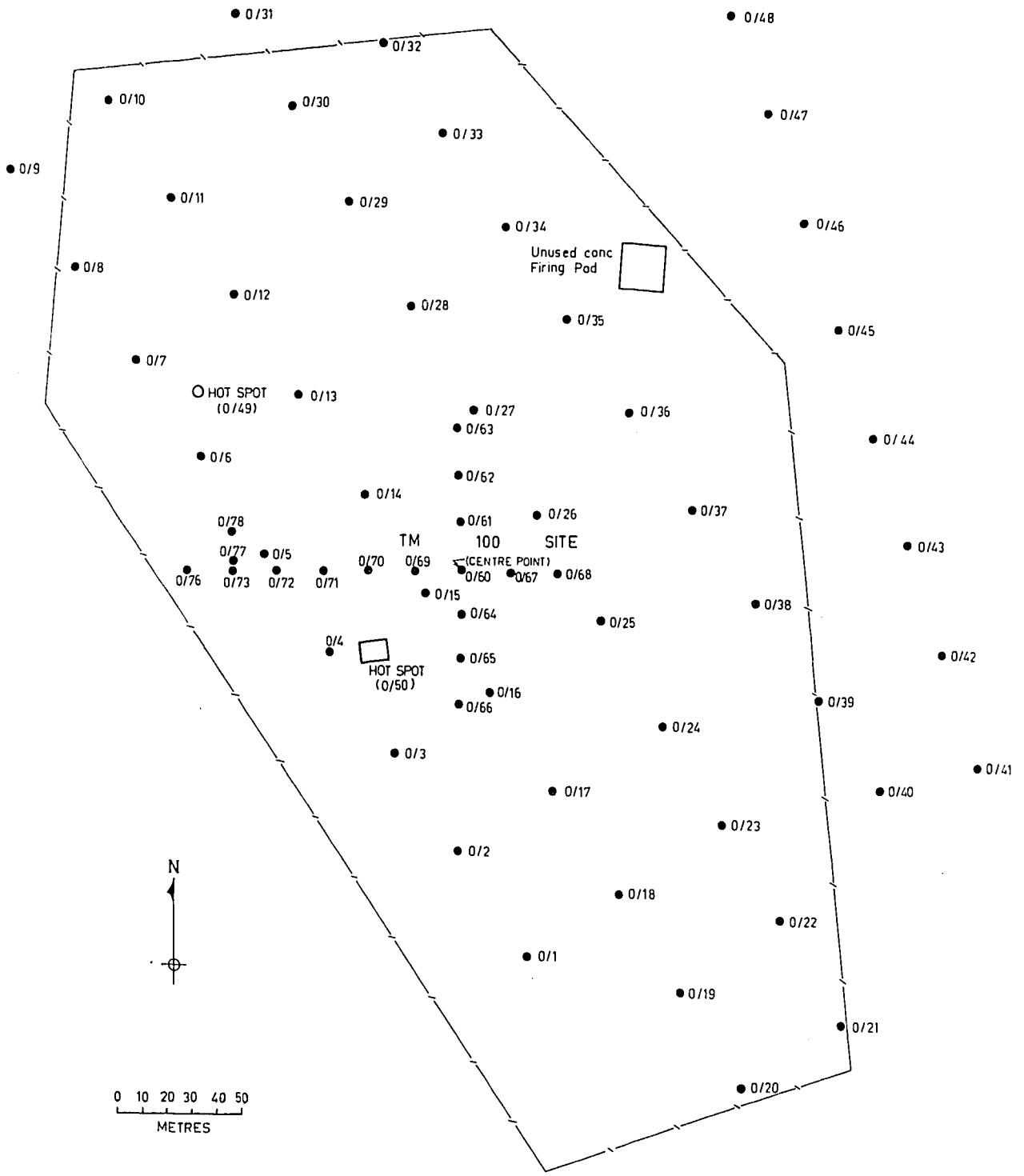


FIGURE 4. SOIL SAMPLES - TM100

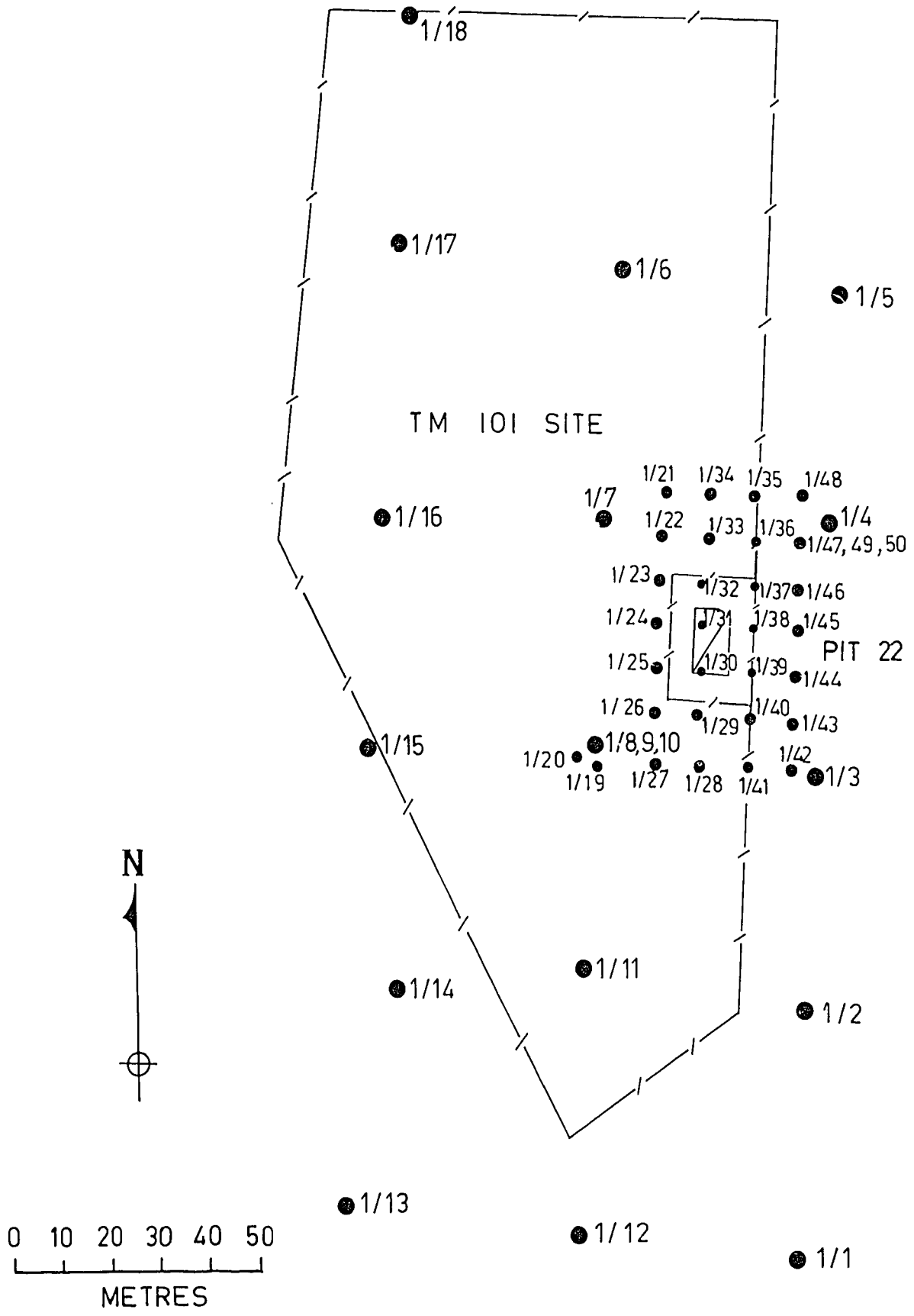


FIGURE 5. SOIL SAMPLES - TM101

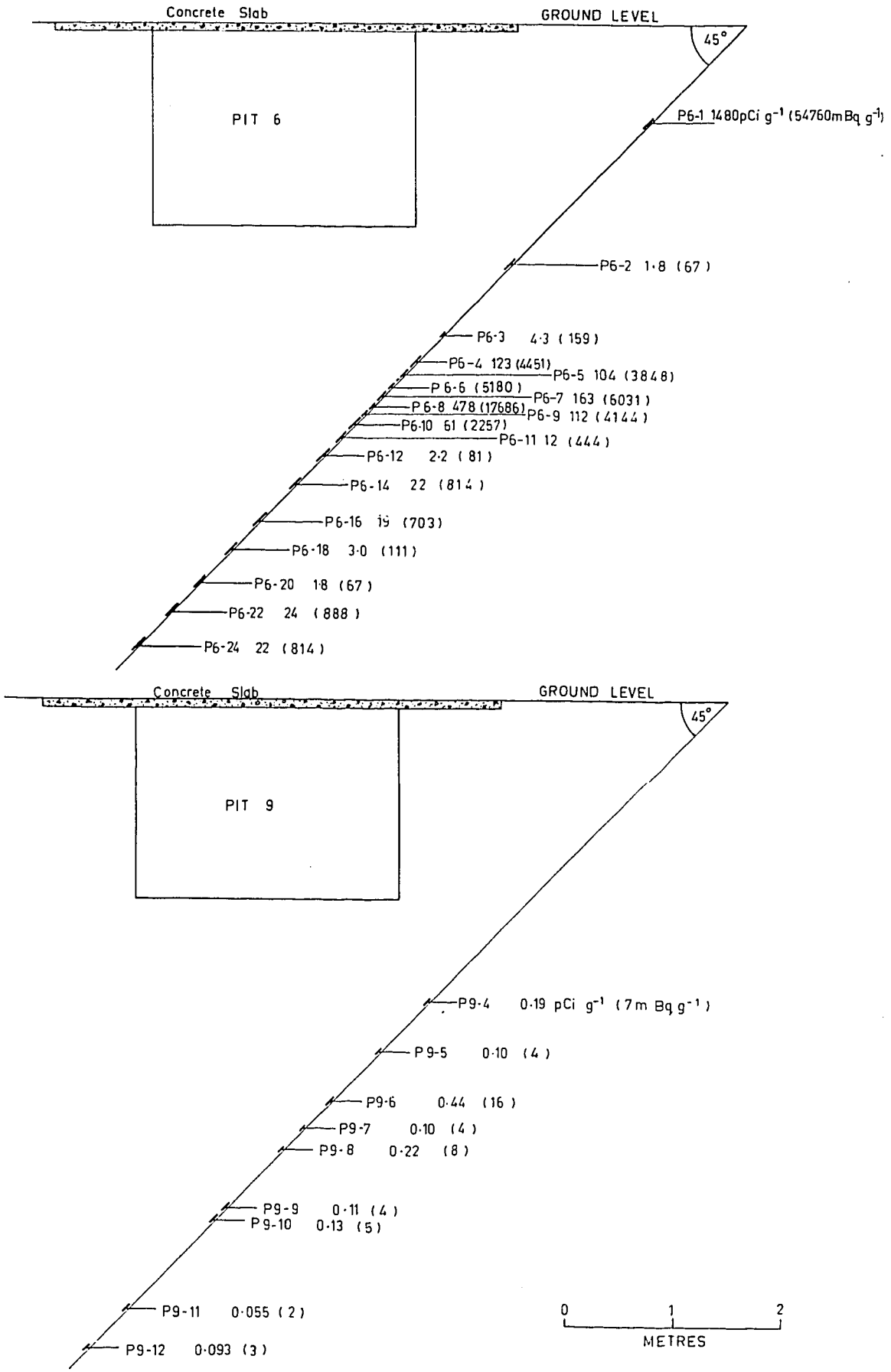


FIGURE 6. PLUTONIUM CONTENT OF CORE SAMPLES FROM BENEATH PITS 6 AND 9

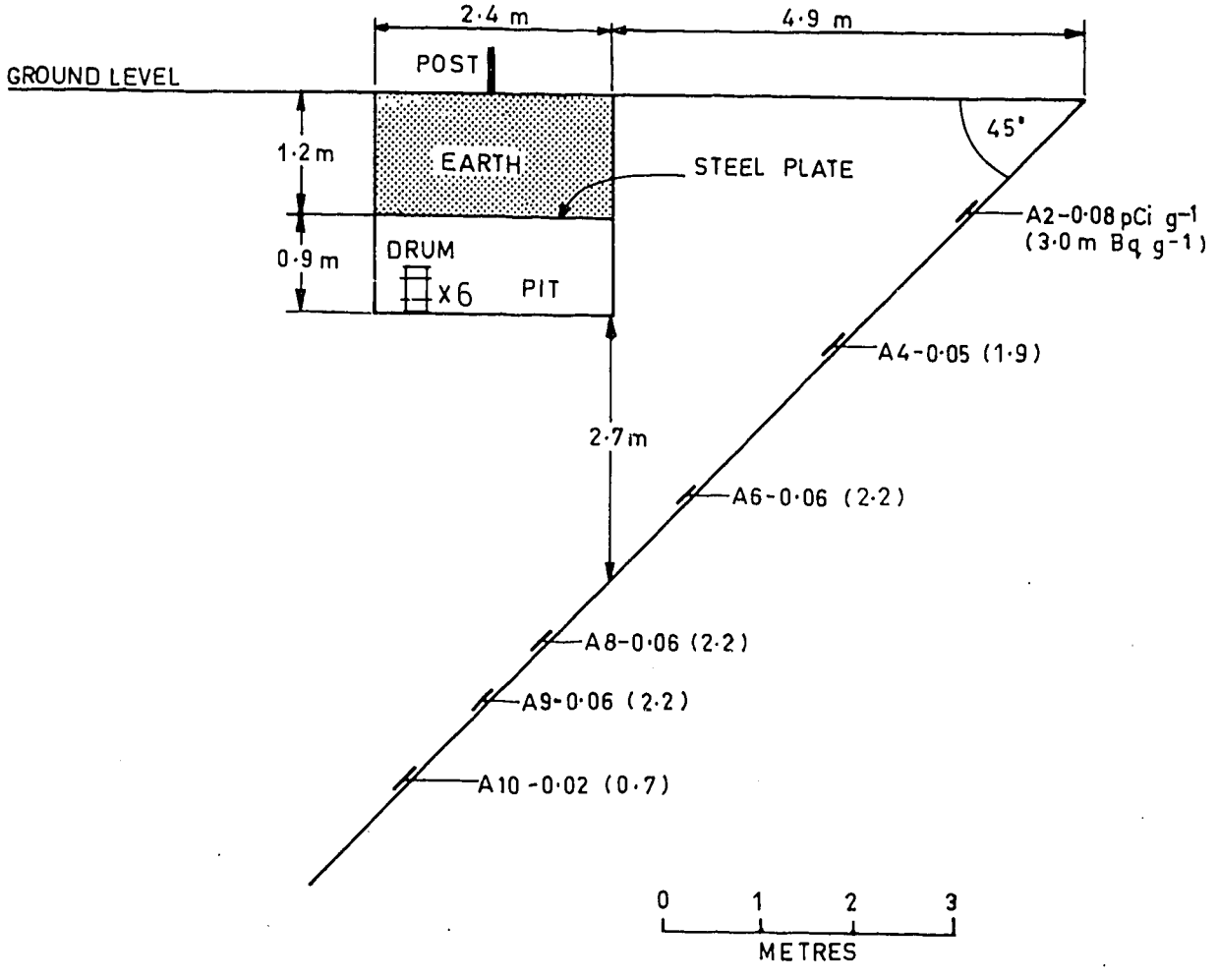
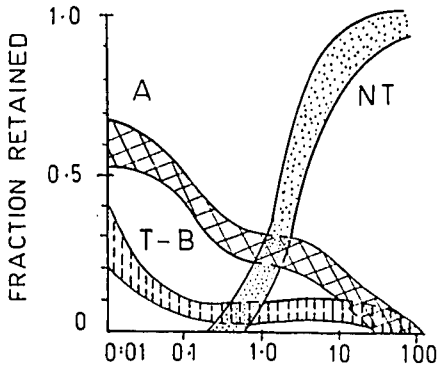


FIGURE 6A. PLUTONIUM CONTENT OF CORE SAMPLES FROM BENEATH PIT I AIRFIELD CEMETERY

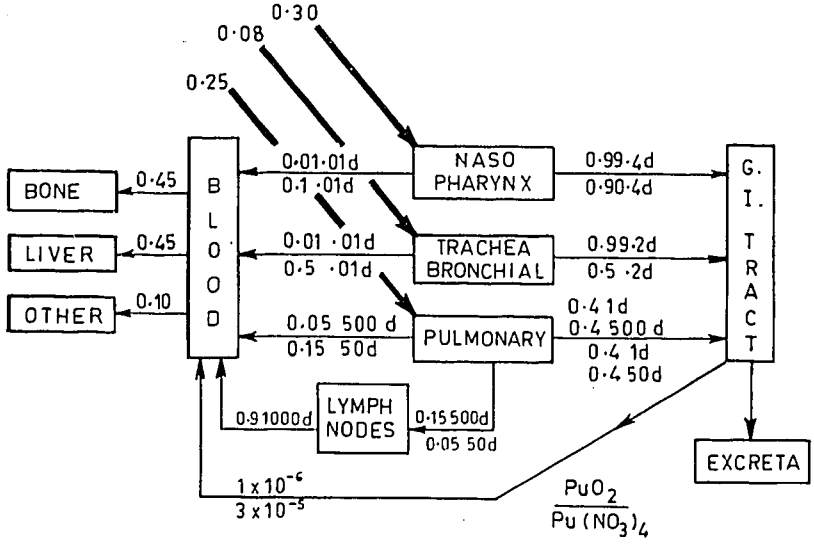


A – DEPOSITION IN ALVEOLAR (pulmonary) TISSUE

T-B – DEPOSITION IN TRACHEA AND BRONCHI

NT – DEPOSITION IN NOSE AND THROAT

FIGURE 7. DEPOSITION AS A FUNCTION OF PARTICLE SIZE



Heavy diagonal arrows from the top are the fractions of dust deposited in each part of the respiratory system. For other transfers the numbers above the lines refer to insoluble compounds like PuO_2, and the numbers below the lines refer to soluble compounds like $Pu(NO_3)_4$. The first figures are the fractional part undergoing transfer by this route, and second figures are the half life in days for the transfer.

FIGURE 8. THE DISPOSITION OF INHALED Pu DUST

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