The Development and Performance of Automated In-Situ Systems to detect Dispersed Radiation and ‘Hot Particles’

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AUSTRALIA
Atomic Weapons Detonations

1952 - 1957

Monte Bello Islands
- 3 detonations

Emu Field
- 2 detonations

Maralinga
- 7 detonations

Contamination from detonations has largely decayed
- No longer a serious health risk
Other Atomic Tests

• 1959 – 1963
  • “Minor Trials”
  • Tests to develop components
  • Safety Trials
  • Dispersal of radioactive material by chemical explosion

• Four Sites Contaminated with Plutonium (mostly $^{239}$Pu)
  • Taranaki, Wewak, TM100, TM101
### Major and Minor Tests - Maralinga

<table>
<thead>
<tr>
<th>Major Tests</th>
<th>Minor Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One Tree</strong> Tower</td>
<td><strong>Kuli</strong> $^{238}\text{U}/\text{Natural U}$</td>
</tr>
<tr>
<td><strong>Marcoo</strong> Ground</td>
<td><strong>Wewak</strong> $^{239}\text{Pu}$</td>
</tr>
<tr>
<td><strong>Kite</strong> Air</td>
<td><strong>TM100</strong> $^{239}\text{Pu}$</td>
</tr>
<tr>
<td><strong>Breakaway</strong> Tower</td>
<td><strong>TM101</strong> $^{238}\text{U}/\text{Natural U}$</td>
</tr>
<tr>
<td><strong>Tadje</strong> Tower</td>
<td><strong>Taranaki</strong> $^{239}\text{Pu}$</td>
</tr>
<tr>
<td><strong>Biak</strong> Tower</td>
<td><strong>238\text{U}/\text{Natural U}#</strong></td>
</tr>
<tr>
<td><strong>Taranaki</strong> Balloon</td>
<td><em># 24kg of enriched uranium also used</em></td>
</tr>
</tbody>
</table>

* 15kT
* 1.5kT
* 3.0kT
* 10kT
* 1.0kT
* 6.0kT
* 27kT

### Minor Tests

- **Kuli**: $^{238}\text{U}/\text{Natural U}$, $> 7000\text{kg}$
- **Wewak**: $^{239}\text{Pu}$, $570\text{g}$
- **TM100**: $^{239}\text{Pu}$, $600\text{g}$
- **TM101**: $^{238}\text{U}/\text{Natural U}$, $86\text{kg}$
- **Taranaki**: $^{239}\text{Pu}$, $22\text{kg}$

* # 24kg of enriched uranium also used
Plutonium Contamination at Maralinga

The plutonium contamination remaining at Maralinga on the completion of the UK weapons testing program existed in three forms:

• Fragments – Plutonium contaminated debris that was visibly identifiable when lying on the surface. This included contaminated metal, plastic, wire, lead etc.

• Particles – sub-millimetre sized pieces of soil or other materials contaminated with Plutonium. These were often indistinguishable from soil on casual inspection but had much higher activities than average for the surrounding soil

• Dust – very finely divided contaminated particles of plutonium oxides which was potentially inhalable
Detecting Plutonium

\(^{239}\text{Pu}\)

- Most significant radiological hazard
- Does not emit significant quantities of \(\gamma\)-rays
- Emitted x-rays are absorbed over very short distances
- Detection of \(\alpha\)-particles is unreliable

\(^{241}\text{Pu}\)

- Minor constituent of plutonium
- Decays with a half-life of 14 years
- Produces \(^{241}\text{Am}\)
- \(^{241}\text{Am}\) produces a \(\gamma\)-ray at 59.5 keV with a probability of 36%. This \(\gamma\)-ray is penetrating enough to detect with Gamma Spectrometry
The Maralinga Rehabilitation Project - Early Considerations of Contamination and Use of Test Areas

- 1967 Operation Brumby
- 1972-1973 AWTSC (Atomic Weapons Tests Safety Committee)
- 1978 AIRAC (Australian Ionising Radiation Advisory Council)
- 1984-1985 ARL (Australian Radiation Laboratory) Assessment
- 1984 Royal Commission into British Nuclear Tests in Australia
- 1986 Australian Government Response to Royal Commission
- 1986-1990 TAG (Technical Assessment Group) Study
- 1993 Formation of MARTAC (Maralinga Technical Advisory Committee)
- 1994-2000 Rehabilitation of Site
Maralinga Rehabilitation Project

AIM: RETURN SITE TO TRADITIONAL OWNERS

- ARPANSA contracted as Radiological Auditor
- RemEDIATE plutonium contamination
  - Remove and bury highly contaminated soil
  - Restrict land use in moderately contaminated areas
- Soil Removed from 2.5 km$^2$
- Restrictions on land use placed on 400 km$^2$
- Remediation started in 1996, completed 2000

Regulatory Requirements: MARTAC Criteria - Soil Removal

Soil was to be removed if:

- The dispersed activity exceeded 40 kBq/m\(^2\) when averaged over 1 hectare (10,000 m\(^2\))
- The area contained fragments
- The area contained particles exceeding 100 kBq activity
- The area contained more than 1 particle above 20 kBq activity per 10 m\(^2\)

Note: All criteria refer to \(^{241}\text{Am}\) activity with a \(^{239}\text{Pu}:^{241}\text{Am}\) ratio of 7:1.
MARTAC Criteria - Clearance

The residual contamination in areas where soil had been removed were to meet the following:

- Dispersed activity less than 3 kBq/m² when averaged over 1ha (10,000 m²)
- No fragments
- No particles exceeding 100 kBq activity
- Density of particles above 20 kBq activity less than 1 per 10m²

Note: All criteria refer to $^{241}$Am activity with a $^{239}$Pu:$^{241}$Am ratio of 7:1
MARTAC Criteria - Unrestricted Land-Use

Permanent occupancy and unrestricted land-use were to only occur in areas where:

- Dispersed activity less than 3 kBq/m² when averaged over 3km²
- No fragments
- No particles exceeding 100 kBq activity
- Density of particles above 20 kBq activity less than 1 per 10m²

Note: All criteria refer to $^{241}$Am activity with a $^{239}$Pu:$^{241}$Am ratio of 7:1
Traditional Survey Methods

**Particle Detection**

**Manual Surveys**
- Time-consuming
- Tedious
- Inefficient for large areas
- Lack complete, objective records - location and all particles

**Dispersed Activity Measurements**

**Aerial Surveys**
- Costly
- Low spatial resolution

**Soil Sampling**
- Time-consuming
- Unreliable - sampling errors

**In Situ Spectroscopy (using a tripod)**
- Time-consuming
- Small area per measurement
Operational Requirements: Dispersed Activity Measurement

• Determine average activity of large areas (1000 m²) with a single measurement
• Provide an unambiguous measurement of $^{241}$Am activity concentration
• Capable of measuring 1 kBq/m² $^{241}$Am activity within a short timeframe (1000 s)
• Highly mobile - 20 measurements over 2 ha in 10 hours
• Record all data
• Easily maintained in the field
Engineering Solutions: Dispersed Activity Measurement - The OKA
Engineering Solutions:
Dispersed Activity Measurement - The OKA
Operation: The OKA Calibration

ICRU53 gives the method for calculating the conversion factor between the full-energy peak count rate and activity concentration.
Operation: The OKA

- Drive to exact measurement location (using DGPS)
- Lower boom to measurement height
- Collect spectrum
- Record Region Of Interest (ROI) information
- Calculate activity concentration
- Record GPS coordinates
- Lower boom over vehicle for travel to next location

Routinely take 20 measurements covering 20,000 m² per day
Performance: The OKA

\[ \text{Grid East (m)} \]
\[ \text{Grid North (m)} \]

\[ \text{Boundary} \]
- 0.0-0.5 kBq/sq.m
- 0.5-1.0 kBq/sq.m
- 1.0-2.0 kBq/sq.m
- 2.0-2.5 kBq/sq.m

\[ \text{241Am Activity Concentrations} \]

\[ \text{152Eu (344 keV) Count Rate} \]
## Results of Dispersed Activity Measurements

<table>
<thead>
<tr>
<th>Work</th>
<th>Taranaki</th>
<th></th>
<th>TM100/TM101</th>
<th></th>
<th>Wewak</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Removal Area Verification</td>
<td>148</td>
<td>46.9</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward Area Facilities Clearance</td>
<td>25</td>
<td>13</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Soil Removal Boundary Verification</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Land-use Restriction Boundary Verification</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Plume Characterisation</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Measurements</strong></td>
<td>4385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Contaminated Soil Removal Area
- Taranaki
Operational Requirements: Particle Detection

• Identify all particles exceeding 100 kBq $^{241}$Am activity

• Measure the density of particles exceeding 20 kBq activity

• Determine the position of the particles

• Demonstrate that 100% of the area had been scanned

• Record all data

• Scan several hectares in a working day

• Easy to maintain in the field
Engineering Solutions:
Particle Detection - The Nissan
Engineering Solutions:
Particle Detection - The Nissan
Operation: The Nissan

Setup in uncontaminated area:

• Attach detectors to vehicle
• Acquire $^{241}$Am spectrum for each detector - simultaneously
• Acquire background for each detector - simultaneously
• Record settings to computer data file

Scan:

• Drive over area at speeds less than 1.7m/s (6kph)
• Drive in a decreasing spiral track
• Computer calculates count rate and particle activity for each 20cm segment of detector path

Routinely scan 30,000 m$^2$ each day
Operation: the Nissan Computer Display

The laptop computer displays:

- The vehicle track (from the DGPS)
- The current GPS coordinates
- The High-Voltage, Threshold and Window values of each detector - with an ‘out-of-acceptable-range’ alarm
- The instantaneous count rate in each detector
- The position of any particle detected above a user-set activity threshold, relative to the vehicle track
- The coordinates and calculated activity of any particles detected above the user-set threshold
Basic Detection System

- Vehicle-Mounted
  - Speed and Operator Comfort
- Incorporate GPS
  - Accurate location of detected particles
  - Record of area surveyed
- Computerised
  - High data rate
  - Record-keeping
- Use Scintillation Detector attached to Single-Channel-Analyzer
  - Only produce signal for 60 keV
Performance: The Nissan
Particle Detection
Defining a Counting Interval
- Basic Geometry
Defining a Counting Interval
- Count Rate

\[ R = \frac{E \cdot S \cdot H}{4 \cdot \pi \cdot (x^2 + H^2 + O^2)^{3/2}} + B \]

Emission Rate: \[ E = a \cdot \beta \]

Effective Frontal Area: \[ S = A \cdot \varepsilon \]

- Particle Activity = \( a \)
- Emission Probability = \( \beta \)
- Detector Area = \( A \)
- Detection Efficiency = \( \varepsilon \)

\( B \) is the rate due to sources other than particle
Defining a Counting Interval

Considerations include:

• The optimum counting interval was defined in terms of distance, NOT time

• Hall-Effect sensor on tail-shaft of vehicle
  — Used to provide a signal for the odometer and speedometer

• Pulses every 21.3 cm
  — Depends on vehicle and tyres

• One Interval = 3 pulses
Optimisation of Counting Interval
- Detector Response

Detector Response
Height = 30 cm
Offset = 25 cm
Area = 100 sq.cm
Activity = 100 kBq
Background = 15 CPS
Optimisation of Counting Interval
- Observed Counts

The observed counts are the time-integral of the detector response

\[ C_P = \frac{E \cdot S \cdot H}{4 \cdot \pi \cdot V} \cdot \frac{1}{H^2 + O^2} \cdot \left[ \frac{x_2}{\sqrt{x_2^2 + H^2 + O^2}} - \frac{x_1}{\sqrt{x_1^2 + H^2 + O^2}} \right] \]

\[ C_B = \frac{B \cdot (x_2 - x_1)}{V} \]

If the particle is centrally located

\[ x_1 = -x_2 = x \]

and \( L = 2 \cdot x \) is the length of the interval
Optimisation of Counting Interval
- Effect of Interval Length

Effect of Counting Interval
Activity = 100 kBq
Offset = 25 cm
Height = 30 cm
Background = 15 CPS
Speed = 1.5 m/s
Optimisation of Counting Interval
- “Signal to Noise Ratio”
Optimisation of Counting Interval
- Counting Uncertainty

![Graph showing Optimisation of Counting Interval - Counting Uncertainty](image)
Optimisation of Counting Interval - Striking a Balance

- Maximise ‘Signal to Noise’
  - Determines maximum interval length – in distance, not time
  - Minimise Uncertainty
  - Determines minimum interval length – in distance, not time
- For:
  - \( H = 30\text{cm}, O = 25\text{cm} \) and \( V = 5 \text{km/hr} \)
  - Optimum counting interval is between 50 and 75 cm
  - A counting interval (distance) of between 50 and 75 cm corresponds to a counting interval (time) of between 0.3 and 0.5 seconds
Improved Counting Methodology
- Random Location

The particle is not always in the centre of the counting interval

Effect Of Particle Position
Activity $= 100 \text{ kBq}$
Interval $= 64 \text{ cm}$
Improved Counting Methodology
- Overlapping Intervals

- Interval is defined by three consecutive pulses
- Define sub-interval terminated by a single pulse
- Integrated counts is running sum over three consecutive sub-intervals

Diagram:

21.3 cm

- Interval 1
- Interval 2
- Interval 3
- Interval 4
Improved Counting Methodology
- Improved Detection Probability

False Negatives
(Threshold = 20 counts)
### Results of Particle Detection Scans

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (ha)</th>
<th>Number of Contaminated Particles Indicated</th>
<th>Number of Contaminated Particles Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Removal Areas</td>
<td>250</td>
<td>~300</td>
<td>121</td>
</tr>
<tr>
<td>Soil Removal Boundaries</td>
<td>120</td>
<td>~250</td>
<td>85</td>
</tr>
</tbody>
</table>
Long-term Management and Post-Rehabilitation Activities - Maralinga

As part of the Maralinga Land and Environment Management Plan (MLEMP), ARPANSA conducts regular Field Surveys of the rehabilitated areas.

The objectives of the ongoing field surveys are:

- Measure the dose-rate at each of the major trial sites
- Conduct in-situ measurements of the $^{241}\text{Am}$ activity concentration in each of the plumes
- Conduct in-situ measurements of the $^{137}\text{Cs}$ activity concentration north of Breakaway
- Conduct hand-surveys for contaminated particles in the windrows north of Taranaki
THANK-YOU