The plumes of Maralinga: Mapping nuclear fallout patterns over sixty years after atomic bomb testing

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SUMMARY

The British government conducted seven nuclear bomb tests and hundreds of other tests with radioactive materials at Maralinga in South Australia during the 1950s and 1960s. Little information was made available to the Australian public at the time of the blasts, and many details of the tests are still not publicly known. Several clean-ups of the nuclear test sites, two shortly after the end of testing by the British in 1964 and 1967, and one by the Australian government in 1994-1998 following a royal commission, focused on the areas closest to the blast sites where the radioactive contamination was greatest.

In this study, we show that the distribution of radionuclides following the nuclear tests at Maralinga over 60 years ago can be extracted from publicly available conventional airborne gamma-ray spectrometry data acquired in 2018. We compare two methods to extract the ^{137}Cs and ^{241}Am signatures. An ENE-trending plume of ^{137}Cs contamination is visible for at least 70 km despite the relatively low spatial resolution of the regional dataset. A clear signature for ^{241}Am, a daughter product of the plutonium dispersed by the so-called "minor" trials, was also extracted. Our results show that, despite the clean-ups at Maralinga, radioactive material remains over an area of approximately 3000 km^2 and is readily detected by regional airborne surveys designed for mineral exploration.

Key words: airborne gamma-ray spectrometry, radiometrics, airborne, Maralinga, nuclear tests, ^{137}Cs (Caesium 137), ^{241}Am (Americium 241), ^{239}Pu (Plutonium 239), ^{241}Pu (Plutonium 241), ^{152}Eu (Europium 152), ^{60}Co (Cobalt 60), ^{238}U (Uranium 238)

INTRODUCTION

Maralinga, South Australia, was chosen by the British government as a site for nuclear testing in the 1950s and 1960s, during development of nuclear weapons. The area was deemed suitable for testing due to its isolation, sparse population, and predictable weather patterns. Very little information about the nuclear tests was made available to the Australian public at the time of the blasts, and many details of the tests are still not publicly known (Walker, 2014). The area remains remote and sparsely populated today, and with the arid climate and low rainfall, provides an ideal study area for the natural decay of radionuclides many decades after a nuclear blast.

In this study, we use airborne gamma ray spectrometry data, collected for mineral exploration, to show that the distribution of ^{137}Cs and ^{241}Am following the seven nuclear test blasts at Maralinga over 60 years ago can be extracted from publicly available conventional airborne gamma-ray spectrometry data acquired in 2018. An ENE-trending plume of ^{137}Cs contamination is visible for at least 70 km despite the relatively low spatial resolution of the regional dataset. A clear signature for ^{241}Am a daughter product of the plutonium dispersed by the so-called "minor" trials was also extracted. Our results show that, despite the clean-ups at Maralinga, radioactive material remains over an area of approximately 3000 km^2.

BACKGROUND

A series of seven atomic bomb tests were conducted by the British government at Maralinga, Australia, in 1956-57 (Table 1). From 1956-63, several hundred minor tests involving radioactive material but not involving nuclear fission were also conducted at Maralinga. Three clean-ups, focusing on most contaminated areas adjacent to the blast sites, were conducted in 1964 and 1967 by the British government, and in 1994-1998 by the Australian government (MARTAC 2003).

In 1986, the Australian government contracted the US Department of Energy (USDE) to conduct an aerial radiological survey to assess the effects from the nuclear tests. The survey was accomplished with a helicopter fitted with a spectrometer containing 26 litres of sodium iodide crystals, flying at 30 m, with a variable line spacing between 200 m and 50 m. Survey data were processed for ^{137}Cs ^{60}Co, ^{152}Eu,^{238}U, and ^{241}Am (Tipton et al.,1988).

Symbol	Series	Name	Date	Yield (kt)
○	Buffalo	One Tree	27/09/1956	15
○	Buffalo	Marcoo	04/10/1956	2
○	Buffalo	Kite	11/10/1956	3
○	Buffalo	Breakaway	22/10/1956	10
△	Antler	Tadje	14/09/1957	1
△	Antler	Biak	25/09/1957	6
▲	Antler	Taranaki	09/10/1957	27

Table 1. Nuclear bomb blasts at Maralinga (MARTAC, 2003). Symbols are used to show locations in Figures 2, 3 and 4

DATA

In 1992 an Australian company, World Geoscience Corporation (WGC) acting on its own initiative, flew an airborne radiometric survey of the Maralinga nuclear test range and detected various radionuclides including ^{137}Cs, ^{60}Co, and ^{152}Eu. This dataset was never published, and unfortunately the original data has been lost but some images have been recovered, and one (^{137}Cs) is used in this study (Fig. 2).

Two more recent airborne radiometric surveys were flown in 2005 (Pace One Tree) and 2018 (Gawler) on behalf of Geoscience Australia for the purposes of promoting mineral exploration. Both surveys flew over the Maralinga nuclear test range, although the survey specifications were not designed for detecting radionuclides from the nuclear test blasts (Table 2). This study uses only the Gawler 2018 survey data, due to the lower flying height and tighter line spacing of the survey.

	World Geoscience 1992 Survey	Pace One Tree 2005	Gawler 2018
Geoscience Project		1101	1298
Survey Company	World Geoscience Corporation	Fugro Airborne Surveys	Thomson Aviation
Client	None	Geoscience Australia	Geoscience Australia
Survey Type	Radiometric	Magnetic and Radiometric	Magnetic and Radiometric
Area Name	Maralinga	Ooldea	Gawler R1B
Flown	March 1993	October-December 2005	September 2017 – May 2018
Datum / Projection	WGS84	GDA94 / MGA52	GDA94 / MGA53
Survey Line Spacing	80 metres	400 metres	200 metres
Survey Line Direction	090-270 degrees	090-270 degrees	090-270 degrees
Nominal Terrain Clearance	40 metres	80 metres	60 metres
Spectrometer	256-channel Exploranium GR800	256 Channel Exploranium GR820	Radiation Solutions RSX 500
Crystal Volume	33.56 litre	33.56 litre	33.56 litre
Recording Interval	1Hz	1 Hz	1 Hz

Table 2. Survey specifications for three airborne radiometric surveys over the Maralinga area between 1992 and 2018.

METHODS

No ground data was available for this study to properly calibrate the airborne data from the Gawler (2018) survey, so the verified values described in Tipton et al. (1988) and described below were adopted by application of the half- lives for ^{137}Cs and ^{241} Am (Table 3).

Tipton et al. (1988) acquired measurements at over 100 ground stations in the survey area using a high purity germanium sensor. The spectra were acquired at each station over a period of 10 minutes. A 4096-channel analyser was employed. The detectable activity for ^{241}Am was 0.1 kBq/m^2 as compared to 1.4 kBq/m^2 for the airborne system which collected spectra at once per second compared to the 600 seconds acquisition time for the germanium spectrometer.

Different methods were for extraction and display of ^{137}Cs and ^{241}Am isotopes from the WGC (1992) data and from the Gawler (2018) data in this study. WGC used standard windowing methods on the 256-channel data employing its proprietary gridding and imaging software.

For the Gawler (2018) data, the ^{137}Cs photopeak at 662 keV was extracted directly by full spectrum fitting method using Monte Carlo derived spectra of multiple radionuclides. The values were then calibrated to those obtained by Tipton et al. (1988) in their ground survey. A ratio of Signal Window and Background Window was used to extract the ^{241} Am response. The Signal Window for the

59.5keV peak was set to 6-80keV whilst the Background Window was set to 100-180keV. The ratio so obtained was converted to activity concentrations by extrapolation of the values described in Tipton et al. (1988) (Table 3).

The spectral line for ^{241}Am sits in the 4th or 5th channel (256-channel spectrum) where there is a lot of scattered radiation from terrestrial and cosmic sources, providing huge statistical noise (Figure 1). Despite this, the full spectrum fitting method and spectral ratio method was able to produce an image showing the plumes of ^{137}Cs radiating from the seven test sites (Fig. 3) and plumes of ^{241}Am emanating from Taranaki, site of the minor trials (Fig. 4).

The maximum activity concentrations determined by Tipton et al. (1988) were 14 kBq/m^2 for ^{137}Cs and 100 kBq/m^2 for ^{241}Am. The maximum value for ^{239}Pu in 1987 was calculated to be 830 kBq/m^2 using a conversion factor of 8.3 for the ^{239}Pu/^{241}Am ratio (Long and Green 2012). It is assumed that value remains virtually the same given its long half -life. The values for ^{137}Cs and ^{241}Am were calculated by applying their half- lives. ^{137}Cs is calculated to decline in accordance with its half-life of 30.17 years whereas ^{241}Am, with a half- life of 432, years increases over time because its parent ^{241}Pu has a shorter half -life of 14 years. (Burns et al 1995) (Table 3).

Isotope	Half Life	1987	1992	2005	2018
		US Dept of Energy	WGC	PACE ONE TREE	GAWLER
		Observed kBq/m^2	Calculated kBq/m^2	Calculated kBq/m^2	Calculated kBq/m^2
Cs-137	30.17 years	14	13	10	7
Pu 239	24,110 years	---	830	830	830
Am-241	432 years	100	106	114	122

Table 3. Maximum activity concentrations in kBq/m^2 of elements present at Maralinga for each of the four surveys. Element concentrations present but not detected are black, those detected by the surveys are marked in red.

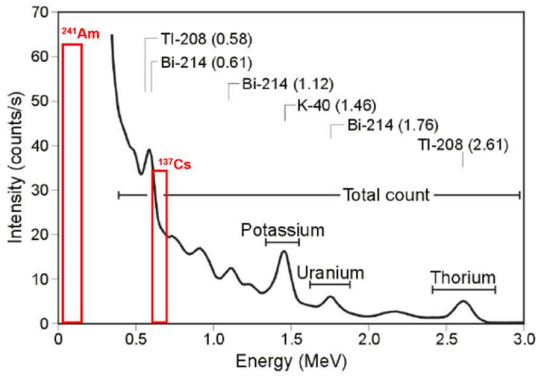

Figure 1. Graph showing a typical gamma ray spectrum from an airborne survey. Note the position of ^{137}Cs, which is close to the lower limit of the normal total count window and is close to and partially overlaps the ^{214}Bi peak, and the position of ^{241}Am which is less likely to be measured due to its position in the low energy part of the spectrum. Modified from IAEA, 2003.

RESULTS

The image of ^{137}Cs distribution from the WGC (1992) survey (Fig. 2) has been artificially illuminated from the east to enhance north/south plumes. It clearly delineates the seven nuclear test sites and the ENE-trending plumes of ^{137}Cs extending beyond the eastern margin of the survey area. The results of this higher resolution survey illustrate the potential to acquire better quality data across a larger area.

The Gawler (2018) regional image of ^{137}Cs distribution shows that the plume extends ENE for more than 70 km (Fig. 3). Minor plumes extend to the east and north, reflecting both the blast directions and the wind conditions at the time of the blasts. NE-trending striations in the NW of the image follow the trend of sand dunes which in turn highlight the prevailing wind direction. (It is evident that the dunes have influenced the fallout patterns.)

The Taranaki site is the most extensively contaminated with plutonium resulting from the so-called “minor” trials (Tipton et al., 1988). The distribution of ^{241}Am in the Gawler (2018) data shows four distinct plumes radiating up to 30 km to the west, northwest, north and northeast from the Taranaki test site (Fig. 4).

Lower levels of ^{137} Cs and ^{241}Am at the Taranaki site (black triangle in Fig. 3 and Fig. 4) show the effects of the Australian government's clean-up of the site in the late 1990s and can be contrasted with the higher levels measured over the same site in 1993 prior to the clean-up (Fig. 2). Much of the contaminated soil at Taranaki was removed and buried in trenches, but the other six sites were not rehabilitated to the same level (MARTAC, 2003).

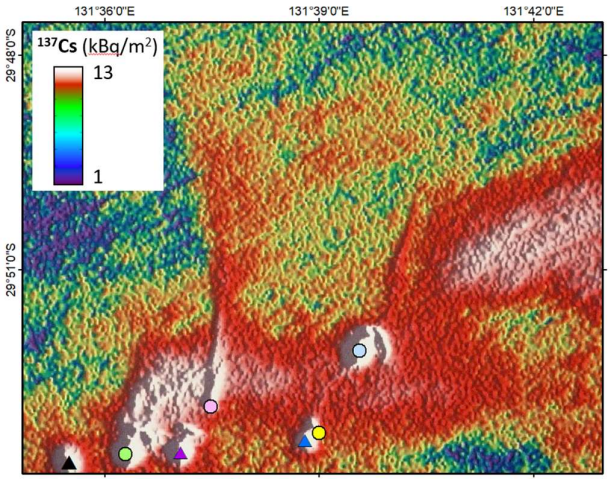

Figure 2.^{137}Cs from the 1992 WGC survey using the gridded and imaged window method. Activity concentrations range from 1kBq/m^2 to 13 kBq/m^2. A sun angle imaging technique highlights the north -south features. Bomb sites indicated by circles and triangles as in Table 1

While the window-based, stripping method can provide reasonable results under conditions where there are stringent sampling specifications, the full-spectrum fitting method using adjusted Monte-Carlo derived spectral responses is the preferred approach. This is especially so when responses of more than one man-made product are present in the radiometric data.

The activity concentration values used in this study (Table 3), derived as they are from the 1987 USDE ground stations (Tipton et al., 1988), take no account of the absorption into the soil and displacement of the isotopes with the soil. They are therefore 'best estimates' only.

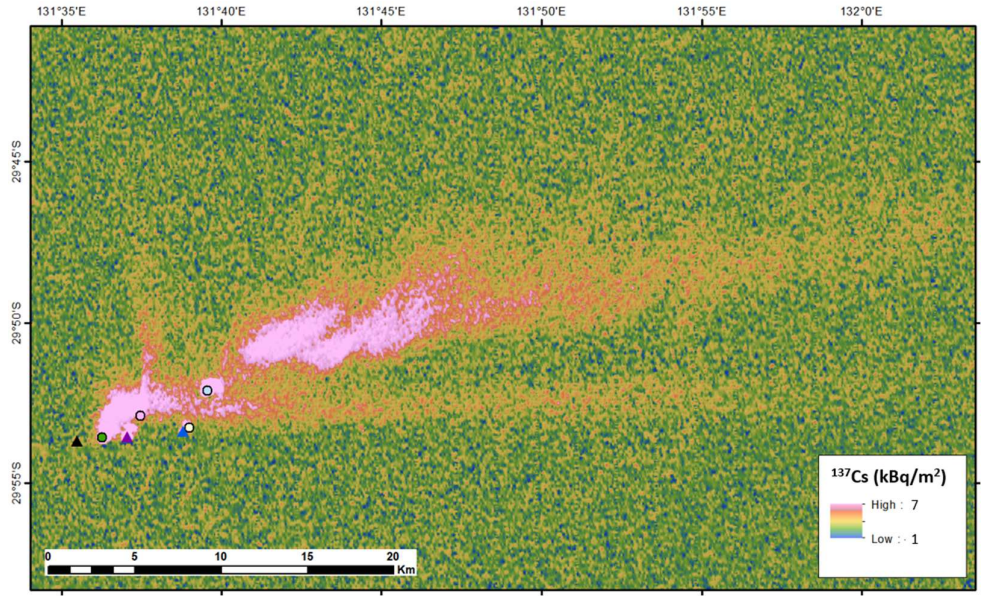

Figure 3. 137Cs from the 2018 Gawler survey using the full-spectrum fitting method with activity values ranging from 1 to 7 kBq/m2 The blast sites are shown by the circles and triangles. The main plume extends at least 70 km to the ENE, with several minor plumes extending to the E and to the N.

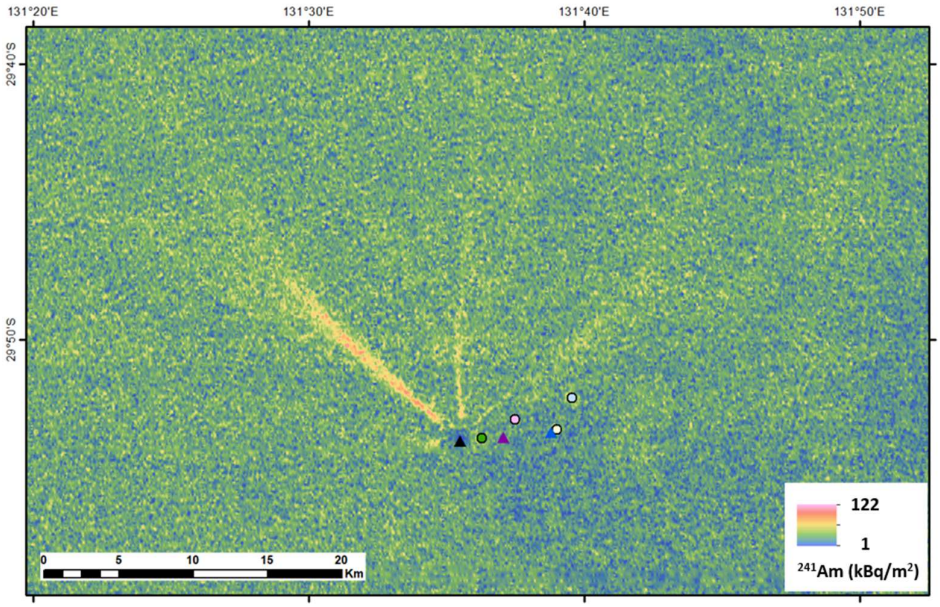

Figure 4. ^{241}Am plume from the Gawler 2018 survey. Values were estimated using calibrated spectral ratio method. The Taranaki test site (black triangle) reflects the cleanups in the 1960s and 1990s, whereas the plumes extending to the NW, North and NE indicate remnant ^{241}Am, a marker isotope for ^{239}Pu.

DISCUSSION

The Maralinga area is a unique site for the study of nuclear fallout and provides an opportunity to develop expertise in the monitoring of nuclear fallout over longer periods of time. Building this expertise is critical as Australia contemplates acquiring nuclear reactors. In more than 60 years since the testing ended, the area remains relatively untouched by human activity and is accessible for ground-truthing of airborne data. The arid climate and low rainfall means that the radionuclides are less mobile than in areas with higher rainfall (such as northern Europe following the Chernobyl accident), and it has flat terrain which allows for very good and consistent ground clearance control of airborne surveys.

The 14-year half-life of ^{241}Pu means that its daughter ^{241}Am with a 432-year half- life has been increasing and is currently at its peak at Maralinga. ^{241}Am is a particularly good marker for the potentially harmful, alpha-emitting ^{239}Pu, which has no gamma emissions capable of detection by an aircraft.

A new, properly designed survey is therefore necessary if the distribution of the radioactive fallout is to be properly monitored. The results from the 1992 WGC survey show that very low flight clearance and tightly spaced flight lines provide a better level of detail than can be extracted from conventional radiometric survey data. Ground truthing measurements to carefully calibrate the survey would allow estimates of radioactivity, not just at the blast sites but also along the 70 km plume of ^{137}Cs mapped in the Gawler 2018 survey (Fig. 3) and better constrain the distribution of ^{241}Am and hence ^{239}Pu (Fig. 4).

There is also potential for improvements in processing. The full-spectrum fitting approach can be adjusted to man-made radionuclide responses extracted directly from data. This approach could be useful not only in understanding the distribution of fallout at Maralinga, but also in environmental monitoring of other nuclear tests sites, accident sites, and in possible future Australian nuclear power stations and nuclear waste sites.

CONCLUSIONS

Airborne gamma-ray spectrometry is well established as a tool for monitoring the spatial extent of radioactive contamination following nuclear tests or nuclear accidents such as the ones at Chernobyl (1986) and Fukushima (2011) (Connor et al., 2016; Thorring et al., 2019; Yoshida and Takahashi, 2012). The Maralinga test site is comparatively undisturbed due to its remote location and arid climate. The number of repeat airborne gamma-ray spectrometry surveys over the area over a period of more than 30 years provides a unique opportunity to study the dispersal and decay of the radionuclides released by nuclear testing. After calibration and using certain assumptions, airborne surveys can provide estimation of concentration of radioactive contaminants on the surface. For a better estimate of contaminants, ground testing at depth will be required.

The fact that the ^{137}Cs and ^{241}Am can be extracted from airborne radiometric survey data, which was not acquired for the purposes of monitoring nuclear fallout, is a testament to the quality of the Gawler (2018) dataset. However, the higher resolution data acquired

in the 1992 WGC dataset indicates that there is potential to better constrain the spatial distribution of the nuclear fallout at Maralinga, and to develop expertise in the monitoring of nuclear fallout through systematic repeat studies over a number of years.

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