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DEPARTMENT OF ENERGY BY EG&G/EM

AN AERIAL RADIOLOGICAL SURVEY OF

MARALINGA AND EMU, SOUTH AUSTRALIA

DATE OF SURVEY: MAY - JULY 1987

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ABSTRACT

An aerial radiological survey was conducted over the former British nuclear test ranges at Maralinga and Emu in South Australia from May through July 1987. The survey was performed for the Australian government by EG&G Energy Measurements, Inc., a contractor of the United States Department of Energy. Helicopter support for the survey was provided by the United Kingdom Royal Air Force. The survey covered an area of approximately 1,550 square kilometers which included the nine major trial sites, where a nuclear yield occurred, and all the minor trial sites, where physics experiments were conducted. Flight lines were flown at an altitude of 30 meters with line spacings of 50, 100, and 200 meters depending on the area and whether man-made contamination was present. Results of the aerial survey were processed for americium-241 (used to determine plutonium contamination), cesium-137, cobalt-60, and uranium-238. The aerial survey also detected the presence of europium-152, a soil activation product, in the immediate vicinity of the major trial ground zeros. Ground measurements were also made at approximately 120 locations using a high-resolution germanium detector to provide supplemental data for the aerial survey. This survey was conducted as part of a series of studies being conducted over a two to three-year timeframe to obtain information from which options and associated costs can be formulated about the decontamination and possible rehabilitation of the former nuclear test sites.

FORWARD

The work described in this report was accomplished through a Memorandum of Understanding between the United States Department of Energy and the Australian Nuclear Science and Technology Organization (formerly the Australian Atomic Energy Commission).

This report has been published by the Commonwealth of Australia (1991) in Volume 1 of the Technical Assessment Group Report "rehabilitation of Former Nuclear Tests Sites in Australia."

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1.0 INTRODUCTION

In February 1986, the Australian Government established a Technical Assessment Group (TAG) to report, in detail, on options and associated costs for the radioactive and toxic decontamination as well as the rehabilitation of the former British nuclear test sites at Maralinga and Emu, located in South Australia. As part of its tasking, the TAG was required to identify additional studies that might be needed to properly address the decontamination and rehabilitation issues. Six studies were recommended. These included:

Study 1 - Anthropology

An anthropological study would investigate the preparation, consumption, and range of bush food in the Aboriginal diet. It would also report the frequency of Aboriginal dust-raising activities.

Study 2 - Radioecology

A radioecological study would attempt to partially quantify the dust inhalation pathway in Aborigines. It would assess their ingested intake of plutonium (Pu) and americium (Am) by collecting animals, vegetables, camp fire ash, and soil from a range of contaminated areas.

Study 3 - Bioavailability

This kind of study would determine the residence time of plutonium and americium from contaminated areas in animal lungs. It would also determine the distribution and target organs following the translocation of plutonium and americium away from contaminated wound sites. It would also determine the animal gut transfer fraction for important bush foods.

Study 4 - Inhalation Hazard Assessment

During this type of study, soil samples and personal air samples would be collected in order to quantify the annual dust inhalation hazard to the Aborigines. The wind-eroded soil at all sampling sites would be characterized with respect to particle size distribution and activity versus particle size and distribution.

Study 5 - Radiochemical and Chemical Analyses

The objective of this study would be to provide both radiochemical and chemical analyses services to support field studies.

Study 6 - Regional Survey

A regional survey study would comprise three key elements:

A. An aerial survey of the potentially contaminated regions to seek the presence of any areas of surface plutonium deposition at a sensitivity of a few bequerels (Bq) of plutonium per gram of soil

B. An aerial magnetometer survey to detect any unknown debris burial pits

C. A ground survey to map any new areas of contamination identified by the aerial survey and to determine isotope contours for a range of acceptable levels of contamination according to various land-use options.

This report describes the results of the aerial survey conducted as part of Study 6. The survey was a joint effort between Australia, the United States (U.S.), and the United Kingdom (U.K.). Equipment and personnel to perform the survey were supplied by EG&G Energy Measurements, Inc. (EG&G/EM), a contractor of the U.S. Department of Energy (DOE). Helicopter support for the survey was provided by the U.K. Funding to EG&G/EM, base support at Maralinga, and overall project management was provided by Australia.

The field portion of the survey was conducted between 1 May and 11 July 1987. Preliminary data processing was performed at Maralinga. Final processing was performed at the EG&G/EM facilities in Las Vegas, Nevada.

2.0 BACKGROUND

Between 1953 and 1963, the United Kingdom conducted a program of nuclear weapons development trials at Maralinga and Emu in South Australia. In all, nine major nuclear trials involving atomic explosions and several hundred smaller scale experiments called minor trials (which dispersed radioactive materials over small areas) were performed at the two locations. The sites of these trials are shown in Figures 1 and 2. In addition, three major nuclear trials were performed at the Monte Bello Islands in Western Australia in 1952 and 1956.

During the period that the Maralinga and Emu Ranges were in use, various radiation surveys and cleanup operations were performed. Once the decision was made to close the Maralinga Range, a final cleanup of all sites was undertaken by the U.K. in Operation Brumby in 1967. The goals of this operation were to reduce the level of contamination and to perform such other operations as were considered necessary for closing the sites.

During the three years prior to this aerial survey, the Australian Radiation Laboratory (ARL) investigated the major and minor trial sites at Maralinga and Emu. Much of the following is based on information obtained during these studies. The intention is to provide background information on the radioactive contamination remaining at Maralinga and Emu at the time that these aerial radiological surveys were conducted.

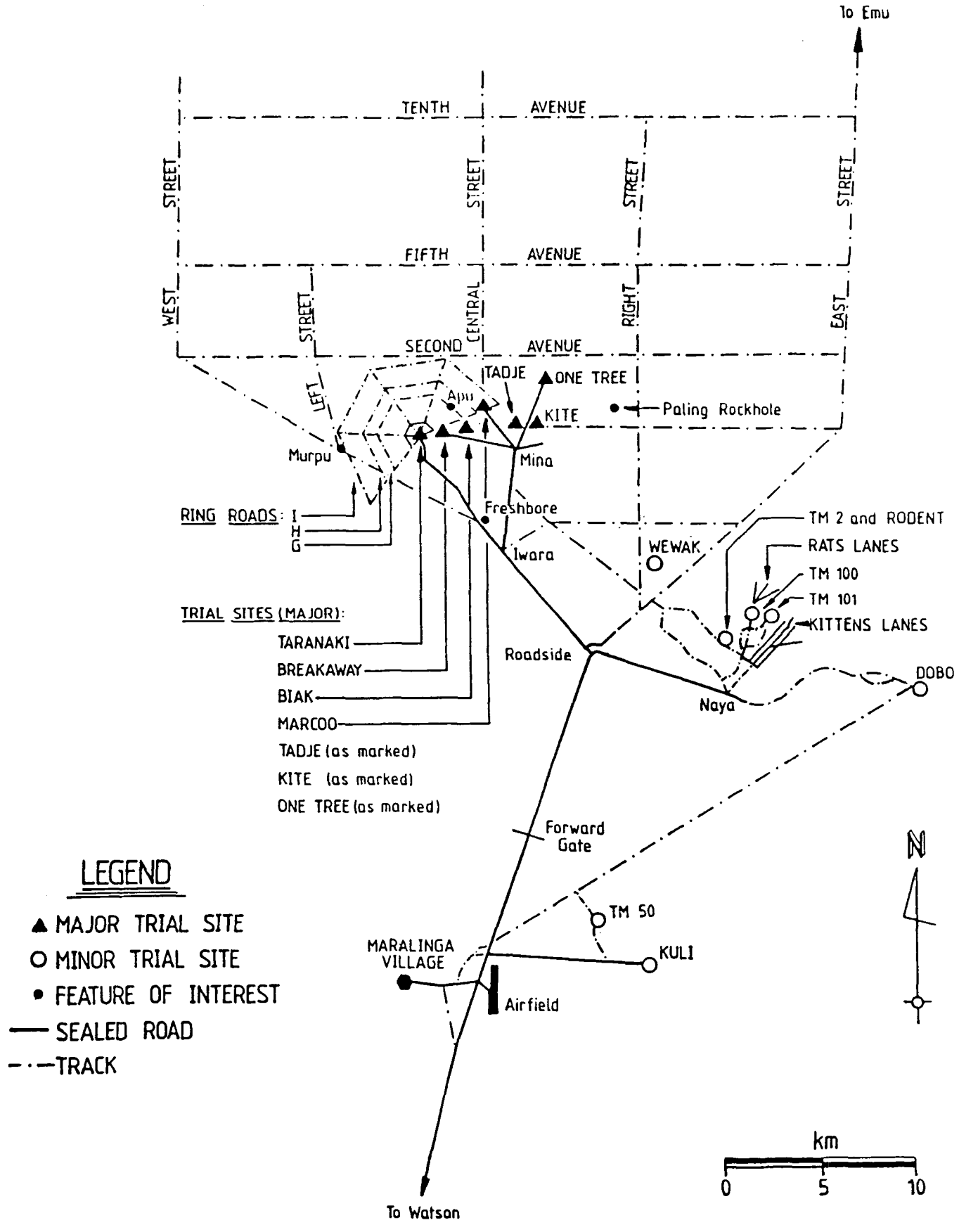


Figure 1. Map Showing the Locations of the Major and Minor Trial Sites at Maralinga

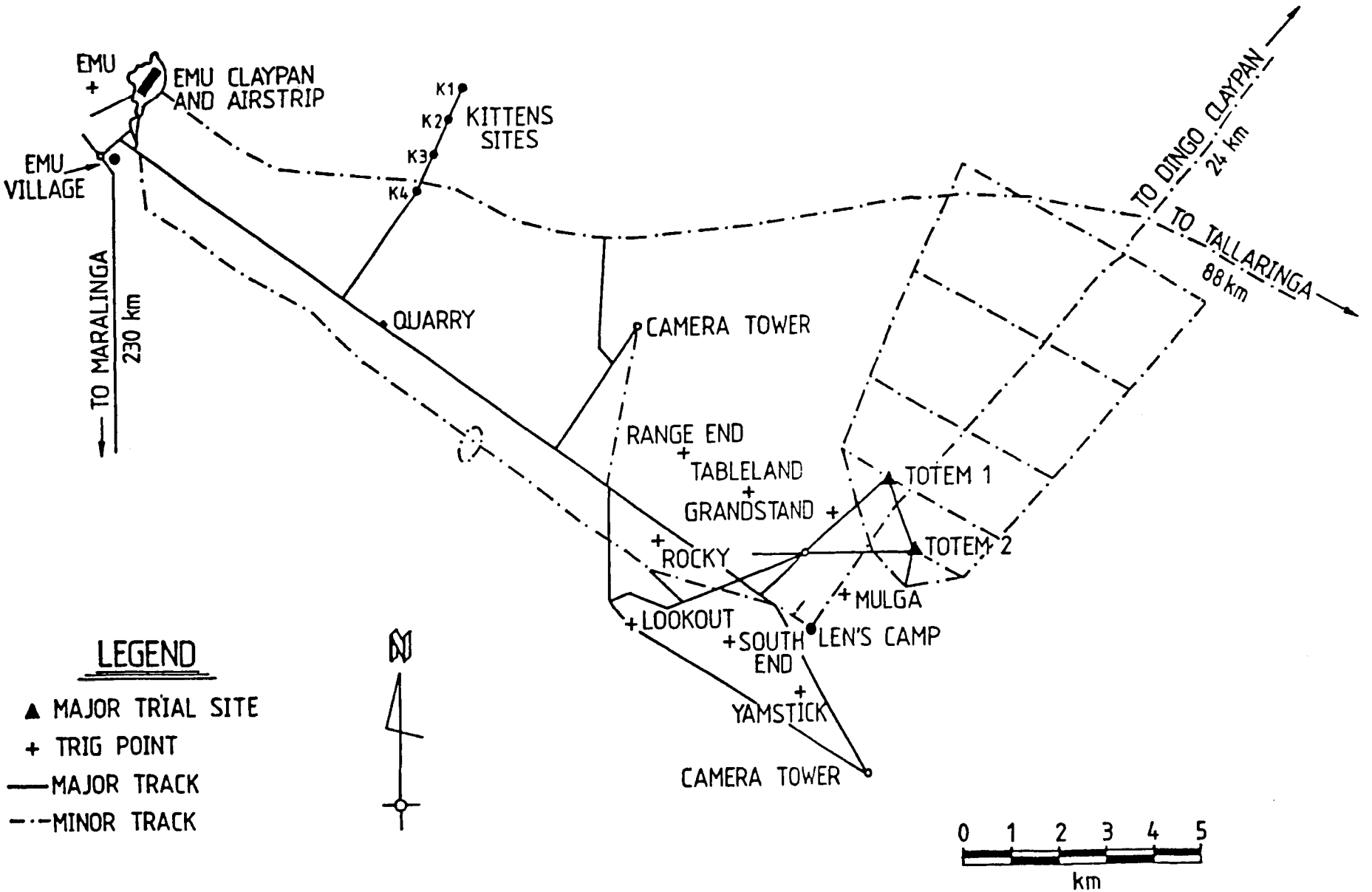


Figure 2. Map Showing the Locations of the Major and Minor Trials Sites at Emu

2.1 Major Trials

In 1953, two major nuclear trials (code-named Totem 1 and Totem 2) were performed at Emu. In 1956, at Maralinga, four major nuclear trials (code-named One Tree, Marcoo, Kite, and Breakaway) were carried out in Operation Buffalo; and in 1957, three trials (code-named Tadje, Biak, and Taranaki) were carried out in Operation Antler. The smallest of these were Tadje and Marcoo, each with an approximate yield of one kiloton. The largest was Taranaki, with an approximate yield of 27 kilotons. All of the ground zeros are now marked with concrete plinths.

All nuclear devices at Maralinga and Emu were exploded on 31-meter towers with the exception of Marcoo (ground level), Kite (an airdrop at 150 meters), and Taranaki (balloon-borne at 300 meters).

In an atomic explosion at the instant of detonation, there is a burst of intense gamma and neutron radiation followed by the formation of a mushroom cloud containing highly radioactive material. This cloud can rise to a considerable height, and the radioactive material may be carried long distances by the wind. The radioactive debris that is deposited downwind on the ground is called fallout. Radioactive contamination on the ground close to the site of an atomic explosion results from both the close-in fallout and the action of the intense pulse of neutrons on elements in the soil, which makes these otherwise stable elements radioactive by a process called neutron activation.

The principal neutron activation products remaining in the soil are cobalt-60 and europium-152; and the principal remaining fallout components are strontium-90, cesium-137, and europium-155. Because of the radioactive decay of the radionuclides of short half-lives, the radiation levels close to all nine ground zeros at Maralinga and Emu are now very low and are insignificant beyond a 200-meter radius. By the year 2030, all ground zeros, with the exception of Tadje, will be safe for continuous occupancy.

At Tadje, because of the nature of the device tested, there is an area extending from ground zero for about 1,000 meters in a north-northeasterly direction which is contaminated with plutonium (and associated americium) as well as some small pellets of cobalt-60. The cobalt-60 has a sufficiently short half-life (5.3 years) that it presents little potential hazard in the long-term, but the half-life of plutonium-239 (24,100 years) is such that this small area north of the Tadje ground zero must be considered a potential hazard well into the future.

The other potential hazard associated with the sites of the six tower-mounted tests at Maralinga and Emu is the presence of glazing (fused sand) which was formed at the time of the explosions. The glazing contains trapped radioactive materials, including plutonium.

2.2 Minor Trials

Five minor trials were performed at Emu in 1953, and several hundred were performed at Maralinga during the years 1955 to 1963 as part of the U.K.

atomic weapons development program. These minor trials were essentially developmental experiments designed to investigate the performances of various components of a nuclear device, separately and in combination. Almost all involved radioactive materials with conventional high explosives. The four main types of minor trials were code-named:

Kittens - performed at Emu and on the Kittens Lanes at Naya.

Rats - performed at the Rats Lanes at Naya, north of TM100, and at Dobo.

Tims - performed at Kuli, TM2 at Naya, TM50, TM100, and TM101.

Vixen - performed at Wewak and Taranaki.

The Australian Radiation Laboratory (ARL) has surveyed the minor trial sites at both Maralinga and Emu. In many cases, the sites have been adequately cleaned up or the radioactive materials used were of sufficiently short half-lives that they are no longer detectable. The sites with significant remaining contamination are as follows:

A. Kuli

Over 7,000 kilograms of uranium were explosively dispersed as well as 65 kilograms of beryllium (a low-density gray metal which is not radioactive, but is chemically toxic). Much of the uranium and beryllium was scavenged at the time of the trials and is

presumed to be buried in a large pit on the northern side of the Kuli site. However, there are many pieces of uranium metal (very dense and having a yellow surface coating) as well as fluffy yellow pieces of uranium oxides near the firing pad in the center of the site and further to the east. Small pieces of beryllium metal can also be found.

B. TM50

Uranium and beryllium were explosively dispersed at this site. A small area east of the roadway, just north of the concrete base of a blockhouse, is contaminated with finely dispersed uranium and beryllium.

C. Kittens Lanes at Naya

Throughout the area surrounding these five lanes, there is a light distribution of metal debris (largely steel) which has been overlooked in earlier cleanup operations. Some of these metal pieces are lightly contaminated on the surface with natural uranium. There is also a smattering of other debris, including old cables and phosphor-bronze or brass canisters, none of which is radioactive.

D. Wewak

Burnings and explosive dispersals of beryllium, uranium, and plutonium occurred here. The remaining hazard results from the dispersed plutonium. The site of the plutonium burning (VK33) was the northernmost of the herringbone pattern of sites on the east side of the roadway. The two explosive dispersals (approximately 570 grams of plutonium) took place at sites VK60A and VK60C, situated on the circular track to the east of the herringbone layout. There are pieces of metal contaminated with plutonium surrounding VK60A and VK60C, and a temporary fence has been erected around most of this debris.

E. TM100 and TM101

Explosive dispersals of plutonium (approximately 800 grams at each site) took place at both of these locations. Five-hundred grams of plutonium from TM101 were returned to the U.K. in 1979. There is a high concentration of plutonium-contaminated fragments and smaller friable particles close to the firing sites, the general locations of which are now marked by concrete plinths. Temporary fences have been erected around these areas to contain much of the contaminated material; but at TM100, contaminated pieces of metal can be found at considerable distances from the site, even as far as the Rats Lanes to the north.

F. Taranaki

Taranaki is the site at Maralinga which is most extensively contaminated with plutonium and, therefore, represents the major remaining potential hazard to health. It was the site of the final major atomic detonation at Maralinga in October 1957. This was a balloon-borne test which left very little contamination. Between 1960 and 1963, the area just north of ground zero was used for 12 Vixen B trials in which approximately 22 kilograms of plutonium were explosively dispersed in a sector of several hundred hectares, extending from the west through north to northeast of the site. Uranium-235 and beryllium were also dispersed in these trials.

The plutonium contamination at Taranaki occurs mainly in three forms: as a fine dust, as small submillimeter particles, and as surface contamination on larger fragments. In the trials, the plutonium was dispersed in narrow plumes; the main ones extended to the west, northwest, north, and northeast of Taranaki. The most extensive of these is the northwest plume which can be detected crossing West Street between Fifth and Tenth Avenues. In the central area at Taranaki, the surface soil was ploughed in Operation Brumby. Beyond the ploughed area, the plutonium contamination tends to be on or near the surface and includes many thousands of contaminated fragments large enough to attract

attention as potential souvenirs. The types of fragments include wire, rusty steel plate, lead, pieces of a low-density gray metal, bitumen, and a yellow plastic material.

A man-proof fence encloses the 21 burial pits, all the firing pads, and most of the contaminated area at Taranaki. A more extensive temporary fence was erected in 1984 to enclose many of the contaminated fragments, but large numbers are known to exist beyond the fenced areas.

2.3 Burial Pits

At Maralinga, radioactive waste was buried in pits at Taranaki, TM50, TM101, Kuli, Dobo, the Tietkens Plain Cemetery, the Airfield Cemetery, and in the Marcoo bomb crater. All burial pits containing plutonium are enclosed in man-proof fences. Vast quantities of nonradioactive material were buried at other sites on the Maralinga Range, in the Marcoo crater, and in deep pits on the north side of the Kuli road.

3.0 SITE DESCRIPTION

Maralinga is situated on the edge of the Great Victoria Desert, approximately 500 kilometers southwest of Alice Springs and 270 kilometers northwest of Ceduna (see Figure 3). The nearest settlement is 40 kilometers south at Watson, a cluster of four houses at the start of the long straight section of the Trans-Australian Railway Line on the northern edge of the Nullarbor Plain. Rock from the limestone quarry at Watson is rich in the fossils of sea creatures, indicative of when the Nullarbor Plain was the bed of an ancient sea.

Maralinga Village and the minor trial sites, Kuli and TM50, are located in sandhill country. However, the other trial sites are situated on an extensive dolomite plain to the north, known as Tietkens Plain. Still further north near Second Avenue, Tietkens Plain gives way to more sandhills.

The whole area is rich in native flora and fauna. At most times of the year, some species of eucalypt (mallee gum) are in flower, and there are some fine large casuarina trees (bull oaks). Lower to the ground, one finds mulga and, on the dolomite plain, salt bush and blue bush. After rains, patches of colorful Sturt's desert pea creeper can be seen; and on the sandhills, there are clumps of triodia (spinifex grass).

Kangaroos are plentiful on Tietkens Plain, especially after rain. There are also dingoes, bustards (bush turkeys), several varieties of lizards, snakes (king brown), various marsupials, foxes, the ubiquitous rabbit, and even an

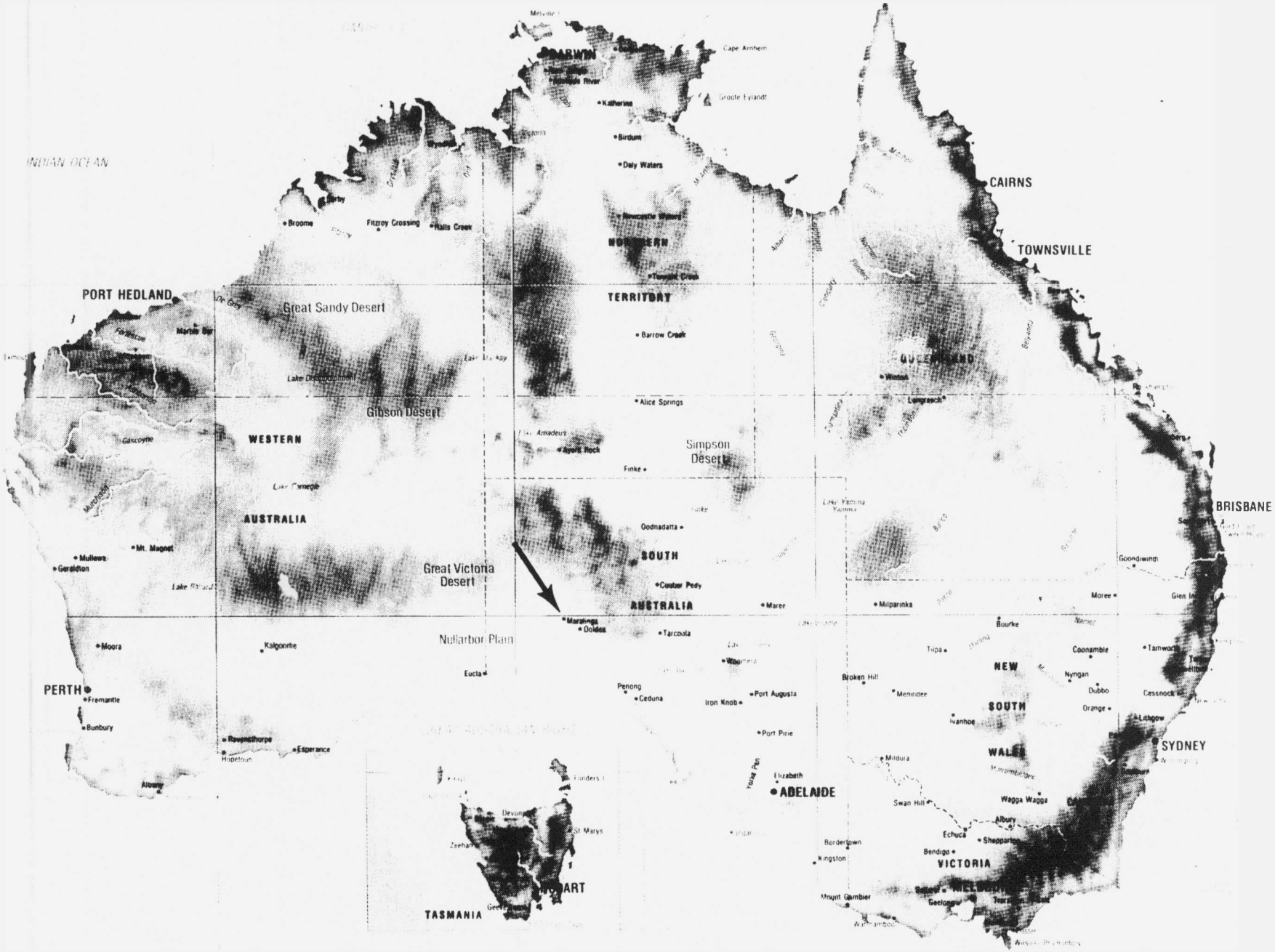


Figure 3. Map of Australia Showing the Location of Maralinga

occasional camel. Birds are plentiful including parrots, hawks, and wedge-tailed eagles.

The area was first visited by Tietken, an explorer in the 1870s, who built a dwelling on the area now known as Tietkens Plain. The remains can still be seen north of Roadside near the concrete plinth erected to commemorate Operation Brumby. On the opposite side of the road is one of the two wells dug by Tietken in a vain search for potable water. The other well is nearby in a southeasterly direction. In fact, the area abounds in underground water with a number of deep bores in the sandhills near the Maralinga Village providing high flow rates of salty water. A feature of the dolomite plain is the presence of depressions which are collection areas for rain. About 5 kilometers south of Taranaki on the east side of the road, in such a depression, is Freshbore, the water of which is quite drinkable albeit with a high-mineral content. An area of approximately 2,000 square kilometers encompassing Maralinga village and the test areas is known as Section 400. The land surrounding Section 400 is Aboriginal territory, and entry onto these Aboriginal lands is forbidden without formal approval.

4.0 SURVEY PLAN

The survey at Maralinga was split into four areas (see Figure 4) based on historical documentation and prior survey work. Area 1 encompassed all the major trial sites and the expected contamination from the minor trials at Taranaki. Area 2 was included as a buffer north of Area 1 in case the measurable contamination extended further than expected based on past measurements. Area 3 included Wewak, TM100, TM101, Kittens, and Dobo. Area 4 included the Maralinga base camp area, the airfield, TM50, and Kuli.

With the exception of Area 2, all these areas were surveyed at an altitude of 30 meters with 50-meter line spacing. This altitude and line spacing was based on a compromise between sensitivity and spatial resolution, on one hand, and the time and associated cost of doing the survey on the other. Except for the known northwest plume from Taranaki, no other contamination was expected in Area 2. Because of this, the initial plan was to survey this area on a 200-meter grid. This was changed to a 100-meter grid during the survey as a result of detecting contamination extending through Area 2 from the north and northeast plumes from Taranaki. In addition to the finer line spacing, Area 2 was also expanded approximately 3 kilometers to the north and 8 to 10 kilometers to the west during the survey to enclose the measurable activity.

A fifth area was also flown at Emu. This area included the Totem 1 and 2 sites, the Kittens Lanes, and the village area. The area was flown at an altitude of 30 meters with 200-meter line spacing. Within the Totem 1 and 2 areas and their respective plumes, however, 100-meter lines were flown.

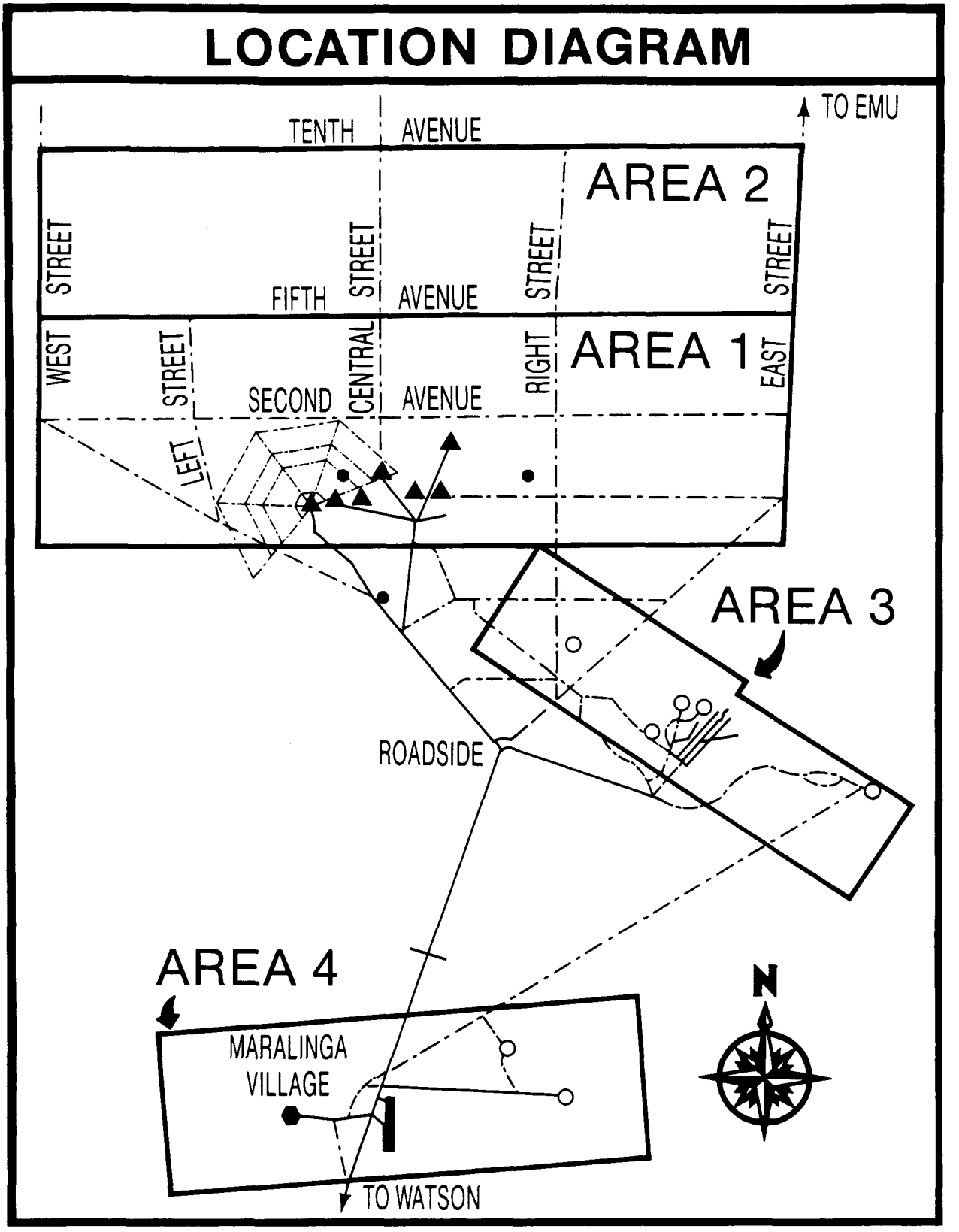


Figure 4. Original Survey Boundaries for the Four Areas Flown at Maralinga

5.0 SURVEY EQUIPMENT

The aerial survey was conducted with an array of forty 12.7-cm diameter by 5.1-cm thick sodium iodide (NaI) scintillation detectors mounted within two pods hung externally on a British Royal Air Force Wessex, HC.Mk2 helicopter (Figure 5). Signals from 39 detectors were combined in four ten-way summing amplifiers, also located in the detector pods. Outputs from the ten-way summing amplifiers were combined in a four-way summing amplifier located within the helicopter. The output from this amplifier was routed through an analog-to-digital converter (ADC) into a 1024-channel multichannel analyzer. Output from the remaining single detector was routed into a separate 1024-channel multichannel analyzer. This second set of spectral data was used in areas of high count rates such as those encountered over several of the major trial sites where spectral distortion, due to pulse pile-up, led to significant errors in processing the primary spectral data. The second set of spectral data also provided a quality control check on the primary data.

5.1 Data Acquisition System

A specially designed data acquisition system called REDAR IV (Radiation and Environmental Data Acquisition and Recorder) was used during this survey. This is a low-power, lightweight system that can operate directly from the 24V DC power normally available within most aircraft. This system is normally operated in a special compression mode that compresses the 1024 channels of data into 256 channels prior to storing them on tape. The spectrum is divided into three groups. Data in the first group, consisting

Figure 5. The Royal Air Force Wessex HC.Mk2 Helicopter Shown with the Gamma Ray Detector Pods Installed

of the first 75 channels, are stored directly. Data in the second group, the next 330 channels, are summed in three-channel increments and then stored. Data in the third group, the next 612 channels, are summed in nine-channel increments and then stored. Data in the next five channels are stored in channel 254. Data in channel 1023, which records the overflow counts, are stored in channel 255. Neither the original 1024 nor the compressed channel 256 are used.

This compression scheme is especially useful with NaI detectors because of their variation in resolution with energy. With the foregoing compression scheme and a full-scale energy of 2-4 MeV, the photopeak widths are approximately the same within each group. Thus, it is possible to gain a factor of four in the amount of data storage required without compromising photopeak identification capability.

The 256 channels of compressed spectral data are recorded every second. The REDAR system has two sets of spectral memories, and each memory can accumulate four individual spectra. The two memories are operated in a flip-flop mode every four seconds for continuous data accumulation. While one memory is storing data, the other is being transferred to magnetic tape.

Two additional memories are used to store nonspectral data. They operate in the same flip-flop mode as the spectral memories. The nonspectral data generally include aircraft position, altitude, time of day, and special labels to code individual flight lines as well as other parameters that might be required such as outside air temperature and pressure.

Both gamma ray spectral and nonspectral data are acquired every second and recorded on four-track cassette tapes every four seconds. The REDAR system has two tape recorders. Each tape can record approximately one hour of data. At the end of the tape, the system automatically switches to the second recorder. If the first tape has been replaced, the system will automatically switch back after the second tape is full. Thus, long flights can be accomplished with very little attention to the recording system.

A display is available for real-time examination of the spectral data. The data can be reset, added to, or subtracted from the display without affecting the recorded information on tape. This real-time display was utilized during the flights to help verify the proper operation of the system.

An energy calibration was performed prior to the start of each flight day using Na-22 and Am-241 calibration sources. The energy gain could be adjusted within the ten-way summing amplifiers and the four-way summing amplifier to normalize the output from each detector. Maintaining power to the system on a 24-hour-a-day basis helped to reduce to a negligible level any gain shift that might occur within a given flight.

5.2 Helicopter Positioning System

Position data were obtained using an ultrahigh frequency ranging system (URS). This system employs two remote units placed some distance apart on

the ground. A master unit is carried aboard the aircraft. The distance of the helicopter from each remote unit is determined by measuring the average round trip time of travel for a pulsed signal. These distances, which are recorded once each second, together with the measured distance between the two remote units allow the aircraft position to be determined relative to any survey coordinate system.

Flight lines, spaced 50 meters or 100 meters apart, were flown with the aid of a steering indicator that utilized the position data supplied by the URS.

All flight lines were flown at an altitude of 30 meters with an approximate ground speed of 60 knots (30 meters per second). Altitude data were obtained from a radar altimeter and were recorded once each second. The radar altimeter data was also fed to the steering indicator to aid in maintaining the survey altitude.

5.3 Data Processing Equipment

Two complete data reduction systems were installed at the laboratory facility established at Maralinga to support the aerial survey. One system was primarily used to perform preflight and postflight checks to verify that all data were properly recorded on tape. This system was also used to transfer the data to nine-track magnetic tape for long term storage. The second system was used to perform preliminary data processing in the field. Final data processing was performed in Las Vegas, Nevada, after completion of the survey.

6.0 SURVEY PROCEDURES

The Maralinga survey was divided into five areas (Areas 1 and 2 were contiguous). The method for surveying each area was much the same. First, URS transponders were set up outside the survey area so that the center of the survey area and the locations of the two transponders approximated an equilateral triangle. The aerial system was then flown at a 30-meter altitude over roads and landmarks appearing on Royal Australian Survey Corps maps of the survey area. An initial "zero" line was flown between two landmarks in the survey area to establish the survey flight line direction. The data from this initial flight were used to obtain flight parameters for subsequent flight lines to be flown parallel to the zero line at predetermined spacings. Initial data were also used to scale the flight path to the roads, etc., appearing on the map.

The survey area was flown at a 30-meter altitude and 60 knots velocity with flight lines parallel to the zero line at predetermined spacings. The pilot flew the lines guided by the REDAR steering indicator which was accurate to within plus or minus 5 meters.

The integrity of the gamma data were checked both before (preflight) and after (postflight) each survey flight. Many automatic checks on data quality have been developed and are integrated into the data reduction system. Some manual checks were also made before and after each flight to accommodate spurious electronic noise arising from the system's helicopter

interfaces. Problems observed in the preflight were corrected prior to launching the aircraft. Errors determined in postflight analysis normally resulted in all or part of the flight having to be reflown.

The survey gamma data were copied from the cassette tapes to industry standard half-inch, nine-track tapes which were processed to obtain the appropriate contour plots. In general, the data was processed within a day or less after completing a flight. This helped to assure data integrity and also allowed variations in the survey plan, such as those required for Area 2, to be made in near real time.

7.0 DATA ANALYSIS

7.1 Processing Techniques

The aerial system collects gamma ray spectra and position information on a second-by-second basis. This information is combined to produce radiation contour maps such as those showing the magnitude and location of man-made radioactivity on the Maralinga test range.

Figures 6 and 7 show a typical spectrum due to naturally occurring radioactivity at Maralinga. Figure 7 is an expansion of the low-energy portion of the spectrum showing the region where the Am-241 photopeak at 59.5 keV occurs. It is from such background spectra that photopeaks from man-made activity must be extracted. As an example, Figure 8 displays the low-energy portion of a spectrum from TM100 showing the presence of Am-241. The significant concentrations of Am-241 make the 59.5 keV photopeak easily visible on the large Compton continuum. The net Am-241, 59.5 keV, photopeak in Figure 9 was obtained by subtracting a neighboring background spectrum from that of Figure 8. Figures 10 and 11 show a gross spectra and a background subtracted spectra, respectively, from a typical fallout area. The photopeak from cesium-137 clearly stands out in the background-subtracted spectra.

The background-subtracted spectral data, as illustrated in Figures 9 and 11 make identification of man-made activity easier. In practice, a slightly different technique was used to remove background contributions during data processing to produce the man-made isotopic contour maps. This procedure

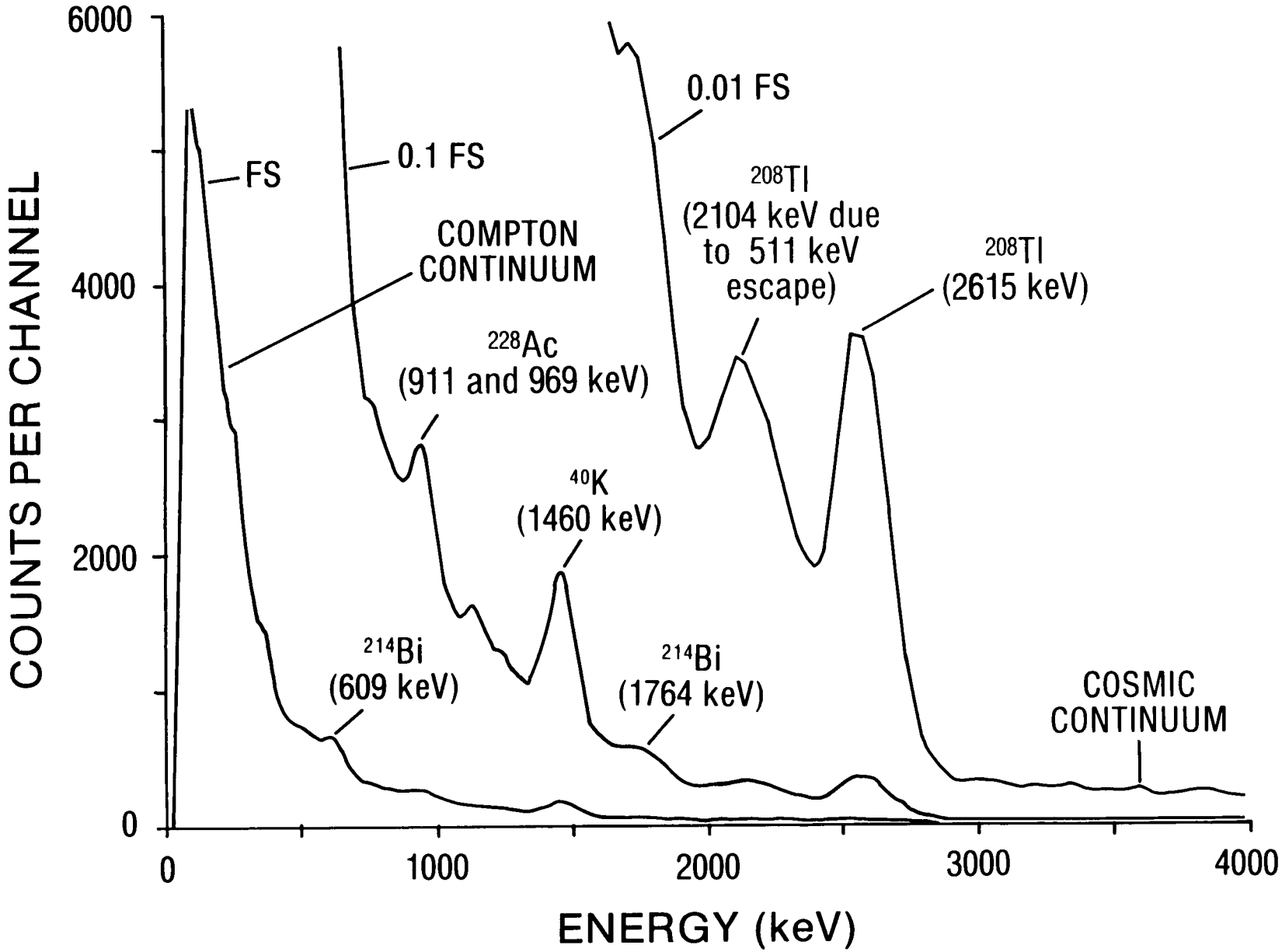


Figure 6. Typical Natural Background Radiation Spectrum Obtained at Maralinga

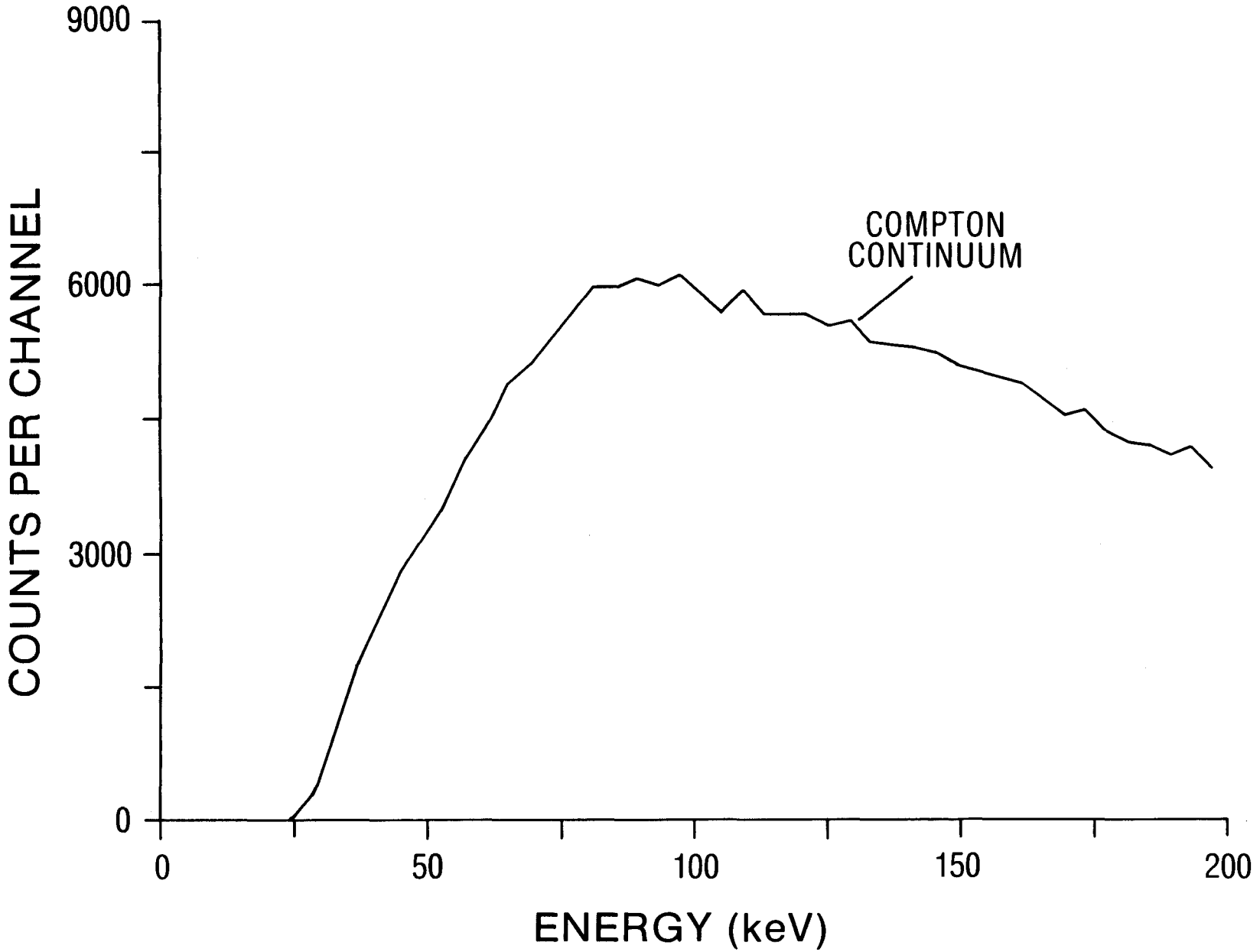


Figure 7. Expanded View of Figure 6 Showing the Low Energy Portion of the Spectrum

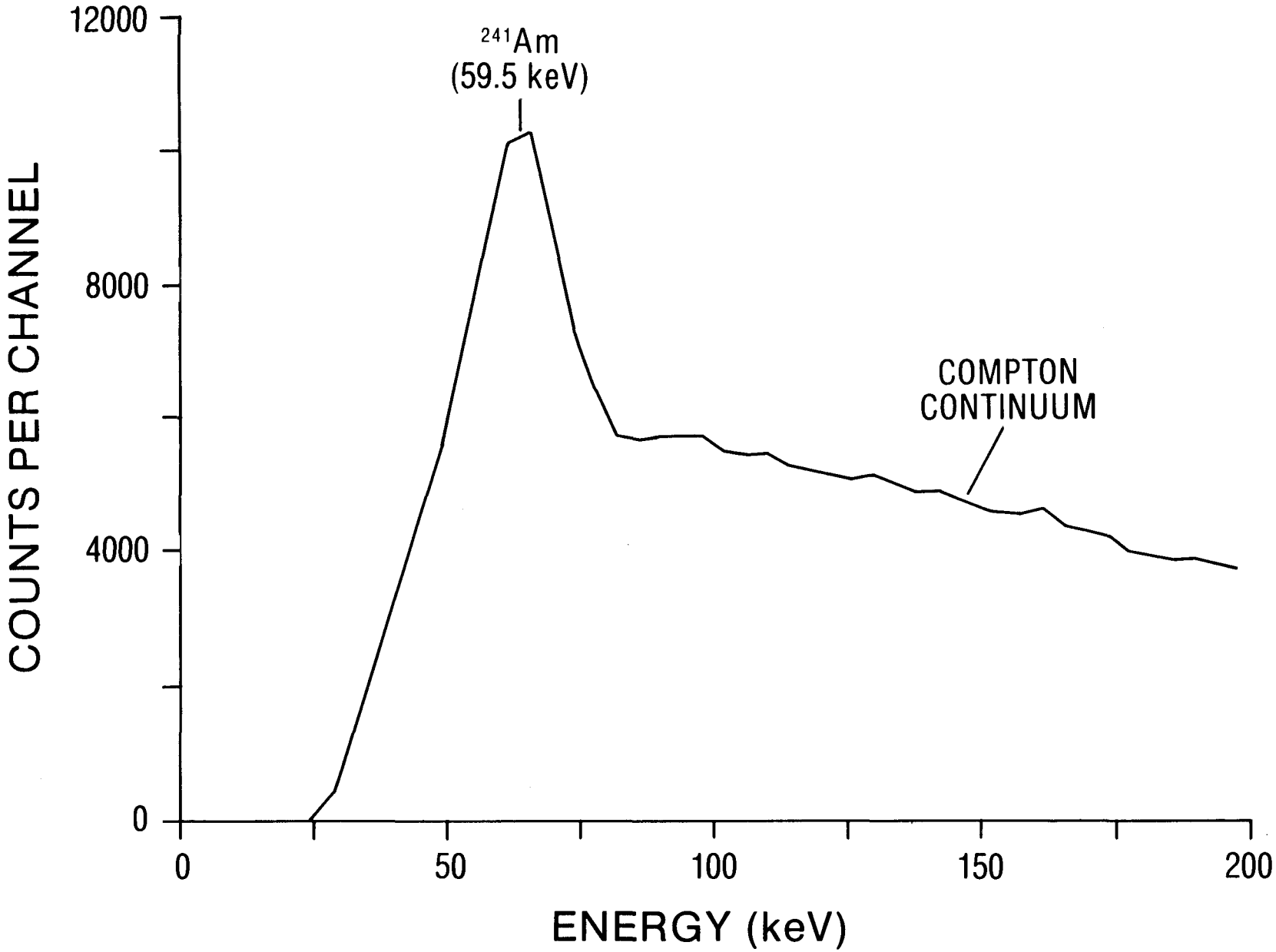


Figure 8. Low Energy Portion of a Spectrum Obtained over TM100 Showing the Presence of Am-241

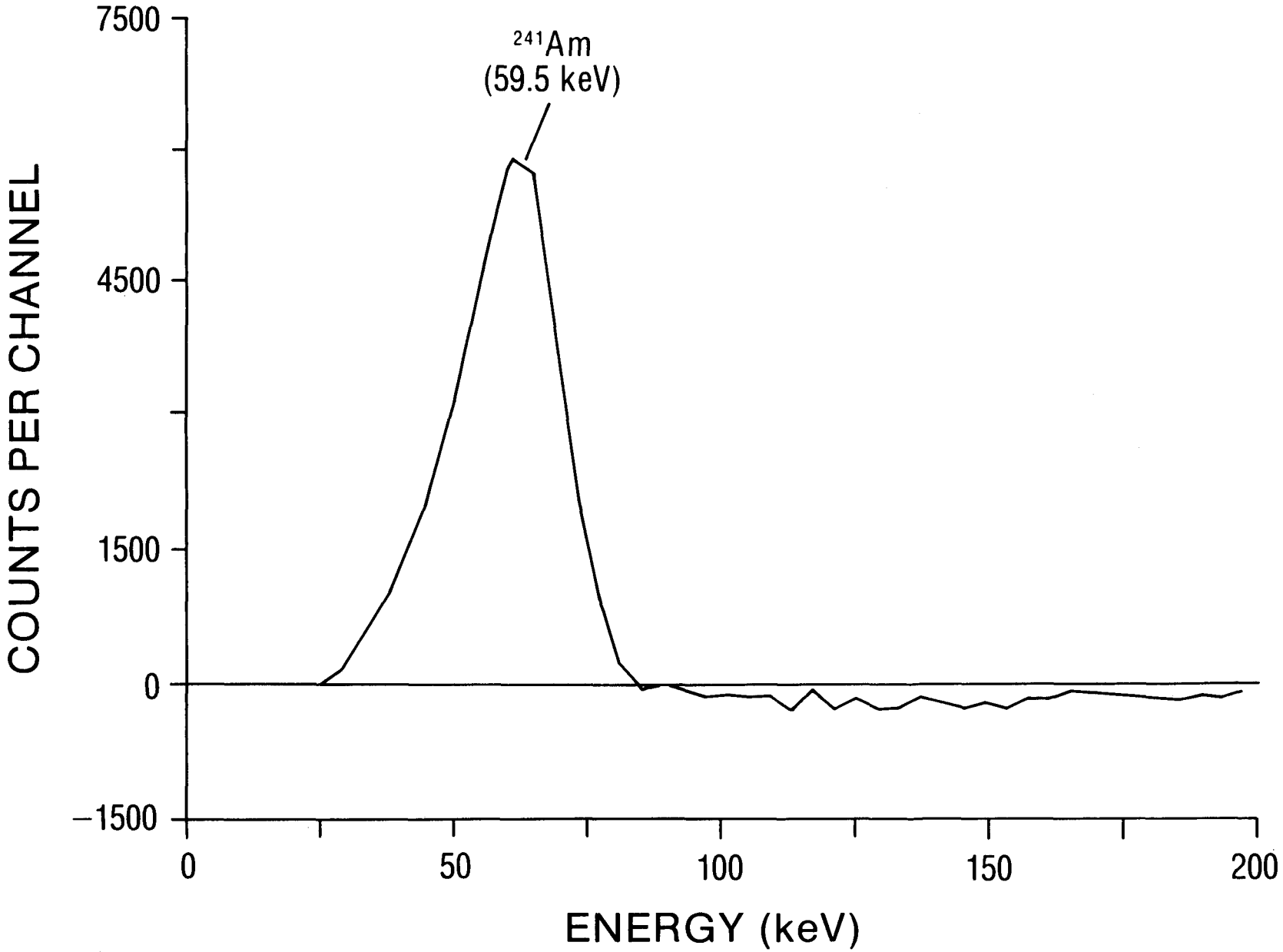


Figure 9. Results of Subtracting the Natural Background Component from the Spectrum Shown in Figure 8

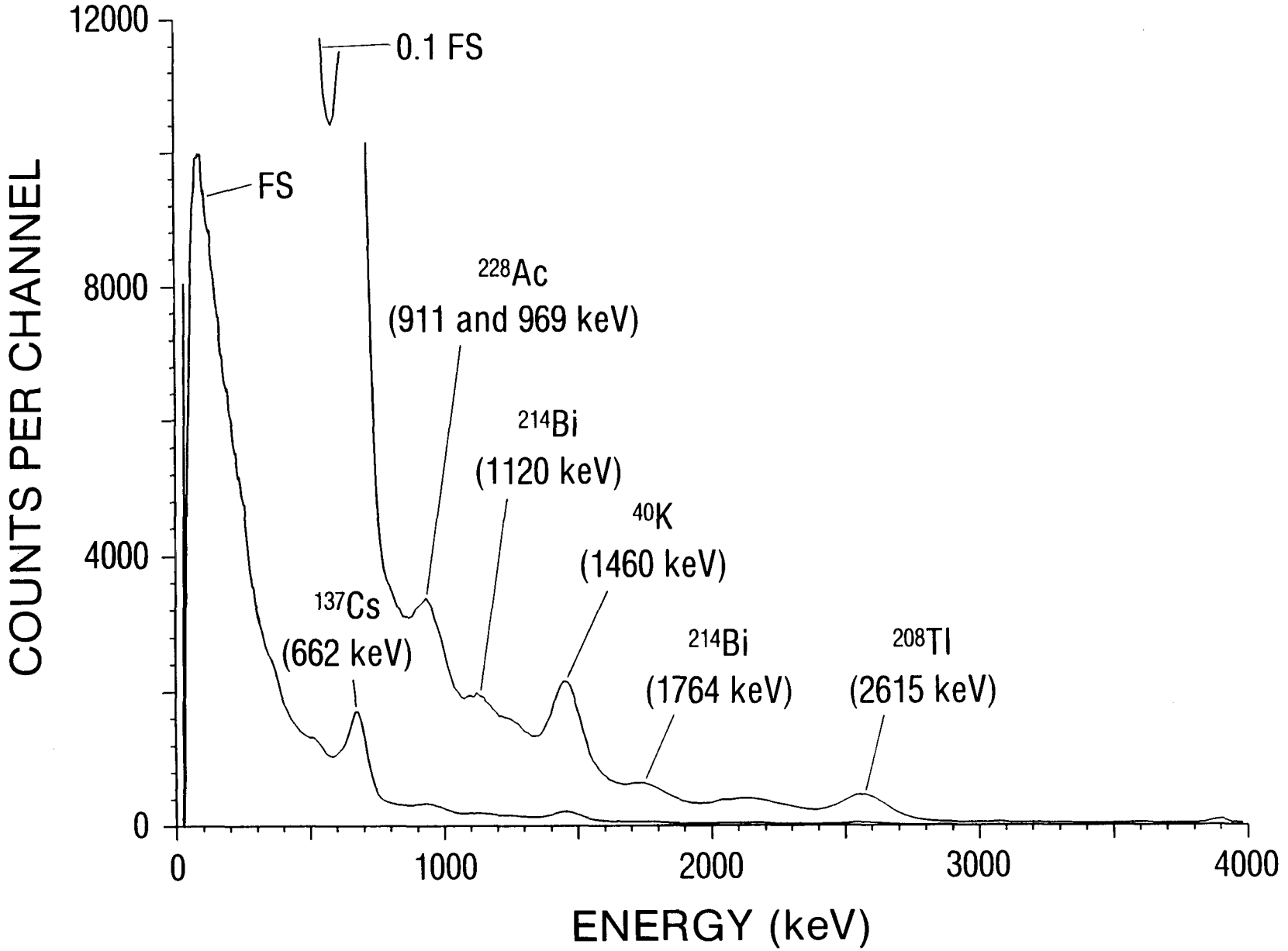


Figure 10. Spectrum Obtained Over the Northeast Portion of Areas 1 and 2 Showing the Presence of Cs-137

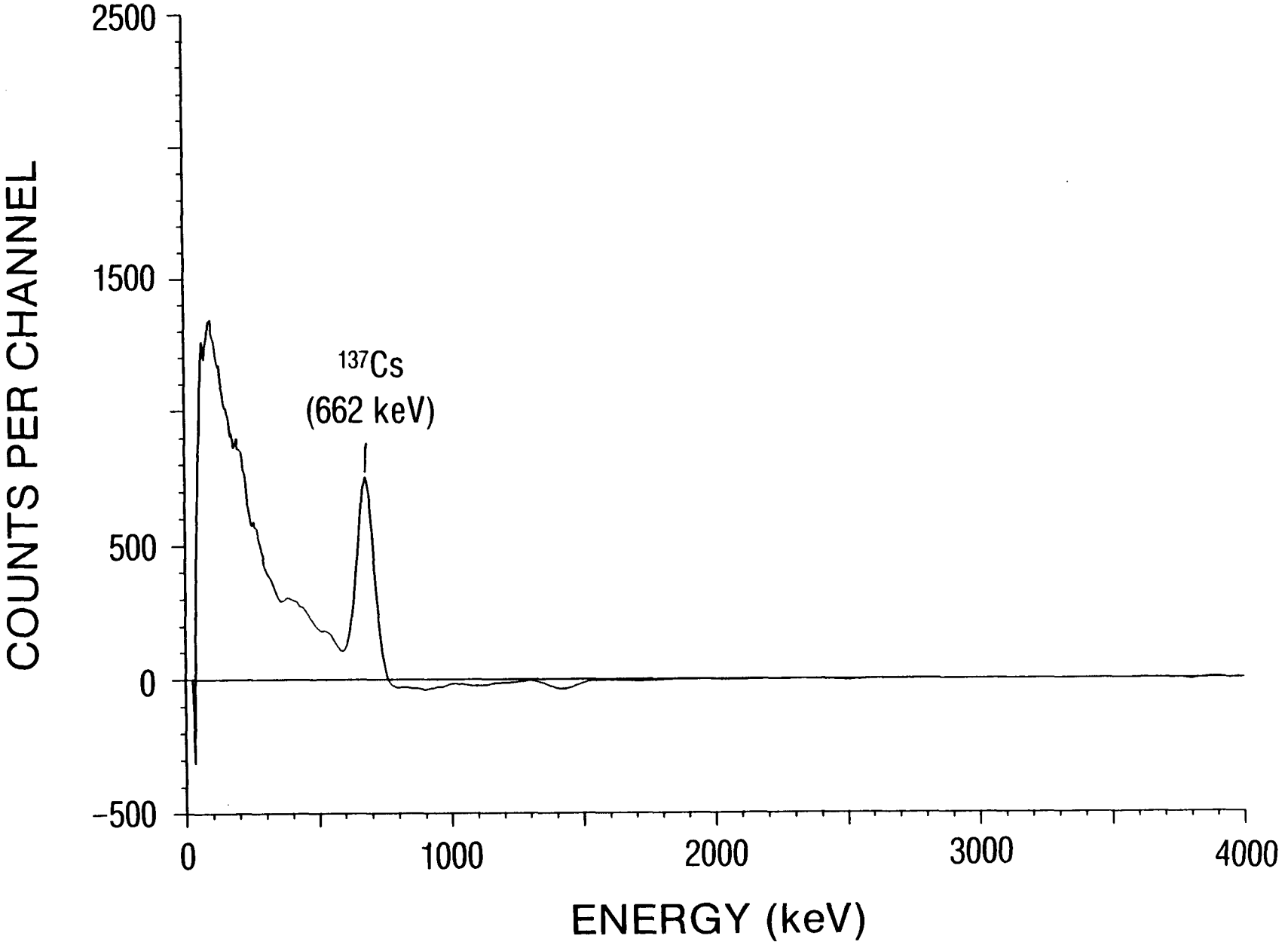


Figure 11. Results of Subtracting the Natural Background Component from the Spectrum Shown in Figure 10

employs the empirically established fact that, although background radiation levels may vary within a given area, the spectral shape remains relatively constant. In particular, the ratio between any two regions of the spectrum is essentially constant within a given area. The following processing procedure makes use of this characteristic of the background spectrum. A section of the spectrum, defined by an energy interval which includes the photopeak of interest, is evaluated for count rate each second along a flight line. This is the signal window, A:

$$A = \sum_{E=a}^{b} ES \tag{1}$$

where E = energy, and

ES = energy spectrum

A second window, B, generally higher in energy range than the photopeak window, is also evaluated along the flight line.

$$B = \sum_{E=c}^{d} ES \tag{2}$$

The ratio (K) of A/B will be relatively constant over a homogeneous natural background. When a photopeak of the isotope of interest appears, the ratio will increase above the constant value. Thus, the presence of the isotope is observable.

The software of the data processing system actually evaluates the following expression each second:

$$S = A - KB \tag{3}$$

The net signal, S, oscillates around zero as a result of counting statistics until an area containing the isotope of interest is encountered, which results in S becoming a positive value. The areas of positive S are then represented by the appropriate contour interval in the isotopic contour map. Table 1 lists the windows used for isotope evaluations at Maralinga. An average ratio, K, was determined for each set of windows over the major portion of the background of each survey area.

Figure 12 shows the results of processing the data for a flight line 460 meters south of Second Avenue at Maralinga for Am-241 using Equation 3. The north and northwest plumes are clearly visible. Also shown are the statistical oscillations around zero in the background areas which result from applying Equation 3 to statistically varying second-by-second count rates. The northeast plume is also visible in Figure 12. This area shows a lot of statistical oscillations similar to the background areas, but the oscillations are around a net positive value rather than zero as in the background areas.

Comparing the signal obtained over the northeast plume with that over background areas illustrates the difficulty in extracting weak signals from background in the aerial data. Several specialized data processing

Table 1. Energy Windows Used for Maralinga Data Processing

Isotope	Signal Window (keV)	Background Window (keV)
All[1] (Gross Count)	38-3026	None
MMGC[2] (Man-Made Gross Count)	38-1394	1394-3026
Am-241	38-74	74-102
Cs-137	590-734	734-854
Eu-152, Co-60[3]	974-1550	1550-3026
Pa-234m[4]	50-1106	1106-3026

[1] The entire terrestrial spectrum (GC) is generally mapped to yield terrestrial exposure and test system integrity.

[2] The Man-Made Gross Count (MMGC) uses a wide signal window to search for any undefined isotopes and as a system check.

[3] A more complex four-window algorithm was used to extract Co-60 from Eu-152 in Areas 1 and 2.

[4] A wide signal window was used for Pa-234m (a decay product of U-238 used to detect its presence) to maximize sensitivity.

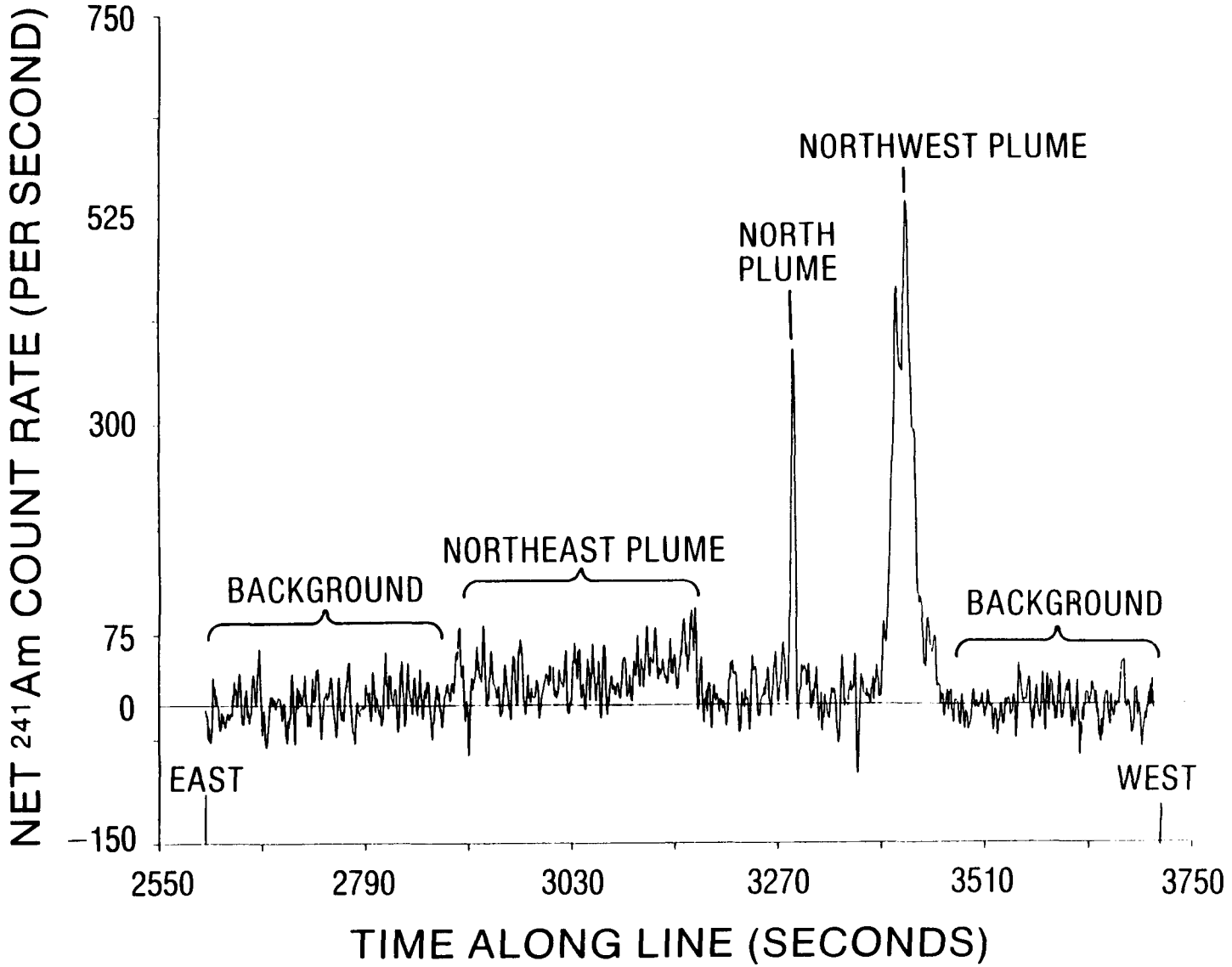


Figure 12. Flight Line Flown in Area 1 Showing the Results of Processing the Aerial Data for Am-241

techniques were utilized to help enhance the ability to detect such small signals. The first involved applying a three-point, sliding interval average to the extracted data. In this procedure, three adjacent data points are averaged with the average value being assigned to the middle position. Adding the next point in line and deleting the first point leads to the next three-point average which is again assigned to the position of the middle point. This procedure is continued along the entire flight line. Only original data are used in the process, and essentially the same number of data points remain after averaging. This process smoothes the data with little degradation in spatial resolution or sensitivity to localized sources. All Maralinga data were processed using this three-point averaging process.

The second procedure involved a much more extensive averaging area which severely distorted the spatial resolution and reduced the sensitivity to localized sources but enhanced the sensitivity to very large area contamination by approximately a factor of three. Twenty-four data points consisting of six points along four adjacent flight lines were averaged together. The average value was assigned to the center of the square (approximately 200 meters on a side) formed by the 24 points, which approximates the field-of-view of the airborne system. The averaging routine then moved to the next 24 points without using any prior data. Thus, the total data points were reduced by a factor of 24.

All Maralinga data were also processed using this averaging technique. Due to the distortions introduced in the large-area averaging, these results were only used to define the outer edges of plumes. To avoid confusion

after combining the two sets of data, the outer contour line obtained from the 24-point average was plotted as a dotted line while the inner contours obtained from the standard three-point, sliding interval average were plotted as solid lines.

Although processing the data using both types of averaging procedures greatly helped to eliminate purely statistical artifacts, it was still necessary to individually investigate a number of areas using spectral data to ensure that the contours shown on the final results actually represented areas of real contamination. This last stage of the data analysis procedure allowed the aerial data to be processed for maximum sensitivity while greatly minimizing the possibility of statistical anomalies being included.

7.2 Conversion Factors

Conversion factors are determined by combining a measurement of the detector efficiency to a given energy gamma ray with a theoretical calculation of the gamma ray flux arriving at the detector as a function of source distribution in the ground. Derivation of the conversion factors for an airborne detector system follows essentially the same procedures as those for a ground-based detector system.

The unscattered gamma ray flux, , from a point source with activity S_o at a distance r from the source is given by:

$$\phi = \frac{S_o}{4\pi r^2} \; e^{-r/\lambda_a} \tag{4}$$

where λ_a is the gamma ray mean free path in air. This can also be written as

$$\phi = \frac{S_o}{4\pi r^2} \; \exp \left[-(\mu/\rho)_a \; \rho_a \; r \right] \tag{5}$$

where

$(\mu/\rho)_a$ = the air mass attenuation coefficient, and

ρ_a = the air density.

This expression can be expanded to the more general case of a source distributed within the ground. In this case, the unscattered flux of gamma rays of energy E at a height h above a smooth air-ground interface due to an emitter distributed in the soil is given by (see Figure 13):

$$\phi = \int_0^\infty \int_0^\infty \frac{S_v}{4\pi r^2} \exp \left[-(\mu/\rho)_a \; \rho_a \; r_a\right] \; \exp \left[-(\mu/\rho)_s \; \rho_s \; r_s\right] 2\pi \; x \; dx \; dz \tag{6}$$

where

S_v = the activity per unit volume $[(\gamma/sec)/cm^3]$,

$r = r_a + r_s$ (cm),

$(\mu/\rho)_a$, $(\mu/\rho)_s$ = the air and soil mass attenuation coefficients (cm^2/g), and

ρ_a, ρ_s = the air and soil density (g/cm^3).

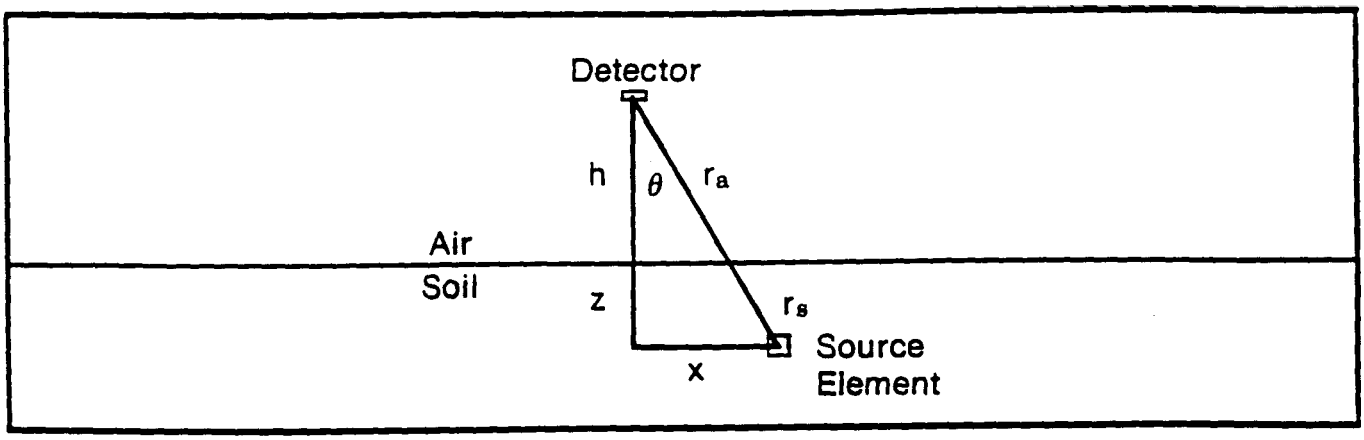


Figure 13. *GEOMETRY USED IN THE DERIVATION OF CONVERSION FACTORS RELATING PHOTOPEAK COUNT RATE DATA TO ISOTOPE CONCENTRATION IN THE GROUND*

This expression assumes a source distribution which varies only with depth. A uniform distribution in the horizontal plane is assumed, which leads to results expressed in terms of an area average over the field-of-view of the detector.

The detector response to a given flux, ϕ, of gamma rays of energy E incident at an angle θ can be given in terms of an effective detector area, A, defined by:

$$A = \frac{N_p}{\phi} \qquad (7)$$

where N_p is the net photopeak count rate normally given in units of counts per second (cps). The effective area, in general, varies as a function of

the gamma ray angle of incidence and is normally written as:

$$A = A_0 R(\theta) \tag{8}$$

where

A_0 = the detector photopeak count rate for a unit flux incident perpendicular to the detector face [(cps)/(γ/cm^2)/sec)] and

$R(\theta)$ = the ratio of the detector response at an angle θ to that at $\theta = 0^0$

Combining equations (7) and (8) with equation (6) leads to an expression which relates the measured photopeak count rate to source activity in the ground. This is given by:

$$N_p = \int_0^{\infty}\int_0^{\infty} \frac{S_v A_0 R(\theta)}{4\pi r^2} \exp\left[-(\mu/\rho)_a \rho_a r_a\right] \exp\left[-(\mu/\rho)_s \rho_s r_s\right] 2\pi x \, dx \, dz \tag{9}$$

In order to evaluate equation (9), it is necessary to make some assumption on the source distribution with depth. Three primary types of source distributions are normally encountered in environmental measurements. Relatively fresh fallout activity is normally represented by a uniform surface distribution. A uniform volume distribution is assumed for naturally occurring background radiation. Fallout activity which has aged into the soil over a period of time is most often represented by an exponential distribution of the form:

$$S_v = S_v^o e^{-\alpha z} \tag{10}$$

where

S_v^o = the activity per unit volume at the surface $(\gamma/\text{sec})/\text{cm}^3$ and

α = the reciprocal of the relaxation length (cm^{-1}).

For this often utilized depth distribution, equation (9) becomes:

$$N_p = \frac{S_v^o A_o}{2} \int_0^{\pi/2} \frac{R(\theta) \tan\theta \exp\left[-(\mu/\rho)_a \rho_a h \sec\theta\right]}{\alpha + (\mu/\rho)_s \rho_s \sec\theta} d\theta \tag{11}$$

This expression relates the measured photopeak count rate (N_p) to the activity per unit volume at the surface (S_v^o). The detector parameters, A_o and $R(\theta)$, are normally obtained empirically for a given system using standard calibration sources. Mass attenuation coefficients for air and typical soils can be found in standard reference tables. Air density varies slowly with outside air temperature and atmospheric pressure and can also be found in standard reference tables. An average soil density of 1.5 g/cm^3 is normally assumed unless actual measured values are available. The detector height can be measured in most cases. The last parameter required to evaluate equation (11) is α which is normally measured in the field since it can vary with location and isotope. Artificial soil disturbance will also affect the value of this parameter.

In general, it is more useful to relate the photopeak count rate data to an average concentration within a given depth rather than a surface concentration as given in equation (11). The average concentration in the top z cm, S_v^z, for a source distributed exponentially with depth is given by:

$$S_V^z = \frac{1}{z} \int_0^z S_V^0 \, e^{-\alpha z} \, dz = \frac{S_V^0}{\alpha z} \, (1 - e^{-\alpha z}) \tag{12}$$

Another result often required is the total activity per unit area. This is given by:

$$S_A = \int_0^\infty S_V^0 \, e^{-\alpha z} \, dz = \frac{S_V^0}{\alpha} \tag{13}$$

The conversion factors derived for all three source distributions relate a measured photopeak count rate, expressed in units of counts per second (cps), to source activity expressed in units of gammas per second per unit area or unit volume. For a specific isotope, the source activity is normally changed to units of curies or bequerels. The average activity per unit volume can also be converted to average activity per unit mass by dividing by the soil density.

Although the man-made radioactivity at Maralinga and Emu has had sufficient time to weather into the soil, adequate values for the depth distribution for specific isotopes had not been obtained prior to the aerial survey. For this reason, all results of the aerial survey have been expressed in terms of equivalent surface activity in units of bequerels per square meter. These values can be converted to more realistic values after depth profile data becomes available. Section 10 provides conversion tables for typical values of the depth distribution determined from previous measurements made at Enewetak and Bikini Atolls and at the Nevada Test Site.

8.0 GROUND MEASUREMENTS

In order to supplement the aerial data, a limited number of ground measurements were made with a high-purity germanium detector. Measurements were made at each of the seven major trial ground zeros at Maralinga and at Totem 1 at Emu. These measurements were made to better resolve the complex gamma ray spectrum present at these locations. In addition, approximately 100 measurements were made in Areas 1 and 2 within and around the plumes from the minor trials at Taranaki.

The detector was an n-type coaxial germanium crystal, 51 millimeters in diameter and 50 millimeters in length, with an efficiency at 1.33 MeV of 23 percent. Measurements were made with the detector on a tripod at a height of 1 meter (see Figure 14). A lightweight, battery-powered 4096-channel analyzer was used to acquire the data. A ten-minute acquisition time resulted in a minimum detectable activity for Am-241 of 0.1 kBq/m^2 as compared to 1.4 kBq/m^2 for the aerial system.

Results of the ground measurements for Am-241 are presented in Section 9.1 along with the aerial survey results. Spectra obtained at the ground zeros are presented in Appendix B.

Figure 14. High-Purity Germanium Detector Used to Obtain Supplemental Ground Measurements

9.0 RESULTS

9.1 Areas 1 and 2

Areas 1 and 2 included the major trial sites of Taranaki, Breakaway, Biak, Marcoo, Tadje, Kite, and One Tree as well as the plumes resulting from the minor trials conducted at Taranaki. The aerial data showed the presence of Am-241, Cs-137, Co-60, and Eu-152. There was no measurable U-235 or U-238. Results for Am-241, Cs-137, and Co-60 are given in Figures 15, 16, and 17, respectively. Contour data for Eu-152 is not presented since this isotope was only found in the immediate vicinity of the major trial ground zeros, with the highest activity at Breakaway, Biak, and One Tree. In addition, the relatively poor resolution of sodium iodide detectors makes it extremely difficult to obtain quantitative data for an isotope with a complex gamma ray spectrum such as Eu-152.

Figure 15 shows the Am-241 results from the aerial survey as well as the ground-based measurements made with the germanium detector. It was not possible to extract Am-241 data from the aerial survey results over Breakaway, Biak, and One Tree due to the high count rates obtained at these locations from Eu-152. Four primary plumes are visible in Figure 15 going to the west, to the northwest, to the north, and to the northeast from Taranaki. There also appear to be several minor plumes associated with both the north and northeast plumes. The limited ground-based measurements seem to correlate reasonably well with the aerial data. The higher sensitivity of the germanium system does show some Am-241 contamination extending beyond the area identified from the aerial survey. In comparing the

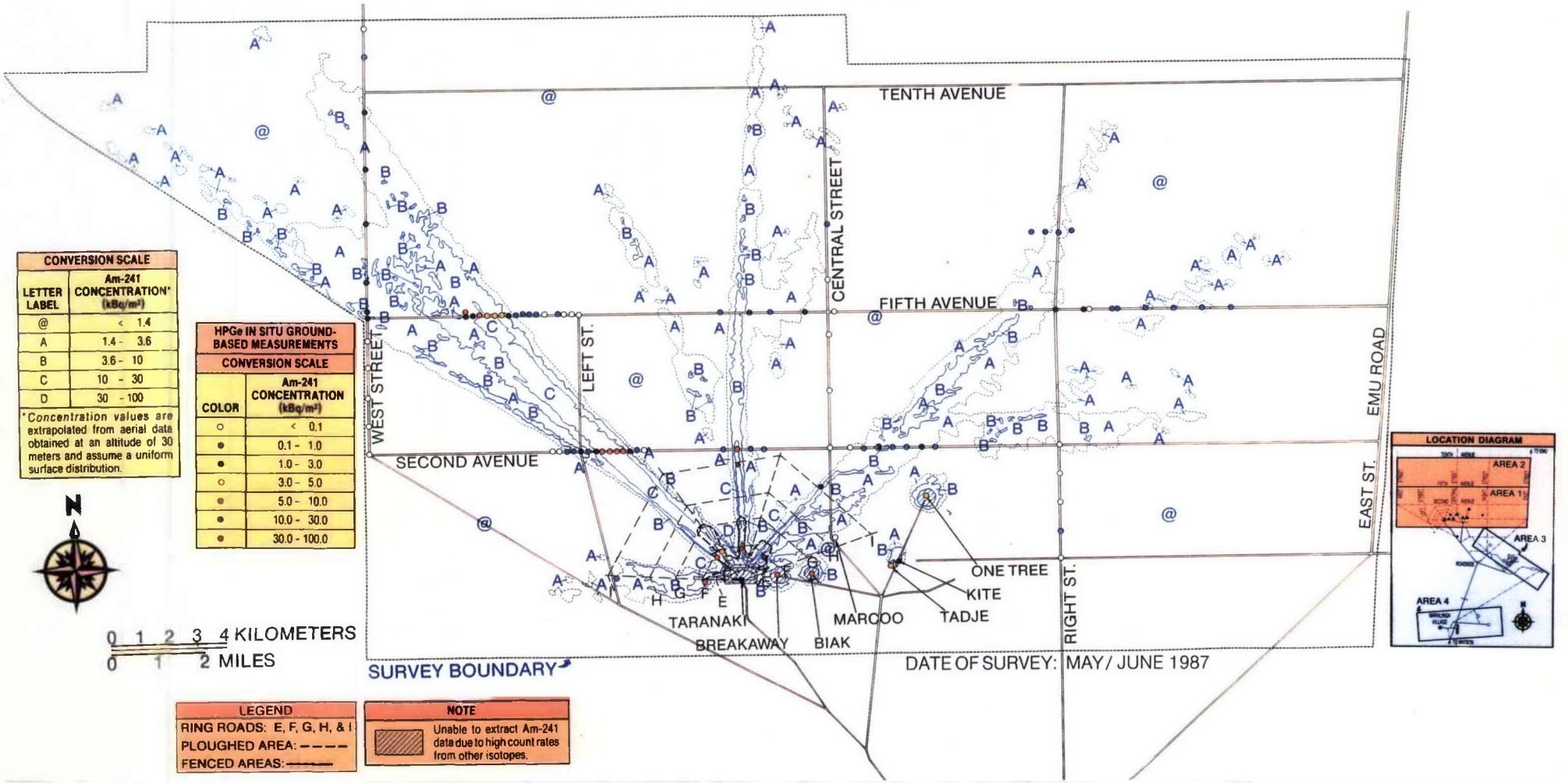


Figure 15. Results of the Aerial Survey Over Areas 1 and 2 Processed for Am-241

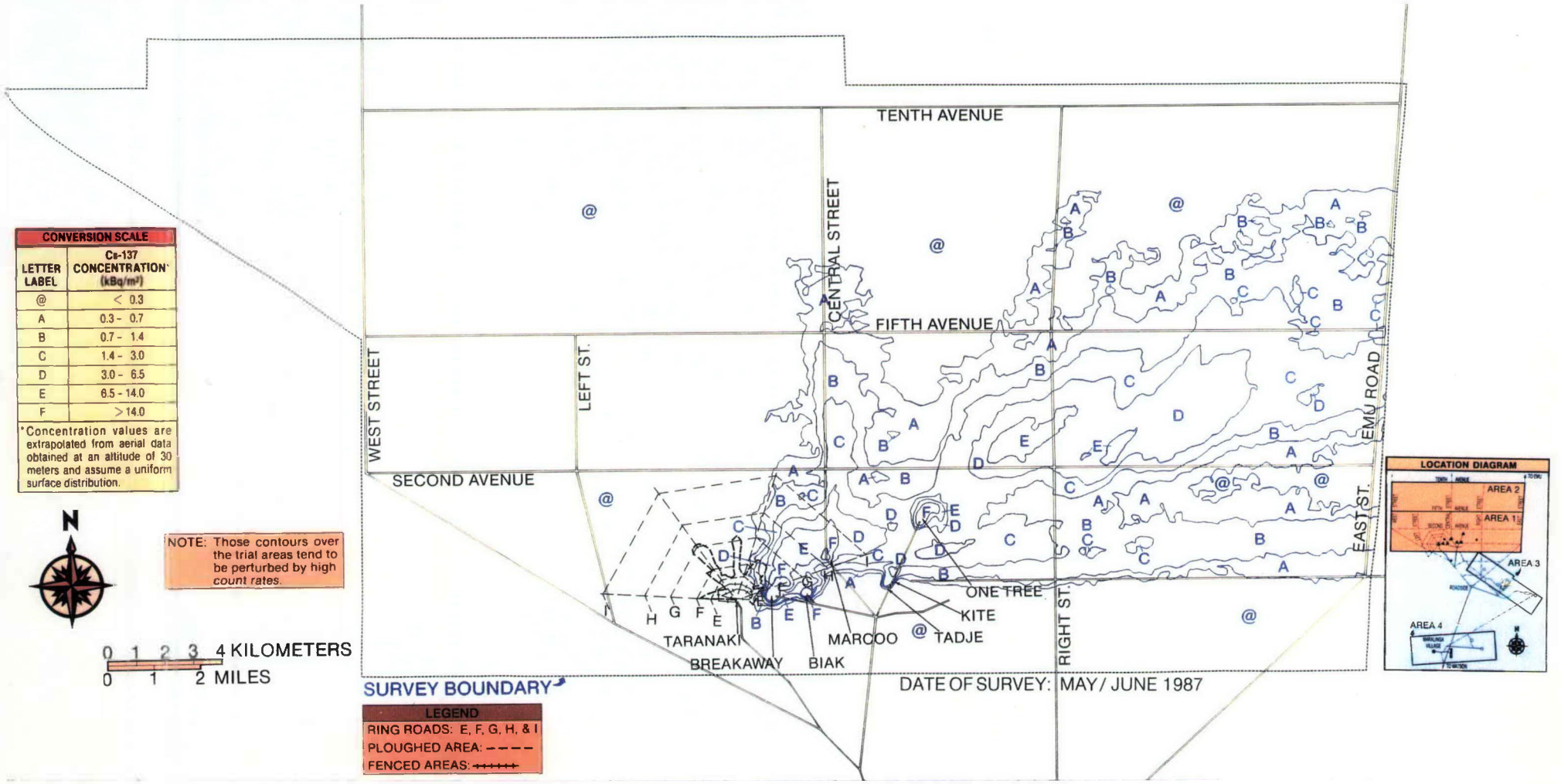
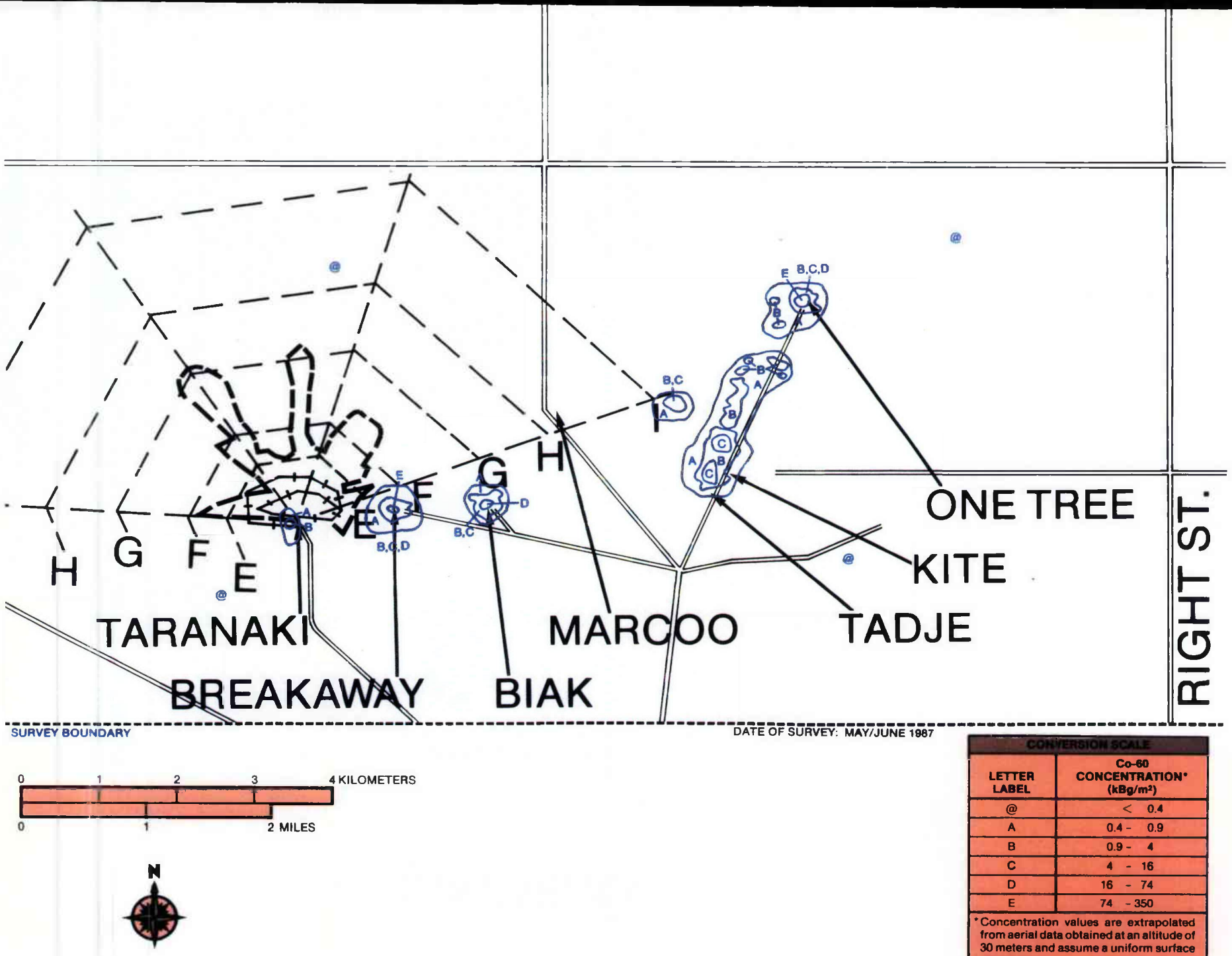


Figure 16. Results of the Aerial Survey Over Areas 1 and 2 Processed for Cs-137



CONVERSION SCALE	
LETTER LABEL	Co-60 CONCENTRATION* (kBg/m²)
@	< 0.4
A	0.4 - 0.9
B	0.9 - 4
C	4 - 16
D	16 - 74
E	74 - 350

*Concentration values are extrapolated from aerial data obtained at an altitude of 30 meters and assume a uniform surface distribution.

Figure 17. Results of the Aerial Survey Over Areas 1 and 2 Processed for Co-60

aerial and ground measurements, it is important to note that each one-second data point from the aerial system represents an average value over an area approximately 300 to 400 times as large as that covered in a single ground measurement.

Fallout patterns from the major trials can be identified from the residual Cs-137 contamination shown in Figure 16. As can be seen, the majority of the fallout was towards the northeast. There is also a plume extending to the north, just east of Central Street, and one to the east lying south of Second Avenue. It is quite possible that some of the low-level Am-241 contamination extending to the northeast in Figure 15 is associated with fallout from the major trials rather than entirely due to the minor trials. The west, northwest, and north plumes shown in Figure 15, however, are not associated with any Cs-137 activity. There is also no Cs-137 activity observed over the Taranaki ground zero, which was a 300-meter balloon-borne test. The germanium data taken at Taranaki and shown in Appendix B also does not indicate any significant Cs-137 activity.

Figure 17 shows contamination due to Co-60. It was necessary to apply a complex four-window stripping algorithm to separate the Co-60 from Eu-152 around the major trial ground zero areas. Co-60 was observed at all the ground zeros expect Marcoo and possibly Kite. The germanium data in Appendix B, however, show some low-level Co-60 at both these locations. In addition to what was observed at the ground zeros, there is also a plume of Co-60 going north-northeast from Tadje. This was a result of cobalt metal being used in that test for radiochemical diagnostic purposes (i.e., as an aid to measuring the nuclear efficiency of the explosion). Tadje was the

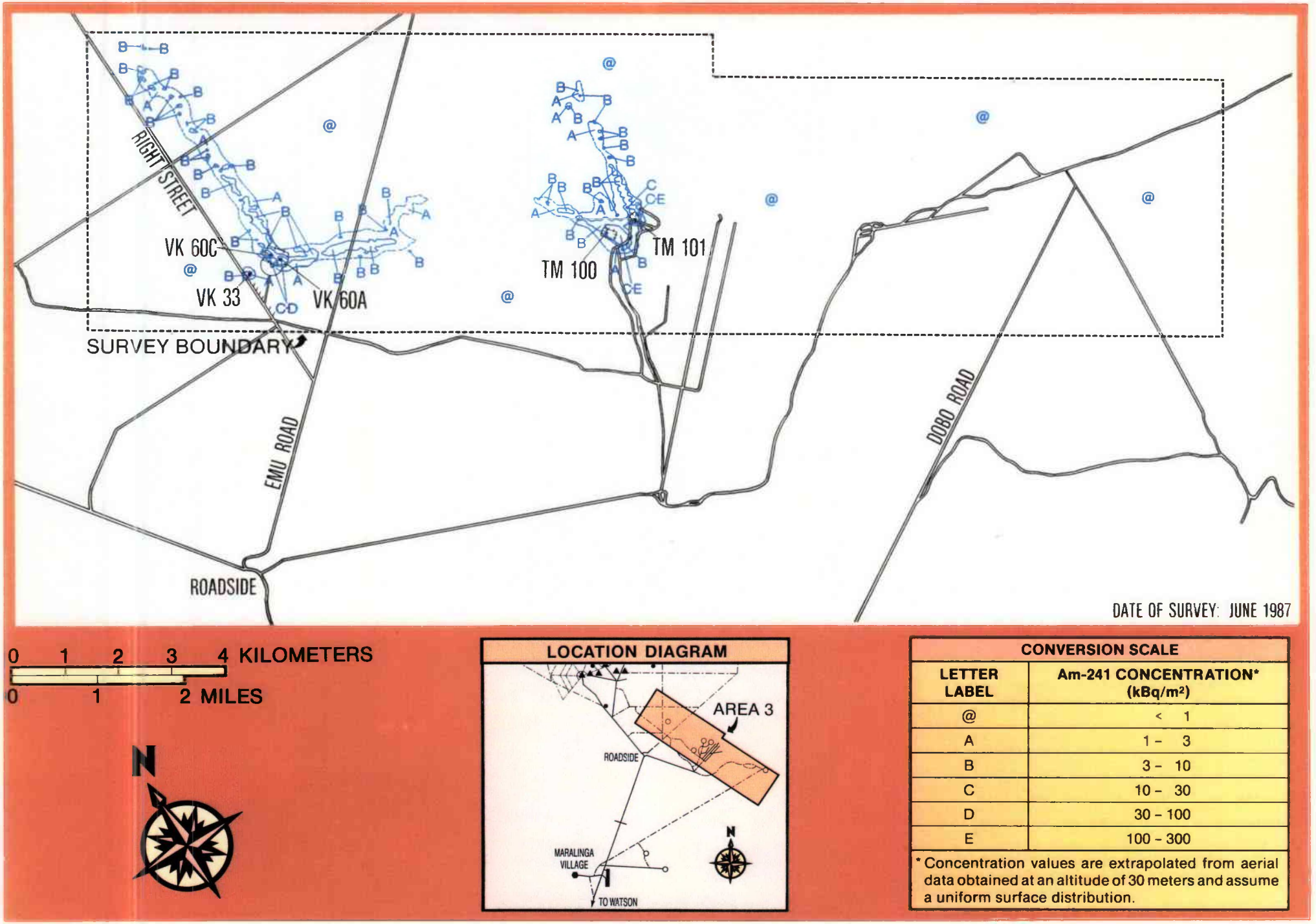
only test where that technique was employed. There is also a localized source approximately 1 kilometer north-northwest from Tadje, well separated from the plume and not associated with any other known tests. Ground measurements will be required to determine the nature and source of this contamination.

9.2 Area 3

Area 3 included the minor trial sites at Wewak, Naya, and Dobo. Only the presence of Am-241 could be detected from the aerial data. These results are shown in Figure 18.

Three areas of contamination were found at Wewak. These were associated with plutonium burning experiments conducted at VK33 and explosive dispersal experiments conducted at VK60A and VK60C. The dispersal experiments resulted in two plumes, one extending approximately 3 kilometers east of VK60A and the other extending approximately 4.5 kilometers north from VK60C. The contamination at VK33 was highly localized.

The only contamination observed at Naya was due to explosive dispersal experiments conducted at TM100 and TM101. These resulted in several plumes, with one extending approximately 1.5 kilometers north-northwest from TM100 and another extending approximately 3 kilometers north-northeast from TM101. There was no residual contamination observed from any of the other tests conducted at Naya or any of the tests conducted at Dobo.



CONVERSION SCALE	
LETTER LABEL	Am-241 CONCENTRATION* (kBq/m²)
@	< 1
A	1 – 3
B	3 – 10
C	10 – 30
D	30 – 100
E	100 – 300

* Concentration values are extrapolated from aerial data obtained at an altitude of 30 meters and assume a uniform surface distribution.

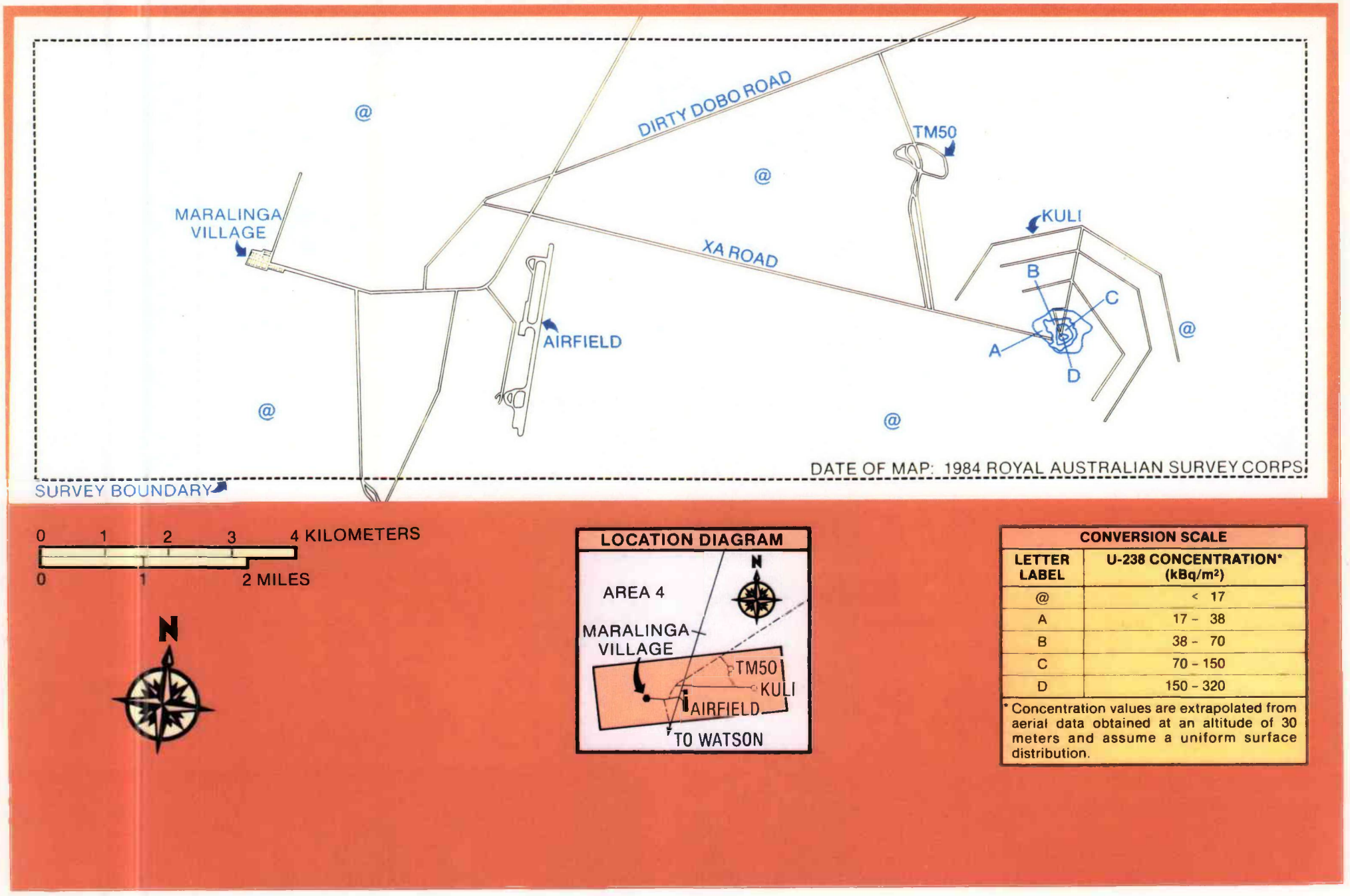
Figure 18. Results of the Aerial Survey Over Area 3 Processed for Am-241

9.3 Area 4

Area 4 included the Maralinga village, the airfield and adjacent burial ground, and the minor trial sites at TM50 and Kuli. The only contamination in this area was the U-238 found at Kuli, which resulted from explosive dispersal experiments. These results are shown in Figure 19. The activity appears to be relatively confined to the area around the firing site.

9.4 Area 5

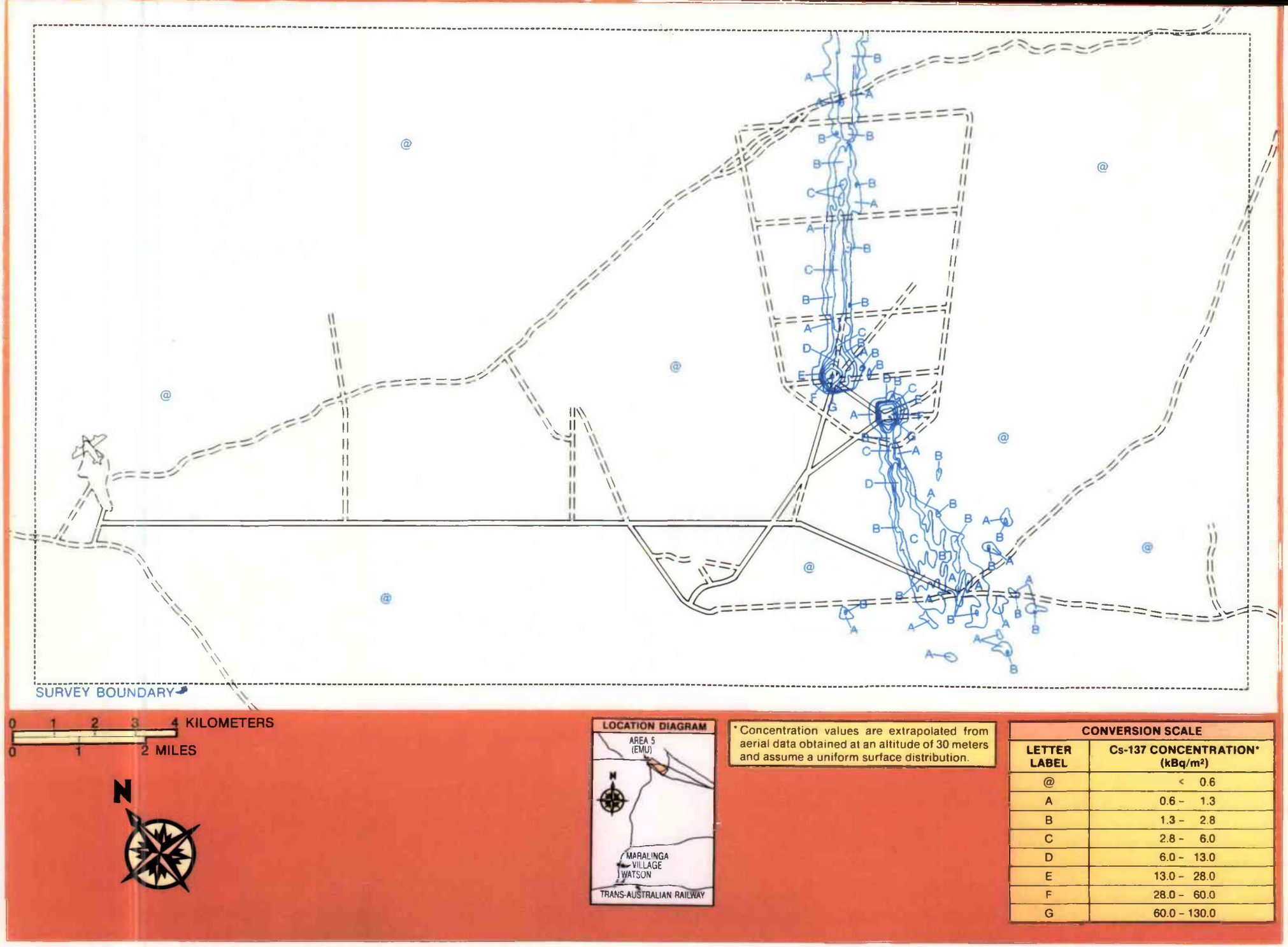
Area 5 covered the test site at Emu, located approximately 200 kilometers north of Maralinga. This was the site of two major trials, Totem 1 and Totem 2, and several minor trials. The aerial survey identified the presence of Cs-137, Eu-152, and Am-241, all associated with the Totem 1 and Totem 2 tests. No contamination was observed from any of the minor trials. Figures 20 and 21 show the results of the Emu survey for Cs-137 and Am-241, respectively. As can be seen from Figure 20, the fallout plume from Totem 1 (located approximately 1.5 kilometers north of Totem 2) extended to the northeast and continued beyond the survey boundary which was approximately 8.5 kilometers away. The fallout plume from Totem 2 was in a southerly direction, extending out approximately 6 to 7 kilometers. Am-241, as shown in Figure 21, is confined to the fallout patterns, the outer edge of which has been drawn on Figure 21 as a reference. As was the case over several major trial areas in Area 1, it was not possible to extract Am-241 data over the ground zeros due to high-count rates in these areas, primarily due to Eu-152. The Eu-152 activity was confined to the ground zero areas and has



CONVERSION SCALE	
LETTER LABEL	U-238 CONCENTRATION* (kBq/m²)
@	< 17
A	17 - 38
B	38 - 70
C	70 - 150
D	150 - 320

* Concentration values are extrapolated from aerial data obtained at an altitude of 30 meters and assume a uniform surface distribution.

Figure 19. Results of the Aerial Survey Over Area 4 Processed for U-238



CONVERSION SCALE	
LETTER LABEL	Cs-137 CONCENTRATION* (kBq/m²)
@	< 0.6
A	0.6 - 1.3
B	1.3 - 2.8
C	2.8 - 6.0
D	6.0 - 13.0
E	13.0 - 28.0
F	28.0 - 60.0
G	60.0 - 130.0

Figure 20. Results of the Aerial Survey Over Area 5 (Emu) Processed for Cs-137

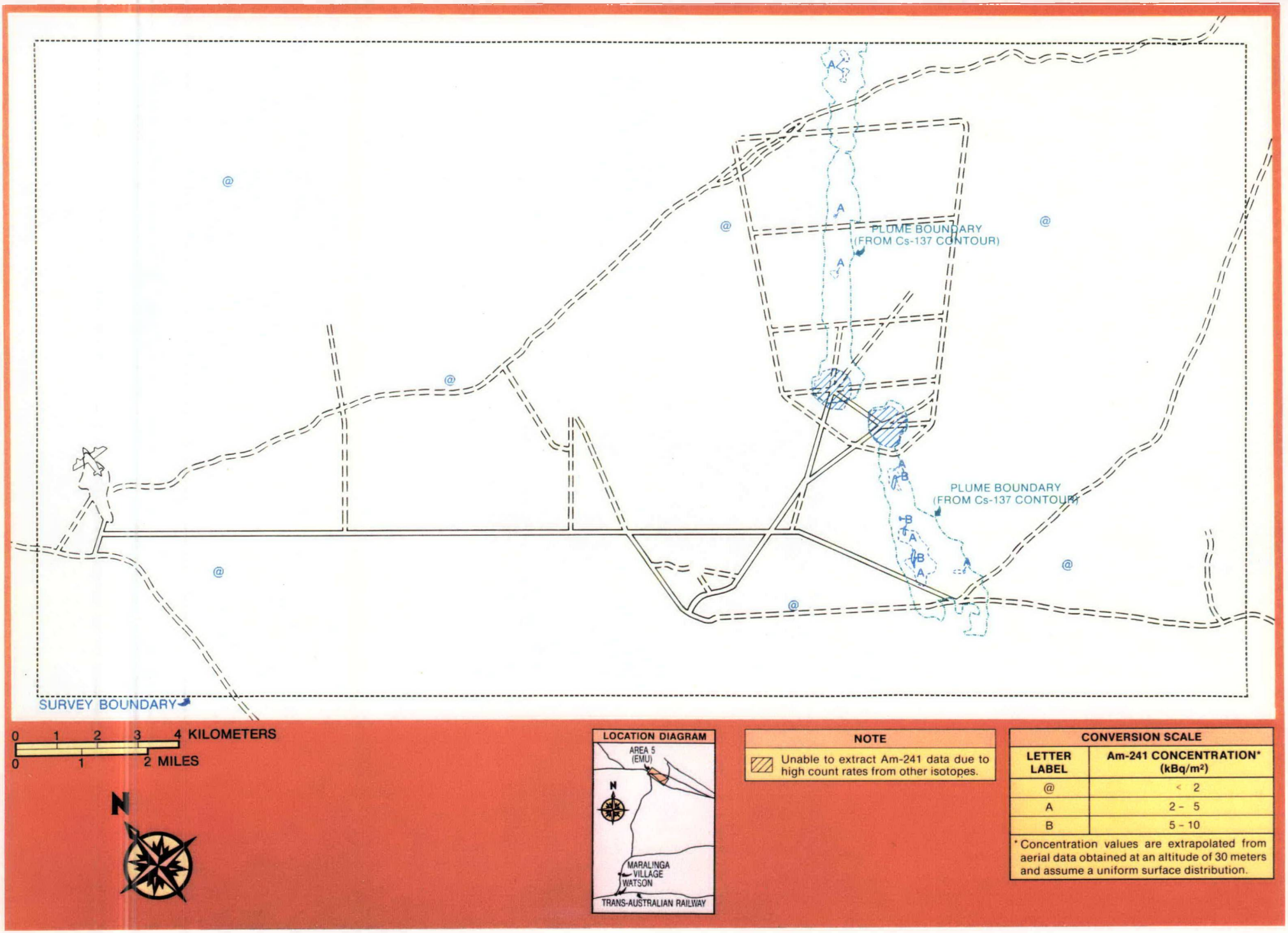


Figure 21. Results of the Aerial Survey Over Area 5 (Emu) Processed for Am-241

not been separately processed. Co-60 is also present at the ground zeros as shown in the the germanium data in Appendix B.

The minimum level of detectability for Am-241 was 2.0 kBq/m^2 in Area 5 as compared to 1.4 kBq/m^2 in the Areas 1 and 2. This difference was a result of the higher natural background radiation levels at Emu compared to Maralinga.

10.0 DISCUSSION

10.1 Am-241 Inventory

One of the data processing routines available provides a means of determining the total integrated activity for a specific isotope within any given portion of the survey area. Essentially, the routine multiplies the activity per unit area for a data point by the area of coverage of each data point, and then it sums all data points within a specified area. In practice, the inventory data was obtained from the large-area averaging procedure where the average value of 24 data points within an area approximately 200 meters on a side was obtained. This procedure gave maximum sensitivity for the aerial data. The inventory routine also provides a value for the total area of contamination.

Table 2 gives the results of applying the inventory program to the Am-241 data obtained in Areas 1, 2, and 3. In Areas 1 and 2, the four primary plumes were investigated separately. Because of the high count rates and associated distortions over the major trial sites, these areas were not included in the inventory. This is also the reason why no data was presented for Area 5 where the majority of the Am-241 activity was located near the two major trial ground zeros. For Area 3, the inventory within the Wewak area and at Naya was obtained separately.

The results presented in Table 2 were based on the assumption that all activity was confined to the surface. Since the actual contamination is distributed within the soil to some degree, the values given in Table 2

Table 2. Am-241 Inventory

Location	Total Activity[1] (10^6 kBq)	Contaminated Area[2] (km^2)
Areas 1 and 2[3]		
West Plume	17	4.5
Northwest Plume	266	58.1
North Plume	78	25.1
Northeast Plume	97	39.8
Area 3		
Wewak (VK33, VK60A, VK60C)	5.7	2.7
Naya (TM100, TM101)	9.1	1.5

(1) For an assumed surface distribution. See Section 10.2 for other possible distributions.

(2) Within the sensitivity limits of the aerial system (1.4 kBq/m^2 in Areas 1 and 2 and 1.0 kBq/m^2 in Area 3).

(3) Does not include the major trial areas.

represent a lower limit on the total activity. The actual activity within a given area will be greater than that given in Table 2. Section 10.2 discusses the conversion of the surface distribution results to more realistic depth distributions. These discussions indicate that the actual activity present may be one and a half to two times greater than the values given in Table 2.

10.2 Depth Distribution Corrections

Results of the aerial survey presented in Section 9 were expressed in terms of an equivalent surface distribution. This was done because depth distribution data were not available for all areas and for all isotopes prior to the aerial survey. In addition, the depth distribution for a specific isotope may vary with location. This is certainly the case when comparing the plowed area in Area 1 with undisturbed areas. Normalizing all the data to an equivalent surface distribution provides a convenient and common base from which more realistic results can be derived as depth distribution data becomes available.

Although precise depth distribution data may not be available, it is anticipated that results at Maralinga and Emu will be similar to those obtained at other locations such as the Enewetak and Bikini Atolls and the Nevada Test Site. These results have shown that the heavier elements such as americium, plutonium, and uranium tend to migrate more slowly into the soil than the lighter elements such as cesium and cobalt. They also show that the depth distribution resulting from natural weathering effects on surface fallout activity tends to follow an exponential decrease with

depth, such as that given in Equation 10 in Section 7.2. Soil activation products, such as Eu-152, tend to follow a uniform distribution with depth down to the limit of the activation region, which typically extends 20 to 30 cm into the soil. Plowing or other soil disturbing activities will mix the contamination within the soil, normally leading to a more uniform distribution within the disturbed region.

Table 3 provides a means of converting the uniform surface distribution data given in Section 9 to a more reasonable estimate based on an exponential distribution. The relaxation lengths ($1/\alpha$) for the exponential distribution were based on typical ranges found in past measurements for fallout activity which has weathered into the soil over a period of 30 years or so. For americium, values typically range from 0.5 to 2.0 cm, with 1.0 cm being a good average value to use when no specific data is available. The relaxation length for cesium and cobalt distributions is typically in the 10 to 15 cm range.

Values given in Table 3 represent the multiplication factor to be used to convert surface distribution activity, in kBq/m^2, to total activity per unit area using Equation 13 in Section 7.2 or to convert it to average activity per unit mass, in Bq/g, in the top z centimeters using Equation 12 in Section 7.2. The values assumed for z in Table 3 are those typically encountered in the literature for each isotope. As an example, if the Am-241 is actually distributed exponentially with depth with a relaxation length of 1 cm, then all values given in Section 9 should be multiplied by 1.6 (from Table 3) to obtain the total activity per unit area. This would also apply to the Am-241 inventory results given in Section 10.1. If a

Table 3. Multiplication Factors Used to Convert Uniform Surface Concentration Values to Activity Based on an Exponential Depth Distribution

Isotope	Assumed Relaxation Length, $1/\alpha$[1] (cm)	Conversion to Total Activity Per Unit Area[2] (kBq/m^2)	Conversion to Activity Per Unit Mass in Top z cm[3] (Bq/g)	
Am-241	0.5	1.3	0.077	(z = 1)
			0.029	(z = 3)
			0.018	(z = 5)
	1.0	1.6	0.068	(z = 1)
			0.035	(z = 3)
			0.022	(z = 5)
	2.0	2.2	0.059	(z = 1)
			0.040	(z = 3)
			0.026	(z = 5)
Cs-137	5.0	2.0	0.017	(z = 5)
			0.012	(z = 10)
			0.005	(z = 25)
	10.0	3.0	0.016	(z = 5)
			0.013	(z = 10)
			0.007	(z = 25)
	15.0	4.0	0.015	(z = 5)
			0.013	(z = 10)
			0.009	(z = 25)
Co-60	5.0	1.8	0.015	(z = 5)
			0.010	(z = 10)
			0.005	(z = 25)
	10.0	2.6	0.013	(z = 5)
			0.011	(z = 10)
			0.006	(z = 25)
	15.0	3.3	0.013	(z = 5)
			0.011	(z = 10)
			0.007	(z = 25)

(1) As defined in Equation 10, Section 7.2.

(2) Based on Equation 13, Section 7.2.

(3) Based on Equation 12, Section 7.2.

relaxation length of 0.5 cm is more appropriate, then a multiplication factor of 1.3 should be used. As another example, for a relaxation length of 1 cm for Am-241, the activity per unit mass, in Bq/g, within the top centimeter is obtained by multiplying the surface values by 0.068. The average activity within the top 3 cm would be obtained by multiplying by 0.035. The minimum detectable activity for Am-241 in Areas 1 and 2 with the airborne system was 1.4 kBq/m^2, assuming a surface distribution. This would equate to 0.1 Bq/g in the top centimeter and 0.05 Bq/g in the top 3 cm for an exponential distribution with a 1 cm relaxation length (1.4 times 0.068 and 1.4 times 0.035 using the values from Table 3).

Table 3 is not intended to be all inclusive, but merely to serve as an indicator of typical results that might be expected once depth profile data are obtained. It can be seen that total activity per unit area is quite sensitive to the actual depth distribution. On the other hand, the activity per unit mass within a given depth is not nearly as dependent on the actual source distribution. Table 3 can also be used as a guide to determine how much effort should be applied to obtaining depth profile data based on the magnitude of the error which results from uncertainty in the actual depth distribution as compared to other possible sources of error.

10.3 Plutonium Determination

Plutonium used in nuclear weapons tests is composed primarily of Pu-239 with approixmately five percent Pu-240 and one-half percent Pu-241 as impurities. The Pu-241 decays via beta decay to Am-241 with a half-life of 14.4 years. Because the gamma ray emission rate for Am-241 is much higher

than that from the plutonium isotopes, it is normally used as an indicator to infer plutonium contamination.

Plutonium-to-americium ratios are normally determined from laboratory measurements using high resolution germanium detectors or alpha spectrometers. For high activity samples, such as might be found on some debris, the high resolution gamma ray data can give results for Pu-239, Pu-240, and Am-241 directly. For lower activity samples, such as most typical soil samples, it is necessary to use alpha spectrometry. Because the alpha energies from Pu-239 and Pu-240 are so close together, these measurements usually give a value for Pu-239 plus Pu-240. Therefore, plutonium-to-americium ratios are sometimes given as Pu-239 to Am-241 ratios or Pu(239 + 240) to Am-241. Often, the quantity of real interest is actually the total alpha activity which would include Am-241 and possibly Pu-238 in addition to the Pu-239 and Pu-240. So care must be taken in using plutonium-to-americium ratios to specify exactly what ratio is being given and to determine what is really required as the final result.

The amount of Am-241 present depends on the amount of Pu-241 initially present as an impurity and the time since the plutonium was last chemically separated. Differences in the plutonium used for different tests would lead to different plutonium-to-americium ratios at a given point in time. The amount of americium present will also increase as a function of time, reaching a maximum value 75 years after separation, which will also change the ratio depending on when a measurement is made. For these reasons (as well as the previously discussed problem about exactly what ratio is really required) there was no attempt made to convert the Am-241 data obtained

from the aerial survey to plutonium activity. This conversion, however, can be easily made once the appropriate ratios are determined for each area of interest.

For reference, the Australian Radiation Laboratory obtained ratio data from various debris collected in the Taranaki area during 1984 and 1985. The average Pu-239 to Am-241 ratio was 7.4, and the Pu-240 to Pu-239 ratio varied from approximately 0.1 to 0.2. These values were obtained from high-resolution gamma ray data.

10.4 External Exposure

The results of the aerial survey indicated that the external exposure rate due to naturally occurring radionuclides at Maralinga was in the 2-3 microroentgens per hour (μR/h) range while that at Emu was in the 3-4 μR/h range. An estimated 4 μR/h, due to cosmic ray contributions, must be added to these values to obtain the total external exposure rate due to natural sources.

For comparison, the results of the aerial data can be converted to external exposure rate by multiplying by the following factors: Am-241 (0.005), Cs-137 (0.06), and Co-60 (0.27). As an example, one of the highest levels measured for Am-241 near Taranaki was approximately 60 kBq/m^2 which would result in an external exposure rate of 0.3 R/h (60 times 0.005). For Cs-137, the highest reading observed in any of the fallout plumes was approximately 15 kBq/m^2 which would lead to an exposure rate of 0.9 μR/h (15 times 0.06). For Co-60, the highest reading away from the immediate

area of the major trial ground zeros was also approximately 15 kBq/m^2, which would equate to an exposure rate of 4.0 μR/h (15 times 0.27). None of these maximum values would lead to a significant increase above normal background levels for the external exposure rate. In the immediate vicinity of the major trial ground zeros, however, the presence of Eu-152 does lead to a significant increase in the external exposure rate. Values several hundred times greater than that, due to natural background, are found at Breakaway, Biak, One Tree, Totem 1, and Totem 2. These are highly localized areas whose activity will decrease with the half-life of Eu-152 (13.2 years).

Appendix A. Survey Statistics

Areas 1 and 2

Location	Area 1 - Surrounding the major trial sites Area 2 - Adjacent to and north of Area 1
Size	Area 1 - 12 km x 35 km rectangle. The area covered was approximately 420 square kilometers. Area 2 - Irregular in shape covering approximately 382 square kilometers.
Number of Flight Lines	Area 1 - 240 with a line spacing of 50 meters Area 2 - 107 with a line spacing of 100 meters
Survey Dates	4 May 1987 through 16 June 1987 to complete both areas

Area 3

Location	Surrounding Wewak, Naya, and Dobo trial areas
Size	5.7 km x 21.0 km rectangle with the long axis at 123 degrees from the north. The area covered is 120 square kilometers.
Number of Survey Lines	114 parallel to the long axis with a line spacing of 50 meters
Survey Dates	17 June 1987 through 20 June 1987

Area 4

Location	Maralinga Village, Kuli Area
Size	20 km x 7 km rectangle (140 square kilometers)
Number of Survey Lines	141 parallel to the long axis at 50-meter spacing
Survey Dates	6 July 1987 through 11 July 1987

Area 5

Location	200 kilometers north of Maralinga
Size	16 km x 30 km rectangle with the long axis 125 degrees from the north (480 square kilometers)
Number of Survey Lines	81 lines, 30 kilometers in length at 200-meter spacings; 42 lines, 5.6 kilometers in length (used to provide 100-meter spacings over Totem 1 and Totem 2 trial areas)
Survey Dates	24 June 1987 through 4 July 1987

Appendix B. Ground Measurement Results at the Major Trial Ground Zeros

The high-purity germanium detector described in Section 8 was used to obtain spectral data at each of the major trial sites at Maralinga and at Totem 1 at Emu. These results are shown in Figures B.1 through B.8. All measurements were taken within approximately 10 to 15 meters of the ground zero location with the detector face at a height of 1 meter above ground. The live time for each measurement was ten minutes.

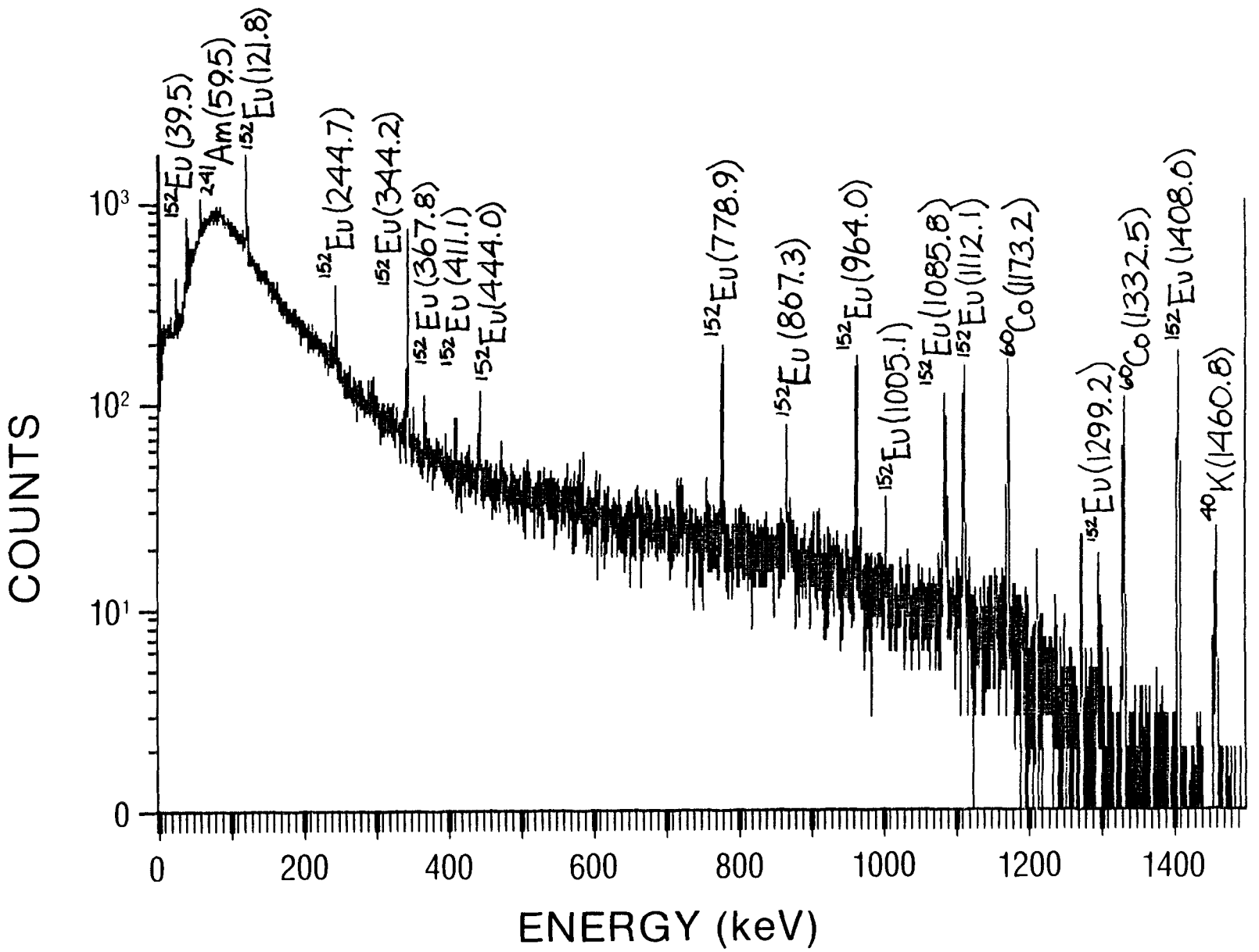


Figure B.1. Spectral Data Obtained at the Taranaki Ground Zero with the Germanium Detector System

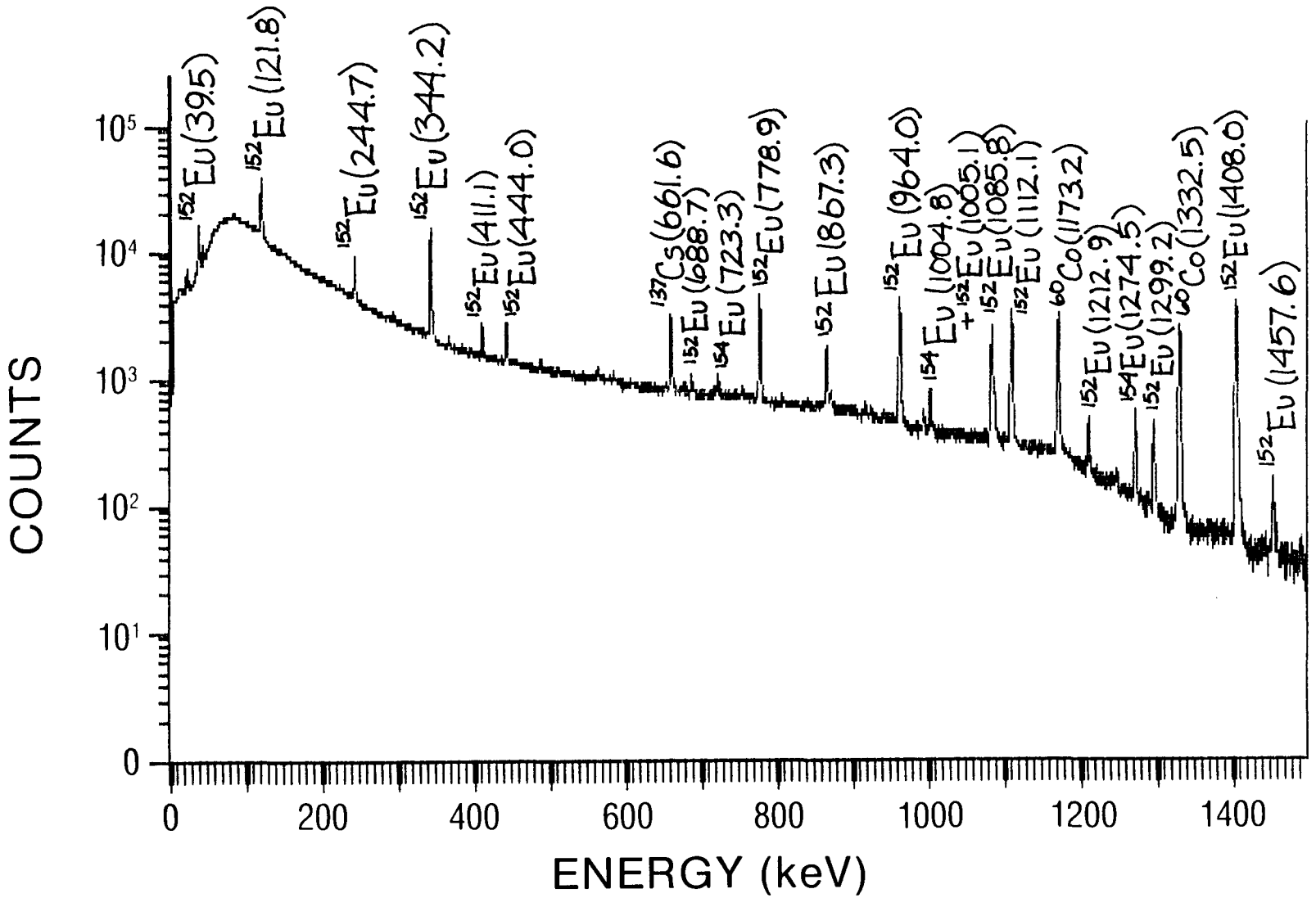


Figure B.2. Spectral Data Obtained at the Breakaway Ground Zero with the Germanium Detector System

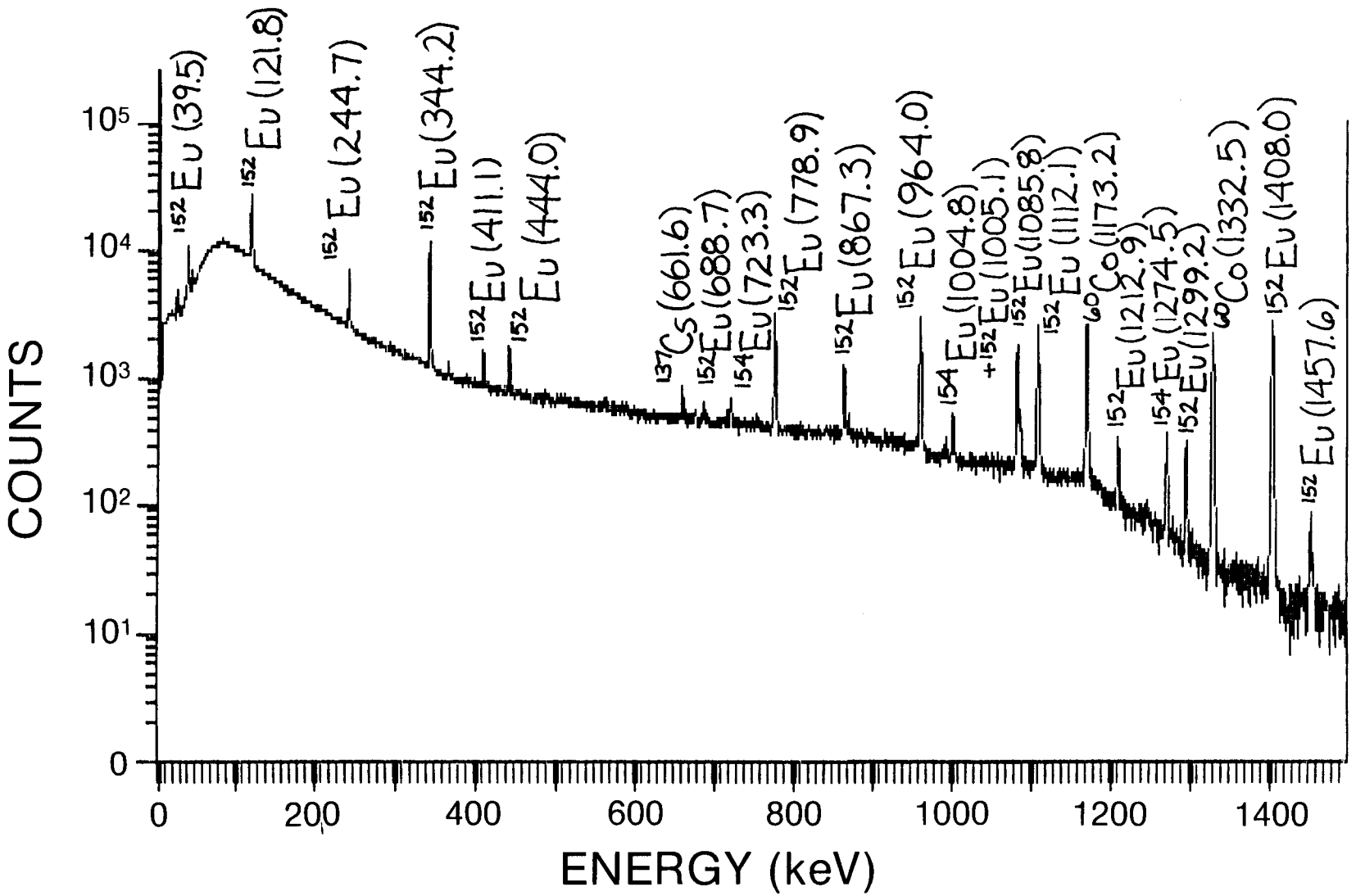


Figure B.3. Spectral Data Obtained at the Biak Ground Zero with the Germanium Detector System

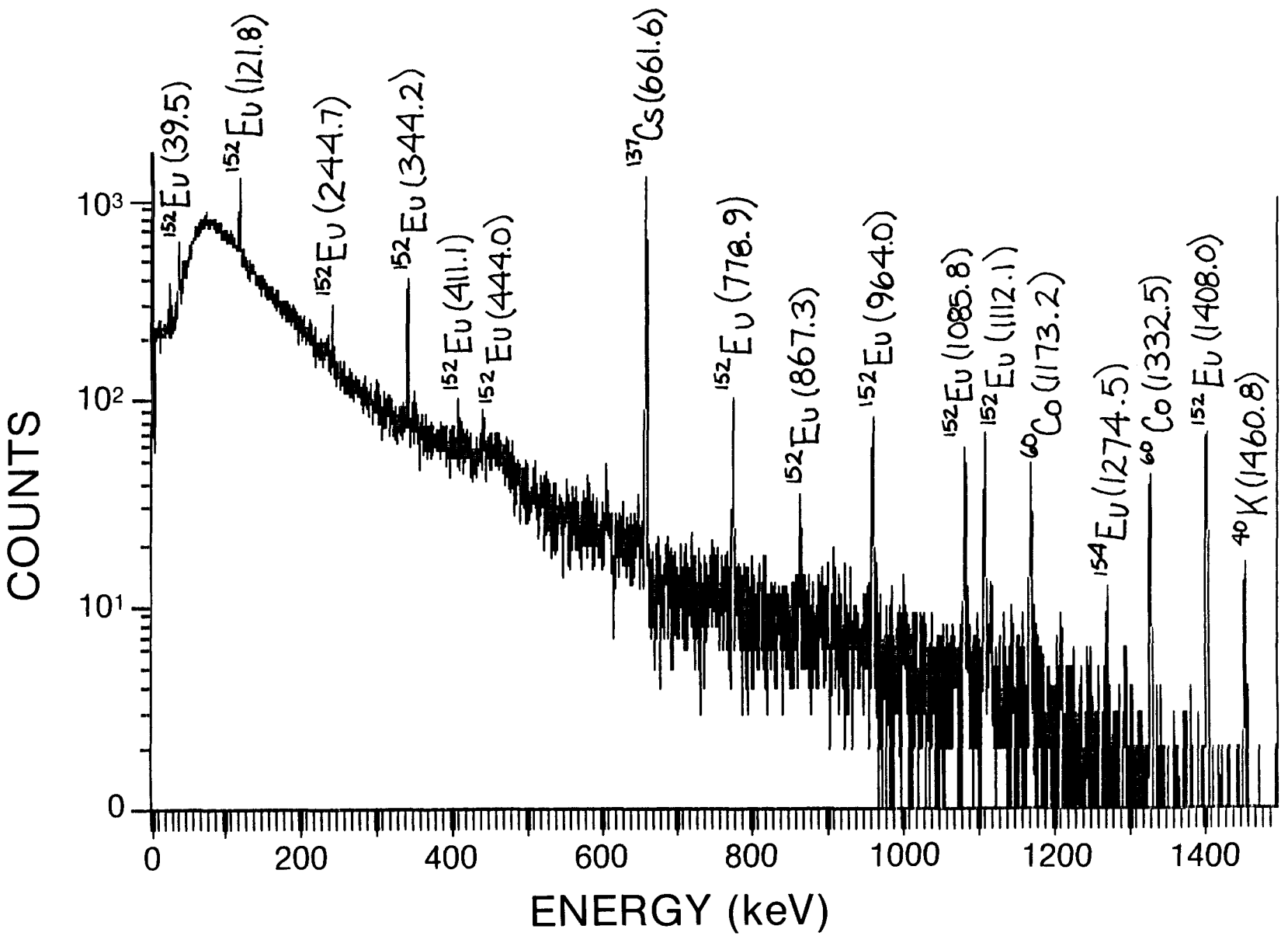


Figure B.4. Spectral Data Obtained at the Marcoo Ground Zero with the Germanium Detector System

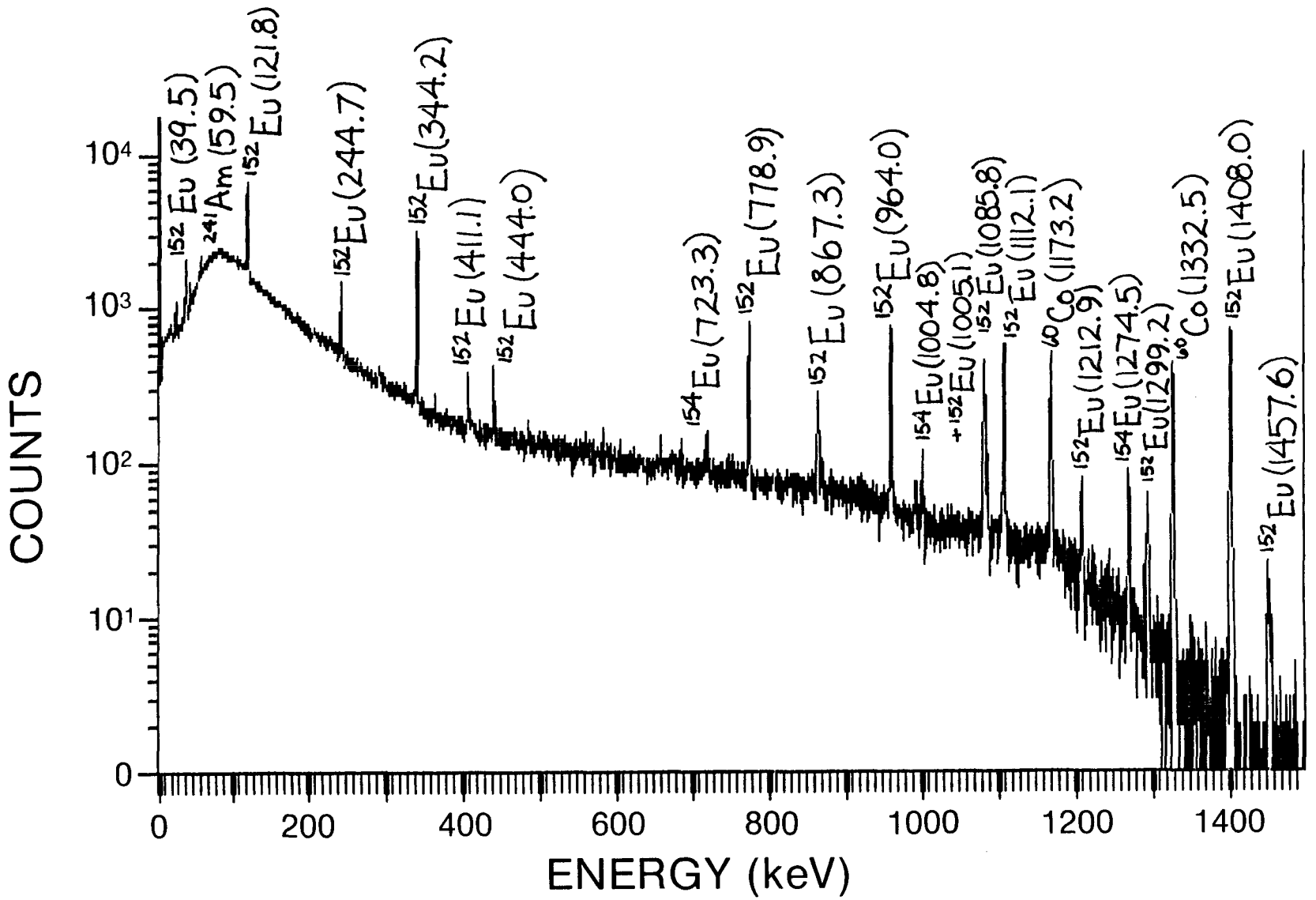


Figure B.5. Spectral Data Obtained at the Tadje Ground Zero with the Germanium Detector System

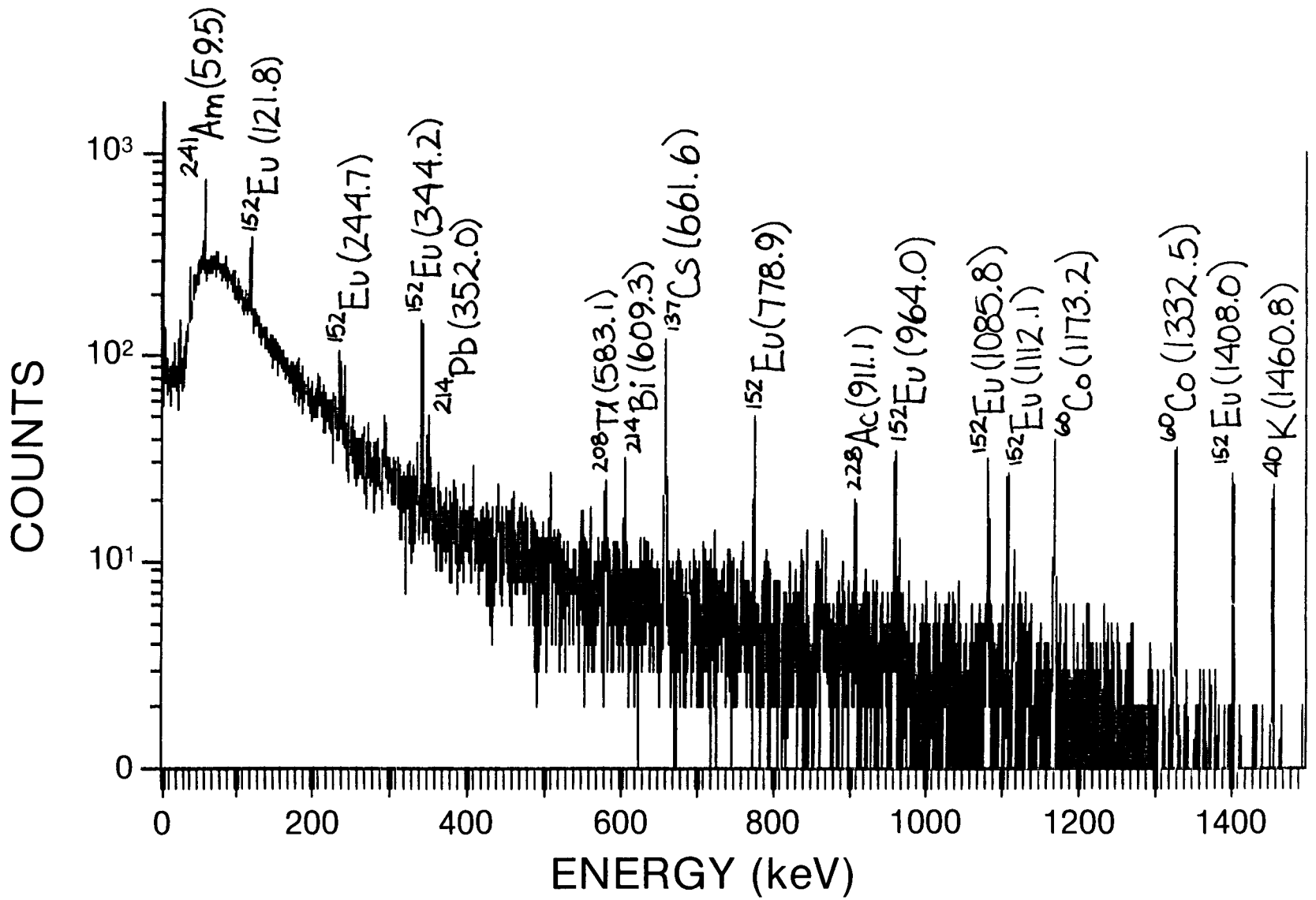


Figure B.6. Spectral Data Obtained at the Kite Ground Zero with the Germanium Detector System

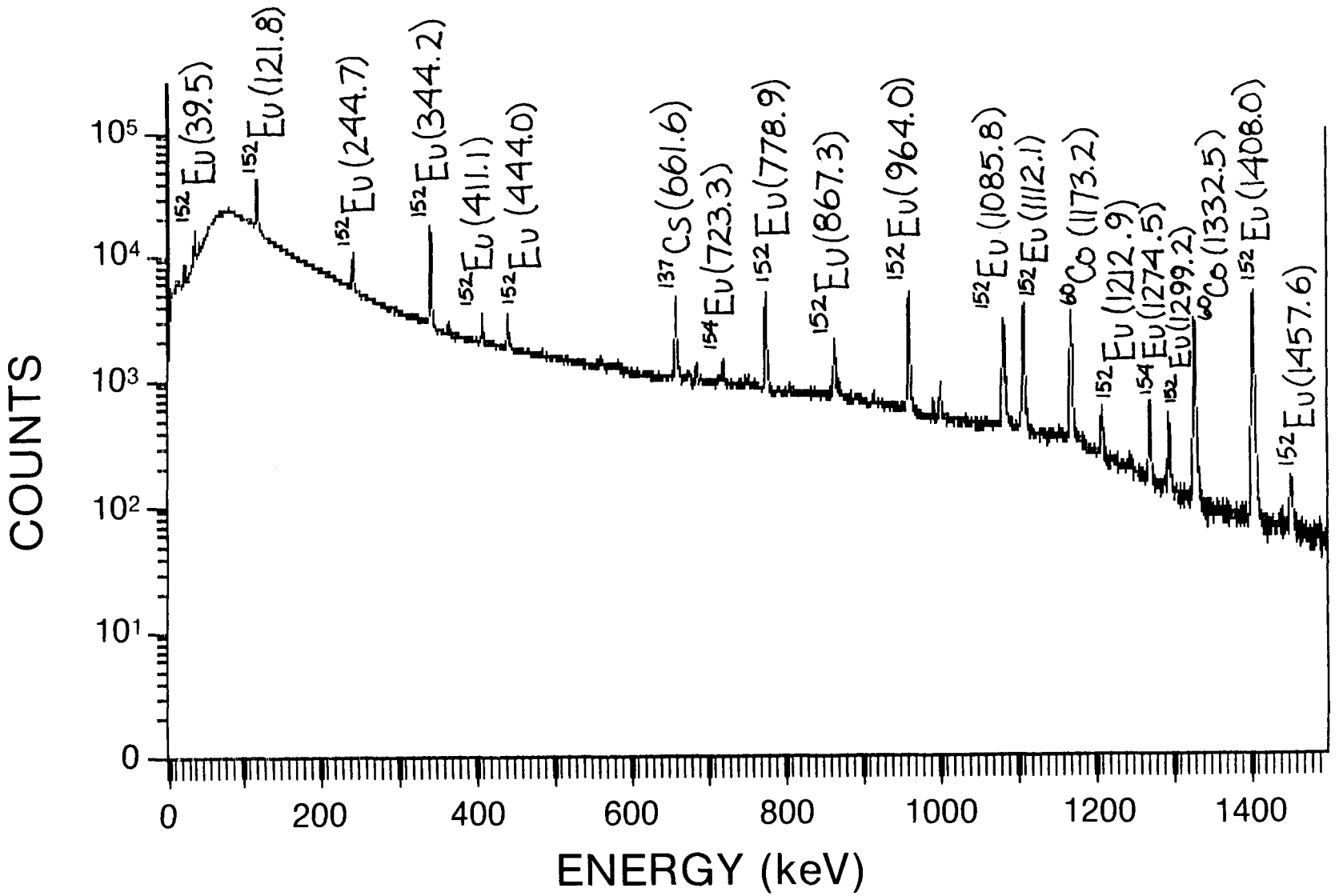


Figure B.7. Spectral Data Obtained at the One Tree Ground Zero with the Germanium Detector System

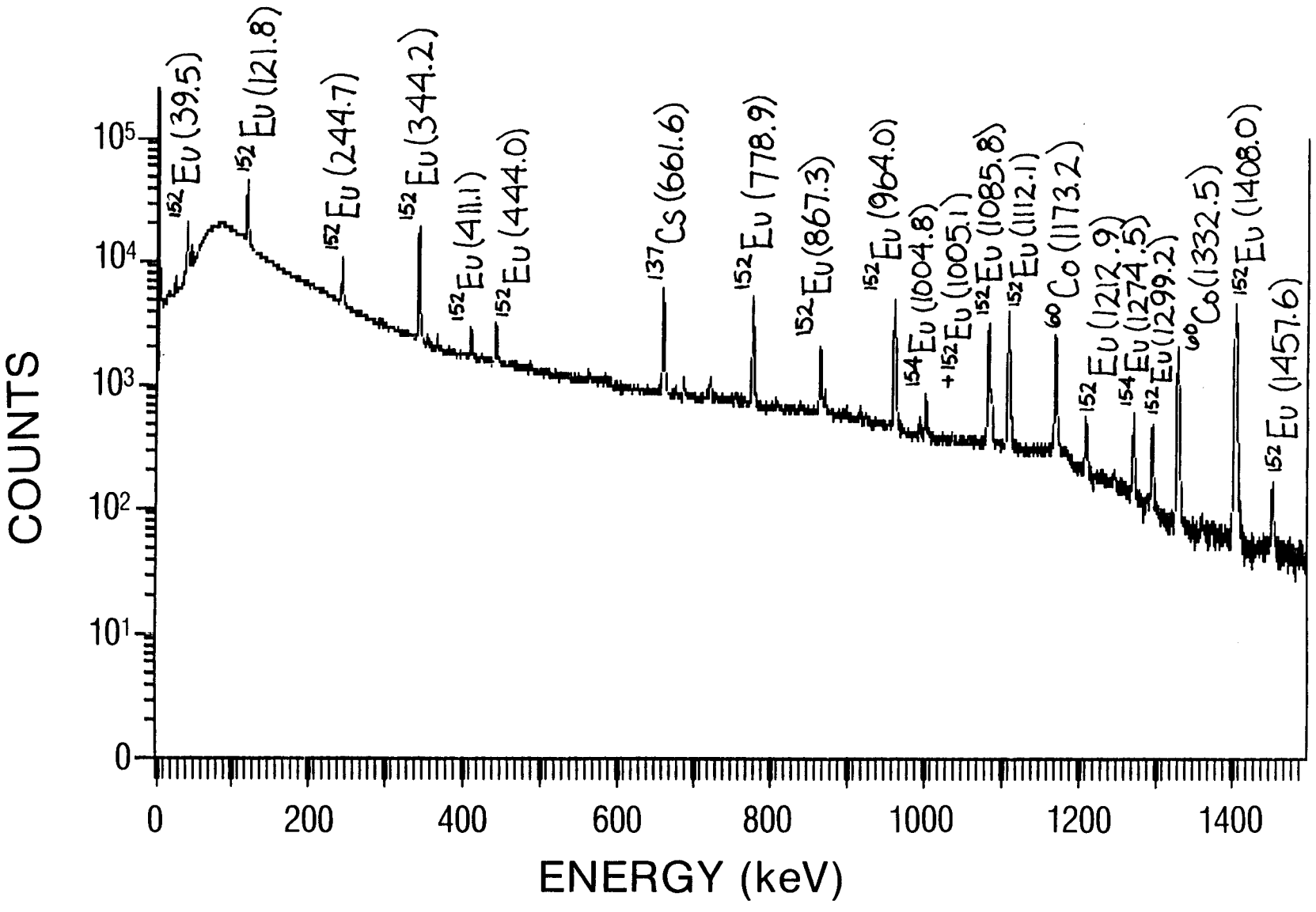


Figure B.8. Spectral Data Obtained at the Totem One Ground Zero with the Germanium Detector System

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