

EGG--1183-1752

DE84 017608

AN AERIAL RADIOLOGICAL SURVEY OF
AREA 13
NEVADA TEST SITE .

DATE OF SURVEY: DECEMBER 1977

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ACKNOWLEDGMENT

In appreciation for his support and encouragement in this program, we thank Paul Dunaway, Director, Transuranics Office, Nevada Operations Office, United States Department of Energy.

ABSTRACT

An aerial radiological survey, conducted from an instrumented H-500 helicopter, was conducted over Area 13, Nevada Test Site, during the period 6-8 December 1977. The objective was to define the location and concentration of ^{241}Am . From these data, the location, concentration, and quantity of ^{239}Pu and ^{240}Pu may be implied. This work was performed by EG&G for the Nevada Applied Ecology Group, Nevada Operations Office, United States Department of Energy.



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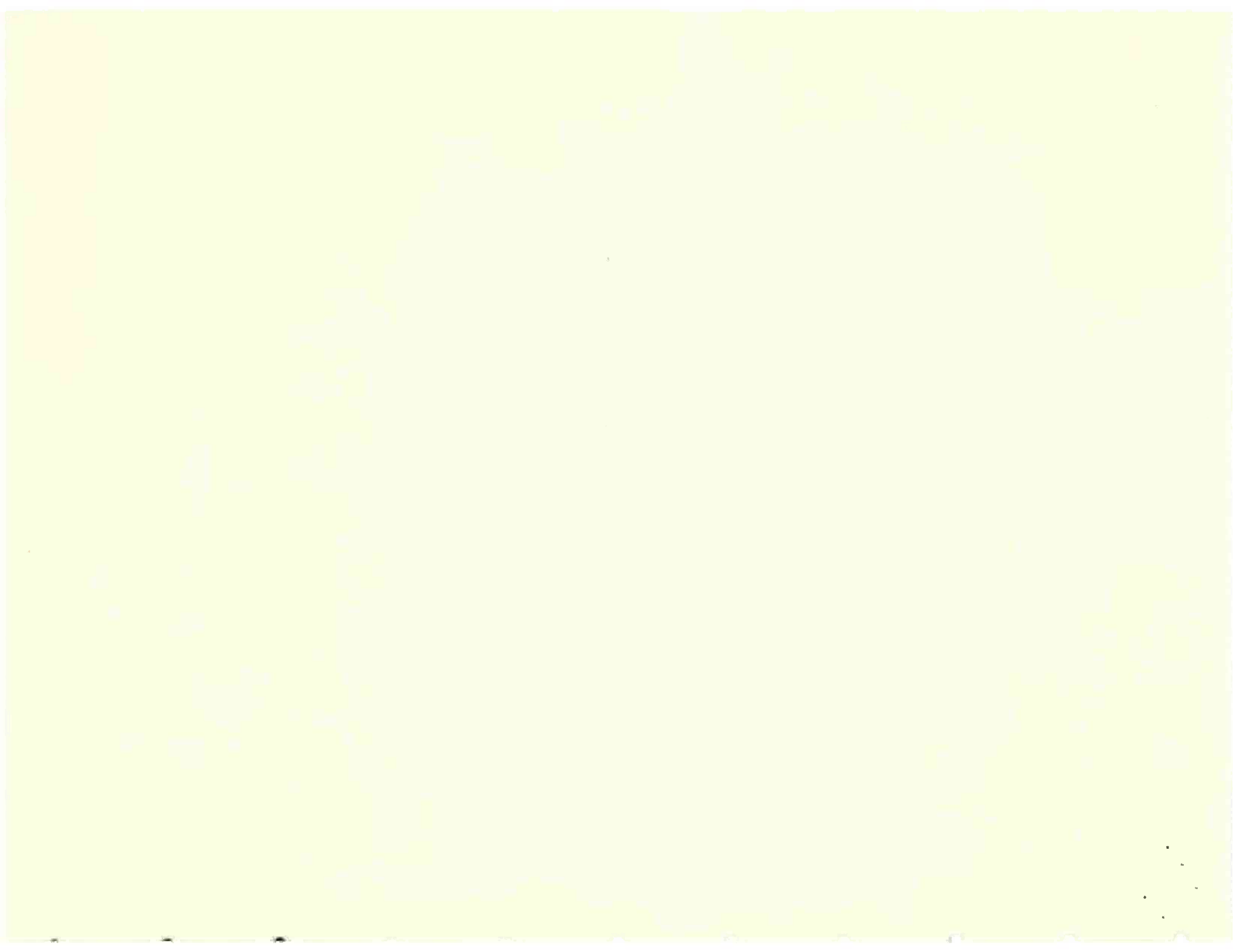
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1.0 INTRODUCTION

The United States Department of Energy (DOE) maintains an aerial surveillance operation called the Aerial Measuring Systems (AMS).^{*} AMS is operated for DOE by EG&G. Begun in 1958, this continuing nationwide program involves surveys to monitor radiation levels in and around facilities producing, utilizing, or storing radioactive materials. AMS is used for various aerial survey operations at the request of DOE, other federal agencies (such as the United States Nuclear Regulatory Commission), and state agencies.

AMS was utilized during the period 6-8 December 1977 to conduct a terrestrial gamma survey from an instrumented H-500 helicopter over Area 13, Nevada Test Site, in support of DOE's Nevada Applied Ecology Group (NAEG).

2.0 SITE DESCRIPTION

Area 13 is located about 16 km north of gate 700 at the Nevada Test Site. The shot ground zero (GZ) is at Nevada coordinates N936092 and E721352.¹ The elevation is 1 400 m above sea level.

Valley Road, a north-south graveled road, passes about 2.1 km west of GZ. A dirt track provides access for ground vehicle traffic to the southern part of the fence which surrounds the major contaminated area.

The area might be described as typically flat Nevada desert with a heavy, if not luxuriant, cover of sagebrush. Over the fenced area the elevation varies only 18 m.

The nearest public population center is Alamo, Nevada, which is about 64 km east of the site.

3.0 SURVEY METHOD

3.1 Method Outline

The Nevada Applied Ecology Group has studied Area 13 intensively in the past. Much documentation is available of the concentrations and extent of the ^{239,249}Pu and ²⁴¹Am.^{1, 2, 3, 4} In addition, EG&G had conducted a limited aerial gamma survey of this area in 1972 during the testing period of the aerial ²⁴¹Am survey technique. From this data, it was concluded that an area about 4.8 km east-west, which included Valley Road, and 3 km north-south would include all the ²⁴¹Am "observable" by the aircraft system.

^{*}Formerly the Aerial Radiological Measuring System (ARMS)

To implement the survey, photographs were taken in November 1977 from the Convair 580-T aircraft, using the Wild RC10 camera system.⁵ The photographs were enlarged to 1 cm per 60 m. Flight lines about 4.8 km long, running nearly east-west along the elevation contours, were drawn on the photos at 61 m intervals to provide adequate coverage of the area.

The H-500 helicopter system, data reduction system, and the Microwave Ranging System (MRS) were transported to the operation base at gate 700, Nevada Test Site, on 5 December 1977. The survey was completed during the following three days.

The fence line was flown first; then the position data from the MRS units were used to scale data plots to the 1 cm per 60 m photograph. Using the newly developed steering indicator, the previously drawn flight lines were flown in an east-west direction, beginning with line 0 over GZ. After each flight of perhaps 10 lines, the data were reduced to ²⁴¹Am count rates and plotted on the same scale as the aerial photograph. Flights were continued until the ²⁴¹Am signal disappeared. A test background line near station 700 was flown during each flight. The plots of total count rate from this line were compared to check the continuity in time of the data acquisition system.

3.2 Equipment and Parameters

3.2.1 H-500 Helicopter System

The H-500 (Figure 1) carried the Radiation and Environmental Data Analyzer and Recorder System (REDAR II). REDAR II consists of twenty 12.7 cm × 5.1 cm NaI(Tl) crystal detectors and the new steering indicator which is based on the microwave range data fed into an HP 9825 calculator.⁶

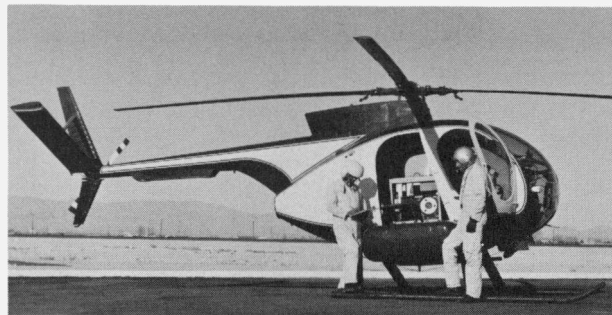


Figure 1. HUGHES H-500 HELICOPTER CONTAINING THE REDAR SYSTEM

Flight parameters were:

Altitude = 30 m

Speed = 60 knots or
approximately 30 m/sec

Line Spacing = 61 m

Data parameters were:

Gamma energy
divisions = 300 channels

Energy range = 4.5-300 keV

Energy windows = 39.5- 49.5 keV

= 49.5- 69.5 keV

= 69.5- 79.5 keV

= 79.5- 300 keV

= 4.5-300 keV

Energy window

acquire rate = 1 each 0.2 sec

Full energy

spectrum

acquire rate = 1 each 3.0 sec

²⁴¹Am photopeak

center location = Channel 60

3.2.2 Microwave Ranging System

The microwave ground units were placed about 6.4 km from GZ, one east and one northwest, and separated by about 6.4 km. These were placed and recovered with the H-500 helicopter.

3.2.3 Data Van System

The standard Radiation and Environmental Data Analyzer and Computer (REDAC) system was located in the van (Figure 2). A REECO ground power unit supplied the 110/220 V power required.⁶

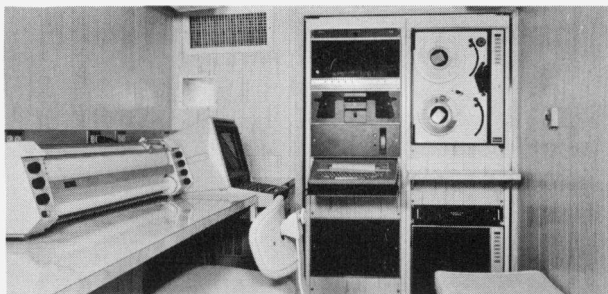


Figure 2. INTERIOR OF THE MOBILE DATA PROCESSING LABORATORY CONTAINING THE REDAC SYSTEM

4.0 DATA PROCESSING METHODS AND RESULTS

The data were processed both in the field and in the EG&G data processing laboratory. Field processing insures that all the data are present and correct. At Area 13 a radiation contour map was also produced: this was used to indicate whether or not sufficient lines had been flown to include all the contaminated area. Also, field processing is efficient in finding system failures and correcting them within a short time after a survey flight has been made.

The REDAR mentioned in Section 3.2.1 accumulates 300-channel gamma spectral data over 3-second time intervals and stores them on magnetic tape. Data from five single channels, whose limits can be set to include any portion of the 300-channel spectrum, are accumulated on the REDAR II every 0.2 second.³ Spectral data of both types are processed according to various algorithms which combine different portions of the spectrum to accentuate nuclides of interest. The REDAC combines radiation data and aircraft position data to produce plots of selected letter symbols which correspond to radiation levels measured along the flight path, scaled to a photograph or map.

Routines are available in the REDAC to smooth count rate vs. time data. The width of the smoothing function is generally chosen so that spatial resolution inherent in the detector/ground plane geometry is not degraded. Point sources of equal magnitude are considered resolved when separated by twice the flight altitude. Wider smoothing functions can be applied to increase sensitivity at the expense of spatial resolution.

Spatial resolution limitations of the processed data should be borne in mind constantly when interpreting aerially measured radiation contours constructed from the x-y plots of letter labels. A point source on the ground will appear to be spread over an area whose lateral dimensions are comparable to twice the survey altitude. Thus, aerial surveys will not compare well with ground surveys in areas that contain sources whose physical dimensions are small relative to flight altitude.

The primary steps in gamma data reduction are:

- (1) Plot window data to observe contaminated areas and background areas.

- (2) Find the average count rate ratio of signal window to background windows in background areas.
- (3) Select smoothing function.
- (4) Select counting levels to be plotted from the observed background and maximum counting rate in the signal and background windows.
- (5) Plot data using letter symbols for each counting interval.
- (6) Hand contour the letter symbols so that contours enclose a given symbol.
- (7) Convert counting rates to equivalent ^{241}Am concentrations in the soil.

4.1 The Search Algorithm

Figure 3 is a sketch of the total energy spectrum taken over an area contaminated with plutonium. The dominant feature of this spectrum is the 60 keV photopeak of ^{241}Am , a daughter of ^{241}Pu . Therefore, the counts in the spectral window extending from 49.5 to 69.5 keV were used as the primary plutonium indicator. Spectral windows on either side of this window were used to monitor background. These window data were accumulated at a rate of once every 0.2 second during survey flights and were summed over each second during data reduction. The energy window arrangement was the same as that used for the Tonopah Test Range survey.⁷

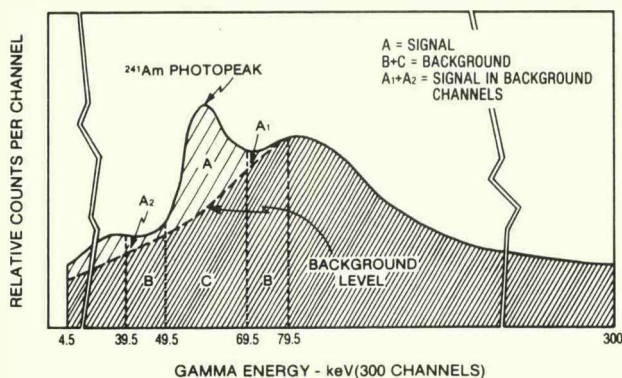


Figure 3. SKETCH OF GAMMA ENERGY SPECTRUM AT AREA 13

Figure 4 is a trace of the 49.5 to 69.5 keV window count rate along the survey line crossing GZ. Note the high count rate in the center of the trace due to the high activity at GZ. The lowest levels on each side are background count rates.

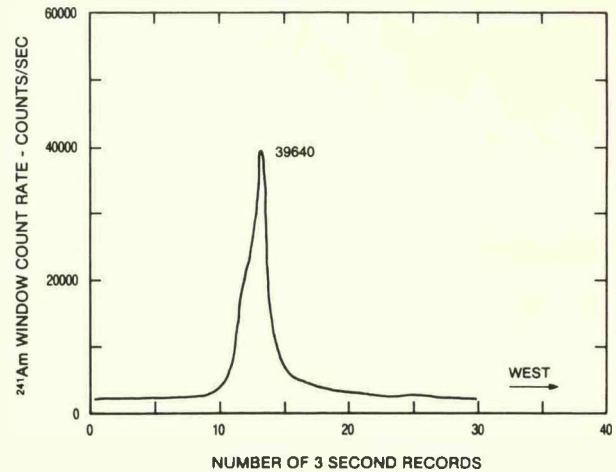


Figure 4. ^{241}Am PHOTOPEAK WINDOW COUNT RATE ALONG THE LINE PASSING OVER GROUND ZERO

Figure 5 is a frequency plot of the ratio of the center window to outer window count rates for the northern three survey lines. The average ratio for these lines was 1.082. The average obtained for the entire Area 13 background area was 1.085.

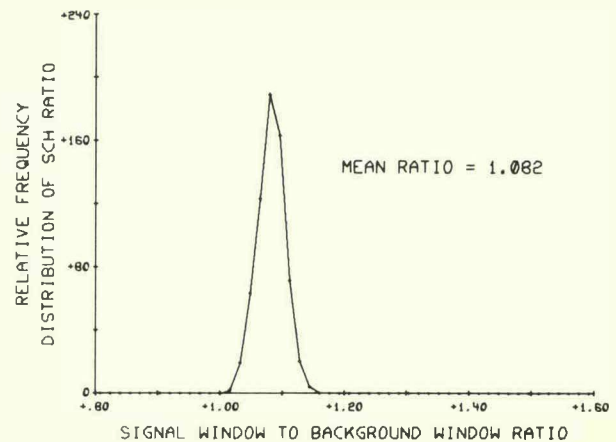


Figure 5. FREQUENCY DISTRIBUTION OF THE SIGNAL WINDOW TO BACKGROUND WINDOWS COUNT RATE RATIO OVER THE EXTREME NORTHERN THREE LINES OF THE AREA 13 SURVEY

The average count rate due to background in the center window was 1 780 counts per second (cps) and 1 640 cps in the sum of the background windows.

After the central to outer window background count rate ratio was determined, a search algorithm was defined:

$$\begin{aligned} ^{241}\text{Am count rate} &= A \\ &= T - 1.085 B \end{aligned} \quad (1)$$

where T = counts in central window
 B = sum of the counts in
 the background or
 outer windows

This algorithm was applied to survey data from Area 13 (Figure 6). Though it does not account for ^{241}Am count rates in the background window (A_1 and A_2 in Figure 3), it was used for convenience.

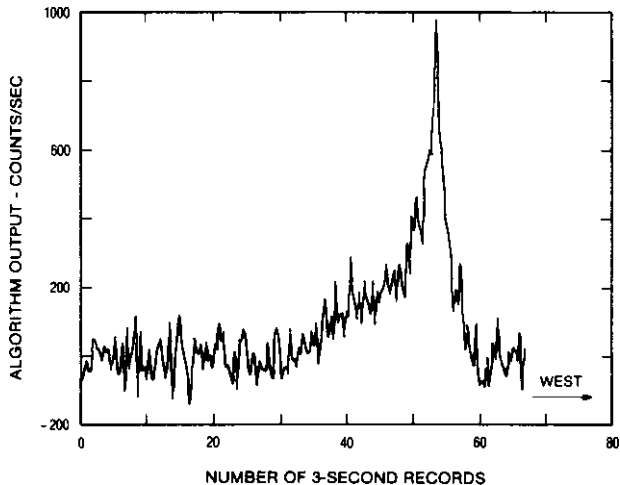


Figure 6. OUTPUT PLOT OF THE ^{241}Am SEARCH ALGORITHM APPLIED TO AN EAST-WEST LINE 180 METERS NORTH OF GROUND ZERO, AREA 13

The results of the search algorithm in equation (1) were corrected to include the effect of ^{241}Am counts in the outer background windows by examining pure ^{241}Am spectra (Figure 7). These were obtained by subtracting a background spectrum from several spectra obtained over

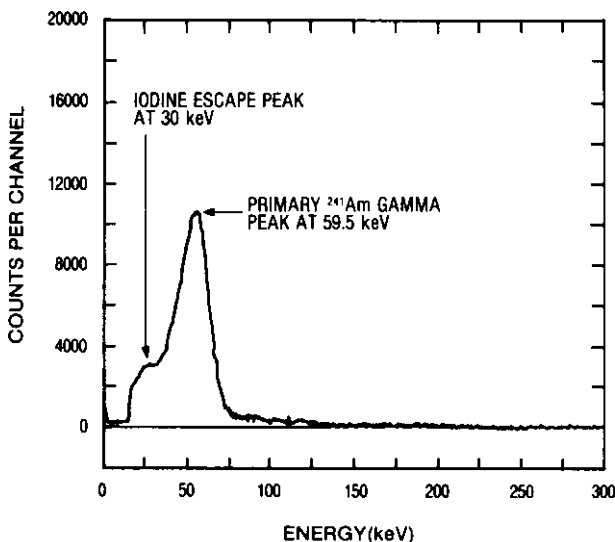


Figure 7. ^{241}Am LESS BACKGROUND GAMMA ENERGY SPECTRUM

contaminated areas. Then, the ratio of the ^{241}Am counts in the outer to central window was obtained. The average ratio was found to be 0.44.

A corrected ^{241}Am count rate, N , can now be defined:

$$\begin{aligned} ^{241}\text{Am count rate} &= N \\ &= T - 1.085(B - 0.44N) \end{aligned} \quad (2)$$

$$\text{or} \quad N = 1.92 A \quad (3)$$

Thus the corrected ^{241}Am count rate, N , is 1.92 times the result, A , used in the computer-aided data reduction process.

4.2 Data Smoothing

Some data smoothing (averaging) is generally employed on airborne data as a practical consideration. Smoothing produces a contour map which is easily read: without smoothing, a map would show so many small bumps and hollows it would be nearly illegible. Of course there is a penalty: boundary positions are more uncertain, contaminated areas of limited extent become larger in area and lower in magnitude, and singular high count rates are made lower.

A three point moving average (averaging data over 3 seconds at 1 second intervals) was applied to the algorithm result of Area 13 before the result was plotted. This degrades spatial resolution inherent in the detector/source geometry to about 90 m in the direction of flight. It also significantly reduces the count rate at the highest point over GZ. This singular highest count rate was recovered, however, from the raw algorithm result.

4.3 Count Rate Level Selection

Letter symbols are used to define ^{241}Am count rate intervals for plotting. The minimum level is selected dependent on the measured background counting statistics. This level is the most difficult because a choice must be made between defining as much of the low level activity as possible and at the same time avoiding definition or containment of many false active areas.

The lowest level was determined from the ^{241}Am counting statistics as follows:

Since: $A = T - KB$, (equation 1)

Then: $\sigma_A^2 = \sigma_T^2 + B^2\sigma_K^2 + K^2\sigma_B^2$ (4)
 $= KB + B^2\sigma_K^2 + K^2B$
 when no signal, A, is present

Where: $\sigma_T^2 = KB$
 $= 1.085 B$
 $K = 1.085$
 $\sigma_K = 0.024$ from ratio analysis
 such as Figure 5
 $\sigma_B^2 = B$
 $= 1640$ cps

Then: $\sigma_A = 72$ cps for 1 sec data

And: $\sigma_A = 44$ cps for the average of 3 sec
 data evaluated for 1 sec

The lower edge of the minimum count rate interval was set at 57 cps or at 1.3 standard deviations of the central window background count rate for a 3-second average. This level corresponds to a false alarm rate of 1 for each ten 1-second measurements.^{8,9} This false alarm rate is large; it was used to identify as much as possible of the contaminated area within the outer fenced boundary of Area 13.

False identification of contaminated areas outside the fenced area was suppressed by requiring that:

- B levels must occur adjacent to each other on neighboring lines. (Only B levels occur outside the fence except immediately adjacent to the fence on the west side.)
- The raw unsmoothed count rate was 220 cps or more, which is about three times the standard deviation of unsmoothed data.

This method of background suppression reduces the false alarm rate to about 1 per one hundred 1-second measurements or less in the area outside the fence.

The maximum uncorrected count rate (37 500 cps) over the GZ consisted of 1 point. A convenient upper level is 40 000 cps. Six levels were then chosen between the maximum and minimum levels so that the natural logarithm of the count rate is proportional to the level or:

Count rate, y, at level x is:

$$y = 22.35 \exp. (0.9362x) \text{ cps} \quad (5)$$

$$x = 1, 2, 3 \dots$$

These levels are revised upwards by a factor of 1.92 to correct the count rates to true count rate (account for the signal in the background windows) before computing ^{241}Am , $^{239,240}\text{Pu}$, or total transuranic concentrations.

Once the algorithm and count rate levels have been defined, the results of the algorithm applied to the data may be plotted and contoured.

4.4 Conversion Factors

The ^{241}Am gamma count rates in the Na(Tl) detectors may be converted to concentrations in the soil by a combination of measurement and computation. Stuart's routine was used here to estimate concentrations from count rates.¹⁰

The value of the relaxation length ($1/\alpha$) in the assumed exponential depth distribution is very important in the conversion factor computation.⁷ The value applicable to Area 13 was obtained by fitting the depth distribution data of Gilbert et al in Reference 1, page 382, with curves:

$$y = y_0 e^{-\alpha z}$$

$\alpha =$ exponential distribution
parameter, cm^{-1}

$z =$ depth in soil, cm

The average α was found to be 1 cm^{-1} . Other parameters affecting the calculation are:

- (1) Altitude of measurements = 30 m
- (2) Density of air = $1.025 (10^{-3}) \text{ g/cm}^3$
- (3) Cross section of air at 60 keV = $0.185 \text{ cm}^2/\text{g}$
- (4) Density of Area 13 soil = 1.14 g/cm^3
(Reference 3, page 628: Martin and Bloom)
- (5) Cross section of soil at 60 keV = $0.25 \text{ cm}^2/\text{g}$
- (6) Effective area of twenty $12.7 \text{ cm} \times 5.1 \text{ cm}$
crystals - $2 534 \text{ cm}^2$
- (7) The response of these detectors vs. angle, θ ,
from the vertical was assumed to be $\cosine \theta$

Since the vertical sample intervals of Reference 1 were rather coarse (2.5 cm intervals), one might suspect that the exponential model may not be adequate for this purpose. For instance, most of the activity could well be in the top 1/10 cm with only a fraction exponentially distributed. For this reason a conversion factor was computed using $\alpha = 625 \text{ cm}^{-1}$, which is equivalent to a surface layer of activity. This model may or may not be closer to the truth.

Basic conversion factors that may be used to convert count rate levels to concentrations are given in Table 1. Those conversions to pCi/g are computed to compare with measurements of average concentration in the top 5 cm of soil.¹¹ Those conversions to $\mu\text{Ci}/\text{m}^2$ include all the activity to infinite depth.

$\alpha \text{ (cm}^{-1}\text{)}$	$\frac{\text{pCi/g}}{\text{cps}}$	$\frac{\mu\text{Ci/m}^2}{\text{cps}}$
0.1	0.098	14.2 (10^{-3})
0.3	0.093	6.8 (10^{-3})
0.5	0.083	5.1 (10^{-3})
<u>1.0</u>	<u>0.070</u>	<u>4.0 (10^{-3})</u>
2.0	0.060	3.4 (10^{-3})
5.0	0.053	3.0 (10^{-3})
<u>625</u>	<u>0.048</u>	<u>2.7 (10^{-3})</u>

- NOTE: (1) α = exponential relaxation depth, cm^{-1} .
- (2) These conversion factors to pCi/g relate to the average value of a 5 cm deep soil sample.
- (3) The conversion factor to $\mu\text{Ci}/\text{m}^2$ relate to the total activity in the soil.
- (4) These conversion factors apply to ²⁴¹Am counts in the central window.
- (5) The underlined values were used in the inventory computations.
- (6) The values for $\alpha = 1 \text{ cm}^{-1}$ were used to compute levels for the transuranic isopleth map.

4.5 Minimum Detectable Activity (MDA)

MDA is dependent on the background level (1 640 cps at Area 13). Further, the MDA may be qualified to three parameters: (1) the fraction of false signals accepted q ;^{8, 12} (2) the fraction of signals missed, β ;^{8, 12} and (3) the spatial resolution of the measurement. Of interest is the MDA associated with the low level contour on the survey map. If one assumes $\alpha = 1 \text{ cm}^{-1}$, the MDA associated with the lower edge of the low level contour on the map then is 7.7 pCi/g for ²⁴¹Am at $q = 0.10$, $1 - \beta = 0.5$, with an area resolution of 2.2 hectares. That is:

$$\begin{aligned} \text{MDA} &= 57 \text{ cps} \times 1.92 \times 0.07 \frac{\text{pCi/g}}{\text{cps}} \quad (6) \\ &= 7.7 \text{ pCi/g} \end{aligned}$$

where:

- (1) The minimum trip level is 57 cps.
- (2) The 1-second data has been smoothed (averaged over a 3-second period).
- (3) The factor 1.92 accounts for the "spillover" of signal counts into the background windows (Section 4.1).
- (4) The sensitivity, 0.07 (pCi/g)/cps, is obtained from Table 1.

4.6 ²⁴¹Am Transuranic Contour Map

The concentration contour map is manually drafted from a computer printout and plot of the count rate level symbols (Figure 8). The original scale is 60 m = 1 cm. Included are Nevada coordinates and the underlying photograph of the area.

The contours or isopleth intervals are labeled in terms of both pCi/g and $\mu\text{Ci}/\text{m}^2$ for the total transuranics. The total was obtained from the product of the aerial ²⁴¹Am measurement and $R + 1$ where $R = 9.4$ is the ^{239,240}Pu to ²⁴¹Am ratio (Reference 1, page 403).

The actual signal count rates, A of equation (1), may be obtained from the average soil activity table in Figure 8 from the following equation:

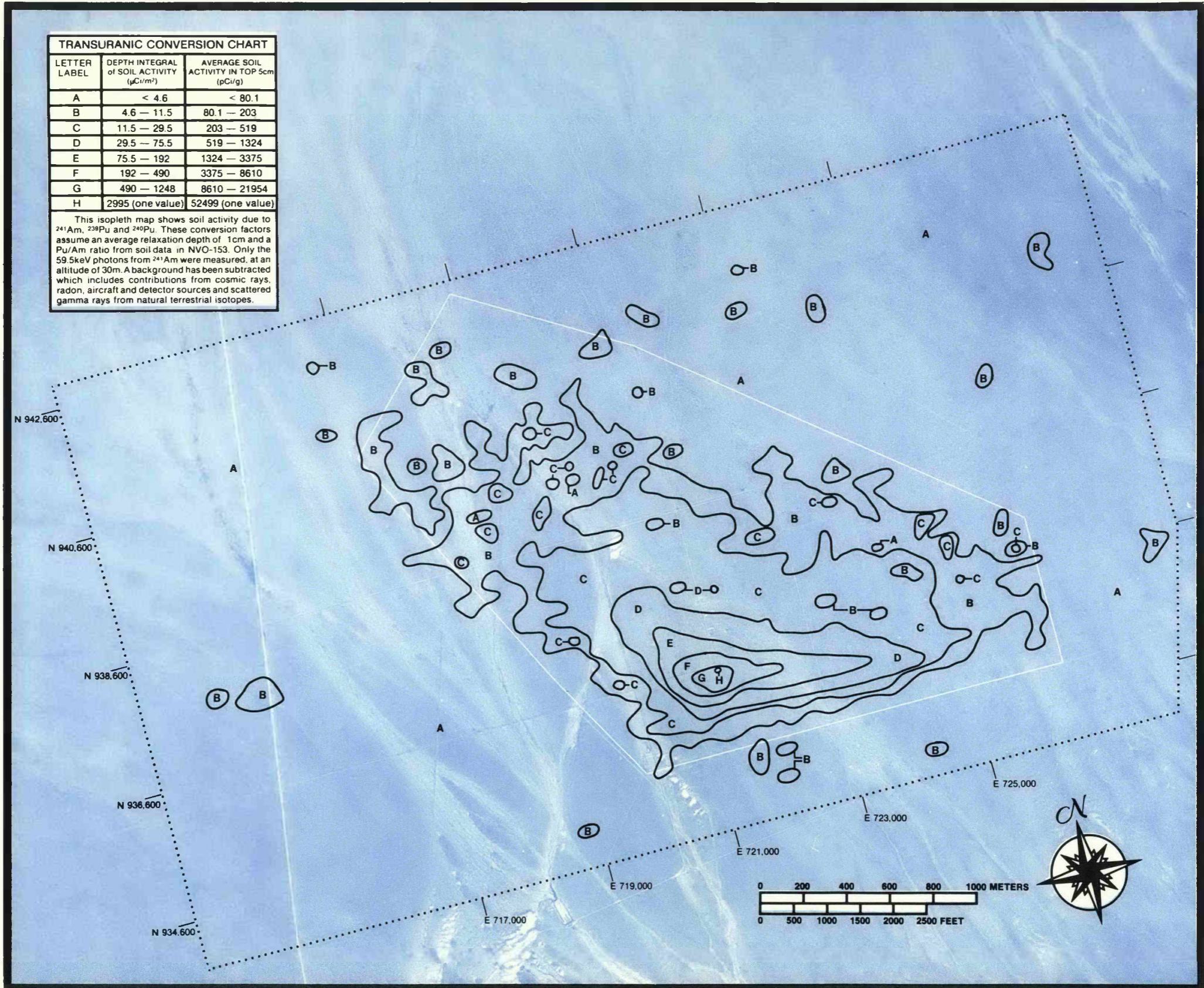


Figure 8. AREA 13 TRANSURANIC ISOPLETH MAP

$$A = T/(R \times C \times S) \quad (7)$$

where

A = measured count rate

T = transuranic activity level

R = ratio of total transuranic to ^{241}Am concentration, 10.4

C = system sensitivity, 0.07 (pCi/g)/cps of ^{241}Am

S = ratio of corrected signal count rate to search algorithm count rate, 1.92 (Section 4.1)

The lower edge of the B level, for example, is 80.1 (pCi/g)/cps of plutonium. Then the measured algorithm result of equation (1) is:

$$A = 80.1/(10.4 \times 0.07 \times 1.92) \\ = 57 \text{ cps}$$

4.7 ^{241}Am and $^{239,240}\text{Pu}$ Inventory at Area 13

It is convenient to compute a total inventory of the ^{241}Am contained in Area 13 from the radiation map. Since the total number of points measured (7 965) and the total area surveyed (14 639 723 m²) are known, the average area per point can be computed as 1 838 m². This is reasonable since point spacing was nearly constant using the steering indicator and flying at a constant 60 knots per hour. Then, using the conversion factor for $\alpha = 1 \text{ cm}^{-1}$ from Section 4.4, the inventory at each interval may be computed:

$$Ci = CR \times N \times A \times S \quad (8)$$

where

Ci = inventory in curies

CR = average count rate at each level

N = number of data points at each level

A = average area per point, 1 838 m²

S = conversion factor 0.004 ($\mu\text{Ci}/\text{m}^2$)/cps

Table 2 is a list of the levels and ^{241}Am inventory in each.

Level Symbol	Average Value (cps)	No. Points at Level	Inventory (Ci)	% of Total
H	72 115	1	0.53	5.50
G	20 994	10	1.53	15.89
F	8 232	26	1.57	16.30
E	3 228	73	1.73	17.96
D	1 266	157	1.45	15.06
C	496	484	1.76	18.28
B	195	669	0.96	9.97
B (Outside Fence)	195	72	0.10	1.04
			9.63	100.00

From Reference 1, page 403, one expects 9.4 Ci of $^{239,240}\text{Pu}$ per Ci of ^{241}Am .

$$\text{then } ^{239,240}\text{Pu inventory} = 9.63 \times 9.4 \quad (9) \\ = 90.5 \text{ Ci}$$

If we assume most of the ^{241}Am is on the surface (depth distribution relaxation coefficient = 625 cm⁻¹), the computed plutonium inventory is 62.1 Ci.

The best estimate of plutonium inventory from soil sample data is 46 ± 9.0 Ci with an upper bound of 64 Ci at the 95% confidence level (Reference 4, page 425).

Since the aerial inventory does not agree with the soil sample inventory, some of the principal sources of error in the aircraft result are listed:

- (1) The depth distribution of activity must be known from a separate measurement in order to convert count rate to ^{241}Am concentration. The range of possible distributions obtained from soil samples results in a range of 62.1 Ci to 90.5 Ci of $^{239,241}\text{Pu}$ inventory.
- (2) The manual method of counting smoothed points at a given level and assigning the average value has an unknown accuracy. Converting each unsmoothed data point to concentration would certainly yield a more accurate answer.
- (3) The use of the computed cosine θ crystal response to a volume source may

overestimate the concentration of ^{241}Am . An average of the cosine and isotropic response yields inventories that are 18% less than those computed for the aircraft. To date, the experiment to determine the exact angular response of the H-500 detector package has not been done. However, when the detailed response experiment is performed, it is expected to be close to cosine.

- (4) The effect of large concentrations located in a small area at the GZ is not known. Since the measurement system is calibrated for a uniform volume of surface source over the detector field-of-view, significant error can result. Indeed, the maximum counting rate at GZ was 72 000 cps (corrected for the background window effect) which implies 5 nCi/g, whereas the soil sample estimate is 14 nCi/g (Reference 3, page 626).

- (5) The aircraft system's minimum detectable activity of 7.7 pCi/g of ^{241}Am leaves an unknown inventory both within and outside the outer fence.
- (6) The effect of the statistical error in level B is small since there are so many of them (669), and level B contributes only 11% of the total inventory.

The aircraft system, then, puts a minimum inventory of 62.1 Ci of Pu at Area 13 when a surface source is assumed. The maximum inventory implied from the aircraft measurement is 90.5 Ci of Pu. It is important to note that the aircraft system will not see source concentrations below 72.4 pCi/g of Pu (7.7 pCi/g of ^{241}Am). Therefore, there is an unknown inventory surrounding the contaminated area indicated in Figure 8.

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