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AN AERIAL RADIOLOGICAL SURVEY OF
THE UNITED STATES DEPARTMENT OF ENERGY'S

ROCKY FLATS PLANT

GOLDEN, COLORADO

DATE OF SURVEY: JULY 1989

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EXECUTIVE SUMMARY

An aerial radiological survey of the Rocky Flats Plant was conducted during July 1989 by EG&G Energy Measurements, Inc. (EG&G/EM) for the United States Department of Energy (DOE). The survey consisted of airborne measurements of both natural and man-made gamma radiation from the terrain surface in and around the Rocky Flats Plant. These measurements allowed an estimate of the distribution of isotope concentrations in the survey area. Results are reported as isoradiation contour maps of total terrestrial exposure rate, man-made count rate, Am-241 count rate, and Cs-137 count rate isopleths superimposed on aerial photographs of the area. Gamma ray energy spectra are also presented for the net man-made radionuclides.

The aerial survey covered an area approximately 9.7 km (6 mi) by 12.9 km (8 mi) for a total survey area of 124 sq km (48 sq mi). The aerial survey was completed in six flying days. It required 24 helicopter flight hours and covered over 1,000 line miles. Over 75,000 data points were collected in the Rocky Flats area.

The 1989 survey was requested by DOE Headquarters to determine if there were any detectable changes in the terrestrial radiation profile of the Rocky Flats area since the routine 1981 survey[1] was conducted.

Germanium detectors and soil samples were also used to verify the aerial data and to increase the detectability and spatial resolution of man-made radioisotopes in the survey area. The soil sample analyses were completed in March, 1990. The soil sample and *in situ* data are summarized in Appendix A.

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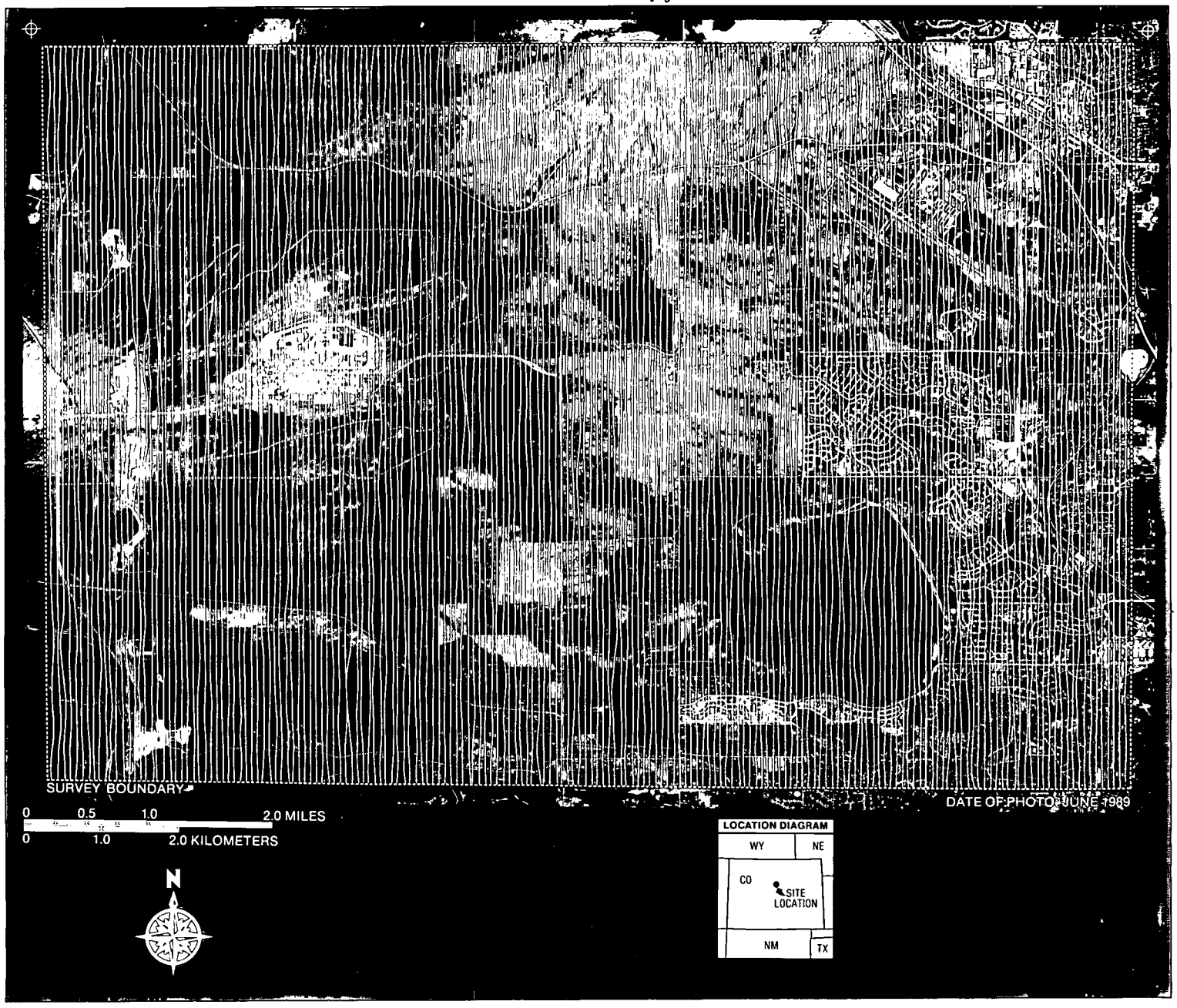

FIGURE 1. ***ACTUAL FLIGHT LINES FLOWN BY THE HELICOPTER***

At the Rocky Flats Plant, there had been allegations that a criticality accident had recently occurred at the facility which had released Am-241, Pu-239, and fission products into the environment. If a criticality accident had occurred since the 1981 survey, a definite change in the Am-241 and Cs-137 contours should have been observable in the radiological profile of the 1989 survey.

In order to characterize the radiological profile of the Rocky Flats Plant and surrounding area, a series of parallel lines were flown over 124 square kilometers (48 square miles) to cover the area of interest. Specifically, the survey was oriented to cover the Rocky Flats site and the natural drainage area leading away from the plant. The flights were conducted at an altitude of 46 m (150 ft) over lines spaced 76 m (250 ft) apart. The aircraft speed was 30 m/sec (100 ft/sec).

All data were scaled to overlay recent photographs (June 1989) of the Rocky Flats area. The data were analyzed for all man-made gamma ray-emitting radionuclides. Man-made radionuclides of primary concern included in this report are Cs-137 (with a single photopeak at 662 keV) and Am-241 (60 keV gamma ray) which is associated with plutonium activity.

The only practical way to monitor for Pu-239 in the environment is to measure the activity of the plutonium daughter product, Am-241. The relationship between Am-241 and Pu-239 is well known.[2,3] See Appendix A for more detailed information. Any other technique to monitor Pu-239 in an area this large would be extremely expensive and take a very long time to take the samples. It would take even longer to get any results from the analyses.

The Cs-137 levels in the plant area were also of major concern. It had been suggested that a "criticality" accident had occurred and released Cs-137 to the environment. Cesium-137 is easy to detect in the environment since it has an energetic gamma ray of 662 keV, a relatively high per entage of gamma rays per disintegrations (85%) and a long half-life (over 30 years). If an accident had occurred at the plant, a ground deposition plume would be detectable in the survey area.

The actual flight lines flown by the helicopter are shown in Figure 1.

3.2 Ground Measurements

Germanium detector measurements and soil samples were taken from the same areas outside the fence around the Rocky Flats facility that indicated Am-241 activity in the 1981 aerial survey. Ground measurements were continued in directions away from the facility until the Am-241 was undetectable. The first priority was to determine the extent of the deposition in an easterly direction and then to determine the northern and southern boundaries.

Measurements were made along Indiana Street to see if Am-241 could be detected at the eastern boundary fence of the facility. Measurements were also made on the streams that drain from the Rocky Flats Plant.

4.0 AERIAL SURVEY EQUIPMENT

A Messerschmitt-Bolkow-Blohm (MBB) BO-105 helicopter (Figure 2) was used for the low altitude survey. The aircraft carried a crew of two and a lightweight version of the Radiation and Environmental Data Acquisition and Recorder (REDAR) system. Two detector pods were mounted on each side of the helicopter. Each contained four 5.08-cm (2-in) thick by 10.16-cm (4-in) wide and 40.64-cm (16-in) long thallium-activated sodium iodide, NaI(Tl), detectors.

The preamplifier signal from each detector was calibrated with Na-22 and Am-241 sources. Normalized outputs of each detector were combined in an eight-way summing amplifier. Finally, the signal was adjusted in the analog-to-digital converter (ADC) so that calibration peaks appeared in preselected channels of the multichannel analyzer of the REDAR.

4.1 REDAR System

REDAR is a multi-microprocessor, portable data acquisition and real-time analysis system. It has been designed to operate in the severe environments associated with platforms such as helicopters, fixed-wing aircraft, and various ground-based vehicles. The system displays all required radiation and system information to the operator in real time via a 5-inch CRT display and multiple LED readouts. All pertinent data are recorded on 3M cartridge tapes for post-mission analysis on minicomputer systems.

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1.0 INTRODUCTION

The United States Department of Energy (DOE) maintains an aerial surveillance system, the Aerial Measuring System (AMS), which is maintained and operated for DOE by EG&G Energy Measurements, Inc. (EG&G/EM), an independent contractor. Since its inception in 1958, this continuing nationwide program has included radiological surveys of nuclear power plants, processing plants for nuclear materials, and research laboratories. AMS aircraft have been deployed to nuclear accident sites and in searches for lost radioisotopes. These aircraft were routinely used during launch operations for Apollo, Viking, and other space vehicles which contained radioisotope thermal generators. AMS aircraft also are equipped with mapping cameras and multispectral camera arrays for aerial photography, a thermal mapper for infrared imagery, a broad array of meteorological sensors, and air sampling systems for particulate and whole gas measurements. All of the survey operations are conducted at the request of federal or state agencies and by the direction of DOE.

The aerial radiological survey of the Rocky Flats Plant and surrounding area was conducted during July 1989 by EG&G/EM for the DOE. The survey consisted of airborne, *in situ*, and soil sample measurements of the natural and man-made gamma radiation sources in and around the plant site. The survey was conducted at the request of DOE Headquarters in support of the Tiger Team investigation to determine if changes had occurred in the radiation profile of the Rocky Flats area as a result of plant operations since a prior survey in 1981.

Germanium detector measurements were made at 1.0 m above ground level (AGL) to verify the aerial data. Since the germanium has a lower minimum detectability for Am-241, it was used to refine the deposition isopleths both spatially and quantitatively. Soil samples were collected at each measurement location.

2.0 ROCKY FLATS SITE DESCRIPTION

The Rocky Flats Plant is a U.S. Government-owned facility for the production of nuclear components. It is located 16 miles northwest of Denver, Colorado, and is situated almost equidistant (within 10 mi) between Golden and Boulder.

The plant consists of a 255-acre complex of manufacturing, chemical processing, laboratory, and support facilities and is situated in the center of a 6,550-acre natural preserve.

The Rocky Flats Plant has been operated by EG&G Rocky Flats* since January 1990 under contract with the U.S. Department of Energy. The primary mission of the plant is the development and production of specific components for nuclear weapons. These include components fabricated from plutonium as well as uranium, beryllium, and stainless steel, and they are shipped outside Colorado for assembly. There are no complete nuclear weapon assemblies or nuclear power reactors at Rocky Flats.

All plutonium operations at the plant are carried out in highly specialized facilities that separate the plutonium from the environment. Plutonium operations involve the use of high-precision equipment and sophisticated techniques for metallurgical casting, rolling, and forming operations; for machining, joining and nondestructive testing; and for the chemical operations necessary for recovery of plutonium for reuse.

Americium, an ingrowth product of plutonium radioactive decay, is a by-product of the chemical recovery operation and is widely used in home and industrial smoke detectors, in oil and gas well logging, and in a variety of other applications. Rocky Flats is the principal U.S. source of this important material.

There are two fences surrounding the Rocky Flats Plant. One is a site perimeter fence that encloses the 255-acre manufacturing facility. The other fence is a boundary fence that surrounds the manufacturing site as well as a buffer zone that is a square area approximately 2 miles on each side.

3.0 SURVEY PLAN

3.1 Aerial Survey

The AMS surveys are designed to cover large areas surrounding nuclear facilities. The gamma ray spectral data are processed to provide a qualitative and quantitative analysis of the radionuclides in the survey area.

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*During the time of the survey, Rockwell International operated the Rocky Flats Plant.

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FIGURE 2. ***MBB BO-105 HELICOPTER WITH DETECTOR PODS***

The system employs five Z-80 microprocessors with AM9511 arithmetic processing chips to perform data collection, data analysis, data display, position and steering calculations, and data recording. These functions are all under operator control. The system allows access to the main processor buss through both serial and parallel data ports under control of the Control Processor.

The system consists of the following subsystems:

1. Two independent radiation data collection systems
2. A general purpose data I/O system
3. A tape recording/playback system
4. A CRT display system
5. A real-time data analysis system
6. A uhf ranging system (URS) with steering calculation and display

The REDAR processing system block diagram is shown in Figure 3.

The multichannel analyzer collected 1,024 channels of gamma ray spectral data (4.0 keV/channel) once every second during the survey operation. The 1,024 channels of data were sent to the single channel processor and were compressed into 256 channels with partitions. Table 1 summarizes the spectral data compression performed by REDAR. The spectrum was divided into the three partitions

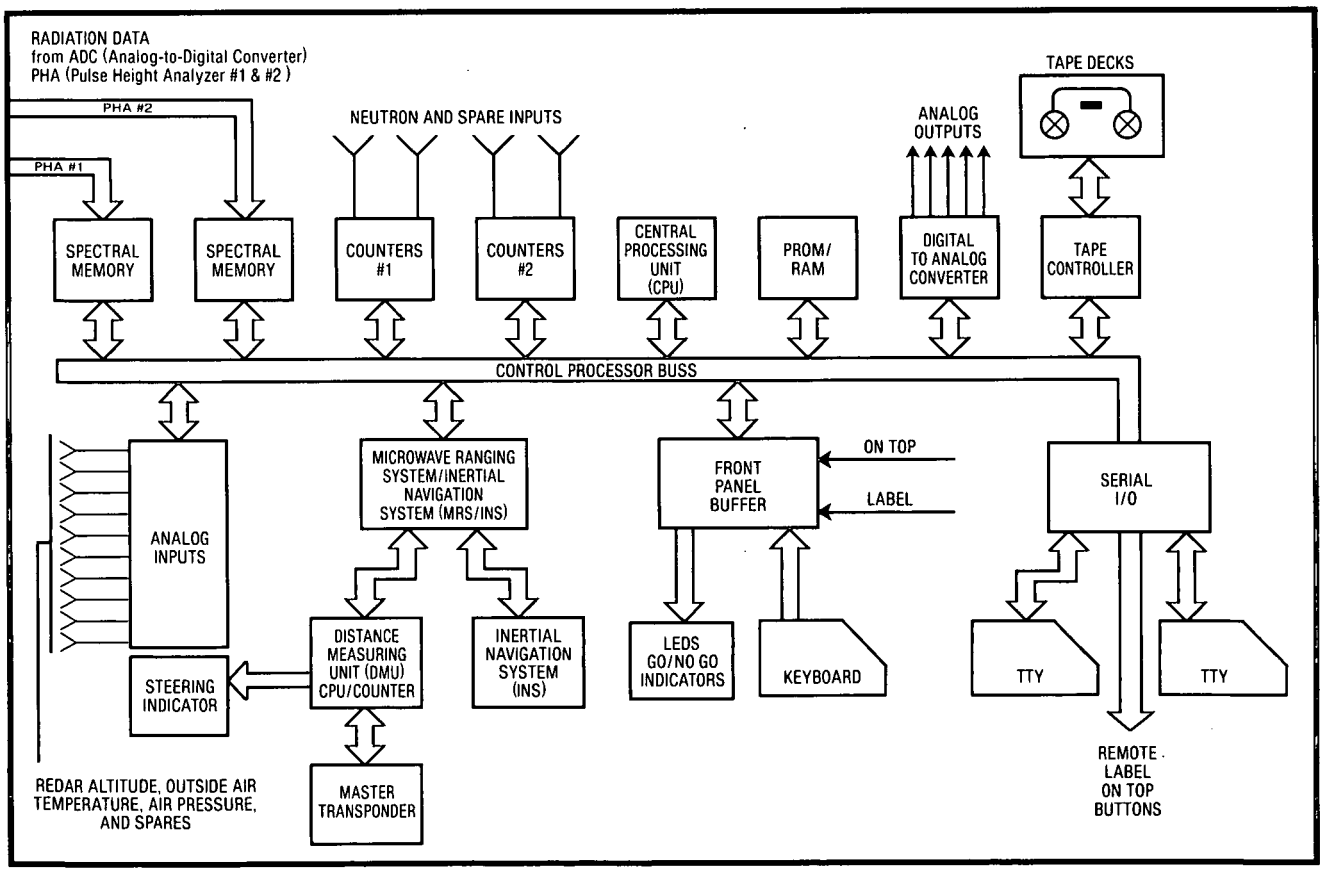

FIGURE 3. ***REDAR PROCESSING SYSTEM BLOCK DIAGRAM***

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Table 1. REDAR Spectral Data Compression			
$E\gamma$ (keV)	Channel Input	Energy Coefficient ΔE (keV/channel)	Compressed Channel Output
0 - 302	0 - 75	4	0 - 75
302 - 1622	76 - 405	12	76 - 185
1622 - 4070	406 - 1017	36	186 - 253
4070 - 4090	1018 - 1022	N/A	254
>4090 - Analog Cutoff	1023	N/A	255
	1024	Unused	256

with the appropriate energy coefficient to make the width of the photopeaks approximately the same in each partition. The resolution of NaI(Tl) crystals varies with energy, permitting the compression of the spectral data without compromising photopeak identification and stripping techniques. In the first partition (channels 0-75), the data were not compressed, permitting stripping of low energy photopeaks such as the 60 keV photopeak from Am-241. The spectral compression technique reduces the amount of data storage required by a factor of four.

The 256 channels of compressed spectral data were acquired every second. The REDAR system has two sets of spectral memories. Each memory accumulated four individual spectra. The two memories were operated in a flip-flop mode, every 4 seconds, for continuous data accumulation. While one memory stored data, the other memory transferred data to magnetic tape.

Figure 4 shows the REDAR data acquisition system.

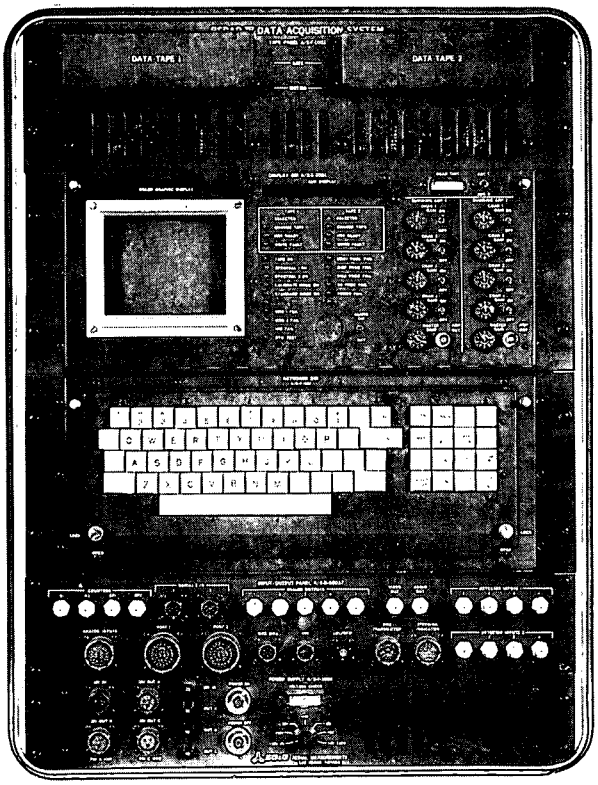

FIGURE 4. *REDAR DATA ACQUISITION SYSTEM*

4.2 Helicopter Positioning Method

The helicopter position was established using two systems: a Del Norte UHF ranging system (URS) and an AL-101 radio altimeter. The URS master station mounted in the helicopter interrogated two remote transceivers outside the survey area. By measuring the round-trip propagation time between the master and remote stations, the master computed the distance to each. These distances were recorded on magnetic tape once each second. They were converted to position coordinates for the steering indicator to direct the aircraft along the programmed flight line. The radio altimeter similarly measured the time lag for the return of a pulsed signal and converted this to aircraft altitude. For altitudes up to 610 m (2,000 ft), the accuracy was ± 0.6 m (2 ft) or $\pm 2\%$, whichever was greater. These altitude data were recorded on magnetic tape so that variations in gamma signal strength caused by altitude fluctuations could be compensated.

The detectors and electronics systems which accumulated and recorded the data are described in considerable detail in a previous report.[4,5]

5.0 GROUND MEASUREMENTS AND PROCEDURES

In situ measurements were made at 75 locations within the Rocky Flats Plant area to measure man-made radionuclide concentrations in the soil. The majority of the measurements were made in the northeast and southeast buffer zones outside the Gate 9 perimeter fence, beginning near the center of the Rocky Flats site and extending east to the boundary fence line along Indiana Street. Measurements were made at each point where drainage areas and creeks cross Indiana Street and other key roadways. Several measurements were also made outside the plant boundary at the Jefferson County Airport. For possible future repeat measurements, each of the 75 locations was numbered and tagged with white flags to indicate no detectable Am-241 or with yellow flags to indicate detectable Am-241 activity. Soil samples were taken at each location to be analyzed at EG&G's Santa Barbara Operations Office soil sample analysis laboratory. Position coordinates were obtained for each location using the same URS remote transponders that supplied the position information for the aerial data.

Gamma ray spectral data were collected with nitrogen-cooled high purity germanium (HPGe) detectors. The gamma signals were processed using 4,096-channel, multichannel analyzers. The measurements were conducted with two systems. One system was mounted on a 4-wheel drive vehicle with the detector suspended from an extendable boom capable of detector heights between ground level and 7.4 meters. The vehicle was also equipped with a generator that supplied power to data processing equipment which allowed immediate analysis of the acquired data. The second system was mounted on a tripod; this system was used in areas where the vehicle could not maneuver (*i.e.*, creek beds, culverts, etc.). Figures 5 and 6 illustrate the detector system setups.

Prior to collecting data each day, the detectors were calibrated with sources measured by or traceable to the National Institute of Standards and Technology. Periodically, measurements were taken in areas where the levels of radiation were typical of the naturally occurring levels in the Broomfield, Colorado, area.

In most cases, the data to characterize Am-241 were collected at 61-meter (200-foot) intervals to cover the area of interest. If Am-241 was detected, the measurements were continued until the Am-241 was completely characterized in that area (*i.e.*, the measurements were continued in all directions until the Am-241 was no longer detectable). Data were collected in all locations with

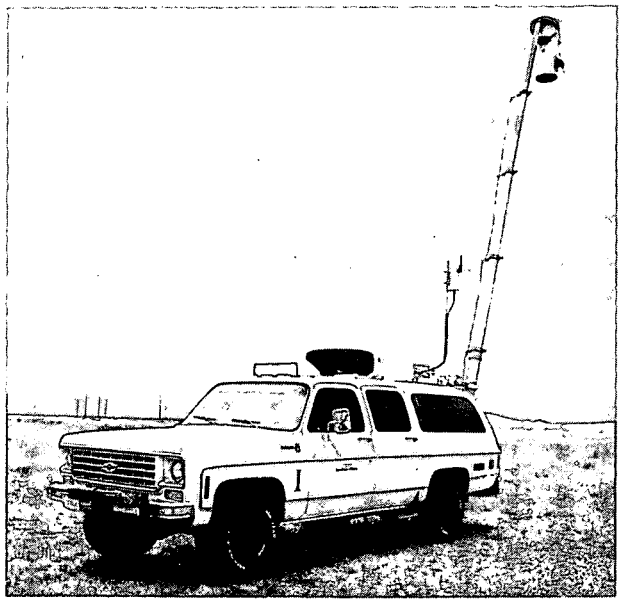

FIGURE 5. ***IN SITU GERMANIUM DETECTOR SYSTEM AND SUBURBAN***

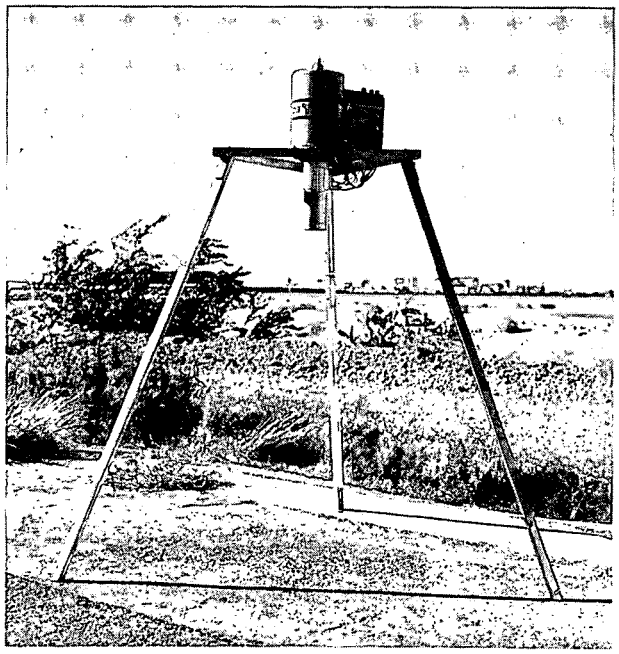

FIGURE 6. ***IN SITU GERMANIUM DETECTOR SYSTEM AND MULTICHANNEL ANALYZER MOUNTED ON A TRIPOD***

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each detector at a height of 1 meter above the ground. To optimize detector sensitivity and data collection time, each measurement was made for 900 seconds (15 minutes). Using these parameters, the minimum detectable activity (MDA) for surface concentrations of Am-241 was 0.006 $\mu Ci/m^2$ and 0.1 pCi/g for uniformly distributed Cs-137. Calibration and operating procedures for the HPGe detector *in situ* measurements are described in detail in separate publications.[6,7]

6.0 AERIAL SURVEY DATA

6.1 Data Processing

Data processing was begun in the field with the Radiation and Environmental Data Analysis and Computer (REDAC) system. This is a computer analysis laboratory mounted in a mobile van (Figure 7). The van and the aircraft were based at JEFFCO Airport in Broomfield, Colorado, during the survey operations.

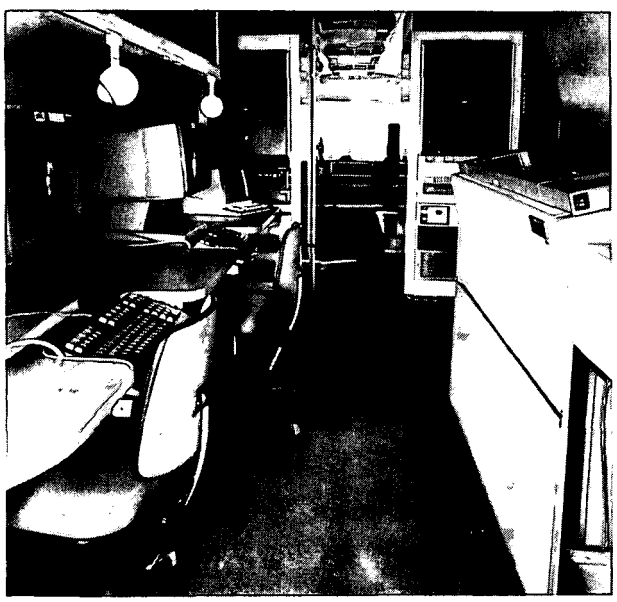

FIGURE 7. ***MOBILE COMPUTER PROCESSING LABORATORY***

The REDAC system utilizes a Data General Corporation (DGC), 32-bit MV7800-XP minicomputer. Peripherals include two 800/1,600 BPI 9-track magtape drives, two 1/4-inch digital cassette drives (used for reading REDAR tapes), two 554-MByte disk drives, a laser printer, a 36-inch incremental plotter, a system terminal, and two alpha/graphics CRT display/hardcopy units. A block diagram of the system is shown in Figure 8. The system provides full multi-user/multi-task capabilities. An extensive set of system and application software packages is available for data analysis.

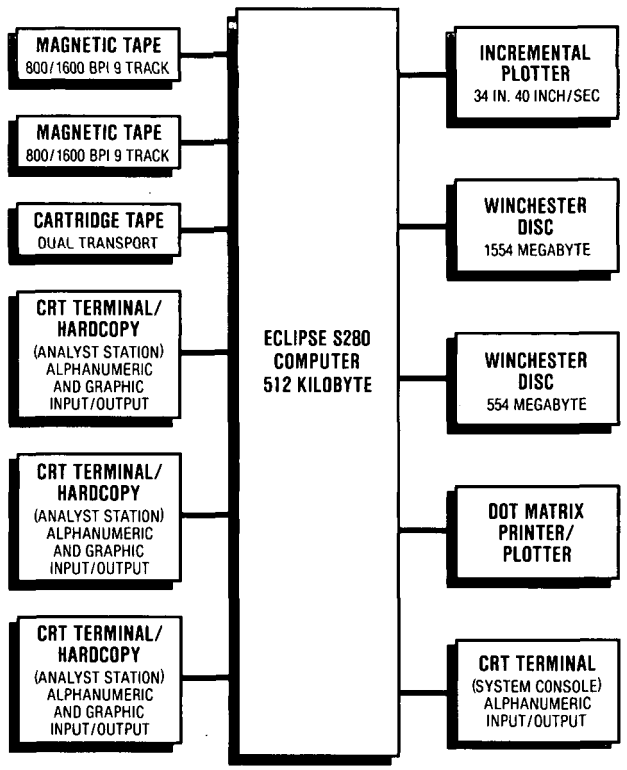

FIGURE 8. ***REDAC ANALYSIS SYSTEM BLOCK DIAGRAM***

Gamma spectral windows can be selected for any portion of the spectrum. Weighted combinations of such windows can be summed or subtracted, and the result can be plotted as a function of time or position. By the proper selection of windows and weighing factors, it is possible to extract the photopeak count rates for radioisotopes deposited on the terrain by human activity. Such isotopes disturb the pattern of natural soil radioactivity. These photopeak count rates can then be converted to isotope concentrations or exposure rates.

The spectral data, which can be summed over any portion of a flight line, can be decompressed into a linear plot. The REDAC displays the linear spectral data or plots it on the incremental plotter for isotopic identification.

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6.2 Data Analysis

In general, the aerial radiation data consisted of contributions from the naturally occurring radioelements, aircraft and detector background, and cosmic rays. For this survey, the major emphasis was placed on extracting that component arising from man-made radioactivity. Isopleth maps were produced by processing the data in different ways: gross count, man-made gross count (MMGC), Cs-137, and Am-241 count rate extractions.

6.2.1 Gross Count

The gross count method was based on the integral counting rate in that portion of the energy spectrum between 0.04 MeV and 3.0 MeV. This count rate (measured at survey altitude) was converted to exposure rate at the 1 m AGL by application of a predetermined conversion factor. This factor assumes a uniformly distributed source covering an area which is large compared with the field of view of the detector (approximately 200 to 300 m at the survey altitude of 46 m). For a finite source distribution which is small compared to the field of view of the detector system, it is necessary to modify the exposure rate values by utilizing the data in Table 2. The exposure rate values could be one to two orders of magnitude higher for an area with a source localized in a small area.

6.2.2 Man-Made Gross Count

The MMGC rate algorithm is designed to sense the presence of changes in spectral shape. Large changes in gross counting rates from natural radiation usually produce only small changes in spectral shape because the natural emitters change in more or less constant ratio as the detector moves from one location to another. The MMGC algorithm senses counts in the lower portion of the spectrum in excess of those predicted on the premise that these counts bear a constant ratio to counts in the upper portion. Since the algorithm is designed to be most sensitive to man-made nuclides, the spectrum dividing line is chosen at an energy (1.4 MeV) above which most long lived, man-made nuclides do not emit gamma rays. It is analytically expressed in MeV as:

$$\text{MMGC} = \sum (0.04 - 1.40) - K \sum (1.40 - 3.00) \quad (1)$$

The counts in the upper energy window (1.40 to 3.00 MeV) are multiplied by a constant, K, to equal the counts in the lower energy window (0.04 to 1.40 MeV), and the resultant MMGC is equal to zero for areas containing normal background radiation.

Spectral data from the survey revealed that all of the gamma rays from the man-made isotopes had energies less than 1.4 MeV. Therefore, the MMGC extraction technique was used to locate man-made activity in the survey area.

The man-made gross count algorithm is general and will respond to a wide range of nuclides. The result of using this generality is the lack of sensitivity to specific nuclides. If the search nuclide is known, more sensitive algorithms can be devised.

Table 2. Correction Factors Versus Area of Contamination

Diameter of Contaminated Circular Area (meters)	Correction Factor
5	300
10	100
25	10
50	6.5
100	2.5
200	1.2
300	1.0
∞	1.0

6.2.3 Cesium-137

The photopeak count rate from Cs-137 was determined by using two spectral windows (see Figure 9). The cesium photopeak window (A) included counts in the energy range 590 keV through 734 keV. The background window (B) included counts in the range 734 keV through 1,046 keV.

For natural isotopes, the ratio $K = A/B$ is nearly constant, so the counts recorded in B accurately predict counts expected in window A. Hence:

$$A \text{ cts (predicted)} = K \times B \text{ cts (measured)} \quad (2)$$

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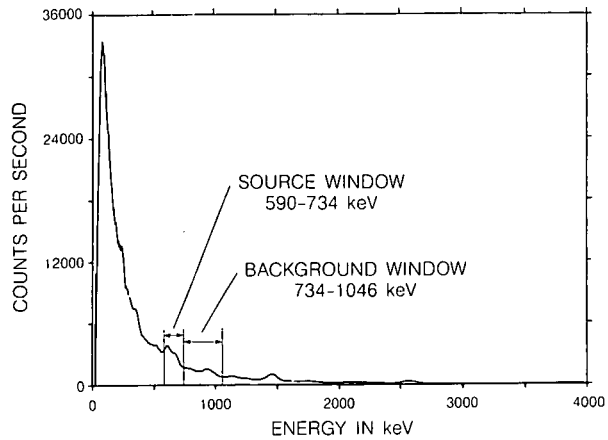

FIGURE 9. ***TYPICAL GAMMA RAY SPECTRUM SHOWING THE LOCATION AND ENERGY WIDTH OF THE WINDOWS USED FOR Cs-137 EXTRACTION***

The difference between the A cts (measured) and A cts (predicted) is a measure of the cesium counts present:

$$\text{Cesium cts} = \text{A cts (measured)} - \text{A cts (predicted)}$$

$$\text{Cesium cts} = \text{A cts (measured)} - \text{K} \times \text{B cts (predicted)} \quad (3)$$

As previously noted, the value of K is obtained from a spectrum over a terrestrial area where cesium is totally absent. Because of worldwide fallout, there is virtually no such area, and an indirect method must be used. Spectral data are summed from the entire area (excluding water and other obviously anomalous areas), and a nominal ratio, K, is determined. Using this nominal, K, apparent cesium counts are calculated for every survey point. A distribution of these count rates is then determined. Spectral data is summed from areas exhibiting low apparent cesium activity and for areas exhibiting high apparent cesium activity. From these two spectra which exhibit different cesium to background activities, two spectra are derived: cesium only and background only. A new K is then determined from the derived background-only spectrum. This new K is then used for final processing of survey data. It should be noted that processing in this manner produces a measure of total cesium in the area, not just the deviation from an average value.

6.2.4 Americium-241

The photopeak count rate from Am-241 was determined using three spectral windows.

Normally occurring background contributions within the Am-241 photopeak window were removed by subtracting two weighted background windows located on each side of the photopeak window. The resulting photopeak count rate data could then be converted to isotope concentration on the ground.

Table 3 gives the correction factor for a finite Am-241 source which is smaller than the field of view of the detector system.

Table 3. Finite Am-241 Source Correction Factors Versus Area of Contamination

Source Diameter (meters)	Correction Factor
10	37
20	9
40	3.5
60	2.2
80	1.6
100	1.3
140	1.1
>140	1.0

6.2.5 Minimum Detectable Activity

Table 4 indicates the minimum detectable activity for Am-241 and Cs-137 as a function of source geometry for the aerial system employed in the Rocky Flats survey. The three geometries assumed were: 1) a point source laying on the surface of the ground, 2) a source uniformly distributed on the surface of the ground, and 3) a source uniformly distributed both horizontally and vertically in the soil.

If the source is not a uniform surface distribution and is not uniformly distributed in the soil, it must be distributed in the soil in some manner in between.

The distributions of a man-made source released to the environment can normally be found in the

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Table 4. Minimum Detectable Activity for Several Selected Radioisotopes as a Function of Source Geometries*			
	Surface Sources		Volume Source $\left(\frac{pCi}{g}\right)^{**}$ $\alpha = 10$ cm
Isotope	Point Source (mCi)	Distributed Source (μCi/m^2) $\alpha = \infty$	
Am-241	2.9	0.35	11.2
Cs-137	0.27	0.028	0.35

* Assuming a survey altitude of 46 meters.

** Conversion factor to pCi/g relate to the average value of a 5-cm deep soil sample.

soil with an exponential vertical distribution of concentration. The exponential equation is in the form of $e^{-\alpha z}$, with alpha (α) being the inverse relaxation depth. At one relaxation depth, that volume of soil will contain 63% of the total activity. At a relaxation depth of two, that volume will contain 86% of the total activity, and at a relaxation depth of three, that volume will contain 95% of the total activity.

Beginning with a vertical concentration distribution:

$$C(z) = C_0\, e^{-\alpha z} \qquad \gamma/cm^3 \cdot s \qquad (4)$$

where

C_0 = the surface concentration, $\gamma/cm^3 \cdot s$

α = exponential concentration factor, cm^{-1}

z = depth in soil, cm

the sensitivity of the pods to a monoenergetic gamma distribution may be written.

$$S_v^0 = \frac{C_0}{cps} = \frac{1}{X} \qquad \gamma/cm^3 \cdot s \cdot cps \qquad (5)$$

where

$$X = \frac{A_0}{2} \int_0^{\theta = 90°} \frac{R(\theta)\, e^{-\mu_a h \sec\theta} \tan\theta\, d\theta}{\alpha + \rho \mu_g \sec\theta}$$

A_0 = detector effective area for monoenergetic gamma total absorption in the detector for fluence perpendicular to the ground surface, cm^2

$R(\theta)$ = relative effective area versus the angle, θ, measured from the ground perpendicular to the pod

μ_a = the air mass attenuation coefficient for the gamma energy in question, cm^2/g

μ_g = the soil mass attenuation coefficient for the gamma energy in question, cm^2/g

h = the detector (aircraft) altitudes in units of air thickness, g/cm^2

ρ = soil density, g/cm^3

The sensitivity, S_v^0, may be used to convert a photopeak count rate from the detector or pod output to the soil surface concentration, C_0.

In practice, the effective area, A_0, is measured with known point sources of different energies. The angular factor, $R(\theta)$, is measured and approximated with unity, cosine θ, or a linear combination of these to fit an angular response at a given gamma energy.

Other useful conversions may be obtained from S_v^0. These are:

1. The sensitivity per unit soil surface area

$$S_A = \frac{S_v^0}{\alpha} \qquad \gamma/cm^2 \cdot s \cdot cps \qquad (6)$$

2. The sensitivity per unit soil surface mass

$$S_\rho^0 = \frac{S_v^0}{\rho} \qquad \gamma/g \cdot s \cdot cps \qquad (7)$$

3. The sensitivity to a soil sample of depth z

$$S_\rho^z = S_v^0 (1 - e^{-\alpha z}) / \rho \alpha z \qquad \gamma/g \cdot s \cdot cps \qquad (8)$$

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It was assumed in Table 4 that no additional shielding existed between the source and the detector array. It was further assumed that distributed sources were spread over an area comparable to several times the survey altitude.

7.0 AERIAL SURVEY RESULTS

7.1 Gross Count Exposure Rate

The gross count exposure rate results are shown in (Figure 10) superimposed on a photograph of the Rocky Flats area. The exposure rates are expressed in units of microroentgens per hour (μR/h) at 1 m AGL and include an assumed cosmic ray exposure rate of 5.6 μR/h. These results also include contributions from any man-made radionuclides that might be present. A typical background spectrum of the natural radionuclides in the Rocky Flats area is shown in Figure 11. The range of exposure rates measured in the survey varied from 5.7 to 76 μR/h.

An anomalous area showing high activity from Bi-214 (a naturally occurring Ra-226 daughter) was located in the southwest corner of the survey area (identified as Area 1 in Figure 10). The activity appears to be concentrated in an area less than 200 to 300 meters in diameter, located outside the Rocky Flats Plant boundary fence. Terrestrial exposure rates from this area are comparable to those measured over the facilities at the Rocky Flats Plant. The spectral data from this area are shown in Figure 12.

7.2 Man-Made Gross Count Isopleth

The presence of man-made activity was detected in the immediate vicinity of the Rocky Flats Plant. The data in this area have been plotted in an expanded scale for better resolution of the location of the man-made activity. The count rate cannot be converted to any meaningful quantifiable results and is used only as an indicator of the presence of man-made isotopes.

Figure 13 shows the MMGC results expressed in counts per second. The count rate is an indicator of the magnitude of the intensity of the sources. The spectral data from Areas 2 through 9, as identified in Figure 13, are plotted in Figures 14 through 21. The most probable isotopes responsible for the man-made activity are indicated on each spectrum. Isotopes identified include Am-241, Pu-239, and Pa-234m (a daughter product in the uranium decay chain indicating the presence of depleted uranium at the facility).

A net spectrum over an anomalous radiation area is obtained by removing the natural background from the spectrum. This is accomplished by using the high energy window (1.40 to 3.00 MeV) as a background monitor. A background spectrum is accumulated in an area that does not indicate man-made activity. After the spectrum is normalized over the area of interest and the background spectrum with the high energy window, the data are subtracted. The result is a net spectrum of man-made activity.

7.3 Cesium-137 Ground Deposition

The 1981 survey did not detect any Cs-137 anomalies above worldwide fallout levels. The data were processed for Cs-137 activity, but were not published as part of the report because they were consistent normal background levels. There was **no** indication of a ground deposition of Cs-137 resulting from plant operations.

The 1989 survey results of the processing for Cs-137 photopeak count rate data are shown in Figure 22. To further enhance detectability of low-level, widespread cesium activity, data for the survey area were partitioned into areas of 1,000 ft per side. Each of these areas contained approximately 32 original data points. Averaging these points improved the statistical signal/noise ratio for the cesium extraction by a factor of 5.7 (square root of 32), a significant improvement. The Cs-137 photopeak count rate can be converted to estimated concentration values for various source distributions by selecting the appropriate conversion factor in Table 5.

As an example of the conversion of Cs-137 photopeak count rate (cps) into units of activity, a "C" level will be used (that is between 65 and 100 counts per second) which is typical from the survey data (see Figure 22).

If it is assumed the activity is "uniform surface distribution" (on the surface of the ground and not distributed in the soil), the desired units would be microcuries per meter squared, and the

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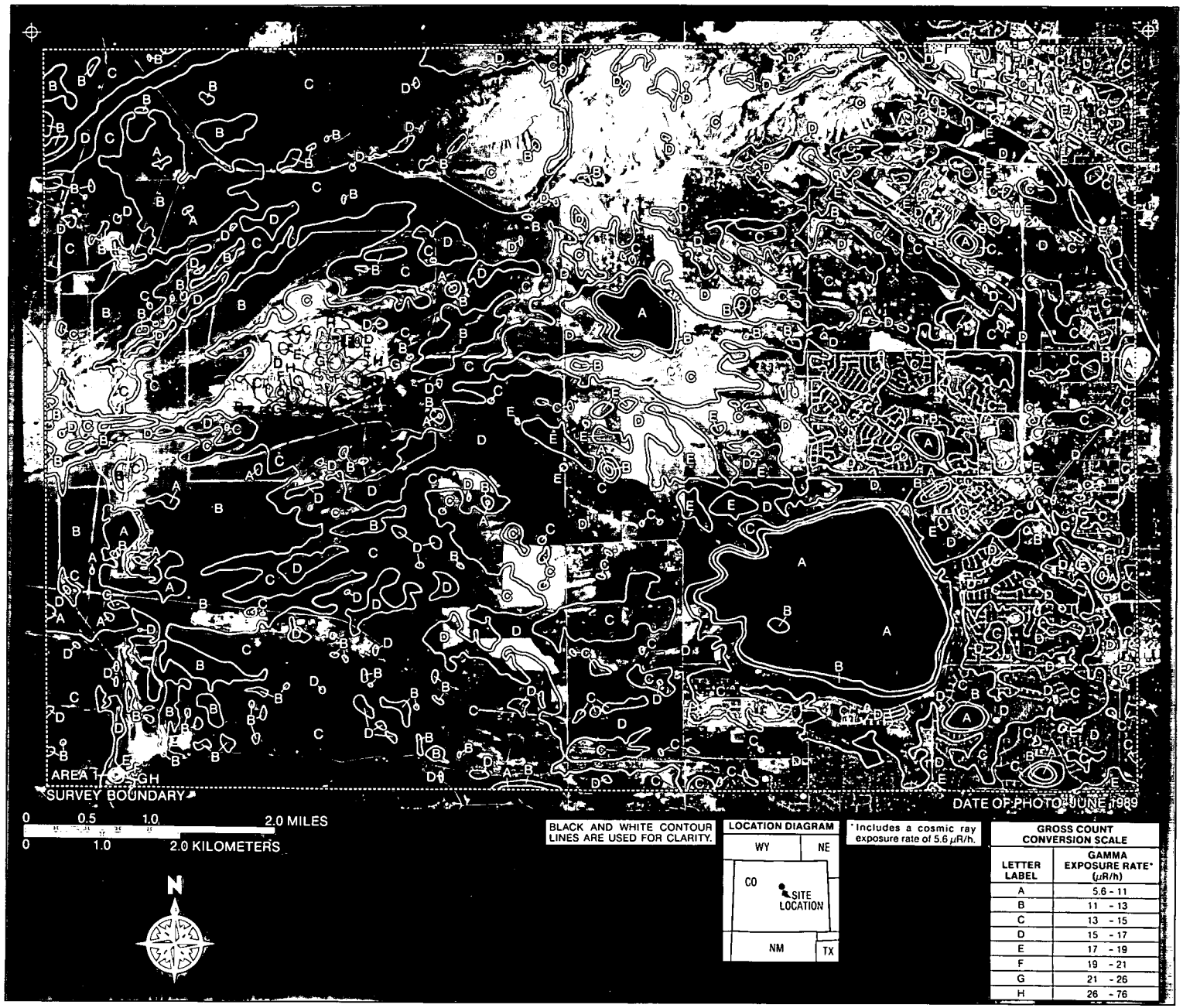

FIGURE 10. ***TERRESTRIAL GAMMA RAY EXPOSURE RATE AT 1 METER ABOVE TERRAIN EXTRACTED FROM THE GROSS COUNT RATE DATA***

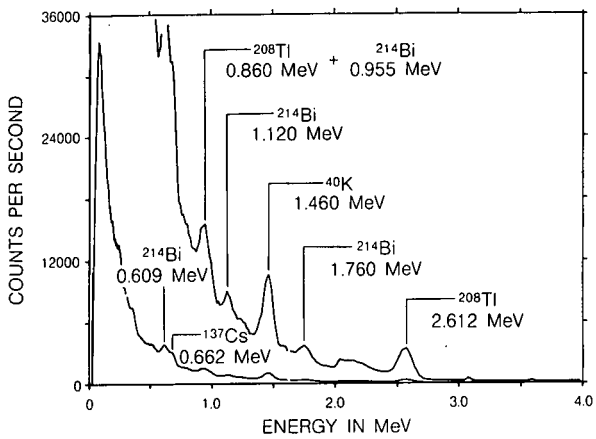

FIGURE 11. ***TYPICAL BACKGROUND SPECTRUM***

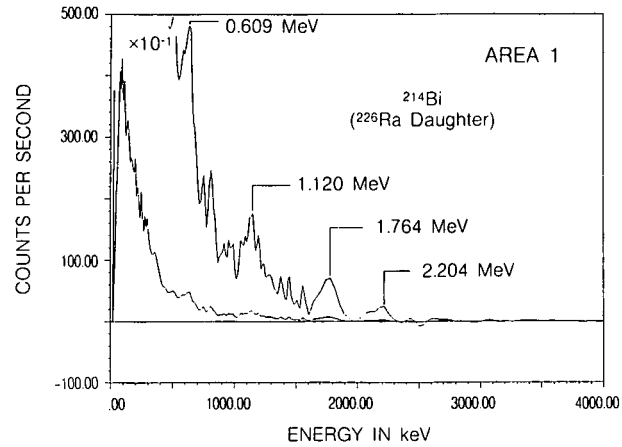

FIGURE 12. ***SPECTRAL DATA FROM AREA 1***

conversion factor would be 9.17×10^{-4} μCi/m^2 per count per second:

where

$$65 \text{ cps} \times 9.17 \times 10^{-4} \frac{\mu\text{Ci/m}^2}{\text{cps}} = 0.060\ \mu\text{Ci/m}^2$$

$$100 \text{ cps} \times 9.17 \times 10^{-4} \frac{\mu\text{Ci/m}^2}{\text{cps}} = 0.0917\ \mu\text{Ci/m}^2$$

or a "C" level which is between 0.060 and 0.917 μCi/m^2 for a surface source.

If it is assummed the activity is "uniform volume distribution" (uniformly distributed both horizontally and vertically in the soil), the desired units would be picocuries per gram of soil, and the conversion factor would be 1.17×10^{-2} picocuries/gram per count per second:

where

$$65 \text{ cps} \times 1.17 \times 10^{-2} \frac{\text{pCi/g}}{\text{cps}} = 0.76 \text{ pCi/g}$$

$$100 \text{ cps} \times 1.17 \times 10^{-2} \frac{\text{pCi/g}}{\text{cps}} = 1.17 \text{ pCi/g}$$

or a "C" level is between 0.76 and 1.17 pCi/g of soil for a volume source.

The observed cesium levels are consistent with known worldwide levels. Areas where soil turnover has occurred since the fallout was produced (Rocky Flats Site, new subdivisions near Stanley Lake, etc.) show appreciably lower indications of cesium than undisturbed areas.

Cesium-137 activity appears to be uniformly distributed over the entire Rocky Flats area and, again, is consistent with worldwide fallout measured throughout the United States. There is no indication of Cs-137 deposition due to Rocky Flats operations.

7.4 Americium-241 Results

The photopeak count rates due to Am-241 are plotted in Figure 23 in units of counts per second. The count rate data can be converted to estimated concentration values for various source distributions by utilizing the conversion factors in Tables 6 and 7.

Area 10 in Figure 23 did not appear in the MMGC results. The Am-241 activity was insufficient to be detected using the MMGC extraction technique. This area of activity did appear using the three-window extraction technique described in Section 6.2.4. The spectral data from Area 10 are shown in Figure 24.

The following are examples of application of conversion factors to aerial survey data:

a. Distributed Source (Table 6)—Assumming a relaxation depth of 10.0 cm, and for a soil sample depth of 10 cm the conversion factor would be 0.1809 pCi/g per count per second in the

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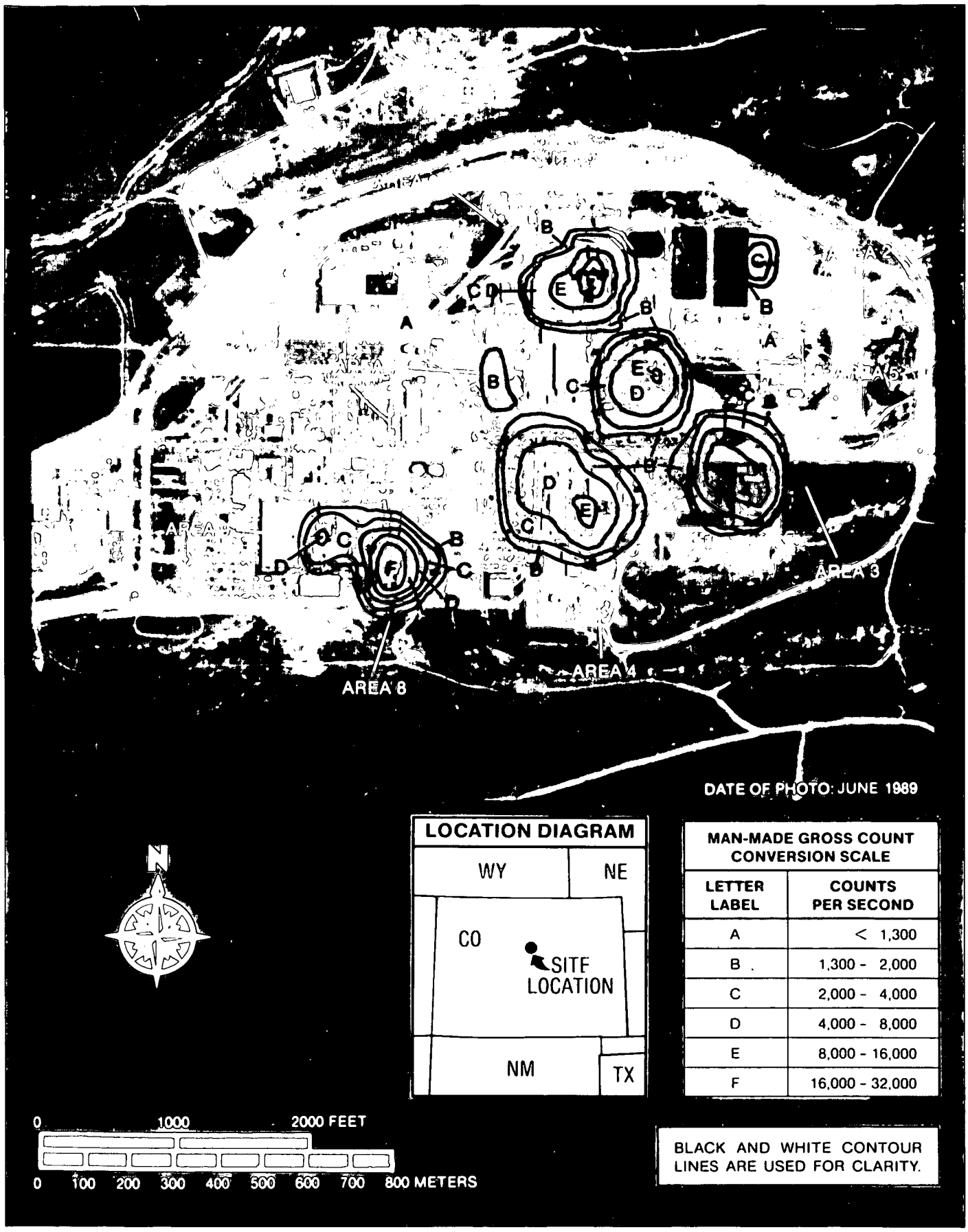

MAN-MADE GROSS COUNT CONVERSION SCALE	
LETTER LABEL	COUNTS PER SECOND
A	< 1,300
B	1,300 - 2,000
C	2,000 - 4,000
D	4,000 - 8,000
E	8,000 - 16,000
F	16,000 - 32,000

FIGURE 13. *MAN-MADE GROSS COUNT ISOPLETH MAP*

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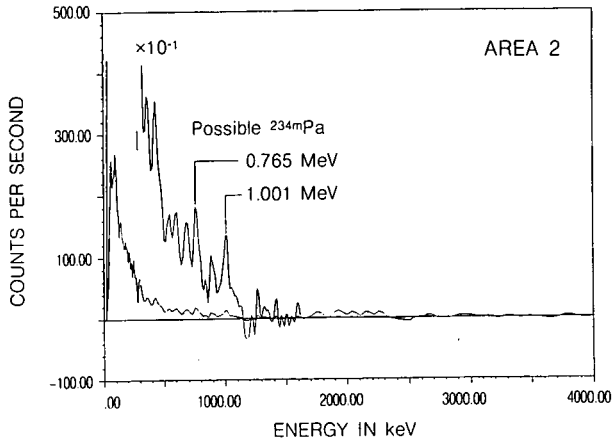

FIGURE 14. ***SPECTRAL DATA FROM AREA 2***

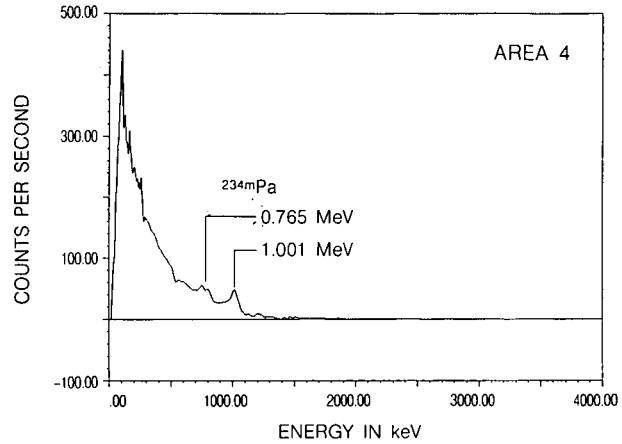

FIGURE 16. ***SPECTRAL DATA FROM AREA 4***

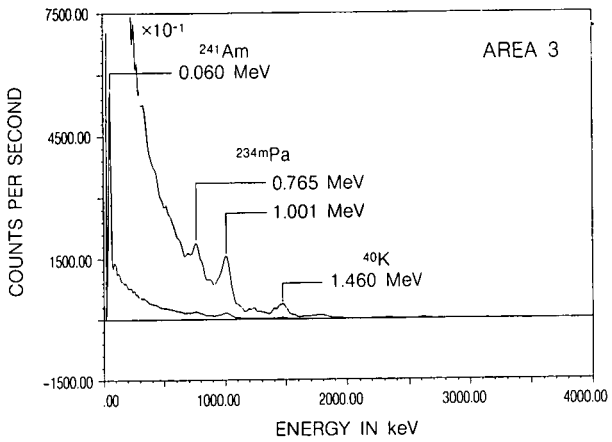

FIGURE 15. ***SPECTRAL DATA FROM AREA 3***

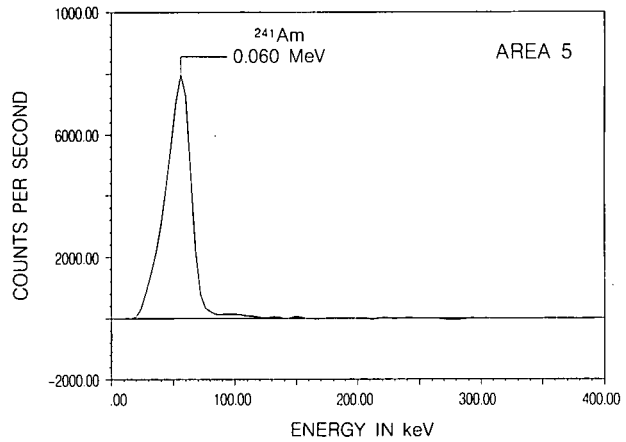

FIGURE 17. ***SPECTRAL DATA FROM AREA 5***

21

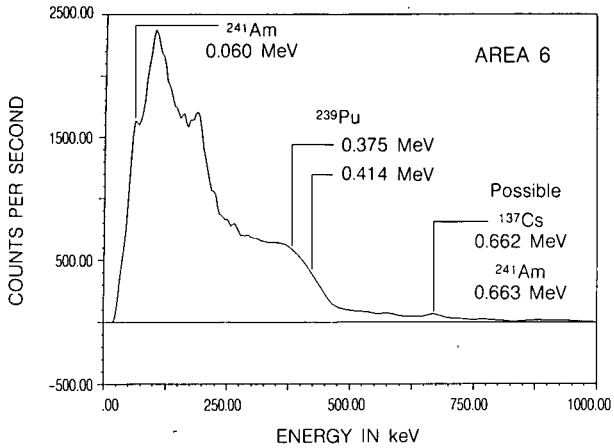

FIGURE 18. ***SPECTRAL DATA FROM AREA 6***

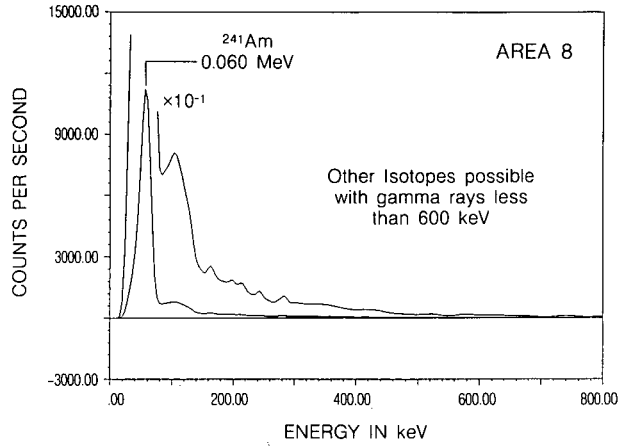

FIGURE 20. ***SPECTRAL DATA FROM AREA 8***

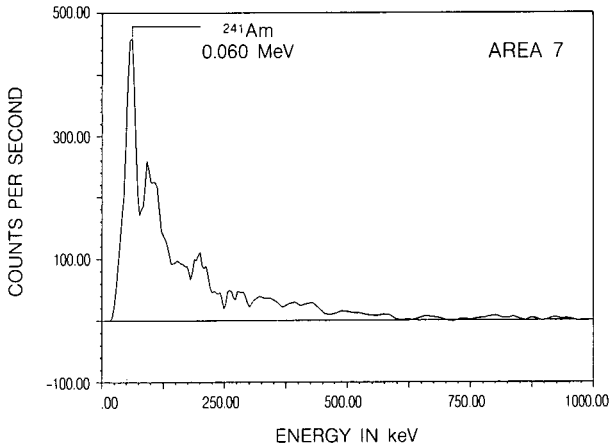

FIGURE 19. ***SPECTRAL DATA FROM AREA 7***

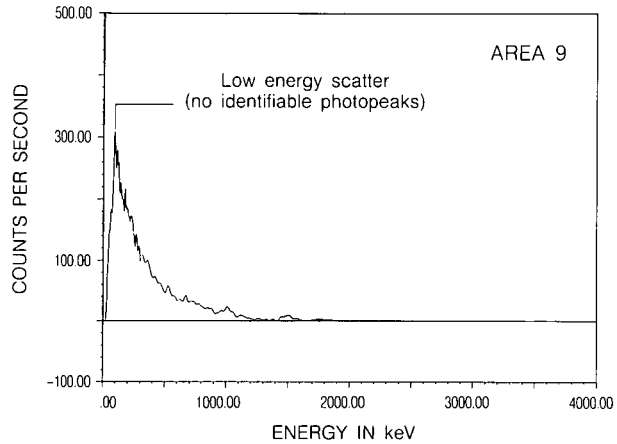

FIGURE 21. ***SPECTRAL DATA FROM AREA 9***

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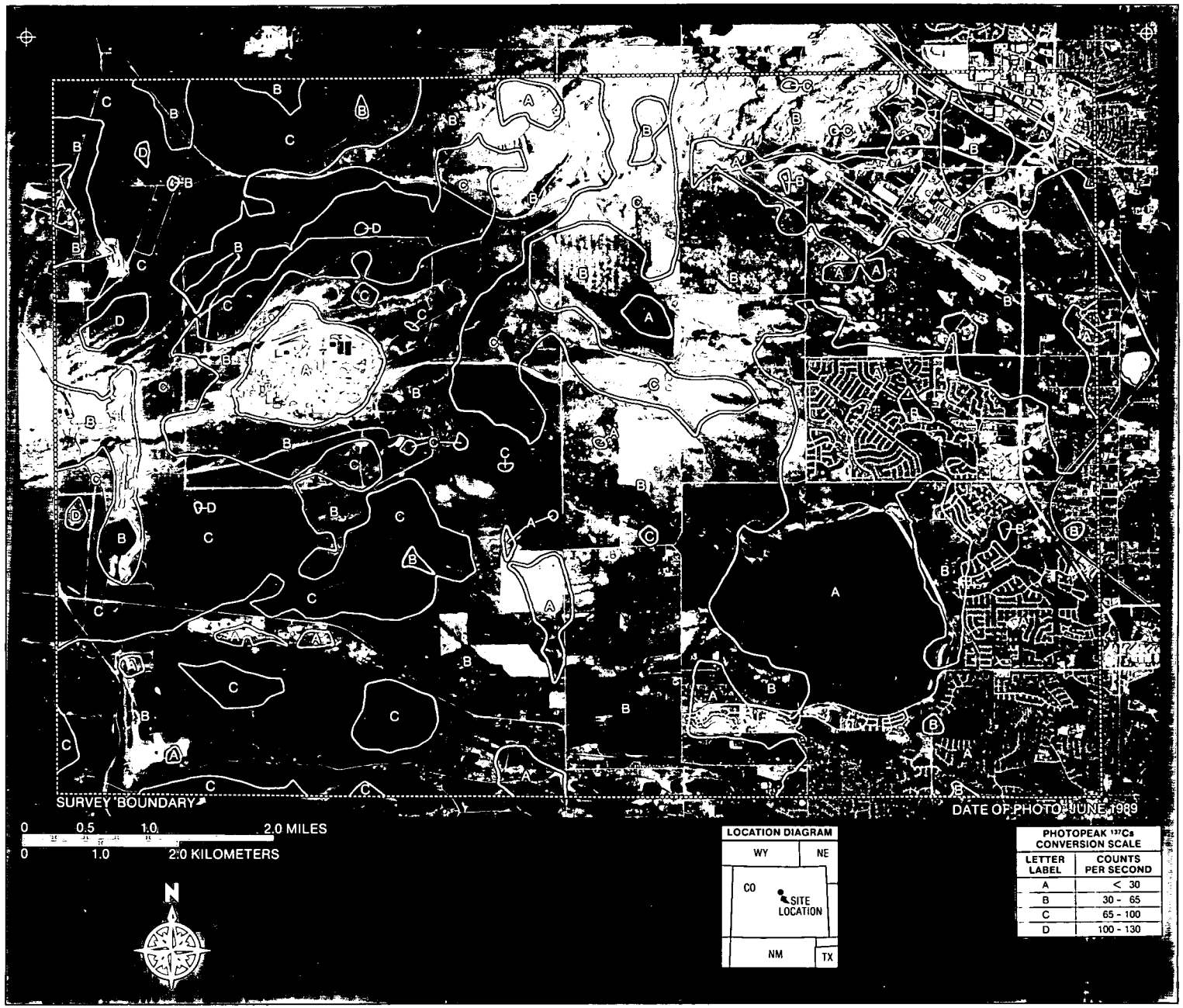


FIGURE 22. ***CESIUM-137 PHOTOPEAK COUNT RATE ISOPLETH MAP***

Table 5. Conversion Factors Relating Aerial Photopeak Count Rate Data to Cesium-137 Concentration on the Ground for a Variety of Source Distribution Geometries

	Conversion Factor[a]								
	Point Source on Surface $\frac{\mu Ci}{cps}$		Uniform Surface Distribution		Exponential Distribution			Uniform Volume Distribution	
Radio-nuclide	Directly under aircraft	At lateral distance of 22 m	$\frac{\mu Ci/m^2}{cps}$	$\frac{\mu R/h^b}{cps}$	Relaxation depth (cm)	$\frac{\mu Ci/m^2}{cps}$	$\frac{\mu R/h^b}{cps}$	$\frac{pCi/g}{cps}$	$\frac{\mu R/h^b}{cps}$
^{137}Cs	9.00	11.8	$9.17\ (10^{-4})$	$1.00\ (10^{-2})$	0.1	$1.00\ (10^{-3})$	$9.17\ (10^{-3})$	$1.17\ (10^{-2})$	$7.33\ (10^{-3})$
					1.0	$1.17\ (10^{-3})$	$7.17\ (10^{-3})$		
					10.0	$3.00\ (10^{-3})$	$7.00\ (10^{-3})$		

[a] Conversion factors are given for the eight rectangular (5-cm × 10-cm × 40-cm) NaI(Tl) detector array at an altitude of 46 meters, assuming an air density of 1.07 g/l and a soil density of 1.5 g/cm³ (10% soil moisture content). All results given are an average between those computed for an isotropic and for a cosine detector angular response.

[b] At the 1-meter level, assuming a smooth air-ground interface (*i.e.*, no surface roughness)

detector system. A "C" level (120-240 cps) from the aerial system would equate to:

$$120 \text{ cps} \times 0.1809 \frac{\text{pCi/g}}{\text{cps}} = 21.7 \text{ pCi/g}$$

$$240 \text{ cps} \times 0.1809 \frac{\text{pCi/g}}{\text{cps}} = 43.4 \text{ pCi/g}$$

b. Point Source (Table 7)—Again assuming a "C" level (120-240 cps) with a point source directly below the aircraft (lateral displacement of 0) would use 0.058 mCi/cps as the converion factor or:

$$120 \text{ cps} \times 0.058 \frac{\text{mCi}}{\text{cps}} = 6.96 \text{ mCi}$$

$$240 \text{ cps} \times 0.058 \frac{\text{mCi}}{\text{cps}} = 13.92 \text{ mCi}$$

The contours of the aerial Am-241 are always extended over an area larger than the actual activity on the ground. This is due to the large field of view of the detector system at the 46 m (150 feet) survey altitude. The detector can actually "see" the source several hundred feet before it is actually above the source. This extension of the contours is apparent in the Am-241 data in Figures 23 and 25. In these figures, there is a strong point source confined to a building, and the contours extend out to cover an area much larger than the building.

8.0 GROUND MEASUREMENT RESULTS

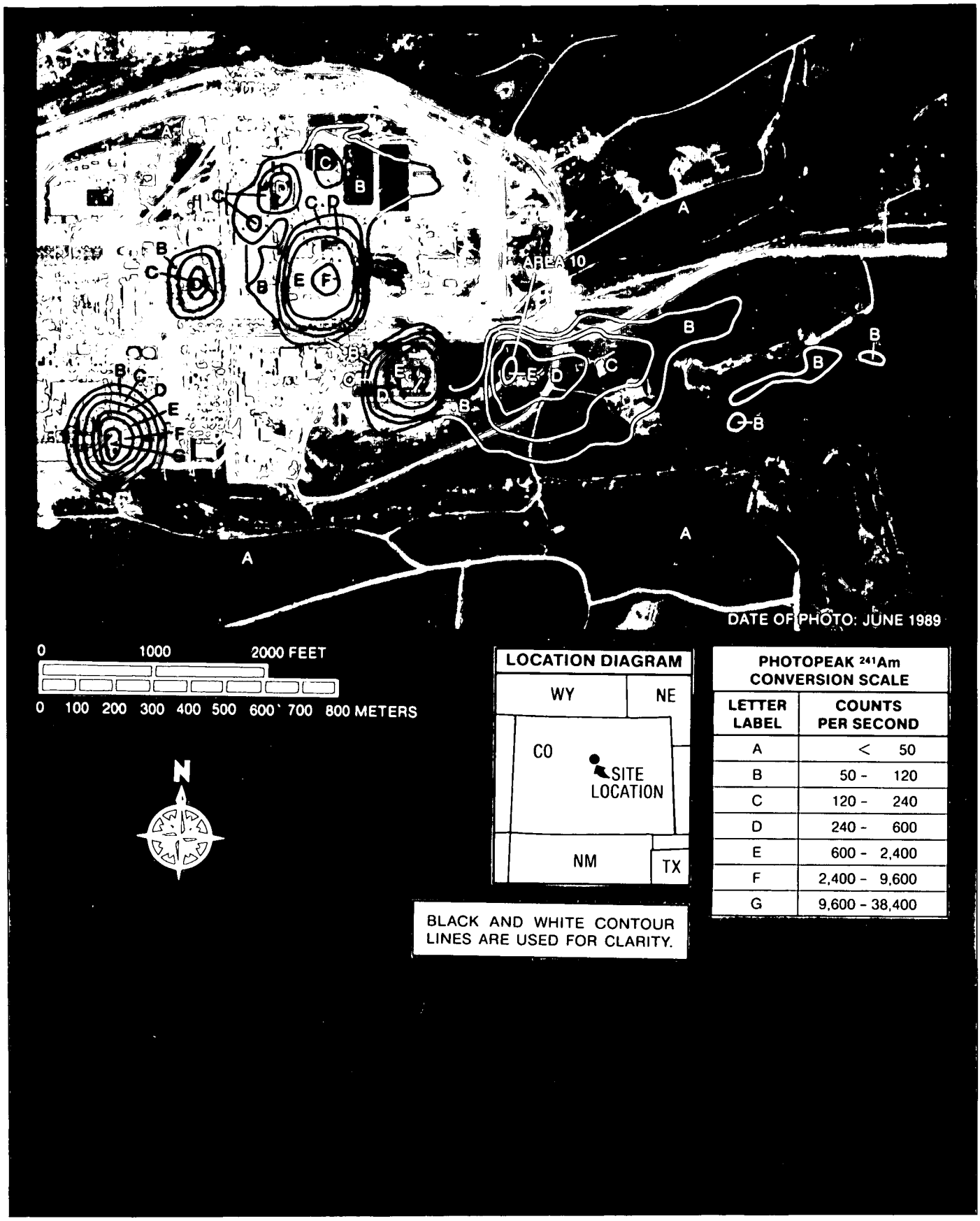
Results of the ground survey using HPGe detectors are presented as levels of concentration represented by color-coded circles with diameters of the order of the field of view of each detector (30 meters). These data were superimposed on a photograph along with isoradiation contour lines generated from the aerial data. Figures 25 and 26 show the results for an assumed uniform surface concentration of Am-241 and an assumed uniform volume distribution of Cs-137, respectively.

The numbers by each of the color-coded circles are the ground sampling location numbers for reference to the soil samples and *in situ* data (see Appendix A for details). The parameters listed in Tables 8 and 9 include factors that convert the concentration values displayed on Figures 25 and 26 to values that bracket other possible source distributions.

For example, a value range of 0.10 to 0.35 $\mu Ci/m^2$ (yellow) surface concentration of Am-241 in Figure 25 converts to 7.2 to 25.2 pCi/g for exponentially distributed Am-241 with a relaxation depth of 1 cm, averaged over the top 2.5 cm of soil as follows:

Find the desired conversion factor in Table 8 for a 1-cm relaxation depth and a soil sample depth of 2.5 cm (value given is 72). Then compute the desired conversion:

$72 \times (0.10 - 0.35)\ \mu Ci/m^2 = (7.2 - 25.2)$ pCi/g of Am-241 in the top 2.5 cm of soil for an exponential distribution with a relaxation depth of 1 cm.



PHOTOPEAK ^{241}Am CONVERSION SCALE	
LETTER LABEL	COUNTS PER SECOND
A	< 50
B	50 - 120
C	120 - 240
D	240 - 600
E	600 - 2,400
F	2,400 - 9,600
G	9,600 - 38,400

FIGURE 23. ***AMERICIUM-241 PHOTOPEAK COUNT RATE ISOPLETH MAP***

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Table 6. Aerial Am-241 Conversion Factors*				
Relaxation Depth ($1/\alpha$) cm	γ/cm²-sec	μCi/m²	Soil Sample Depth 5 cm pCi/g	Soil Sample Depth 10 cm pCi/g
Infinite	0.0093	0.0070	—	—
0.10	0.0098	0.0073	0.0983	0.0491
0.50	0.0118	0.0089	0.1183	0.0592
1.0	0.0143	0.0108	0.1420	0.0715
3.00	0.0239	0.0179	0.1941	0.1154
5.00	0.0334	0.0251	0.2116	0.1448
10.00	0.0572	0.0429	0.2253	0.1809
Uniform	—	—	0.2379	0.2379

* Multiply photopeak Am-241 count rate (in counts per second) by the appropriate conversion factor.

Table 7. Aerial Am-241 Point Source Conversion Factors	
Lateral Displacement	mCi per counts per second*
0	0.058
9	0.061
18	0.073
27	0.097
36	0.137
45	0.200

* Assuming an aircraft velocity of 31 m/sec and an altitude of 46 m.

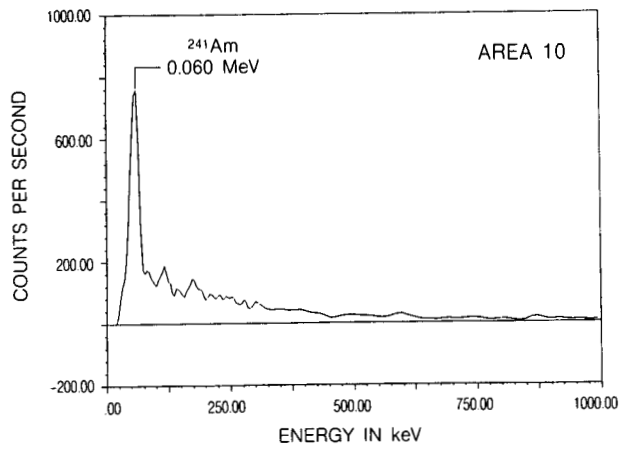

FIGURE 24. ***SPECTRAL DATA FROM AREA 10***

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FIGURE 25. ***AMERICIUM-241 IN SITU (HPGe) DATA ACQUISITION LOCATIONS AND COLOR-CODED SURFACE CONCENTRATION VALUES SUPERIMPOSED ON THE AERIAL Am-241 DATA***

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FIGURE 26. ***CESIUM-137 IN SITU (HPGe) DATA AND COLOR-CODED SURFACE CONCENTRATION VALUES FOR A UNIFORMLY DISTRIBUTED SOURCE IN THE SOIL***

Table 8. Factors that Convert Am-241 Surface Concentration to Mean Soil Sample Concentrations[a,b] at Selected Soil Depths and Concentration Distributions					
Distribution Parameters		Soil Sample Depth (cm)			
		Limit[c]	1.0	2.5	5.0
α^a cm^{-1}	$1/\alpha$ cm	Factors = pCi/g/μCi/m^2			
1	1	196	124	72	39
0.333	3	130	111	88	63
0.1	10	104	99	92	82

[a] Distributions as described in Section 6.2.5, Equations 4 and 5

[b] The result of multiplying the surface concentrations (μCi/m^2) by the factor above yield, pCi/g

[c] The limit of Equation 5 as the sample depth approaches 0

Similar conversions can be done for Cs-137 data in Figure 26 using Table 9.

Surface concentrations of Am-241 varied between 0.006 μCi/m^2 and 0.84 μCi/m^2 over areas of measurable activity outside the facility perimeter fence. These values were consistent with the concentrations inferred from aerial data. Figure 27 is a typical gamma energy spectrum from the HPGe detector system from the survey indicating the presence of Am-241. The 59.5-keV gamma ray line is depicted. Figure 28 shows a similar HPGe spectrum in a typical background area.

Detected concentrations of Cs-137 were between 0.01 and 1.3 pCi/g over all the measured points. These values were consistent with the aerial data as well as those values expected from worldwide fallout. Ground measurement results are summarized in Appendix A.

9.0 SUMMARY

The survey information presented in this report is intended for technically qualified environmental measurement personnel. The explanations included, therefore, are technical in nature and have not been extensively defined for nontechnical readers.

If the aerial detector system used in this survey has been properly characterized (measurement of its energy and angular response), the detector can be assumed to be a unit with a definite effective area which produces extremely accurate

Table 9. Factors that Convert Uniformly Distributed Cs-137 to Mean Soil Sample Concentrations[a] at Selected Soil Depths and Concentrations Distributions					
Distribution Parameters		Soil Sample Depth (cm)			
		Limit[b]	1.0	2.5	5.0
α^a cm^{-1}	$1/\alpha$ cm	Factors = pCi/g (exponential)/pCi/g (uniform)			
.2	5	1.73	1.56	1.36	1.09
.1	10	1.39	1.32	1.22	1.09
.0667	15	1.26	1.22	1.17	1.08

[a] Distributions as described in Section 6.2.5, Equations 4 and 5

[b] The limit of Equation 5 as the sample depth approaches 0

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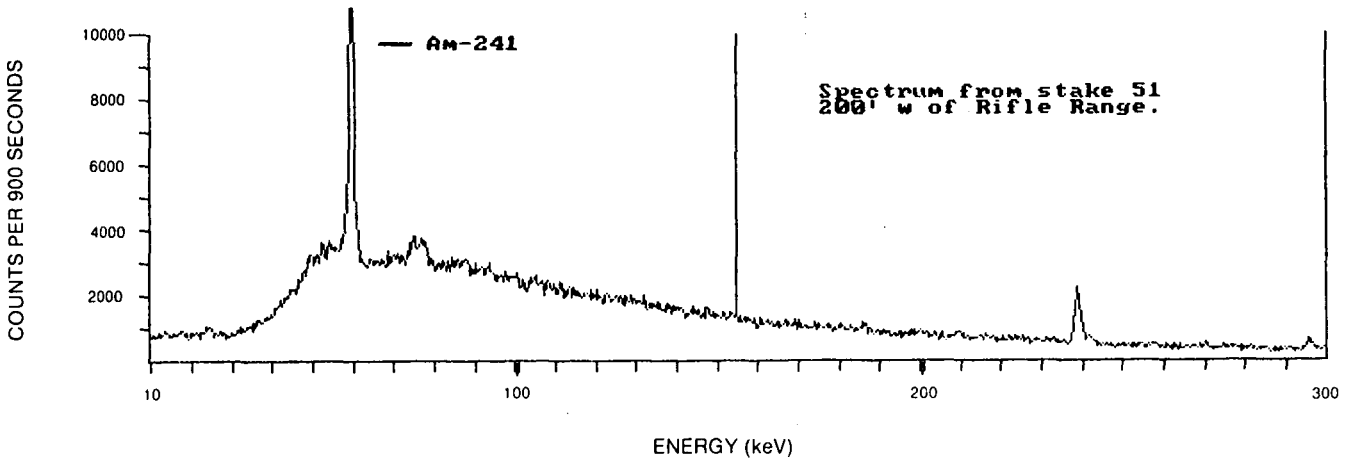

FIGURE 27. ***TYPICAL HIGH PURITY GERMANIUM SPECTRUM (0-300 keV) SHOWING THE PRESENCE OF Am-241 NEAR THE ROCKY FLATS PLANT***

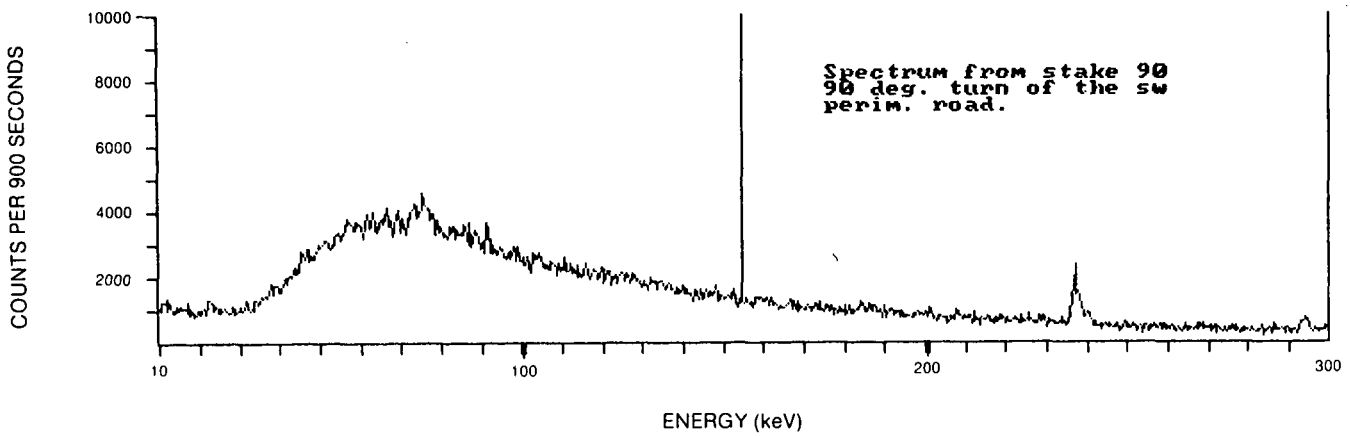

FIGURE 28. ***TYPICAL HIGH PURITY GERMANIUM SPECTRUM (0-300 keV) IN A BACKGROUND AREA***

results. The largest potential error in the aerial data comes from the uncertainty in the assumptions of the source distribution, both horizontally and vertically. For example in Table 8, a wrong assumption of the source vertical distribution (relaxation depth = 1 or 10) could produce an error of approximately a factor of 2 in the pCi/g calculation.

Soil samples have similar problems. Although the samples can accurately quantify the activity in the sample, the measurement is limited to the specific area where the sample was collected (in this case, an area of 100 cm^2). In addition, the soil samples are expensive to collect and analyze, thus significantly increasing the cost of the survey. An effective combination of the aerial, *in situ*, and soil sample data can produce high quality characterization of a large-area survey at a reasonable cost to the customer.

The Rocky Flats survey results indicate the presence of Am-241, Pu-239, and Pa-234m. The Pa-234m is a daughter product in the decay chain of uranium. The major portion of the activity was detected over buildings which are known storage and working areas. The activity in the buildings is the result of the normal operations at the Rocky Flats Plant. There were differences in the location of man-made materials inside the Rocky Flats facility between the 1981 and the 1989 surveys. This was obviously due to new facility construction and movement of materials within the plant perimeter fence.

Some Am-241 was detected outside the building area. The activity is in a controlled area and is

maintained by the Rocky Flats personnel. The activity appears to be in the same location and magnitude as detected in the 1981 survey. The small "B" areas to the east of the activity detected in the 1981 survey are probably due to the increase in the detector effective surface area (more sensitivity) and better data processing techniques used in the 1989 survey.

The Cs-137 activity appears to be consistent with worldwide fallout and not due to any release from the Rocky Flats Plant. There is no indication of a plume that originated at the facility and left detectable Cs-137 activity anywhere in the survey area.

Appendix A will cover soil sampling techniques and results, along with Q.A. procedures to verify the authenticity of the quantification of the data.

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APPENDIX A

GROUND-BASED MEASUREMENTS

A.1.0 PHILOSOPHY OF THE MEASUREMENT OF Pu-239 IN THE ENVIRONMENT

It is virtually impossible to measure low levels of plutonium, specifically Pu-239, directly in the environment. Remote measurement of plutonium, particularly at low concentration, is impractical for techniques which rely upon detection of gamma radiation. This is because plutonium is primarily an alpha emitter and emits very few energetic gamma rays per disintegration. Direct assessments of plutonium concentration are usually performed by measuring the alpha activity or x-ray production. Direct measurements of small concentrations require laboratory analyses which employ expensive and time-consuming techniques such as chemical separation, low level counting, alpha spectroscopy, and mass spectroscopy. None of these techniques is appropriate to monitor an area as large as Rocky Flats.

Remote measurement of plutonium can only be accomplished by indirect methods. That is, one measures a radionuclide closely associated with plutonium which can be easily detected by gamma radiation emissions. Americium-241 (Am-241), which is a decay daughter of Pu-241, is such a radionuclide. Although the plutonium used in nuclear weapons is principally Pu-239, it also contains other isotopes of plutonium. Generally, it will contain between 0.5% to 1.0% Pu-241[2,3]. This ratio of Pu-241 to Pu-239 depends only upon its initial value at production and the time since production. Likewise, the quantity of Am-241 present depends only on the initial isotopic mix and the age of the plutonium since production. As the Pu-241 decays, its daughter, Am-241, "grows in." The ratios at any future time can be easily calculated from the original isotope mix and mixture age. The amount of Am-241 present is quite significant if the plutonium is more than 2 years "old," even if Am-241 were not initially present.[2] Therefore, the quantity of plutonium, specifically Pu-239, can be inferred from direct measurements of Am-241 and a known ratio of Pu-239 to Am-241.

This ratio can be established either by experimental measurement, or it may be estimated from historical information and technical data. As previously mentioned, this is very time consuming. In the interest of timely reporting of results, the required ratios presented in this report were estimated.

Soil samples were acquired during this aerial survey to corroborate the aerial results. Preliminary results of the soil measurements are summarized in Tables A-1 and A-2. They were initially analyzed exploiting the Am-241 present, but detailed analyses to directly measure the present amount of plutonium are planned. These later analyses will better refine the Pu-239 to Am-241 ratio to be used with these aerial survey results.

The measurement of the Am-241 activity in the environment has been a reliable and relatively accurate measure of Pu-239. Although the proper ratio of Pu-239 to Am-241 cannot presently be determined, a reasonably good estimate and limits can be established. This ratio could be as high as 15, if the original material was very "young" (less than 2 years old), or it could be as low as 5, if the material is very "old" (more than 10 years old).[2] Published data for the Rocky Flats area indicate that this ratio was approximately 6 to 7 at the time of a 1969-1970 soil sampling program[3]. This sampling program also indicated that the Pu-239 was released to the environment at least 20 years ago and that the ratio of Pu-239 to Am-241 probably has not changed significantly because of its age. Therefore, the ratio should now be expected to lie between 5 and 7.

It is possible that this ratio could be perturbed by a release of plutonium containing a large initial concentration of Am-241 or a release of pure

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Am-241. An error of this kind would result in an overestimate of the plutonium present. The ratios observed by the soil sampling program suggest that the Am-241 is simply a product of the decay of Pu-241 due to the release of plutonium from the Rocky Flats Plant.

A.2.0 SOIL SAMPLING AND GAMMA FLUX MEASUREMENT AT *IN SITU* SITES

A.2.1 Collection and Preparation Procedure

Soil samples were collected at each location where a measurement of the local gamma spectrum was made with the HPGe germanium detector. Each sample was taken from about 100 sq cm of surface soil to a depth of 4-5 cm. This yielded approximately 1 kg of material after drying. At some sites, an attempt was also made to gather additional profile samples to a depth of 15 cm in 5-cm increments. This was not always possible, however, as the surface soil layer is very thin in most areas around the plant, and the deeper samples tended to be coarse gravel or even a few large rocks (the rocks and gravel only have a limited ability to contain much fine-particle contamination and do not represent source distribution in the soil).

Samples were dug with a soil auger or hand shovel, placed in sealable plastic bags, and identified by spectrum ID number. They were later shipped to the EG&G Santa Barbara Laboratory in rigid cases for analysis.

Upon receipt at SBO, each sample was weighed, dried in a vented oven for 48 hours at 40° C, and reweighed. This eliminated both the varying amounts of water in each sample and the uncertain effect it would have on its gamma emission. It also gave a measure of the general soil moisture content of the area for use with the aerial data. After drying, the lumps in each sample were broken up to render a uniform mixture, and the mix was sealed in a 32-oz, widemouth polyethylene jar. The samples were then aged for three weeks before counting to allow radon daughters to "grow in" and equilibrium to be established. Excess soil was returned to its plastic sampling bag, and all data were recorded in a laboratory log book.

A.2.2 Counter Description and Calibration

The soil samples were analyzed by gamma ray spectroscopy using a two-detector, automated counter system with sample changer. This system has been completely characterized in the publication *Low Background Ge(Li) Detector Gamma-Ray Spectroscopy System with Sample Changer*, Report No. EGG-1183-2383, Santa Barbara, CA: EG&G/EM. The system was developed to provide high efficiency counting capability for large soil samples and routine analyses for uranium, thorium, cesium-137, and potassium-40.

Basically, the mechanism of the sample changer is composed of a sample storage ring (conveyer belt) and a shielded cave containing the two Ge detectors. These detectors have horizontal cryostats which are positioned coaxially, "nose-to-nose," with enough spacing to allow a sample jar to be placed between them and rotated at 1/2 RPM. Signal pulses from the detectors are amplified, combined in a multiplexer unit, and sorted with a pulse height analyzer (PHA). At the end of a counting period, the spectral data is transferred from the PHA to a data file in the VAX mainframe computer which also controls the sample changer. These data files are later examined with a peak fitting code, and isotope concentrations are calculated from the fitted photopeak areas.

The changer system efficiency was measured using three standard source materials diluted in sand and contained in typical sample jars. The uranium and thorium standard materials (ore) were obtained from the former AEC New Brunswick Laboratory and are certified as to elemental uranium or thorium concentration by weight, and in the case of uranium, the radium to uranium ratio. The third standard was prepared by Isotope Products Laboratories in Burbank, California, and it contains 1 gram of NIST SRM-4276C, uniformly mixed in sand and sealed in the

usual sample jar. This mixed isotope source contains Sb/Te-125, Eu-154, and Eu-155 and is certified as to the gamma/x-ray emission rates for the principle photons. Together, the three standards provide strong, well-defined photopeaks over the 27 keV to 2.61 MeV range. Efficiency values between the points measured with these standards are found by linear interpolation.

For the routine analysis of soil samples for U-238, Th-232, Sb-125, and Eu-154/155, simply comparing the net photopeak areas (normalized to sample mass) of the unknown to that of the appropriate standard is adequate to determine concentrations. All other isotopes, including Am-241 activity, must be calculated from the photopeak areas and the (usually) interpolated efficiency values.

A.2.3 Exposure Rate Measurements

In addition to soil sampling, gamma field exposure rate measurements were also made at each *in situ* site with a pressurized ion chamber (Reuter Stokes Model RSS-112). This environmental monitor readily measures background levels of gamma radiation and employs an 8-liter stainless steel sphere filled with argon gas at 25 atmospheres pressure as the sensing chamber. The chamber ionization current is measured with a high gain, dc electrometer, and the system sensitivity is 20 mv/μR/h.

Reuter Stokes calibrates the instrument using Co-60 sources and specifies the accuracy to be $\pm$5% or $\pm$0.5 μR/h, whichever is larger. It is also calibrated at SBO with an NBS-certified Ra-226 source to verify the accuracy for a gamma spectrum that is more like natural background.

However, because the sensing chamber has a thick wall that is more opaque to low energy gamma rays, the system's Roentgen response is only uniform above 100 keV; it falls quickly at lower energies. And since the only significant gamma emission from Am-241 (59.5 keV) is below the instrument's sensitive range, its readings are not a good indication of the presence of that isotope. The data only confirm the gamma background caused by cosmic radiation and naturally occurring isotopes in the soil.

A.3.0 SOIL SAMPLES AND HPGe RESULTS

The results of the soil analyses and ion chamber measurements are shown in Tables A-1 and A-2. The number range in parentheses following some *in situ* site numbers indicate profile samples at the approximate depth (in inches) at which they were taken. The profile samples indicate the Am-241 is exponentially distributed in the soil with a relaxation depth between 7 and 10 cm. The Cs-137 appears to be uniformly distributed in the soil. This information is very important in the selection of the appropriate conversion factors for the aerial and *in situ* data.

The error shown in the four isotopes usually assayed (U, Th, Cs, and K), reflect the high precision possible when multiple photopeaks can be evaluated, or if the peaks are intense and statistically significant, or when the presence of many calibration lines in a small energy range yields a more accurate efficiency value. The analysis for Am-241, however, is based on the area of a single photopeak at an energy where the efficiency is not as well defined, and the given error value reflects this.

The detection limit for Am-241 in these soil samples is calculated from the size of the continuum on which the 59.5 keV photopeak is superimposed. This is, of course, different for every sample, and the value shown (0.2 pCi/g) is from the worst case with a large continuum. For many samples, a smaller amount could probably be measured, but with less precision.

The final, right hand column in Table A-2 presents the exposure rate data as measured with the pressurized ion chamber (PIC).

A.4.0 SUMMARY

The *in situ* detector at one meter above ground level averages the activity over the entire 30-m diameter circle and assumes the activity is uniformly distributed horizontally. If the activity were not originally uniformly distributed or the distribution had been altered by some mechanism,

substantial differences could be seen between the *in situ* and soil sample data. In this case, additional soil samples could be taken in these areas to determine the distribution of the isotope horizontally, but the average activity in the area will approach that measured by the *in situ* system.

Comparison of the three measuring systems (soil sampling, *in situ* HPGe, and aerial) could be made in an area outside of the Rocky Flats facilities where the aerial system detected quantities of Am-241 above background levels. The ground sampling points were 50, 51, 52, 53, and 87A.

Table A-3 shows an excellent comparison of the activity calculations (using the proper relaxation depth for the Am-241 in the soil) of the three systems. The data indicate the activity in this area is uniformly distributed horizontally and has the same relaxation depth over an area of at least 140 meters in diameter.

The Rocky Flats survey is a superb example of the proper way to respond to an environmental monitoring emergency:

1. Use the airborne monitoring system to rapidly survey and locate areas that require further investigations.
2. Use the HPGe *in situ* system to resolve the areas both quantitatively and spatially.
3. Take soil samples at all sites to permanently document the areas and also provide a means of measuring lower levels of activity.

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Table A-1. Ground Measurements of Man-Made Isotopes				
	Am-241		Cs-137	
Sampling Location Number[a]	Soil Sample pCi/g ±20%	*In Situ* pCi/g[b]	Soil Sample pCi/g ±10%	*In Situ* pCi/g[c]
2	[d]	0	0.38	.38
5	4.4	2.87	2.28	1.19
6	2.6	2.16	1.56	1.09
7	2.5	2.0	2.32	1.18
9	0.55	0	0.94	.91
11	0.27	0	0.76	.81
12	0.22	0.7	0.51	1.15
13	0.27	0	0.47	1.13
14	[d]	0	0.63	1.37
15	[d]	0	0.71	.86
17	0.61	0	1.02	0.75
18	0.60	0	0.71	0.73
19	0.67	0	1.29	0.86
20	0.29	0.69	0.47	1.05
21	0.30	0	0.60	1.22
22	0.45	0	1.19	1.11
23	0.21	0	0.35	1.15
26 (0-2)	1.4	1.54	1.28	.93
(2-4)	0.34		0.30	
(4-6)	0.21		0.18	
27 (0-2)	1.7	1.68	0.85	.95
(2-4)	0.79		0.40	
(4-6)	0.55		0.31	
28 (0-2)	2.1	N/A	1.26	N/A
(2-4)	0.34		0.18	
(4-6)	0.38		0.24	
29 (0-2)	0.85	1.45	0.73	1.27
(2-4)	0.31		0.27	
(4-6)	0.22		0.20	
30 (0-2)	1.1	1.38	0.93	1.17
(2-4)	0.63		0.26	
(4-6)	0.32		0.16	

[a] (X-X) - Profile Sample Depth in inches

[b] HPGe data, assuming a relaxation depth of $\alpha = 0.10\ cm^{-1}$ and soil sampling depth of 4 cm

[c] HPGe data, assuming a uniform distribution in the soil

[d] At or below detection limit of 0.2 pCi/g

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Table A-1. Ground Measurements of Man-Made Isotopes (Continued)				
	Am-241		Cs-137	
Sampling Location Number[a]	Soil Sample pCi/g ±20%	*In Situ* pCi/g[b]	Soil Sample pCi/g ±10%	*In Situ* pCi/g[c]
31 (0-2)	0.82	1.36	0.93	1.17
(2-4)	0.36		0.36	
(4-6)	0.30		0.22	
32 (0-2)	0.71	1.47	0.85	1.05
(2-4)	0.42		0.50	
(4-6)	0.27		0.33	
33	[d]	N/A	0.14	N/A
34	0.23	1.18	0.40	1.15
35	0.58	N/A	1.03	N/A
36	0.65	.80	1.86	1.06
38	[d]	0	0.11	.49
39	0.34	0	0.30	.48
41	2.6	1.58	2.10	1.12
42	1.8	1.42	1.52	1.27
43	1.2	0	1.13	0.97
44	2.5	0	3.09	0.93
45	1.1	0	1.46	.82
46	1.1	.61	1.74	.94
48	1.8	0	1.33	.58
49	1.6	N/A	1.63	N/A
50	97.0	51	1.48	.77
51 (0-2)	20.0	13.3	1.09	.77
(2-4)	9.8		0.58	
(4-6)	5.3		0.32	
52	48.0	25.2	1.71	.66
53	6.8	16.1	0.41	1.26
59	3.8	2.2	1.26	.68
60	3.0	N/A	1.28	N/A
61	0.71	0	2.12	1.04
62	N/A	0	1.96	1.02
63	[d]	0	1.39	.80
64	[d]	0	0.07	.37

[a] (X-X) - Profile Sample Depth in inches

[b] HPGe data, assuming a relaxation depth of $\alpha = 0.10\ cm^{-1}$ and soil sampling depth of 4 cm

[c] HPGe data, assuming a uniform distribution in the soil

[d] At or below detection limit of 0.2 pCi/g

Table A-1. Ground Measurements of Man-Made Isotopes (Concluded)				
	Am-241		Cs-137	
Sampling Location Number[a]	Soil Sample pCi/g ±20%	*In Situ* pCi/g[b]	Soil Sample pCi/g ±10%	*In Situ* pCi/g[c]
65	[d]	0	1.04	.42
68	0.40	0	1.17	.57
69	[d]	0	0.74	.60
70	[d]	0	0.30	.36
71	[d]	0	0.29	.10
72	[d]	0	0.13	.18
73 (0-1)	12.0	6.4	1.17	.75
(1-2)	7.7		0.81	
(2-3)	4.0		0.44	
74	[d]	0	0.15	.18
75	[d]	0	0.11	.09
76	1.3	0	2.88	1.01
79	1.2	0.006	0.13	.43
80	0.54	0	1.08	.35
81	0.44	0	0.88	.46
83	[d]	0	0.12	.14
84	N/A	0	0.32	.28
85	[d]	0	0.03	0
87	9.8	.81	1.00	.19
87A	36.0	9.8	0.35	.29
88	[d]	0	0.47	.67
89	0.62	0	1.22	.56
89A	0.70	0	1.28	.63
90	N/A	0	1.43	1.34
91	[d]	0	0.33	.42
101	N/A	0.69	N/A	0.12
103	1.0	5.26	2.52	0.94

[a] (X-X) - Profile Sample Depth in inches

[b] HPGe data, assuming a relaxation depth of $\alpha = 0.10\ cm^{-1}$ and soil sampling depth of 4 cm

[c] HPGe data, assuming a uniform distribution in the soil

[d] At or below detection limit of 0.2 pCi/g

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Table A-2. Ground Measurements of Natural Isotopes and Exposure Rate				
Sampling Location Number[a]	U-238 ppm ±5%	Th-232 ppm ±5%	K-40 pCi/g ±12%	Pressurized Ion Chamber Exposure Rate at 1 m AGL (μR/h)
2	4.0	15.9	17.3	15.3
5	2.9	17.3	17.8	13.1
6	2.9	11.9	12.9	13.0
7	3.5	12.2	12.8	12.9
9	2.3	11.7	10.9	14.0
11	4.1	16.0	15.9	16.2
12	3.2	16.6	14.8	16.0
13	3.8	16.0	15.7	16.1
14	3.5	14.6	16.8	15.5
15	3.9	12.2	14.1	14.4
16	3.2	12.9	12.6	13.6
17	2.7	14.9	13.7	14.5
18	4.0	18.3	17.5	14.7
19	4.0	17.5	16.8	15.7
20	4.2	17.5	17.9	15.6
21	3.7	19.3	16.5	15.4
22	3.8	17.1	15.0	14.1
23	4.1	16.8	13.5	14.2
26 (0-2)	3.1	12.8	14.3	12.3
(2-4)	3.2	8.0	6.4	
(4-6)	1.7	7.4	4.7	
27 (0-2)	1.6	9.1	9.3	12.5
(2-4)	2.1	8.0	7.3	
(4-6)	1.6	7.8	6.5	
28 (0-2)	3.5	15.9	16.9	14.9
(2-4)	2.6	11.8	11.0	
(4-6)	2.1	10.8	9.4	
29 (0-2)	2.4	8.1	6.5	12.1
(2-4)	1.6	6.6	4.4	
(4-6)	1.2	5.6	5.1	
30 (0-2)	1.9	7.5	7.4	12.8
(2-4)	1.9	6.9	6.5	
(4-6)	2.4	8.0	8.1	
31 (0-2)	2.4	11.0	10.9	14.7
(2-4)	2.8	11.4	11.8	
(4-6)	2.4	10.2	10.4	

[a] (X-X) - Profile Sample Depth in inches

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Table A-2. Ground Measurements of Natural Isotopes and Exposure Rate (Continued)				
Sampling Location Number[a]	U-238 ppm ±5%	Th-232 ppm ±5%	K-40 pCi/g ±12%	Pressurized Ion Chamber Exposure Rate at 1 m AGL (μR/h)
32 (0-2)	1.8	8.6	8.6	13.1
(2-4)	1.8	7.6	7.8	
(4-6)	2.2	8.7	8.9	
33	2.0	7.6	11.5	11.9
34	2.1	7.4	9.6	12.2
35	2.7	9.0	10.0	12.4
36	2.2	10.5	12.1	12.2
38	2.7	14.9	17.5	15.1
39	2.1	7.9	7.2	12.0
41	2.4	14.7	15.4	13.8
42	2.8	14.8	15.6	15.2
43	2.3	11.9	15.0	14.1
44	2.8	12.9	14.6	13.9
45	3.1	17.0	19.9	15.1
46	3.1	16.5	18.7	15.5
48	2.1	10.1	11.6	12.5
49	2.1	11.2	14.7	13.6
50	4.0	21.2	21.8	16.4
51 (0-2)	3.7	15.4	16.1	14.8
(2-4)	2.7	15.1	16.8	
(4-6)	2.7	13.8	14.4	
52	2.4	15.2	21.6	13.1
53	3.3	17.1	18.5	13.1
58	N/A	N/A	N/A	14.4
59	3.2	19.9	18.4	15.8
60	3.2	17.5	15.8	15.0
61	2.6	11.7	12.7	12.6
62	3.2	16.1	18.8	15.3
63	3.7	15.7	18.5	15.4
64	3.7	18.0	13.7	14.3
65	2.8	15.2	16.7	14.3
68	2.0	11.1	16.4	14.9
69	3.0	15.5	17.8	14.8
70	2.9	16.4	15.9	15.7
71	3.2	20.0	18.9	16.9
72	2.5	12.3	16.3	14.6

[a] (X-X) - Profile Sample Depth in inches

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Table A-2. Ground Measurements of Natural Isotopes and Exposure Rate (Concluded)				
Sampling Location Number[a]	U-238 ppm ±5%	Th-232 ppm ±5%	K-40 pCi/g ±12%	Pressurized Ion Chamber Exposure Rate at 1 m AGL (μR/h)
73 (0-1)	3.3	19.0	18.4	16.2
(1-2)	3.3	18.1	18.1	
(2-3)	3.1	16.4	15.2	
74	3.2	14.3	16.5	14.6
75	3.0	13.2	26.2	13.8
76	2.5	13.4	16.4	13.0
79	3.0	12.2	15.3	15.6
80	3.2	19.7	19.3	16.0
81	3.6	20.9	19.4	15.7
83	2.7	12.5	16.9	15.6
84	2.5	12.8	12.0	14.0
85	2.1	11.1	15.5	13.9
87	2.1	11.2	15.9	14.1
87A	1.9	11.3	16.7	13.9
88	3.5	13.7	18.2	15.2
89	3.2	16.7	17.8	16.6
89A	2.8	17.6	18.8	15.2
90	3.0	14.6	9.3	12.3
91	2.5	18.8	21.8	12.9
103	2.6	13.5	14.3	13.4

[a] (X-X) - Profile Sample Depth in inches

Table A-3. Comparison of Am-241 Concentration Estimates from Soil Samples, *In Situ*, and Aerial Data			
Ground Sampling Point Numbers	Soil Samples (pCi/g)	*In Situ* HPGe (pCi/g)*	Aerial "C" Level (pCi/g)*
50	97	51	27 - 54
51	20	13	27 - 54
52	48	25	27 - 54
53	7	16	27 - 54
87A	36	10	27 - 54

* Using a relaxation depth of 0/10 cm^{-1} and a soil sampling depth of 5 cm

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