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AN AERIAL RADIOLOGICAL SURVEY OF THE AREA SURROUNDING AND ENCOMPASSING THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

JEFFERSON COUNTY, COLORADO

Survey Dates – June 12 to 15, 2005

National Nuclear Security Administration

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JEFFERSON COUNTY, COLORADO

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Abstract

An aerial radiological survey of the Rocky Flats Environmental Technology Site (RFETS) was conducted from June 12 to 15, 2005, and encompassed a 33.2 square kilometers (12.8 square miles) area. The survey was conducted by the U.S. Department of Energy National Nuclear Security Administration's Remote Sensing Laboratory-Nellis, which is located in Las Vegas, Nevada. The aerial survey was conducted at the request of the U.S. Department of Energy's Office of Environmental Management.

The primary objective of the survey was to provide verification data that all radioactively contaminated surface soil, beyond the known and suspected contaminated areas, had been identified for the final cleanup efforts at the RFETS. As part of that verification process, the survey measured and mapped the exposure-rate levels that currently existed within the survey area and defined any possible areas of man-made radiation activity. The inferred aerial exposure rates were relatively uniform and typical of the natural terrestrial background radiation, which varied from 11 to 19 microroentgens per hour.

Four locations were identified as containing elevated levels of radioactivity. Three of those locations were known radioactive waste storage or remediation areas that existed at the time of the survey flyover, and were not unexpected anomalies and/or contaminated surface soil areas. The first corresponded with the location of more than 1,000 radioactive waste containers being stored within the 750 Pad tents. The second corresponded with the location of more than 500 DiRT[a] bags staged just south of the railroad tracks. These DiRT bags contained low-level radioactive soils from the B-series ponds accelerated action. The third corresponded with the open excavation associated with the remediation of the B776 under building contamination (UBC).

The only exception was the fourth location, which required further investigation. The aerial survey had identified and attributed this fourth location to the presence of americium-241 (^{241}Am). The presence of ^{241}Am is a remnant of past plutonium operations conducted at the RFETS and current cleanup operations. However, subsequent follow-up ground-based high purity germanium (HPGe) scans (scanning covered the entire aerial detection system field-of-view area) performed by Kaiser-Hill, LLC, indicated zero detectable ^{241}Am activity at this location. Hence, the aerial result was listed as a "false-positive" with no further investigation or action required.

It should be noted that no excess levels of ^{234}Th, ^{234}U or ^{235}U were detected. No other significant (non-statistical) man-made radiation activity was detected within the remainder

[a] Brand name for super sack—bags were designed specifically for the Rocky Flats clean-up effort

of the survey area nor along the special low-altitude flight conducted over the three drainage areas and alongside the three major power lines.

In summary, no significant areas of previously unknown surface radiological contamination were found within the RFETS survey area, with the exception of a fourth location, which was later investigated.

A series of ground-based, pressurized ionization chamber exposure-rate measurements were also acquired on June 15, 2005, at five locations within the survey area boundaries. The results of the ground-based *in situ* measurements were compared to the inferred aerial exposure rate results. The inferred aerial exposure-rate results were found to be within 2 to 6 percent of the ground-based *in situ* exposure rate results.

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Acronyms, Abbreviations, and Symbols

μ_{air}	gamma ray air attenuation coefficient in m^{-1}
µR/h	microroentgens per hour (a unit of exposure rate)
γ/sec	gamma rays per second
^{228}Ac	actinium-228 (part of the thorium decay chain)
^{241}Am	americium-241
^{214}Bi	bismuth-214 (part of the uranium decay chain)
^{137}Cs	cesium-137 (worldwide fallout due to atmospheric weapons testing)
^{40}K	potassium-40 (radioactive potassium)
^{22}Na	sodium-22
^{239}Pu	plutonium-239 (weapons grade plutonium)
$^{239/240}Pu$	plutonium-239 and plutonium-240 (combined total grouping)
^{241}Pu	plutonium-241 (first daughter product is americium-241)
^{232}Th	natural thorium
^{234}Th	thorium-234 (part of the uranium decay chain)
^{208}Tl	thalium-208 (part of the thorium decay chain)
^{234}U	uranium-234 (part of the uranium decay chain)
^{235}U	uranium-235 (fissile component of natural uranium)
^{238}U	uranium-238 (predominant component of natural uranium)
AGL	above ground level
AMS	Aerial Measuring System
BKG	background
Ci	curie (a unit of activity equal to 3.7×10^{10} disintegrations per second)
cm	centimeter
cps	counts per second
DGPS	Differential Global Positioning System
DOE	U. S. Department of Energy
ft	feet
FOV	field-of-view
g/cm^3	grams per cubic centimeter
GC	gross count
GPS	Global Positioning System

HPGe	high purity germanium
in	inches
JEFFCO	Jefferson County
keV	kiloelectron volt
km	kilometer
km^2	square kilometers
LT	live time (in seconds)
m	meter
m^1	inverse or per meter (1/m)
m^2	square meters
m/s	meters per second
MCA	multi-channel analyzer
MDA	minimum detectable activity
mi	mile
mi^2	square miles
MMGC	man-made gross count
MSL	Mean Sea Level
N	north
NaI(Tl)	thallium-activated, sodium iodide gamma ray scintillation detector
NNSA/NSO	National Nuclear Security Administration Nevada Site Office
pCi/g	picrocuries per gram (a unit of soil concentration)
pCi/g/cps	picrocuries per gram per counts per second
PIC	pressurized ionization chamber
RDGPS	Real-time Differential Global Positioning System
REDAR V	Radiation and Environmental Data Acquisition and Recorder, Version V
RFETS	Rocky Flats Environmental Technology Site
RSL-N	Remote Sensing Laboratory-Nellis
SE	southeast
SW	southwest
UBC	Under Building Contamination
W	west

1.0 INTRODUCTION

An aerial radiological survey of the Rocky Flats Environmental Technology Site (RFETS) and surrounding area was conducted from June 12 to 15, 2005. The survey area included 33.2 square kilometers (km^2) (12.8 square miles [mi^2]) located approximately 24 kilometers (km) (15 miles [mi]) northwest of Denver, Colorado, in Jefferson County. The survey was conducted by the U.S. Department of Energy's (DOE) Remote Sensing Laboratory-Nellis (RSL-N), located in Las Vegas, Nevada. The RSL-N is maintained and operated by Bechtel Nevada, the management and operating contractor for the DOE National Nuclear Security Administration Nevada Site Office (NNSA/NSO). The survey was conducted at the request of the DOE Office of Environmental Management, which is responsible for the cleanup at Rocky Flats.

The primary objective of the survey was to provide verification data that all radioactively contaminated surface soil, beyond the known and suspected contaminated areas, had been identified for the final cleanup efforts at the RFETS. As part of that verification process, the aerial survey was conducted to measure and map the natural and man-made gamma radiation emanating from within, and surrounding, the RFETS. This was the fourth time that the RFETS was surveyed using the aerial radiological measuring techniques.[1,2,3] The last aerial survey was conducted in 1989.

Results are reported as radiation isopleths superimposed on an IKONOS Satellite Image of the survey area, which was acquired on July 8, 2005 by the IKONOS Hi-Res Satellite Imagery Project for Kaiser-Hill, LLC, who supplied the geo-rectified (WGS-84 datum) image to RSL-Nellis. Areas of elevated levels of terrestrial exposure rate and man-made or specific isotopic gamma radiation activity are reported.

On June 15, 2005, five ground-based, pressurized ionization chamber (PIC) exposure-rate measurements were also acquired from within the survey area for comparison with the aerial results.

2.0 SITE DESCRIPTION

The RFETS, a former nuclear weapons facility located approximately 24 km (15 mi) northwest of Denver, Colorado, is a DOE-owned cleanup and closure site operated by the Kaiser-Hill, LLC, under an accelerated closure contract. The RFETS and the surrounding area are sparsely populated and the majority of the RFETS will be transferred to the U.S. Fish and Wildlife Service as the Rocky Flats National Wildlife Refuge (Figure 1) when cleanup and closure operations are completed. Elevations range between 1700 and 1900 meters (m) (5600 to 6200 feet [ft]) mean sea level (MSL).

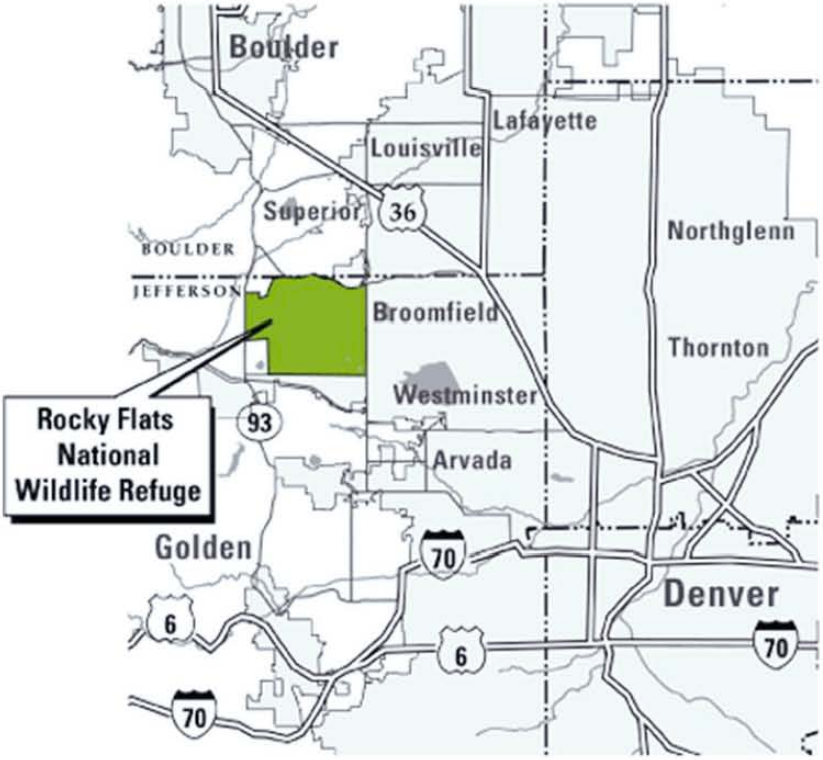


Figure 1. Rocky Flats National Wildlife Refuge Encompasses the Rocky Flats Environmental Technology Site (http://www.rfets.gov)

Historically, the RFETS had more than 800 structures located on a 300-acre "Industrial Area" surrounded by 6,000 acres of controlled open space called the "Buffer Zone".[4] In the Industrial Area, components for nuclear weapons were fabricated from plutonium, uranium, and metals such as beryllium and stainless steel. Other activities included chemical recovery, as well as research and development related to component fabrication. At the time of this survey, nearly all of the facilities had been deactivated, decommissioned, demolished, dismantled, and removed.

The RFETS also had 417 areas of suspected contamination that were investigated and dispositioned through appropriate accelerated remedial actions or by determining that no

action was required. All decisions were taken in accordance with the Rocky Flats Cleanup Agreement (RFCA), a Federal Facility Agreement and Consent Order signed by DOE, the U. S. Environmental Protection Agency, and the Colorado Department of Public Health and Environment. The vast majority of the 417 areas required no action; however, approximately 10 of the highest risk areas required significant action. These locations included areas of past chemical and radioactive contamination in the environment at Rocky Flats. The primary radioisotopes of concern for the cleanup efforts were: americium-241 (^{241}Am), plutonium-239 and plutonium-240 ($^{239/240}$Pu), uranium-234 (^{234}U), uranium-235 (^{235}U), and uranium-238 (^{238}U).

Although not required by the RFCA, the DOE chose to undertake an additional survey effort to provide an added degree of confidence and assurance that the land would be safe for its future users, namely wildlife refuge workers and wildlife refuge visitors. This survey effort included a wide-area aerial radiological survey that was used to confirm that all potential significant areas of surface soil contamination had been identified.

Following the completion of the cleanup and closure of the RFETS, it is anticipated that the majority of the Buffer Zone will be designated as a Wildlife Refuge and that DOE will retain control over the former Industrial Area. The DOE Office of Environmental Management, which is responsible for the cleanup, will transfer management to the DOE's Office of Legacy Management for the long-term management of the DOE-retained lands, and to the U.S. Fish and Wildlife Service for the long-term management of the Rocky Flats National Wildlife Refuge.

3.0 SURVEY PLAN

3.1 Aerial Survey

The aerial radiological survey covered an area of 33.2 km^2 (12.8 mi^2) that included the RFETS, as shown in Figure 2. The area was surveyed by a Bell-412 twin-engine helicopter flying at a nominal ground speed of 60 knots (31 meters per second [m/s]), at a nominal altitude of 15 m (50 ft) above ground level (AGL), and along a set of 195 parallel flight lines spaced 30 m (100 ft) apart (Appendix A). Flight lines were oriented and flown in either a southwesterly or northeasterly direction (nominally parallel to the rugged terrain features).

To ensure adequate coverage of the natural drainage areas (Walnut Creek North [A-Pond], Walnut Creek South [B-Pond] and Woman's Creek [C-Pond]) leading away from the former RFETS Industrial Area and the areas residing underneath/beside the three major power lines, a special low-altitude flight was flown (flight path shown in Figure 2) at a nominal altitude of 15 m (50 ft) AGL down the center of each of the three main drainage areas and along both sides of the three major power lines.

To ensure data integrity and to monitor and correct variations in the detector's background radiation due to radon, cosmic rays, and the aircraft, repeated measurements were made over a land test-line and water test-line at the beginning and end of each flight. The land test-line was located between the Jefferson County (JEFFCO) Airport take-off/landing runway and taxiway. The water test line was located over Standley Lake, approximately 5 km (3 mi) south of the airport.

3.2 Ground-Based Exposure Measurements

On June 15, 2005, five corroborative ground-based exposure-rate measurements were acquired from within the survey area boundaries. The results of these measurements were used to cross calibrate the inferred aerial exposure-rate results. These measurements were not near any known radiation anomalies and were acquired using a PIC and collected at a height of 1 m (3.3 ft) AGL. At each sampling location, the field team collected three 300-second PIC measurements. The average value of the three measurements and its statistical deviation was reported.

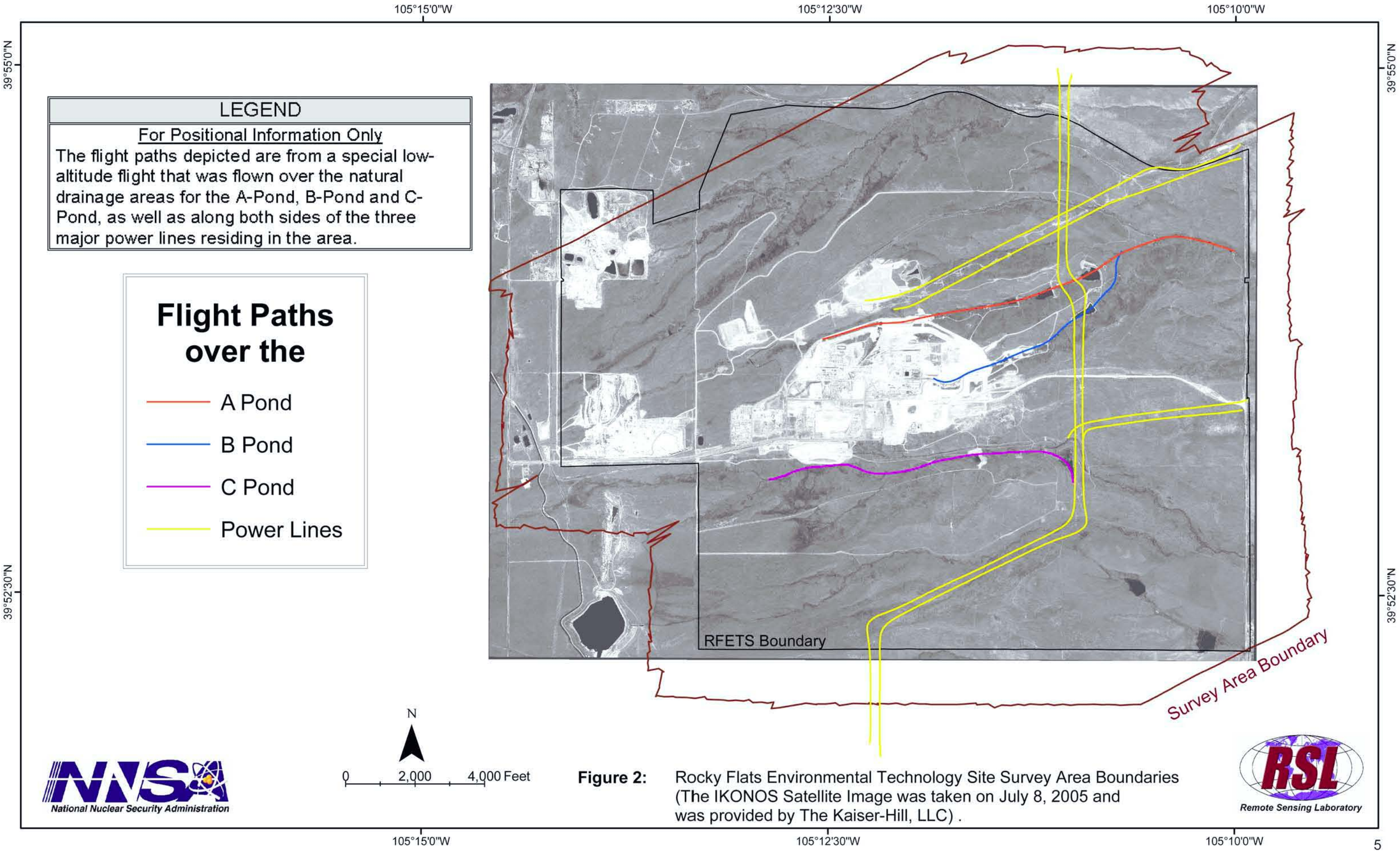


Figure 2: Rocky Flats Environmental Technology Site Survey Area Boundaries (The IKONOS Satellite Image was taken on July 8, 2005 and was provided by The Kaiser-Hill, LLC) .

3.3 Plutonium Measurements

The presence of plutonium, specifically ^{239}Pu, is difficult to establish directly from aerial measurements. Remote measurements of plutonium, particularly at low concentrations, are impractical for techniques that measure gamma radiation, because plutonium emits very few energetic gamma rays per disintegration. Direct measurements of small concentrations of plutonium require laboratory analyses, employs expensive and time-consuming techniques such as chemical separation, low-level counting, alpha spectroscopy, and mass spectroscopy. All of these techniques have been employed at the RFETS.

Remote measurement of plutonium for an area as large as the RFETS can only be accomplished by measuring a radionuclide closely associated with plutonium, which can be detected by gamma radiation emissions (indirect method). Americium-241, a decay daughter of plutonium-241 (^{241}Pu), is such a radionuclide. Although plutonium used in nuclear weapons is principally ^{239}Pu it also contains other isotopes of plutonium. Generally, the ratio of ^{241}Pu to ^{239}Pu present in the material depends only upon its initial value at production. Likewise, the quantity of ^{241}Am present depends only on the initial isotopic mix and the age of the plutonium since production. As the ^{241}Pu decays, the amount of its daughter, ^{241}Am, increases. The ratios at any future time can be easily calculated from the original isotopic mix and mixture age. Therefore, the quantity of plutonium, specifically ^{239}Pu, can be inferred from direct measurements of ^{241}Am and a known ratio of ^{239}Pu to ^{241}Am. For the RFETS cleanup effort, the primary isotope of concern is based on the combined total amount or concentration of ^{239}Pu and ^{240}Pu, which is determined by multiplying the measured ^{241}Am concentration (in picocuries per gram [pCi/g]) by 5.7. The conversion factor of 5.7 is applied when calculating the plutonium concentrations from the measured americium concentrations for all RFCA-related soil activities conducted at the RFETS in accordance with the RFCA.[5]

4.0 AERIAL RADIOLOGICAL SURVEY EQUIPMENT

4.1 Aerial Survey

Standard aerial radiological survey techniques developed for large-area gamma radiation surveys were used.[6] The survey methodology has been successfully applied to more than 500 individual surveys at various locations beginning in the late 1960s.

This aerial radiological survey was conducted using the Aerial Measuring System (AMS), which included a Bell-412 helicopter; a Radiation and Environmental Data Acquisition and Recorder, Version V (REDAR V); and a Real-time Differential Global Positioning System (RDGPS) (Figure 3). The helicopter was equipped with two large detector pods mounted on the side of the aircraft. Each pod contained six 5.1- x 10.2- x 40.6-cm (2- x 4- x 16-in) thallium-activated sodium-iodide, NaI(Tl), scintillation gamma-ray detectors.

Figure 3. Bell-412 Helicopter with Detector Pods

The signal from each detector was calibrated using ^{22}Na and ^{241}Am gamma-check sources. Normalized outputs from each of the twelve NaI(Tl) detectors were combined in a twelve-way analog-summing amplifier. The signal was adjusted in the analog-to-digital converter so that the calibration photopeaks appeared in pre-selected channels in one of the four REDAR V multi-channel analyzers (MCAs). In addition, the calibrated output from one of the NaI(Tl) detectors was fed to a separate MCA to provide increased dynamic range when viewing higher-radiation areas.

4.1.1 REDAR V System

Data were acquired using the REDAR V system designed for use in aircraft. The REDAR V is a portable, real-time, UNIX-based multi-processor data collection instrument. The REDAR V runs multiple, dedicated processors and operating systems, including four 4096-channel MCAs, 16 analog inputs, and 6 serial input/output ports, that can gather a multitude of data. All data are acquired in 1-second increments and stored to hard drives. Typical data collected includes four 1024 channel gamma-energy spectra, ambient air temperature, absolute barometric pressure, and aircraft altitude and position. This information can be displayed in real-time while in flight.

4.1.2 Helicopter Positioning

The position of the helicopter was established by using two systems: a RDGPS and a radar altimeter. The RDGPS is a space-based navigational system that provides continuous positional information accurate to ± 3 m (10 ft) using a minimum of 4 of the 24 Global Positioning System (GPS) satellites orbiting the earth. The radar altimeter determines the altitude by measuring the round-trip propagation time of a signal reflected off the ground. The accuracy of the radar altimeter is ± 2 percent or ± 0.6 m (2 ft), whichever is larger.

4.1.3 Data Processing

The raw spectral and positional data collected and reported by the AMS were first examined in the field using a portable PC-based analysis system which was installed at the DOE Rocky Flats Mountain View facility located adjacent to the JEFFCO Airport near the survey area. Preliminary contour maps of the terrestrial exposure rate, man-made radioactivity, ^{241}Am soil concentration, and the survey's flight altitude, were created in the field to verify data quality and to indicate areas where further survey work might be necessary. After returning to the RSL-N in Las Vegas, Nevada, the data were further processed, using the same type of analysis system, to produce the principal data products.

4.2 Ground-Based Exposure Rate Measurements

A series of ground-based exposure-rate measurements were acquired using a Reuter-Stokes PIC Model RSS-112, (Appendix B). The PIC is portable and battery-powered and incorporates a 25-cm- (10-inch-) diameter metal sphere filled with 25 atmospheres of argon gas, a high voltage bias supply, an electrometer, and readout components. This unit has a sensitivity of approximately 3 x 10^{-14} amperes per microroentgens per hour (µR/h) and has the capability of digitally and graphically displaying the total exposure rate and integrated dose data. The position of each measurement was established to within ± 10 m (~ 30 ft) using a Garmin Personal Navigator handheld unit, Model GPS-45.

5.0 DATA ANALYSIS PROCEDURES

Standard techniques were used for analyzing the survey data. Terrestrial exposure rates were computed from gross count data with a correction for variations in altitude. Activity or count-rates due to man-made radioactivity (e.g., ^{241}Am, ^{235}U) were determined through differences between total counts in the appropriate gamma energy spectral windows (Appendix C). All necessary refinements of the data were also applied at this stage of processing. These refinements included subtraction of more accurate estimates of the background radiation, and application of more accurate altitude and dead-time corrections. Finally, contours were superimposed on a properly scaled and geo-rectified (WGS-84 datum) IKONOS Satellite Image of the survey area. The ground-based corroborative exposure-rate data were processed and compared with the inferred aerial terrestrial exposure rate results.

5.1 Aerial Radiological Data Analysis

Aerial radiation data generally contain contributions from the naturally occurring radionuclides, man-made radionuclides, airborne radon, cosmic rays, and aircraft-induced electronic noise. For this survey, principal products of the analysis of the aerial survey data are contour maps of the terrestrial exposure rate, man-made radioactivity, and isopleth contour maps of the soil concentrations for ^{241}Am, $^{239/240}$Pu (inferred from the ^{241}Am results), ^{235}U, and ^{238}U (specifically thorium-234 [^{234}Th]). The basic procedures involved in constructing these products from the gamma energy spectral data are briefly reviewed in this section. More detailed information can be found in separate publications.[6,7]

5.1.1 Terrestrial Exposure Rate (Gross Count)

The terrestrial exposure rate or gross count method is based on the integral count-rate in the gamma energy spectral range between 38 and 3,026 kiloelectron volts (keV):

$$CR_{GC} = \sum_{E=38}^{3026} S(E) - NTB \qquad (1)$$

where

CR_{GC} = total terrestrial count-rate or gross count in counts per second (cps).

S(E) = energy spectrum containing the number of gamma rays collected at the given energy *E* per second.

E = the photon energy in keV.

NTB = non-terrestrial background in cps produced by the effects of airborne radon, cosmic rays, and the aircraft background.

The gross count, measured in cps at survey altitude, was converted to an exposure rate in µR/h at a height of one meter above ground level by application of a conversion factor derived (cross calibrated) from the ground-based corroborative PIC exposure rate measurements that were collected at the RFETS on June 15, 2005.

The conversion equation used is:

$$ER = \frac{CR_{GC}}{1833} e^{(A-15)\mu_{air}} \tag{2}$$

where

ER = exposure rate extrapolated to one-meter AGL in µR/h.

A = survey altitude in meters.

μ_{air} = gamma ray air attenuation coefficient in m^{-1}.

1833 = conversion factor relating the gross count to exposure rate in cps/(µR/h).

The air attenuation coefficient, μ_{air}, deduced empirically from the altitude profile data acquired over the survey's land-test line, was 0.0049 m^{-1} (0.0015 ft^{-1}). The derived conversion factor, obtained from the cross-calibration comparison with the acquired RFETS ground-based exposure-rate measurements, was 1833 cps per µR/h for a survey altitude of 15 m (50 ft) AGL. The applicability of the conversion equation assumes a uniformly distributed radiation source covering an area that is large when compared to the field of view of the detection system (a circle with a diameter roughly twice the altitude of the aircraft).

5.1.2 Man-Made Gross Count

The aerial data were also used to determine the location of non-naturally occurring gamma sources (i.e., man-made radionuclides). Man-made gross count (MMGC) is the portion of the gross count, which is directly attributed to the gamma rays from man-made radionuclides. Large amounts of man-made radionuclides can be found from increases in the gross count. However, slight variations in the gross count are generally not considered adequate proof to suspect the presence of a man-made anomaly since these variations can result naturally from geological fluctuations or changes in the ground coverage (e.g., rivers, vegetation, buildings).

In order to increase the sensitivity of the AMS to detect man-made anomalies, a man-made gross count algorithm has been developed that uses differential spectral energy extraction techniques to identify changes in the gamma energy spectral shapes. This algorithm takes advantage of the fact that while background radiation levels often vary by a factor of two or more within a survey area, background spectral shapes remain essentially constant. More

specifically, the ratio of natural components in any two sections (windows) of the energy spectrum will remain nearly constant.

Although this procedure can be applied to any region of the gamma energy spectrum, the most common practice is to place all counts below 1,394 keV into the man-made window (low-energy sum), where most of the long-lived, man-made radionuclides emit radiation. All counts above 1,394 keV are placed into the natural window (high energy sum), where mostly the naturally-occurring radionuclides and only a few man-made radionuclides emit radiation. The MMGC rate can be expressed analytically in terms of the integrated count-rates in specific gamma energy spectral windows (keV):

$$MMGC = \sum_{E=38}^{1394} S(E) - K_{mm} * \sum_{E=1394}^{3026} S(E) \tag{3}$$

where K_{mm} is defined over an area that contains only gamma radiation from naturally-occurring radionuclides as

$$K_{mm} = \frac{\sum_{E=38}^{1394} S(E)}{\sum_{E=1394}^{3026} S(E)} \tag{4}$$

This MMGC algorithm has been found to be sensitive to low levels of man-made radiation even in the presence of large variations in the natural background. Once a region of man-made radioactivity has been identified, a detailed analysis of the gamma energy spectrum is conducted to ascertain which radionuclides are present.

It should be noted that in areas where the aircraft's altitude changes significantly from the planned altitude and/or in areas exhibiting excess concentrations of natural potassium, uranium, and/or thorium, the ratio of low-energy to high-energy gamma rays may be different even though the gamma rays are emitted by naturally occurring radionuclides. In such cases, the MMGC algorithm may generate a set of "false positive" anomalies on the MMGC contour map. A background-subtracted gamma spectrum in this case will show only natural radionuclides or a smoothly varying background with no discernable peaks.

5.1.3 Isotopic Extraction Algorithms

The determination of an individual isotope's contribution to the gross count requires an algorithm that can identify an isotope's specific gamma-energy photopeak count-rate. The simplest of these algorithms is the two-window strip, which is very similar to the algorithm used to extract the MMGC. The two-window stripping method assumes that the photopeak count-rate from a specific isotope can be determined from the sum of the counts in the isotope's gamma energy source window minus a scaled background contribution. The

equation for a two-window strip is similar to that shown in Equation 3, but the appropriate energy limits for both the source and background windows need to be inserted. The two-window proportionality factor, *K,* is derived in a method that is similar to the method for deriving K_{mm} (Equation 4) from a region in the survey area that does not contain any of the isotopes of interest. The photopeak window contains only its background counts and therefore is directly related to the number of counts in the background window. If the principal source of background radiation in the photopeak window is from scattered gamma rays from photopeaks at higher energies, this is a good assumption. If there are other isotopes present within the background area whose gamma energy photopeak(s) also reside within the algorithm's gamma energy source window, then this algorithm is less accurate.

If an area cannot be found that is free of the specific isotope of interest, or if the composition of the other isotopes drastically changes between the chosen background area and the rest of the survey area, then a simple multiplicative factor will not relate the counts in the photopeak window to the counts in the background window. To solve this problem, the three-window algorithm will be used where

$$CR_{3\text{-}Window} = \sum_{E=E2}^{E3} S(E) - K_3 * [\sum_{E=E1}^{E2} S(E) + \sum_{E=E3}^{E4} S(E)] \tag{5}$$

with

$$K_3 = \frac{\sum_{E=E2}^{E3} S_{bkg}(E)}{\sum_{E=E1}^{E2} S_{bkg}(E) + \sum_{E=E3}^{E4} S_{bkg}(E)} \tag{6}$$

E_1, E_2, E_3, and E_4 represent the limiting energy ranges of the two background windows. The three-window algorithm is also very useful in extracting low-energy photopeak counts where the shape of the Comptom-scatter contributions from other isotopes is changing significantly.

For the case of extracting the ^{241}Am, ^{234}Th (^{238}U), and ^{235}U counts, the three-window algorithm was used. The background energy limits that were used for each isotopic extraction are shown in Appendix C. The extracted isotopic count-rates, measured in cps at survey altitude, were converted to soil activity in pCi/g by application of a conversion factor (Appendix C), which was derived from a radioactive transport matrix model developed by Beck, et al.[8] This method mathematically models the gamma ray flux through a detector located at some distance above a source distribution. A brief synopsis of this model is discussed in the next section.

5.2 Conversion Factors

Conversion factors have been calculated which relate the measurement photopeak count-rate data to the radionuclide activity in the soil. The values are determined by combining a laboratory measurement of the detector efficiency to a given gamma ray energy with a theoretical calculation of the gamma ray flux arriving at the detector as a function of source distribution in the soil.

The unscattered gamma ray flux, φ, from a point source with activity S_0 at a distance r from the source is given by

$$\phi = \frac{S_o}{4\pi r^2} e^{-r/\lambda_a} \tag{7}$$

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

$$\phi = \frac{S_o}{4\pi r^2} e^{-(\mu/\rho)_a \rho_a r} \tag{8}$$

where

$(\mu/\rho)_a$ = air mass attenuation coefficient, cm^2/g.

ρ_a = air density, g/cm^3.

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

$$\phi = \int_0^\infty \int_0^\infty \frac{S_v}{4\pi r^2} e^{[-(\mu/\rho)_a \rho_a r_a]} e^{[-(\mu/\rho)_s \rho_s r_s]} 2\pi x dx dz \tag{9}$$

where

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

r = $r_a + r_s$ in cm.

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

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

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

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

$$A = \frac{N_p}{\phi} \tag{10}$$

where N_p is the net photopeak count-rate, normally given in units of cps. The effective area, in general, varies as a function of the gamma ray angle of incidence and is usually written as

$$A = A_o R(\theta) \tag{11}$$

where

A_o = detector photopeak count-rate for a unit flux incident perpendicular to the detector face, (cps)/(γ/cm^2-sec).

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

Combining Equations 10 and 11 with Equation 8 leads to an expression, which relates the measured photopeak count-rate to source activity in the soil. This is given by

$$N_p = \int_0^\infty \int_0^\infty \frac{S_v A_o R(\theta)}{4\pi r^2} e^{[-(\mu/\rho)_a \rho_a r_a]} e^{[-(\mu/\rho)_s \rho_s r_s]} 2\pi x dx dz \tag{12}$$

In order to evaluate Equation 12, it is necessary to make some assumptions on the source distribution depth. Three basic types of vertical source distributions are normally encountered in environmental measurements. Naturally occurring background radiation is normally represented by a uniform volume distribution (i.e., distributed uniformly as a function of depth). Relatively fresh fallout activity is normally represented by a uniform surface distribution (i.e., the radioactivity lies in a thin layer of material on the ground). Fallout activity, which has aged into the soil over a period of time, is most often represented by an exponential distribution of the form

$$S_v = S_v^o e^{-\alpha z} \tag{13}$$

where

S_v^o = activity per unit volume at the surface, (γ/sec)/cm^3.

α = reciprocal of the relaxation depth, cm^{-1}.

z = source distribution depth in the soil, cm.

This implies that the representative volume of soil at a depth of 1/α is assumed to contain approximately 63% of the source's total activity. At a depth of 2/α and 3/α, respectively, the representative volume of soil is assumed to contain approximately 86% and 95% of the total activity.

For the exponential soil depth distribution model, Equation 12 becomes

$$N_p = \frac{S_v^o A_o}{2} \int_0^{\pi/2} \frac{R(\theta)\tan(\theta) e^{[-(\mu/\rho)_a \rho_a h \sec(\theta)]}}{\alpha + (\mu/\rho)_s \rho_s \sec(\theta)} d(\theta) \tag{14}$$

This expression relates the measured photopeak count-rate, N_p, to the activity per unit volume at the surface. The detector parameters, A_o and $R(\theta)$, are normally obtained empirically for a given system using standard calibration sources. Mass attenuation coefficients for air and typical soils can be found in standard reference tables. An average soil density of 1.5 g/cm^3 and air density of 0.001205 g/cm^2 at 20°C are normally assumed, unless actual measured values are available. The detector height, *h*, can be measured in most cases.

In general, it is more useful to relate the photopeak net count-rate data to an average concentration within a given depth, rather than a surface concentration as given in Equation 14. The average concentration in the top *z* cm of soil, $S_v(z)$, for a source distributed exponentially with depth is given by

$$S_v(z) = \frac{1}{z} \int_0^z S_V^o e^{-\alpha z} dz = \frac{S_v^o}{\alpha z}(1 - e^{-\alpha z}) \tag{15}$$

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

$$S_A = \int_0^\infty S_v^o e^{-\alpha z} dz = \frac{S_v^o}{\alpha} \tag{16}$$

The conversion factors derived for all three source distribution types relate a measured photopeak net count-rate, expressed in units of cps to source activity expressed in units of gamma rays per second (γ/sec) per unit area or unit volume. For a specific isotope, the source activity is normally changed to units of curies or becquerels. The average activity-per-unit volume can also be converted to average activity-per-unit mass by dividing S_v^o by the soil density.

In the above model, the values for *"α"* and *"z"*, which were assumed and not measured in the field, are usually poorly known, and are highly dependent upon the actual soil

conditions and isotopes present. Also, artificial soil disturbance (farming, construction, etc.) will affect the value of these parameters.

5.3 Minimum Detectable Activity

Since the detectors employed on the aerial system are not shielded, the detector footprint or field-of-view (FOV) has no firm boundary. The main factors that define the footprint are the energy of the gamma rays and the attenuation of the gamma rays by the atmosphere. The detector array is thus capable of detecting gamma rays from large distances, but the atmospheric attenuation acts to shield gamma rays from large distances (i.e., “infinite”). The conversion factors used for converting the measured aerial gamma count-rate into activity concentrations are based on calculations that assume the radioactivity is uniformly dispersed over an area on the ground that is “large” compared to the FOV of the detector array. Furthermore, the accuracy of the derived conversion factors is also dependent on a specific knowledge of the radioactivity distribution within the soil, specifically the soil depth (assumed to be homogenous to a depth of 2.5 cm), and to a lesser extent knowledge of the soil density (assumed to be 1.5 picocuries per gram), soil moisture content (assumed to be 10%) and chemical composition (i.e., a wide range of the naturally occurring radionuclides, such as radioactive potassium and the thorium and uranium decay products). All of these variables are unknown and may vary considerably from the norm (site to site and within each site) due to differences in the terrain (pastures, excavations, rocky culverts, woodlands, facilities, etc.). The calculations also assumed that all daughters are in radioactive equilibrium with their parents, which is not true for the radon daughters.

Since the inferred soil concentration measured by the aircraft is an average over the nominal surface footprint of the detector system, the observed aerial values are a function of both the surface soil concentration and the size of the contaminated surface area. For contaminated surface areas that are not “infinite”, significant correction factors must be applied or a larger MDA threshold value needs to be assumed. For instance, an observed measurement just above the cited MDA threshold may imply that the surface activity of part of the detector footprint is at, or even well above, the cited MDA value. Only when the uncorrected, observed, inferred aerial soil concentration is above the cited MDA can one be certain that at least some portion of the detector footprint exceeds the cited MDA threshold value. Thus, for surface activity areas larger than the size of the detector footprint, the reported detector activity is nominally equivalent to the surface activity. If the region of surface activity is smaller than the detector footprint, the detector activity related to the surface activity is approximated by the relationship:

$$(\text{Detector Activity}) = (\text{Surface Activity}) * (\text{Activity Area})/(\text{Footprint Area}) \qquad (17)$$

For estimation purposes, the detector footprint radius is approximately the same as the height of the detector (which is its full-width at half maximum value), but it is actually somewhat larger (10 to 20 percent, dependent on the gamma photopeak energy of

interest). For a detector height or altitude of 15 m (50 ft) AGL, the FOV for the aerial detection system is approximately 729 m^2 (7,850 ft^2). For the three primary isotopes of interest, the system's nominal a priori MDA in picocuries per gram (pCi/g) at the 95% confidence level for a source distribution size that is equivalent to the above cited FOV, assumptions and the averaged statistical variation of the soil composition and characteristics of the RFETS are shown in Table 1 (second column). Alternatively, if the source distribution size is smaller than the detector's FOV, then its surface activity needs to be proportionally larger in order for it to be detectable by the aerial system. Thus, the nominal a priori MDA for the three primary radioisotopes of interest having a source distribution size of 151-, 80-, and 1.2-m^2 are also shown in Table 1.

Table 1. Aerial Survey Minimum Detectable Activities (MDA) [a, b]

Isotope ID	729 m^2 area MDA (pCi/g)	151 m^2 area MDA (pCi/g)	80 m^2 area MDA (pCi/g)	1.2 m^2 area MDA (pCi/g)
Am-241	1.81	8.7	16.5	1100
U-235	1.40	6.8	12.8	850
U-238 (Th-234)	11.2	54.1	102	6800

[a] Derived for ground speed of 31 m/s, nominal altitude of 15 m AGL, and line spacing of 30 m.
[b] Derived for a soil sample depth (z) of 2.5 centimeters (cm) and inverse relaxation depth (α) of 0.33 cm^{-1}.

As previously mentioned, aerial detection systems provide an "average" over large areas. This average is a result of the limited angular resolution of the detectors and the motion of the aircraft. The angular resolution of the detectors depends primarily on their angular response, air attenuation of the gamma energy photons in the air and soil and, the detector-source separation distance (i.e., aircraft height over the terrain). Due to the rugged terrain of the RFETS, the helicopter was unable to maintain a constant flight altitude of 15 m (50 ft) AGL. Only 37 percent of the survey area was flown to within ±10 percent of this preferred nominal flight altitude. As a result, the inferred aerial ^{241}Am MDA for the majority (~ 94 percent) of the survey area, ranged from 1.8 to 3.0 pCi/g (or 10.3 to 17.0 pCi/g $^{239/240}$Pu), see Table 2. Also, for a $^{239/240}$Pu soil concentration of 50 pCi/g, the minimum detectable source distribution size as a function of altitude for the aerial system was estimated to range from 151 to 992 m^2 (0.04 to 0.25 acre). At altitudes higher than 46 m (150 ft) AGL, the 50 pCi/g $^{239/240}$Pu concentration is not detectable by the aerial system. A plot of the inferred $^{239/240}$Pu MDA versus its distribution size as a function of altitude is shown in Figure 4. A plot of the ^{241}Am and $^{239/240}$Pu MDA as a function of altitude for an "infinite" source surface area is presented in Appendix C, Figure C-1.

Table 2. Inferred ^{241}Am and $^{239/240}$Pu MDAs for the RFETS Survey Area

Aircraft Flight Altitude		RFETS Survey Altitude Coverage (% of area)	Aerial System MDA (Distribution Size = FOV)			AMS Scanned Area MDA[a] (Distribution Size = 151 m^2)		Estimated $^{239/240}$Pu Distribution Size (Pu Concentration = 50 pCi/g)	
m	ft		FOV[b] (m^2)	^{241}Am (pCi/g)	$^{239/240}$Pu (pCi/g)[c]	^{241}Am (pCi/g)	$^{239/240}$Pu (pCi/g)[c]	m^2	acre
13.7 – 15.2	45 – 50	37	730	1.81	10.3	8.7	50	**151**	0.04
15.2 – 18.3	50 – 60	21	1,051	2.04	11.7	14.2	81	**245**	0.06
18.3 – 21.3	60 – 70	14	1,430	2.28	13.0	21.6	123	**372**	0.09
21.3 – 24.4	70 – 80	7	1,868	2.51	14.3	31.1	177	**535**	0.13
24.4 – 27.4	80 – 90	4	2,364	2.75	15.7	43.0	245	**740**	0.18
27.4 – 30.5	90 – 100	11	2,919	2.98	17.0	57.6	328	**992**	0.25
30.5 – 45.7[d]	100 – 150	6	6,567	4.74	27.0	206.0	1,174	**3,546**	0.88
45.7 – 91.4+[d]	150 – 300+	< 0.1	26,268	17.0	97.0	2961.0	16,876	**ND**	ND
		100							

[a] In accordance with the Rocky Flats Cleanup Agreement, the smallest $^{239/240}$Pu concentration of interest is 50 pCi/g which for the aerial survey is equivalent to a field-of-view or source distribution size of 151 m^2 at an altitude of 15 m (50 ft) above ground level. The source distribution size of 151 m^2 will be used to calculate the aerial survey isotopic MDAs.

[b] AMS field-of-view (FOV, where the radius of the FOV is approximately the height of the aircraft)

[c] In accordance with the Rocky Flats Cleanup Agreement, the $^{239/240}$Pu concentration is determined by multiplying the measured ^{241}Am concentration (in pCi/g) by 5.7.

[d] Flight altitudes greater than 31 m (100 ft) AGL were flown in order to safely avoid obstacles, such as the three major power lines within the survey area boundaries. At altitudes higher than 46 m (150 ft) AGL, the 50 pCi/g Pu concentration is too small in comparison with the aerial survey MDA and cannot be detected by the aerial system.

ND = Not Detectable

5.4 Anomaly Verification

Radioactive decay is a random process. Consequently, any measurement based on observing the radiation emitted is subject to some degree of statistical fluctuation. These inherent fluctuations represent an unavoidable source of uncertainty in all nuclear measurements and often can be the predominant source of imprecision or error. The term “counting statistics” includes the framework of statistical analysis required to process the results of nuclear measurements and to make predictions about the expected precision of quantities derived from these measurements. In a typical nuclear measurement, such as in an aerial survey where data is collected once every second, counting statistics can be used to predict the inherent statistical uncertainty in a single measurement and to provide an estimate of the sample variance to be expected if the measurement were to be repeated many times. The square root of the sample variance would be a measure of the typical deviation (sigma [σ]) of any one measurement from the true mean value, $\bar{x}$, and thus would serve as an indication of the degree of precision for that measurement. However because only a single measurement was acquired, the sample variance (σ^2) cannot be calculated directly and must be estimated by analogy with an appropriate statistical model.

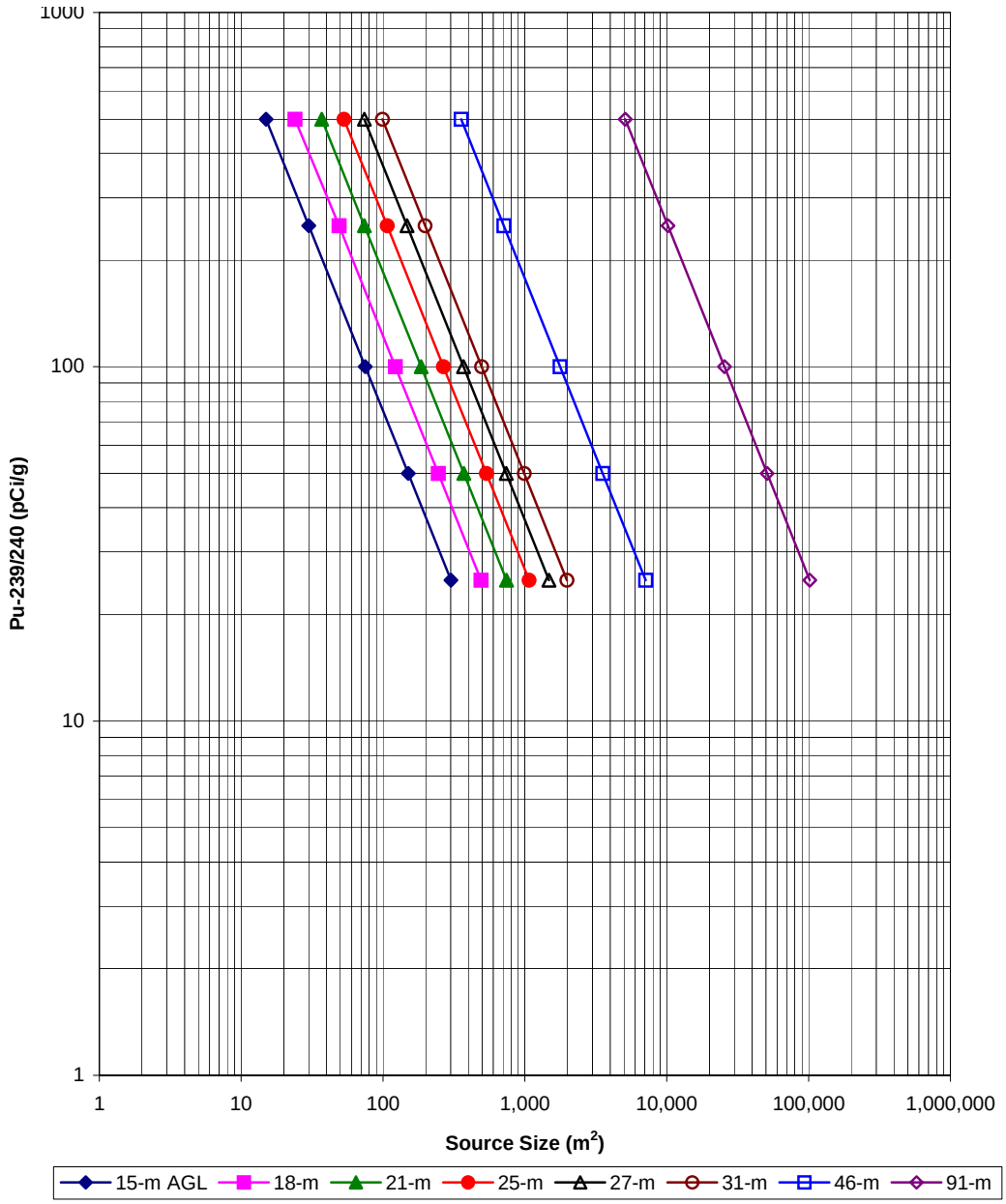


Figure 4. Inferred $^{239/240}$Pu Concentration versus Source Distribution Size as a Function of Altitude

For this aerial survey, the number of measurements is large (> 44,000 samples) and the values of adjacent measurements are not greatly different from each other. In other words, the distribution is slowly varying, and as a continuous function, can be assumed to be a Gaussian (or normal) distribution. If plotted, the distribution is roughly centered about its true mean value ($\bar{x}$), where any asymmetry of the distribution is evidence of an anomaly that would require further evaluation by means of gamma spectral examination. The size of the standard deviation (σ) gives some indication of the width of the distribution or the amount of scatter (uncertainty) predicted by the distribution. The range of values ($\bar{x} \pm \sigma$)

will contain the true mean value ($\bar{x}$) of the measurement with an 84.1% probability. However, for aerial surveys and the highly variable nature of the background gamma radiation, a variance of one standard deviation is too small to be used to accurately identify any anomalous behavior or patterns within the distribution.

For aerial and ground-based gamma radiation surveys, the “3σ” (99.87 percent probability) criteria test has proven to be, and is widely accepted for, ascertaining the location of widely distributed contamination (i.e., a non-point source). The “6σ” test is primarily used to pinpoint and confirm the location of any isolated, individual point sources. Although the “3σ” test is routinely used, there is still a small probability (0.13 percent or ~ 57 out of 44,000 events) that the reported/detected low-value (3σ to 4σ) anomaly may be only “statistical” and not representative of the radioisotope in question. Caution needs to be observed when evaluating any observed anomalies in the data. Anomalies detected over several adjacent or contiguous sampling points with values > 4σ are deemed to be genuine, whereas single point anomalies with values < 6σ may be only statistical. In such cases, these possible “false-positive” anomalies will need to undergo gamma spectral examination where a background-subtracted gamma spectrum will be made and evaluated to reveal either the radioisotope of interest, excess levels of natural background radiation, or a smoothly varying background with no discernable peaks.

6.0 RESULTS

The primary purpose of the survey was to identify any significant areas of previously unknown surface radiological contamination at the RFETS. To accomplish this task, the aerial survey measured and mapped the natural and man-made gamma radiation emanating from within the RFETS survey area, and reported any areas that exhibited elevated levels of terrestrial exposure rate, and man-made or isotopic gamma radiation activity (specifically for ^{241}Am, ^{234}Th, ^{234}U, and ^{235}U).

Radiation isopleth contour maps of the terrestrial gamma exposure rate and the activity or count-rates due to the non-naturally occurring gamma sources of radiation (i.e., the man-made gross count radioactivity, ^{241}Am, ^{234}Th, and ^{235}U soil concentrations) were generated. However, the contours representing the excess levels of ^{235}U and ^{234}Th soil concentrations revealed that no significant (non-statistical) source activity was evident within the RFETS survey area. There was also no activity detected along the special low-altitude flight conducted over the three drainage areas and alongside the three major power lines. Therefore, the maps for those contours are not presented in this report.

Due to the close proximity of the primary gamma energy photopeak for ^{234}U (53.2 keV) to that of ^{241}Am (59.5 keV), no separate ^{234}U activity contour map could be generated. Therefore, only by closely examining the net gamma energy spectrum of any suspect ^{241}Am anomaly could the presence of either or both the ^{241}Am or ^{234}U radionuclides be specifically confirmed.

The net gamma energy spectrum is the resultant spectrum when the natural component has been removed. For the spectra presented in this document, an identifying key has been added to the upper right-hand side of the figure that provides the spectrum's live-time (LT) sampling interval and its corresponding number/location identifier on the MMGC or ^{241}Am contour map. It should be noted that only the net gamma energy spectra that identify or denote anomalous radioactivity and not elevated levels of the natural background are presented in this report.

6.1 Terrestrial Exposure-Rate Contour

The terrestrial gamma exposure rates inferred from the aerial radiological data are shown in Figure 5 as a contour map superimposed on a July 2005 IKONOS Satellite Image (color-coded contours with designators). The exposure rates are expressed in units of µR/h at a height of 1 m AGL and include an estimated cosmic-ray contribution of 6.5 µR/h at 1 m AGL.

The inferred aerial exposure rates are relatively uniform and represent normal fluctuations in the natural background radiation. The exposure rates were observed to vary primarily between 11 to 19 µR/h. No appreciable differences in exposure rate were evident between

105°15'0"W 105°12'30"W 105°10'0"W

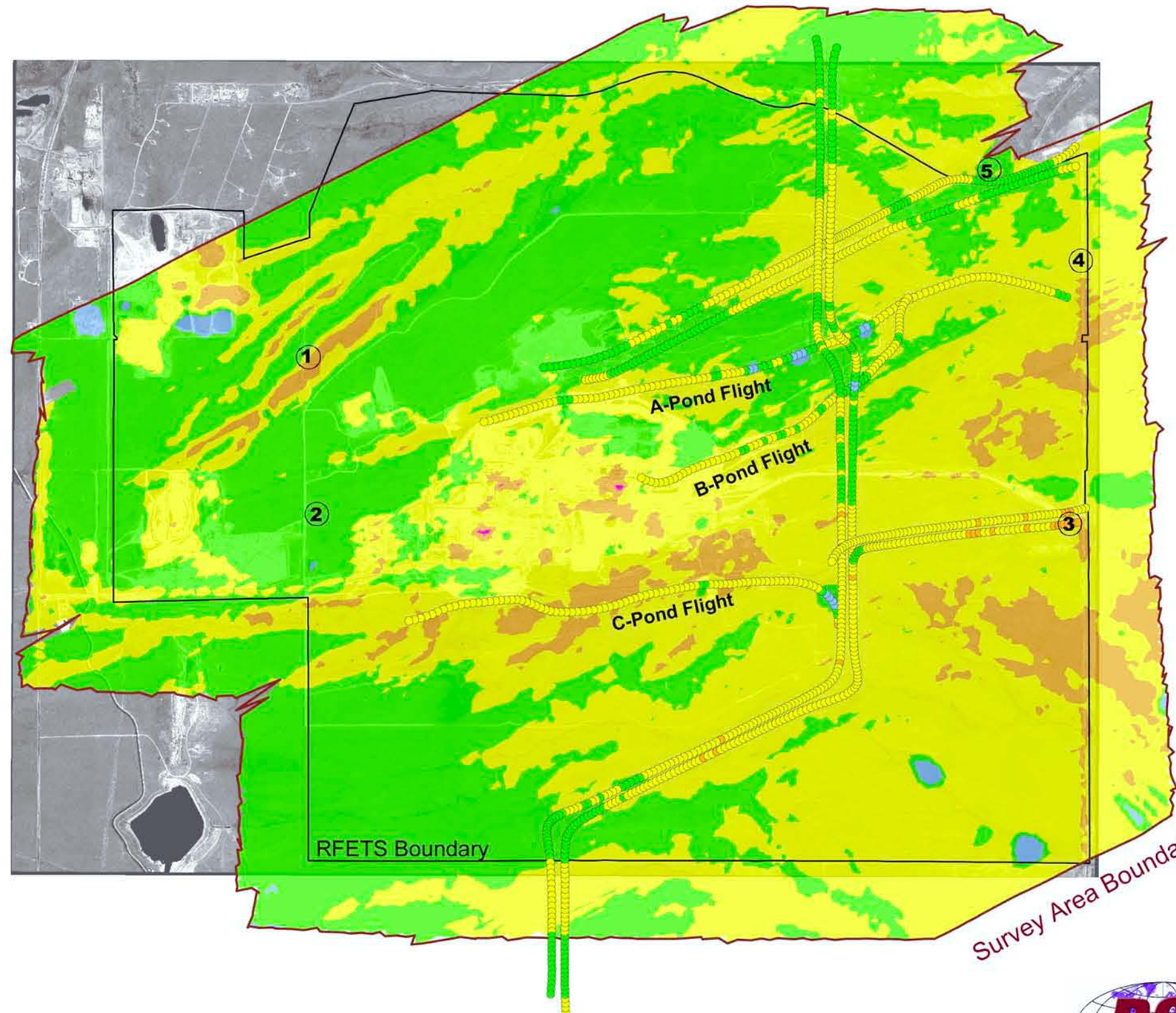
39°55'0"N

39°52'30"N

LEGEND
① PIC Measurement Locations

CONVERSION SCALE	
Color Code	Gamma Exposure Rate at 1 m AGL (μR/h)[a]
	< 11
	11 – 13
	13 – 15
	15 – 17
	17 – 19

[a] The exposure rate is inferred from the aerial gross count rate obtained at an altitude of 15 meters (50 feet) and a line spacing of 30 m (100 ft) and includes an estimated 6.5 μR/h cosmic ray contribution.



N

0 2,000 4,000 Feet

National Nuclear Security Administration

Figure 5: Terrestrial Gamma Radiation Exposure Rate Map of the RFETS Survey Area Superimposed on a July 2005 IKONOS Satellite Image.

Remote Sensing Laboratory

105°15'0"W 105°12'30"W 105°10'0"W

the Industrial Area and the Buffer Zone. Exposure rates observed in the eastern and southeastern portion of the survey area tended to be somewhat greater (2 to 4 µR/h) than those observed elsewhere. The inferred exposure rates observed on the special low-altitude flight over the Woman's Creek (C-Pond) drainage area were lower, by approximately 2 µR/h, than were indicated on the survey's overall exposure-rate contour. This difference may be attributed to the difference in the detector's field-of-view (different altitudes and detector-terrain geometries) and area-averaging effect.

The inferred RFETS exposure rates are well within the range found throughout the contiguous United States, Hawaii, and Alaska.[9] A typical gamma energy spectrum of the natural background gamma radiation within the RFETS survey area is shown in Figure 6.

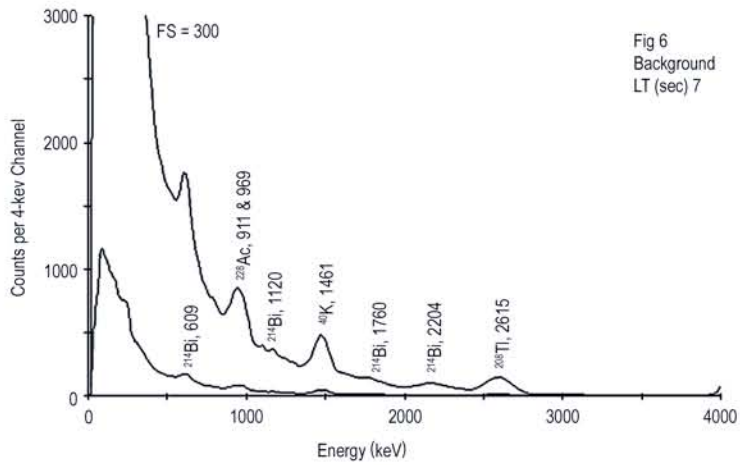


Figure 6. Typical Background Gamma Energy Spectrum of the RFETS Survey Area.

6.2 Man-Made Gross Count Results

Figure 7 shows the distribution of radiation due to the MMGC activity (color-coded contours with designators) superimposed on a July 2005 IKONOS Satellite Image of the RFETS survey area. The levels shown are in units of cps and are representative of the intensity of the detectable man-made radioactivity. The general locations where elevated levels of MMGC activity (> 3σ) were detected are listed in Table 3 with their corresponding number/location identifier on the MMGC contour map.

MMGC ID #M1 (or correspondingly ^{241}Am ID #A6), located southwest of the Industrial Area and northeast of Rocky Flats Lake, was identified and attributed by the aerial survey to the presence of only ^{241}Am and not ^{234}U. Its net gamma energy spectrum is shown in Figure 8. This location, which was flown at a flight altitude of 21 m (69 ft) AGL, had an inferred ^{241}Am activity of 2.9 pCi/g (or 16.5 pCi/g $^{239/240}$Pu) for an "infinite" distribution size source (estimated ^{241}Am MDA of 2.3 pCi/g). For this same aerial response, a 50 pCi/g

LEGEND
Numbers M1 through M8 on Figure 7 correspond to ID Numbers M1 through M8 in Table 3

CONVERSION SCALE	
Color Code	Man-Made Gross Counts (cps)[a]
	< 1,900
	1,900 – 2,500
	2,500 – 3,100

[a] Data were processed to suppress the natural background. Count rates due to gamma-ray energies between 40 and 1,400 keV are routinely used as indicators of activity due to man-made radionuclides.

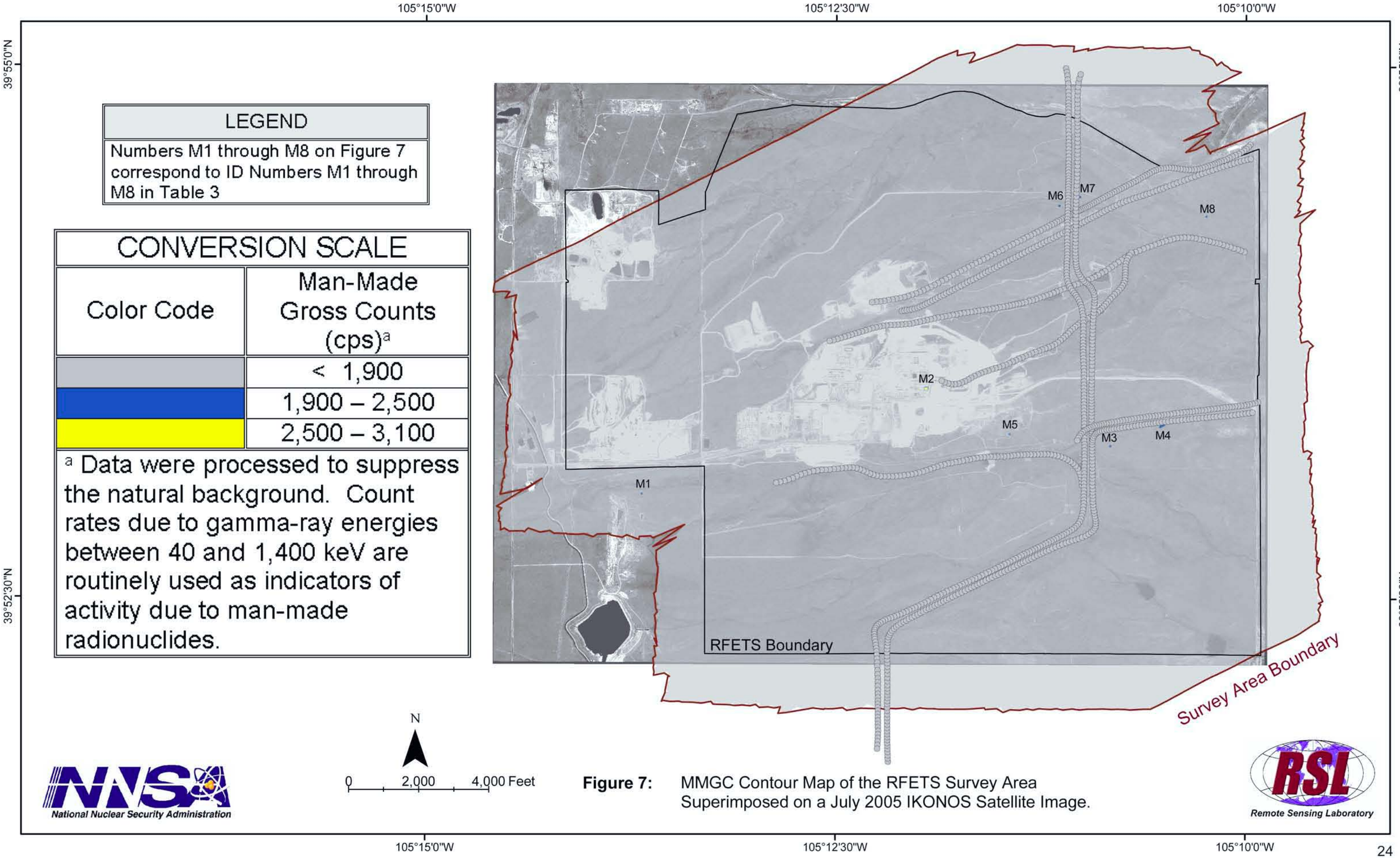


Figure 7: MMGC Contour Map of the RFETS Survey Area Superimposed on a July 2005 IKONOS Satellite Image.

Table 3. MMGC Anomalies

ID #[a]	Latitude	Longitude	Altitude (m)	^{241}Am MDA (pCi/g)[b]	Radionuclide[b,c]	Comments
M1	N 39° 52' 59.2"	W 105° 13' 41.5"	21	2.3	^{241}Am (2.9 pCi/g)	Same as ^{241}Am ID #A6
M2	N 39° 53' 28.8"	W 105° 11' 57.6"	24	2.5	No identifiable radionuclides	750 Pad Tents – 1000 radioactive waste containers
M3	N 39° 53' 13.1"	W 105° 10' 49.6"	55	6.3	Naturals	SE Buffer Zone – 0.8 km west of Indiana St.
M4	N 39° 53' 19.1"	W 105° 10' 29.9"	38	3.9	Naturals	SE Buffer Zone – 1.3 km west of Indiana St.
M5	N 39° 53' 16.4"	W 105° 11' 26.5"	19	2.1	Naturals	SE Industrial Area – 0.3 km east-southeast of the 903 Pad
M6	N 39° 54' 20.8"	W 105° 11' 08.3"	40	4.1	Naturals	NE Buffer Zone – west side of the power line
M7	N 39° 54' 23.3"	W 105° 11' 00.8"	61	7.3	Naturals	NE Buffer Zone – east side of the power line
M8	N 39° 54' 18.1"	W 105° 10' 14.0"	16	1.8	Naturals	NE Buffer Zone – 0.4 km west of Indiana St.

[a] ID # corresponds to the number/location identifiers shown in Figure 7.

[b] The inferred aerial ^{241}Am soil and/or MDA concentrations were derived for an "infinite" distribution size source at each of the cited flight altitudes.

[c] Naturals" is used to denote areas containing only elevated levels of natural background radiation (e.g., ^{40}K and the ^{238}U and ^{232}Th decay chains).

$^{239/240}$Pu source would require a minimum distribution size of 372 m^2. In August 2005, Kaiser-Hill, LLC, performed subsequent ground-based scanning of this area using an *in situ* high-purity germanium (HPGe) detector with a 10 m diameter field-of-view (78 m^2).[10] MDAs of the HPGe scans ranged from 0.95 to 1.10 pCi/g ^{241}Am. The HPGe scan results (scanning covered the entire aerial FOV area) indicated zero detectable ^{241}Am activity. Therefore, the results of the Kaiser-Hill, LLC, investigation did not confirm the aerial result and therefore, the aerial result was classified as a "false positive" anomaly with no further investigations or actions required.

MMGC ID #M2, located within the Industrial Area in the vicinity of the 750 Pad tents, specifically the eastern half of Tent Number 12, was a known radioactive waste storage area. MMGC ID #M2 corresponds to the location of more than 1,000 radioactive waste containers that existed within the 750 Pad tents on the date of the flyover

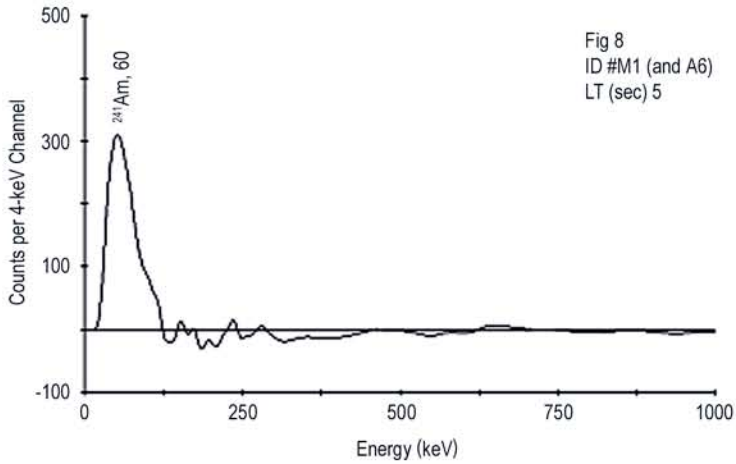


Figure 8. Background-subtracted Gamma Energy Spectra for MMGC ID #M1 on Figure 7 (also ^{241}Am ID #A6 on Fig.10)

(June 12, 2005).[10] The net gamma energy spectrum of this aerial result is shown in Figure 9. The spectrum does not have any identifiable photopeaks but rather a continuum. This is often a result of shielded radionuclides or high count-rates. Those spectra having low count-rates and no identifiable photopeaks are good examples of shielded sources, which is the case for MMGC ID #M2. Spectra with high count-rates and no identifiable photopeaks are good examples of spectral distortion. It should be noted that none of the spectra examined from this survey exhibited high count-rates.

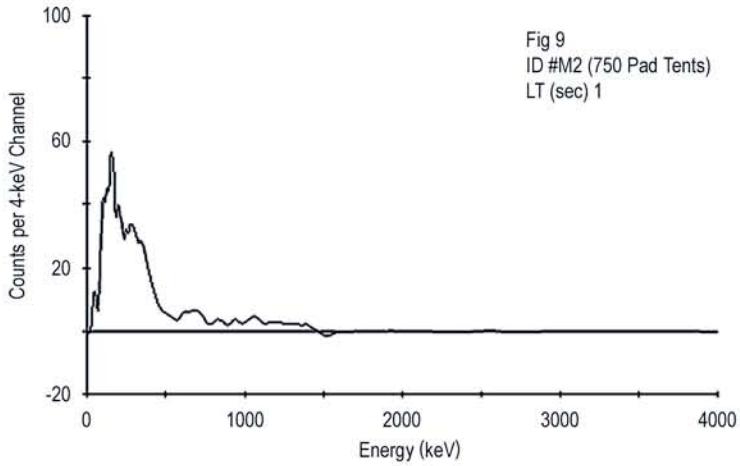


Figure 9. Background-subtracted Gamma Energy Spectra for MMGC ID #M2 on Figure 7 (No identifiable photopeaks)

Upon examination of their net gamma energy spectra, the remaining six MMGC anomalies (ID #s M3 to M8) were determined to be “false positives” attributable to elevated levels of the natural background radiation. It should also be noted that no man-made radioactivity anomalies were detectable by the aerial survey on the special low-altitude flight that was conducted over the three drainage areas and alongside the three major power lines.

Furthermore, it should be noted that the special low-altitude flight along the major power line parallel with the former East Access Road did not confirm the presence of the MMGC ID #M4 anomaly. Thus, that first pass measurement result was verified as being only statistical.

It should be mentioned that a majority of the natural background gamma radiation of the RFETS survey area contains the presence of cesium-137 (^{137}Cs), which was not of primary interest to this survey but appears to be uniformly distributed over the entire RFETS survey area except for those areas where the soil had been disturbed by construction, demolition, and/or current cleanup operations. The observed ^{137}Cs soil activity levels within the RFETS are consistent with known worldwide fallout levels that have been measured throughout the United States[11] and there is no indication that any of the ^{137}Cs deposition detected is due to past RFETS operations. However, due to this uniform residual ^{137}Cs background radiation, the effectiveness of the MMGC algorithm was diminished.

6.3 Americium-241 Results

The presence of plutonium contamination was investigated by measuring the ^{241}Am net count-rate. Figure 10 shows the inferred ^{241}Am soil concentration (color-coded contours with designators) superimposed on a July 2005 IKONOS Satellite Image of the RFETS survey area. The levels shown are in units of pCi/g. The ^{241}Am net count-rate data was converted from cps to pCi/g for a nominal flight altitude of 15 m (50 ft) AGL for two different distribution size sources (“infinite” and 151 m^2) utilizing the conversion factors cited in Appendix C, which were derived as described in Section 5.2. The 151 m^2 distribution size source concentration estimates were presented because they represent what the predicted aerial response would be if the aerial system had detected a 151 m^2 50 pCi/g $^{239/240}$Pu size source at a flight altitude of 15 m (50 ft) AGL. The inferred $^{239/240}$Pu soil concentration (in pCi/g) was determined by multiplying the ^{241}Am concentration (in pCi/g) by 5.7.

The ^{241}Am algorithm, Equation 5 using the source and background energy windows cited in Appendix C, was used to search the aerial data for enhanced activity levels of ^{241}Am. The resulting ^{241}Am isoradiation contour map, Figure 10, denoted 15 suspect locations, that had passed the 3σ criteria test (anticipated 57 out of 44,000 events would be statistically not real [Section 5.4]). The general location of these 15 anomalies are listed in Table 4 with their corresponding number/location identifier shown on the ^{241}Am contour map. The ^{241}Am concentrations and MDAs cited in Table 4 were derived for an “infinite” distribution size source for the actual flight altitudes flown (Table 4, Column 4) and not the nominal 15 m (50 ft) AGL flight altitude.

105°17'30"W 105°15'0"W 105°12'30"W 105°10'0"W

39°55'0"N

39°52'30"N

LEGEND
Numbers A1 through A15 on Figure 10 correspond to ID Numbers A1 through A15 in Table 4

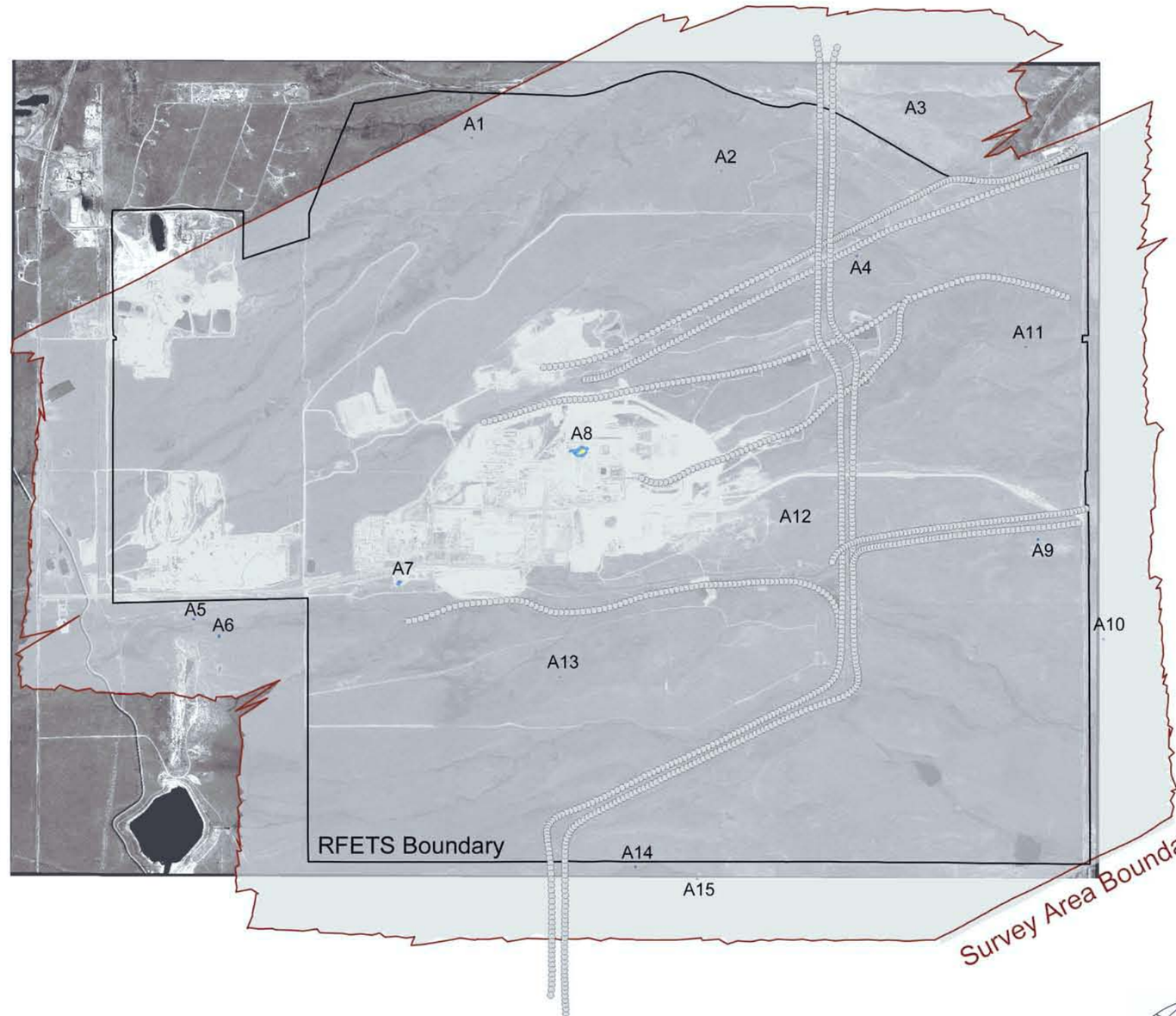
CONVERSION SCALE				
Color Code	^{241}Am Soil Concentration [a]		$^{239/240}$Pu Soil Concentration [d]	
	729 m^2 (pCi/g)[b]	151 m^2 (pCi/g)[c]	729 m^2 (pCi/g)[b]	151 m^2 (pCi/g)[c]
	< 1.8	< 8.7	< 10.3	< 50
	1.8 – 3.6	8.7 – 17.4	10.3 – 20.7	50 – 99
	3.6 – 5.4	17.4 – 26.1	20.7 – 30.8	99 – 149
	5.4 – 7.3	26.1 – 35.2	30.8 – 41.3	149 – 201

[a] Soil concentrations for ^{241}Am inferred from net 60-keV photopeak count rates observed at an altitude of 15 m (50 ft) AGL and a line spacing of 30 m (100 ft). Concentration conversion factors presume an inverse relaxation depth of 0.33 cm^{-1} and a soil distribution depth of 2.5 cm.

[b] Concentrations applicable only as averages over large areas comparable to the detector's full field-of-view which at an altitude of 15 m AGL is 729 m^2.

[c] Concentrations applicable if the contaminated surface activity size within the detector's field-of-view is 151 m^2.

[d] Soil concentrations for $^{239/240}$Pu are derived and computed from the ^{241}Am inferred soil concentrations using the reported $^{239/240}$Pu to ^{241}Am ratio of 5.7.



N

0 2,000 4,000 Feet

National Nuclear Security Administration

Figure 10: Americium-241 Soil Concentration Contour Map of the RFETS Survey Area Superimposed on a July 2005 IKONOS Satellite Image.

Remote Sensing Laboratory

105°17'30"W 105°15'0"W 105°12'30"W 105°10'0"W

Table 4. ^{241}Am Anomalies

ID #[a]	Latitude	Longitude	Altitude (m)	^{241}Am MDA (pCi/g)[b]	Radionuclide[b,c]	Comments
A1	N 39° 54' 39.6"	W 105° 12' 35.6"	11	1.5	Naturals	280 m south of CO-28 highway
A2	N 39° 54' 33.2"	W 105° 11' 30.6"	18	2.0	Naturals	520 m south of CO-28 highway
A3	N 39° 54' 43.2"	W 105° 10'40.5"	20	2.1	Naturals	Outside northeastern RFETS boundary
A4	N 39° 54' 15.9"	W 105° 10' 56.0"	33	3.3	Naturals	NE Buffer Zone – south side of power line
A5	N 39° 53' 03.2"	W 105° 13' 47.2"	24	2.5	Naturals	SW Buffer Zone – 61 m south of West Access Rd
A6	N 39° 52' 59.2"	W 105° 13' 41.5"	21	2.3	^{241}Am (2.9 pCi/g)	SW Buffer Zone – 191 m south of West Access Rd
A7	N 39° 53' 10.6"	W 105° 12' 53.7"	15	1.8	^{241}Am (2.8 pCi/g)	Industrial Area – 500 DiRT bags staged south of railroad tracks
A8	N 39° 53' 36.6"	W 105° 12' 07.1"	18	2.1	^{241}Am (4.0 pCi/g)	Industrial Area – UBC open excavation of the B776
A9	N 39° 53' 19.2"	W 105° 10' 07.9"	19	2.1	Naturals	SE Buffer Zone – 213 m south of East Access Rd
A10	N 39° 52' 59.4"	W 105° 09' 50.5"	18	2.0	Naturals	Outside eastern RFETS boundary
A11	N 39° 53' 57.9"	W 105° 10' 11.2"	28	2.7	Naturals	NE Buffer Zone – 350 m east of Indiana St.
A12	N 39° 53' 21.2"	W 105° 11' 11.3"	36	3.6	Naturals	SE Industrial Area – 0.6 km east of the 903 Pad
A13	N 39° 52' 51.5"	W 105° 12' 12.5"	19	2.1	Naturals	South of Industrial Area – 0.7 km south of 881 complex
A14	N 39° 52' 13.6"	W 105° 11' 52.2"	37	3.7	Naturals	Outside southern RFETS boundary
A15	N 39° 52' 11.2"	W 105° 11' 36.3"	30	2.9	Naturals	Outside southern RFETS boundary

[a] ID # corresponds to the number/location identifiers shown in Figure 10.

[b] The inferred aerial ^{241}Am soil and/or MDA concentrations were derived for an "infinite" distribution size source at each of the cited flight altitudes.

[c] Naturals" is used to denote areas containing only elevated levels of natural background radiation (e.g., ^{40}K and the ^{238}U and ^{232}Th decay chains).

Twelve of the 15 anomalies (with activities less than 4σ) were determined to be "false positives" attributable to elevated levels of natural background radiation. However, the other three anomalies (ID #s A6, A7 and A8) had better statistics and were examined spectrally for the presence of ^{241}Am and/or ^{234}U.

As stated in Section 6.2, ^{241}Am ID #A6 (or correspondingly MMGC ID #M1), was located southwest of the Industrial Area and northeast of Rocky Flats Lake. The aerial survey had identified and attributed this anomaly to the presence of ^{241}Am, Figure 8. However, subsequent follow-up ground-based HPGe scans performed by Kaiser-Hill, LLC, indicated zero detectable ^{241}Am activity. Hence, the aerial result was listed as a "false-positive" with no further investigations or actions required.

^{241}Am ID #A7, located on the southwest side of the Industrial Area, corresponds to the known location of more than 500 DiRT bags staged just south of the railroad tracks. These DiRT bags contained low-level radioactive soils from the B-series ponds accelerated action.[10] The net gamma energy spectra of this aerial result is shown in Figure 11 and shows the presence of ^{241}Am and not ^{234}U. This location, which was flown at a flight altitude of 15 m (50 ft) AGL, had an inferred ^{241}Am activity of 2.8 pCi/g (or 16.0 pCi/g $^{239/240}$Pu) for an "infinite" distribution size source (estimated ^{241}Am MDA of 1.8 pCi/g). For this same aerial response, a 50 pCi/g $^{239/240}$Pu source would require a minimum distribution size of 151 m^2.

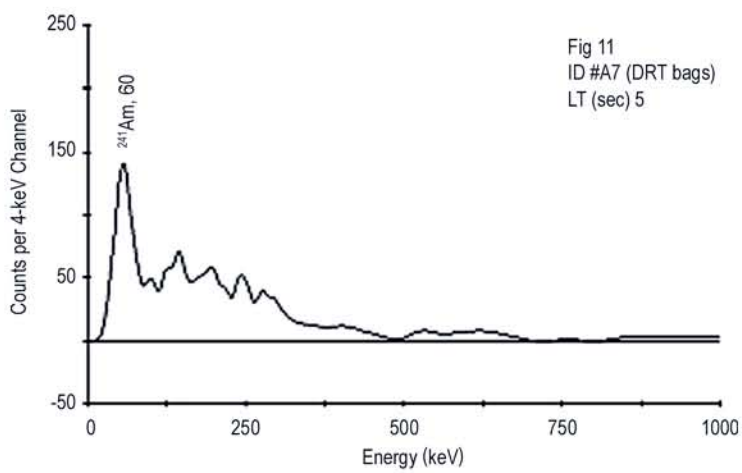


Figure 11. Background-subtracted Gamma Energy Spectra for ^{241}Am ID #A7 on Figure 10

^{241}Am ID # A8, located near the center of the Industrial Area, corresponds to the location of the open excavation associated with the remediation of the B776 UBC.[10] The net gamma energy spectra of this aerial result is shown in Figure 12 and shows the presence of ^{241}Am and not ^{234}U. This location, which was flown at a flight altitude of 18 m (60 ft) AGL, had an inferred ^{241}Am activity of 4.0 pCi/g (or 12.0 pCi/g $^{239/240}$Pu) for an "infinite" distribution size

source (estimated ^{241}Am MDA of 2.1 pCi/g). For this same aerial response, a 50 pCi/g $^{239/240}$Pu source would require a minimum distribution size of 245 m^2.

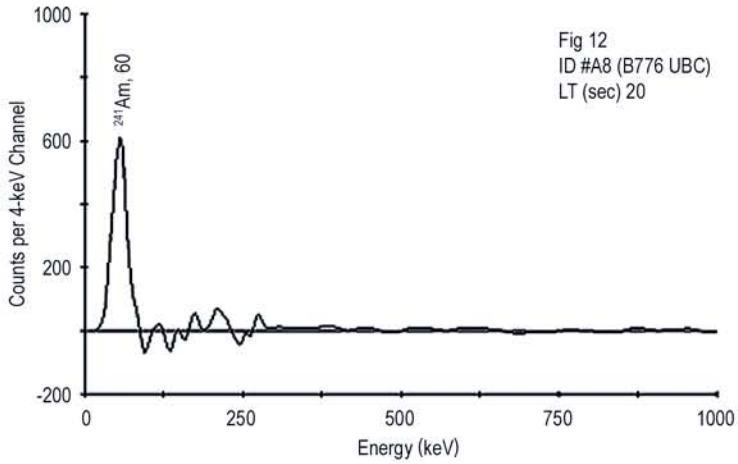


Figure 12. Background-subtracted Gamma Energy Spectra for ^{241}Am ID #A8 on Figure 10

It should be noted that two of these three locations of elevated ^{241}Am activity (ID #s A7 and A8) were known radioactive waste storage or remediation areas that existed at the time of the flyover. The only exception was the third location (^{241}Am ID # A6 / MMGC ID # M1), which required further investigation.

It should be further noted that these same two elevated ^{241}Am activity areas (ID #s A7 and A8) had not appeared in the MMGC results (Figure 7). The ^{241}Am activity at those two locations was insufficient to be detected using the MMGC extraction technique but did appear using the three-window extraction technique described in Section 5.1.3 and Appendix C.

No ^{241}Am (and/or ^{234}U) anomalies were detectable on the special low-altitude flight conducted over the three drainage areas and alongside of the three major power lines.

6.4 Uranium-235 and Thorium-234 Results

The ^{235}U algorithm (Equation 5 with the source and background energy windows cited in Appendix C) was used to search the aerial data for locations of ^{235}U activity in excess of the expected natural isotopic ratios. The resulting ^{235}U isoradiation contour map, which is not presented, denoted 20 single-point suspect locations that had passed the 3σ criteria test (anticipated 57 out of 44,000 events would be statistically not real [refer to Section 5.4]) but less than 4σ and were determined to be “false positives” and attributable to elevated levels of the natural background radiation.

The ^{234}Th (^{238}U) algorithm (Equation 5 with the source and background energy windows cited in Appendix C) was used to search the aerial data for locations of ^{234}Th (^{238}U) activity in excess of the expected natural isotopic ratios. The resulting ^{234}Th isoradiation contour map, which is not presented, denoted 31 single-point suspect locations that had passed the 3σ criteria test (anticipated 57 out of 44,000 events would be statistically not real [refer to Section 5.4]) but less than 4σ were determined to be "false positives" and attributable to elevated levels of the natural background radiation.

It should also be noted that no excess levels of ^{235}U or ^{234}Th (^{238}U) were detectable on the special low-altitude flight conducted over the three drainage areas and alongside of the three major power lines.

6.5 Ground-Based Exposure Rate Results

A comparison of the ground-based exposure rate measurements with the inferred aerial exposure-rate results is presented in Table 5. The ground-based measurement location (i.e., PIC location) reference numbers cited in this document correspond with the encircled-numerals shown in Figure 5. As shown, three of the five measurement locations (①, ②, and ③) reside within the boundaries of the RFETS, and the other two reside outside but near the eastern (④) and northeastern (⑤) site boundaries, respectively. The ground-based exposure rate results ranged from 12.7 to 15.7 µR/h with a mean value of 14.0 $\pm$ 1.4 µR/h.

A comparison (not shown) of the gross count-rates from the aerial system versus the ground-based exposure-rate results was made to determine if the data sets were consistent and could then be used to validate the inferred aerial terrestrial gamma exposure-rate data. The data set was found to have an averaged terrestrial exposure-rate conversion factor of 1833 cps per µR/h with an inherent "cosmic + aircraft + radon" contribution of 6.9 µR/h. The derived conversion factor of 1833 cps per µR/h agreed to within 12.5 percent of the conversion factor of 2095 cps per µR/h, which had been derived from comparison measurements made over the RSL-Nellis Lake Mohave Calibration Test Line near Las Vegas, Nevada. Additionally, the inferred aerial exposure rates reported in Table 5 were derived using the conversion factor of 1833 cps/µR/h.

The inferred aerial exposure-rate results (including an estimated cosmic contribution of 6.5 µR/h for a nominal elevation of 1860 m [~ 6100 ft] MSL) ranged from 12.0 to 15.0 µR/h with a mean value of 13.6 $\pm$ 1.3 µR/h. Overall, the inferred aerial exposure-rate results agreed well and were found to be within 2 to 6 percent (average of 3 percent) of the ground-based exposure-rate results.

Table 5. Exposure-Rate Comparison Results

PIC Location[a]	GPS Coordinates (degree-minutes-seconds)		Exposure Rates in µR/h (± 1 Standard Deviation)b	
	Latitude	Longitude	PIC[c]	Aerial [d]
1	N 39° 53’ 55.5”	W 105° 13’ 18.0”	15.7 ± 0.6	15.0 ± 0.1
2	N 39° 53’ 24.0”	W 105° 13’ 15.8”	12.7 ± 0.6	12.0 ± 1.6
3	N 39° 53’ 22.3”	W 105° 09’ 59.5”	15.4 ± 0.8	14.7 ± 0.3
4	N 39° 54’ 15.2”	W 105° 09’ 56.8”	13.3 ± 0.6	13.5 ± 0.2
5	N 39° 54’ 33.5”	W 105° 10’ 20.7”	13.0 ± 0.6	12.7 ± 0.2
Mean Value			**14.0**	**13.6**
Standard Deviation			**1.4**	**1.3**

[a] The PIC Measurement Location designators correspond to those encircled identifier numbers shown on Figure 5.

[b] Reported error represents a one sigma statistical counting error.

[c] At each of the five PIC locations, three exposure rate readings were acquired. Each reading was collected by a Reuter-Stokes PIC (Model RSS-112) using a counting interval of 300 seconds and at a detector height of one meter. The exposure-rate reading reported in Table 5 represents the averaged result of the three readings collected at each PIC location, which includes contributions from the cosmic rays but not airborne radon.

[d] Includes an estimated cosmic-ray contribution of 6.5 µR/h at an elevation ranging between 1740 to 1870 m (5700 to 6130 ft) MSL.

No significant disagreements between individual measurements and the inferred aerial survey exposure rates were noted. It should be noted that the inferred aerial exposure-rate results included an estimate for the cosmic contribution (which was variable due to the differences in the terrain elevation) but not a radon contribution, both of which were measured directly by the PIC. The nominal radon contribution to the ground-based PIC results was mathematically determined to be 0.4 µR/h, which had not been subtracted from the comparison results.

7.0 CONCLUSION

An aerial radiological survey of the Rocky Flats Environmental Technology Site and surrounding area was conducted from June 12 to 15, 2005. The aerial survey was flown at a nominal altitude of 15 m (50 ft) AGL. Terrestrial exposure rates over the majority of the survey area were due to the natural background gamma radiation and ranged from 11 to 19 µR/h (including a 6.5 µR/h cosmic contribution), which is well within the range found throughout the contiguous United States, Hawaii, and Alaska.

Four locations were identified as containing the presence of elevated levels of radioactivity. Three of those locations were all known radioactive waste storage or remediation areas that existed at the time of the survey flyover and were not unexpected anomalies and/or contaminated surface soil areas. The first (MMGC ID # M2) corresponded with the location of more than 1,000 radioactive waste containers being stored within the 750 Pad tents. The second (^{241}Am ID # A7) corresponded with the location of more than 500 DiRT bags staged just south of the railroad tracks. These DiRT bags contained low-level radioactive soils from the B-series ponds accelerated action. The third (^{241}Am ID # A8) corresponded with the open excavation associated with the remediation of the B776 UBC.

The only exception was the fourth location (MMGC ID # M1/^{241}Am ID # A6), which required further investigation. The aerial survey had identified and attributed this fourth location to the presence of ^{241}Am. The presence of ^{241}Am is a remnant of past plutonium operations conducted at the RFETS and current cleanup operations. However, subsequent follow-up ground-based HPGe scans (scanning covered the entire aerial detection system field-of-view area) performed by Kaiser-Hill, LLC, indicated zero detectable ^{241}Am activity at this location. Hence, the aerial result was listed as a “false-positive” with no further investigations or actions required.

It should be noted that no excess levels of ^{234}Th, ^{234}U or ^{235}U had been detected. Neither had any other significant (non-statistical) man-made radiation activity been detected within the remainder of the survey area. The same can be said for the area along the special low-altitude flight conducted over the three drainage areas and alongside the three major power lines.

In summary, no significant areas of previously unknown surface radiological contamination had been found within the RFETS survey area, with the exception of MMGC ID # M1, which was later investigated.

A comparison of the inferred aerial exposure-rate results, with a series of ground-based exposure-rate measurements, were also made. The inferred aerial exposure-rate results were found to be within 2 to 6 percent of the ground-based exposure-rate results.

8.0 REFERENCES

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APPENDIX A
AERIAL SURVEY PARAMETERS

Survey Site	Rocky Flats Environmental Technology Site
Survey Location	Jefferson County, Colorado
Survey Dates	June 12 to 14, 2005
Survey Altitude	nominal 15 m (50 ft) above ground level
Average Ground Speed	31 m/s (60 knots)
Line Spacing	30 m (100 ft)
Number of Survey Lines	195
Navigation System	Trimble DGPS System
Line Direction	Southwest-northeast (nominally parallel with the rugged [highly variable] mountainous terrain features)
NaI(T*l*) Detector Configuration	Twelve 5.1-x10.2-x40.6-cm (2- x 4- x 16-in) logs
Acquisition System	REDAR V
Aircraft	Bell-412 Helicopter Tail Number: N411DE
Mission Scientist	D.P. Colton

APPENDIX B
IN SITU SURVEY PARAMETERS

Survey Site	Rocky Flats Environmental Technology Site
Survey Location	Jefferson County, Colorado
Survey Date	June 15, 2005
Detector Height	1 m (3.3 ft)
Positioning System	Garmin Personal Navigator, Model GPS-45
Pressurized Ionization Chamber (PIC)	Reuter-Stokes Model No. RSS-112
Sampling Time	300 seconds per PIC measurement

APPENDIX C
DATA ANALYSIS PARAMETERS

The conversion factors used for converting the measured aerial gamma count-rate data into activity concentrations are based on calculations that assume the radioactivity is uniformly dispersed over an area on the ground that is “large” compared to the field-of-view (FOV) of the detector array. Furthermore, the accuracy of the derived conversion factors is also dependent on a specific knowledge of the radioactivity distribution within the soil, specifically the soil depth (assumed to be homogenous to a depth of 2.5 cm), and to a lesser extent knowledge of the soil density (assumed to be 1.5 picocuries per gram), soil moisture content (assumed to be 10 percent) and chemical composition (i.e., a wide range of the naturally occurring radionuclides, such as radioactive potassium and the thorium and uranium decay products). All of these variables are unknown and may vary considerably from the norm (site to site and within each site) due to differences in the terrain (pastures, excavations, rocky culverts, woodlands, facilities, etc.). The calculations also assumed that all daughters are in radioactive equilibrium with their parents, which is not true for the radon daughters.

Since the inferred soil concentration measured by the aircraft is an average over the nominal surface footprint of the detector system, the observed aerial values are a function of both the surface soil concentration and the size of the surface area. For source surface areas that are not “infinite”, significant correction factors must be applied or a larger minimum detectable activity (MDA) threshold value assumed. A plot of the RFETS ^{241}Am and $^{239/240}$Pu MDA soil concentration as a function of altitude for an “infinite” source surface area is presented in Figure C-1.

For estimation purposes, the detector footprint radius is approximately the same as the detector distance (i.e., height) above the source. For this survey, the ^{241}Am net count-rate data was converted from “counts per second” (cps) to picocuries per gram (pCi/g) for a nominal flight altitude of 15 m (50 ft) AGL for two different distribution size sources: “infinite” (which has a detector FOV of ~ 729 m^2) and 151 m^2. The 151 m^2 distribution size source concentration estimates are presented because they represent what the predicted aerial response would be if the aerial system had detected a 151 m^2 50 pCi/g $^{239/240}$Pu size source at a flight altitude of 15 m (50 ft) AGL.

The inferred $^{239/240}$Pu soil concentration (in pCi/g) was determined by multiplying the ^{241}Am concentration (in pCi/g) by 5.7.

Terrestrial Exposure Rate (Gross Count)

Source Energy Window	38 – 3026 keV
Conversion Factor	1833 cps/(µR/h)
Cosmic Ray Contribution	6.5 µR/h
Air Attenuation Coefficient	0.0049 m^{-1} (0.0015 ft^{-1})

Man-Made Gross Count Rate (MMGC)

Source Energy Window	38 – 1394 keV
Background Energy Window	1394 – 3026 keV

Americium-241 Count Rate (^{241}Am)

Major Radiation Energy (Abundance)	59.5 keV (35.9%)
Source Energy Window	50 – 70 keV
Background Energy Window	38 – 50 and 70 – 82 keV
Exponential Distribution (α)	0.333 cm^{-1}
Soil Sample Depth (z)	2.5 cm
Soil Concentration Conversion Factor	1.51E-02 (pCi/g)/cps) for 729 m^2 7.29E-02 (pCi/g)/cps for 151 m^2
Minimum Detectable Activity @15m AGL	1.8 pCi/g for 729 m^2 8.7 pCi/g for 151 m^2

Thorium-234 Count Rate (^{234}Th)

Major Radiation Energy (Abundance)	92.3 and 92.8 keV (54.1%)
Source Energy Window	82 – 102 keV
Background Energy Window	70 – 82 and 102 – 114 keV
Exponential Distribution (α)	0.333 cm^{-1}
Soil Sample Depth (z)	2.5 cm
Soil Concentration Conversion Factor	8.23E-02 (pCi/g)/cps for 729 m^2 3.97E-01 (pCi/g)/cps for 151 m^2
Minimum Detectable Activity @15 m AGL	11.2 pCi/g for 729 m^2 54.1 pCi/g for 151 m^2

Uranium-234 Count Rate (^{234}U)

Major Radiation Energy (Abundance)	53.2 keV (0.1%)
Source Energy Window	Lies within ^{241}Am Energy Window

Uranium-235 Count Rate (^{235}U)

Major Radiation Energy (Abundance)	185.7 keV (54.0%)
Source Energy Window	150 – 210 keV
Background Energy Window	122 – 150 and 210 – 258 keV
Exponential Distribution (α)	0.333 cm^{-1}
Soil Sample Depth (z)	2.5 cm
Soil Concentration Conversion Factor	6.49E-03 (pCi/g)/cps for 729 m^2 3.13E-02 (pCi/g)/cps for 151 m^2
Minimum Detectable Activity @15 m AGL	1.4 pCi/g for 729 m^2 6.8 pCi/g for 151 m^2

CONVERSION SCALE			
Color Code	Nominal Altitude (m)	Soil Concentration (pCi/g) [a,b,c]	
		^{241}Am	$^{239/240}$Pu
	≤ 15	< 1.8	< 10.3
	15 – 21	1.8 – 2.3	10.3 – 13.0
	21 – 27	2.3 – 2.8	13.0 – 15.7
	27 – 34	2.8 – 3.3	15.7 – 19.0
	34 – 46	3.3 – 4.7	19.0 – 27.0
	46 – 61	4.7 – 7.4	27.0 – 41.9
	61 – 76	7.4 – 12.2	41.9 – 69.4
	76 – 91	12.2 – 17.0	69.4 – 97.0
	91 – 107	17.0 – 33.6	97.0 – 191.7
	107 – 122	33.6 – 50.2	191.7 – 286.3
	122 – 137	50.2 – 66.9	286.3 – 381.0

[a] Soil concentrations for ^{241}Am inferred from net 60-keV photopeak count rates observed at the nominal indicated mean altitude AGL and a line spacing of 30 m (100 ft). Concentration conversion factors presume an inverse relaxation depth of 0.33 cm^{-1} and a soil distribution depth of 2.5 cm.

[b] Concentrations applicable only as averages over large areas comparable to the detector's full field-of-view whose radius is approximately the height of the aircraft.

[c] Soil concentrations for $^{239/240}$Pu are derived and computed from the ^{241}Am inferred soil concentrations using a $^{239/240}$Pu to ^{241}Am ratio of 5.7.

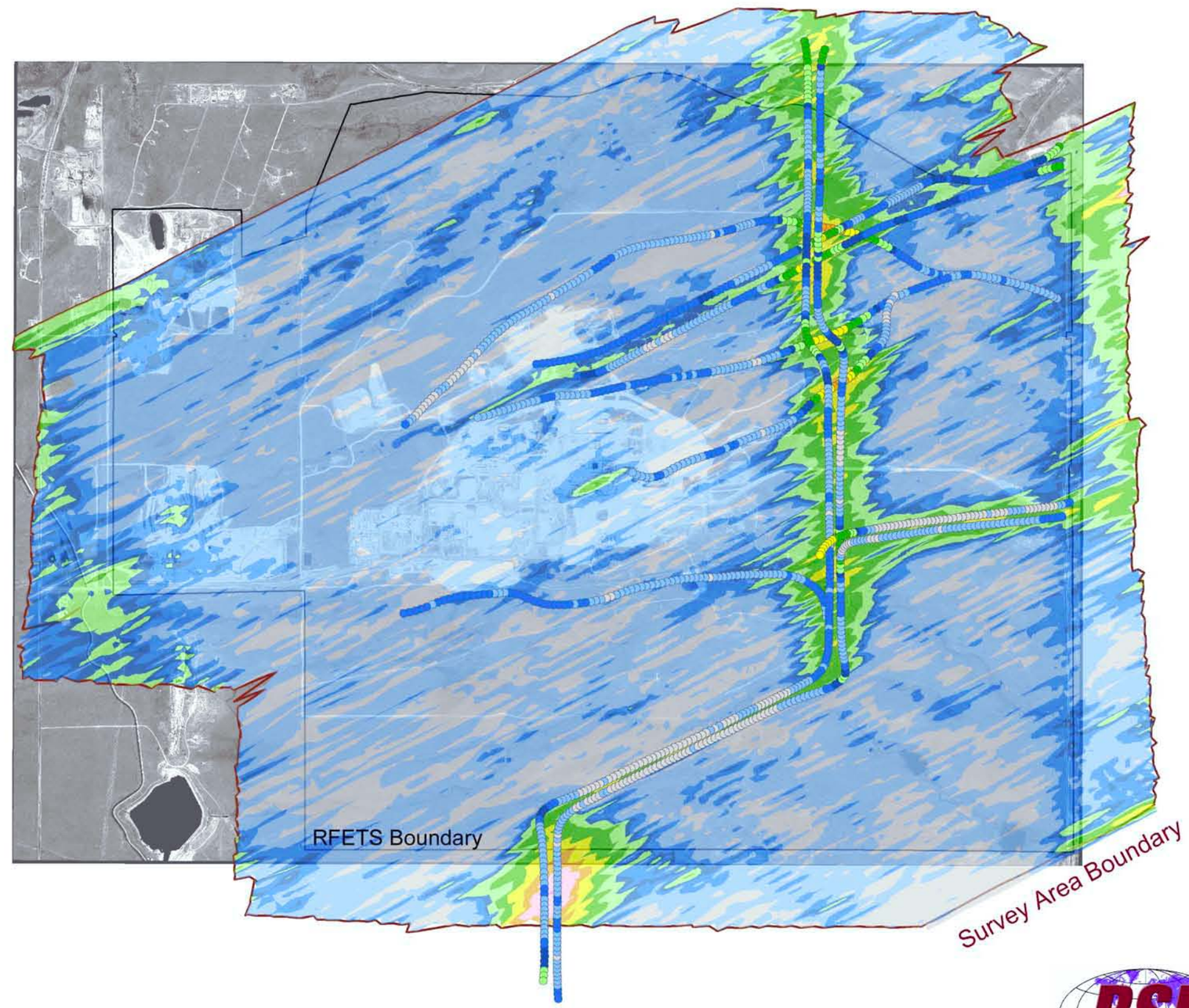

Figure C-1: Inferred ^{241}Am and $^{239/240}$Pu Minimum Detectable Soil Concentration Contour Map for an Infinite Size Source Superimposed on a July 2005 IKONOS Satellite Image (based on the actual survey flight altitudes).

National Nuclear Security Administration

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AN AERIAL RADIOLOGICAL SURVEY OF THE
AREA SURROUNDING AND ENCOMPASSING THE
ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

JEFFERSON COUNTY, COLORADO

DOE/NV/11718--1153

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