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National Nuclear Security Administration

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August 2001

An Aerial Radiological Survey of Abandoned Uranium Mines in the Navajo Nation

Overview of Acquisition and Processing Methods
Used for Aerial Measurements of Radiation Data
for the U.S. Environmental Protection Agency
by the U.S. Department of Energy
under IAG DW 8955235-01-5
October 1994 - October 1999

Survey conducted in
Arizona, New Mexico, Utah

Thane J. Hendricks
Bechtel Nevada
Las Vegas, Nevada

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Thane J. Hendricks
Project Scientist

Reviewed by

F. Larry Zajac
F. Larry Zajac, Engineer
Consequence Management Work for Others Project

Steven Riedhauser
for Clifton M. Bluitt, Manager
Radiation Science Section

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David P. Colton
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Abstract

Aerial radiological surveys of forty-one geographical areas in the Navajo Nation were conducted during the period of October 1994 through October 1999. The surveys were conducted at the request of the U.S. Environmental Protection Agency (EPA) Region 9 and were performed by personnel of the Remote Sensing Laboratory (RSL) located in Las Vegas, Nevada, a facility of the U.S. Department of Energy, National Nuclear Security Administration Nevada Operations Office.

The aerial survey and subsequent processing characterized the overall radioactivity levels and excess bismuth 214 activity (indicator of uranium ore deposits and/or uranium mines) within the surveyed areas. A total of 772,000 aerial gamma spectra and associated position parameters were obtained and analyzed during the multi-year operation. The survey determined that only 15 square miles (39 square kilometers) of the 1,144 square miles (2,963 square kilometers) surveyed (approximately 1.3 %) had excess bismuth indications above the minimum reportable activity, thus reducing the area requiring further investigation by a nominal factor of 76.

Radiation contour data files, produced by RSL, were converted to Geographic Information System-compatible digital files and provided to EPA and EPA contractors for inclusion in numerous reports and graphics products.

Acronyms and Abbreviations

cps	counts per second
ENR	enhanced natural radiation
FWHM	full width at half maximum
GIS	geographical information system
MMR	man-made radiation
MRA	minimum reportable activity
Na(Tl)	thallium-activated sodium iodide
NOR	naturally occurring radiation
RDGPS	real-time global positioning system
REDAC	Radiation and Environmental Data Analysis Computer
REDAR	Radiation and Environmental Data Acquisition and Recorder System
RSL	Remote Sensing Laboratory
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Contents

1.0 Introduction

This report documents work conducted in the Navajo Nation for the U.S. Environmental Protection Agency (EPA) by Remote Sensing Laboratory (RSL), a facility of the U.S. Department of Energy, National Nuclear Security Administration Nevada Operations Office.

Since 1958, Aerial Measuring System capabilities have been used to document radiological conditions at hundreds of locations both within and outside the continental United States. These study areas include power plants, manufacturing and processing plants, research laboratories, medical facilities, etc., which produce or use man-made nuclear materials, and mines and mills which extract or concentrate naturally occurring radioactive materials.

Aerial radiological surveys of forty-one geographical areas in the Navajo Nation were conducted during the period of October 1994 through October 1999. The surveys were conducted at the request of EPA Region 9 and were performed by personnel of the RSL located in Las Vegas, Nevada.

Areas within the Navajo Nation were mined in the 1940s through the 1960s. Concern about the risk of excessive exposure to radiation from remaining mining debris led the Navajo Environmental Protection Agency Superfund Program to ask the EPA to assess the risks in mined areas and determine what action, if any, was needed.

While considerable historical information regarding the general mining areas was available, specific location and relative radiological activity information, suitable for defining risk-assessment areas, was not generally available. Spatial uncertainties in the location of mines of large fractions of a mile were not uncommon, and radiological information existed for very few of the study areas. These uncertainties created severe problems for the risk assessment process.

Aerial radiological technology was identified as the most likely solution to the EPA spatial and radiological uncertainty problem. Such surveys have been used for many years to fully characterize larger areas and to identify smaller areas requiring higher spatial resolution measurements. The EPA initially requested that demonstration aerial surveys be conducted over three small areas in the Four Corners region. These demonstration surveys validated the applicability of aerial surveys to the EPA task, and additional survey activities were initiated throughout the Navajo Nation. Survey parameters were chosen to record aircraft location and the radiological activity averaged over an area of approximately 1 acre (4,050 square meters), balancing resolution and productivity considerations. Special processing identified sites of mines, spoils piles, transfer stations, high natural uranium deposits, and other activities potentially related to uranium mining, by identifying locations where uranium radioactivity is out of balance with radioactivity from other naturally occurring isotopes (potassium and thorium).

2.0 Study Area Description

The study areas are shown in the wide-area map of the Navajo Nation and surrounding areas, Figure 1.

Locations for the general regions of interest defined by EPA were extracted from every source imaginable. U.S. Geological Survey (USGS) official reports, EPA source material, letters, telephone communications, and personal communications were all used. Virtually none of these sources had quoted uncertainties; most were simply spots on maps or locations relative to some known landmark. Map information often showed every indication of being redrawn, copied, drawn as artists' conceptions rather than maps, etc. Every point from these resources (including questionable data) was extracted and placed on working maps. Many points in each given area were likely duplicates of each other, looking like additional points because of the positional uncertainties. Boundaries were drawn around these clusters of locations, leaving wide boundary tolerances to allow for individual point spatial uncertainties. Flights were conducted over these defined boundaries. Individual point locations, used to determine survey boundaries, are not presented in this report because of the high potential of misinterpretation of their locations.

Many other areas of known mining activity were considered for future surveys but were dropped because of jurisdictional considerations and termination of the overall project. The areas not surveyed comprise a significant fraction of the total mining activities conducted in the Navajo Nation.

3.0 Radiation in the Environment

The primary purpose of the aerial survey activities in the Navajo Nation was to specifically identify areas of excess bismuth (an indicator of uranium) as pointers to areas of mining and associated activities. Aerial gross count activity is also important as it looks at total activity in much the same way as many instruments used for ground measurement. That is, it measures the total activity without specifically identifying the contributor. Because bismuth is not the only radioactive material in the environment, a brief discussion of the other contributors seems appropriate.

Radiation in the environment takes several forms, among which are alpha, beta, gamma, x-ray, cosmic ray, and neutron radiation. Alpha and beta radiation have little penetrating power and cannot be seen by the airborne radiological measurement system. X-ray and neutron radiation are man-made. Naturally occurring and enhanced

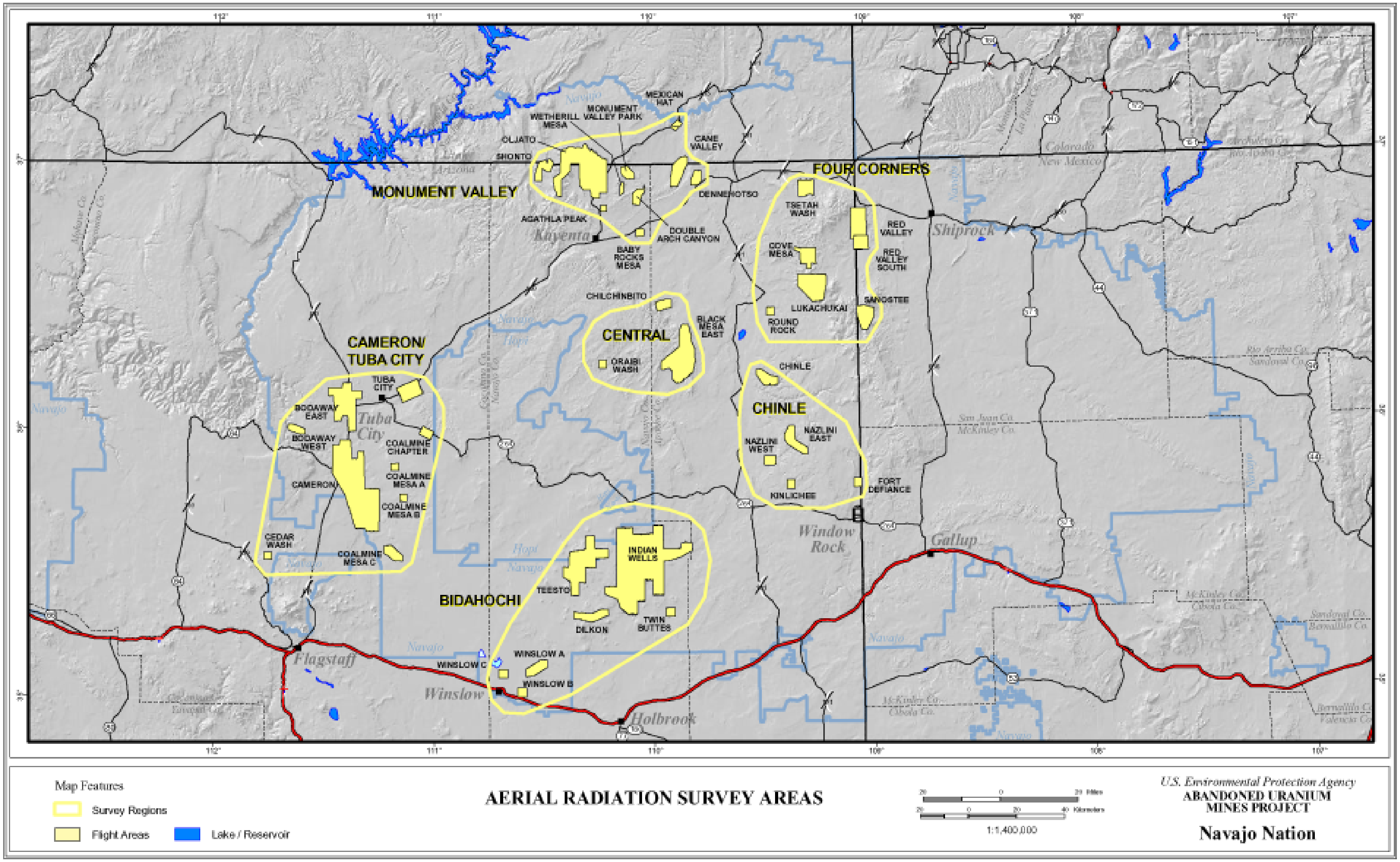

Figure 1. Wide-area Map of the Navajo Nation and Surrounding Area.

natural radiation are the primary contributors to radioactivity in the Navajo Nation. With the exception of insignificant trace amounts of fallout cesium-137, man-made radioactivity was not expected nor was it detected during Navajo survey activities. For report completeness, each contributor found in the modern environment is briefly described in this section. The contributors are discussed in order of their relative likelihood of occurrence in the Navajo project, with the highest likelihood being listed first.

3.1 Naturally Occurring Radiation

Naturally occurring radiation (NOR) originates from three main sources: radioactive elements present in the soil and rock, airborne radon, and cosmic rays of extraterrestrial origin.

Gamma radiation from soil and rock comes from the radioactive decay of elements found therein, namely, radioactive potassium and radioactive components of naturally occurring uranium and thorium. Soil and rock-originated natural radiation levels at the surface typically range from 1 to 15 μR/h throughout much of the world. However, many anomalous areas exist where natural levels far exceed these nominal values. In some parts of Brazil and India, natural levels exceed 100 μR/h. In the southwestern United States, high natural concentrations of uranium, thorium and potassium (occurring singly or together) create local anomalies with radiation levels nearly as high as those occurring in Brazil and India.

One radioactive member of the NOR group is radon, a gas that can diffuse through the soil and travel through the air. Because radon can travel through the air, the activity attributable to radon and its daughter products depends on a variety of factors, including meteorological conditions (winds, air temperature, atmospheric pressure, rainfall during or immediately preceding the survey), mineral content of the soil, and soil permeability. Typically, airborne radiation from radon and daughter products contributes from 1 to 10 percent of the natural background radiation activity. The airborne radiation from radon is typically higher in the generally calm morning hours than later in the day after winds have mixed the air over the survey area.

Cosmic rays (high-energy radiation originating from outer space) interact with elements of the earth's atmosphere and soil, producing an additional source of gamma radiation. Across the United States, radiation levels due to cosmic rays vary with altitude from 3.3 μR/h at sea level to 9.8 μR/h at elevations of 9,000 feet (2,700 meters).

3.2 Enhanced Natural Radiation

Enhanced natural radiation (ENR) is radiation from natural materials but it is generally of a higher level than typical NOR because of human intervention.

Many human activities enhance the external radiation originating from naturally occurring radioactive materials. While the materials producing ENR are natural, the enhancements are such that ENR is discussed separately from NOR. ENR has been observed in debris piles from mining operations for uranium, coal, iron, rare earth elements, and fertilizers; in mineral deposits from geothermal wells where subsurface minerals are deposited on the surface; in oil extraction operations where naturally radioactive materials plate out in pipes; in ash piles from conventional coal fired plants; and in separation operations which intentionally concentrate uranium, thorium and potassium. ENR is often orders of magnitude greater than NOR in the same area.

3.3 Man-Made Radiation

Man-made radiation (MMR) is defined as radiation that comes from man-made materials or processes not of natural origin. The sources of MMR may be a radioactive material used for radiography or medical treatment, an x-ray or similar machine, a research accelerator, or a nuclear power plant.

Cesium 137, a by-product of nuclear fission, is the only source of MMR that is present worldwide. It exists as fallout from aboveground nuclear weapon tests conducted prior to the early 1960s by the United States and the former Soviet Union and, subsequently, by China and France. External radiation rates due to cesium 137 in the environment, outside of isolated weapons test areas, are a small fraction of NOR and ENR (typically less than 1 μR/h). The quantities of cesium 137 detected during the Navajo uranium mines surveys were negligible.

4.0 Survey Operations

Data were acquired utilizing helicopter-based acquisition platforms equipped with custom flight-path steering systems, gamma detectors, and data acquisition systems. Survey altitude, line spacing, and speed were chosen to examine approximately 1 acre (4,050 square meters) of survey area every second. The data were verified and analyzed in the field using a vehicle-mounted or a motel-based multi-task analysis system.

4.1 Data Acquisition

The medium-altitude aerial surveys were flown using either a Messerschmitt-Bolkow-Blohm BO-105 helicopter (Figure 2), or a Bell B-412 helicopter (Figure 3). Both are twin-engine helicopters which carry a pilot(s), an instrument operator, and a version of the Radiation and Environmental Data Acquisition and Recorder System, Version IV (REDAR IV) or Version V (REDAR V). Detector pods mounted on the sides of the skid rack on the helicopter contained 2- x 4- x 16-inch log-type thallium-activated sodium

Figure 2. Messerschmitt-Bolkow-Blohm BO-105 Helicopter.

Figure 3. Bell B-412 Helicopter.

iodide (NaI[Tl]) scintillation detectors. The BO-105 was outfitted with a total of 8 log detectors; the B-412 had 12 log detectors.

4.2 Flight Procedures

Helicopters were flown at an altitude above the terrain of 150 feet (46 meters). At the 150-foot (46-meter) altitude, the nominal footprint of the detector is 300 feet (91 meters). Please refer to Section 6.0, *Spatial Considerations* for details. The normal line spacing for a detailed survey is the width of the footprint – for this survey, 300 feet (91 meters). Anticipating some difficulty in flying accurate parallel lines in mountainous terrain, a conservative line spacing of 250 feet (76 meters) was initially chosen for the demonstration surveys to assure that 300-foot (91-meter) coverage would be achieved. Evaluation of the data from the demonstration surveys showed that the 250-foot (76-meter) conservative line spacing was unnecessary. The remaining surveys were flown using a normal grid pattern of parallel flight lines spaced 300 feet (91 meters).

Aircraft position was established using a Real-time Differential Global Positioning System (RDGPS) and a radar altimeter. In the early surveys, a GPS base station transmitted a positional correction to a GPS unit housed in the helicopter. In later surveys, positional corrections were transmitted by a space-based system. The transmitted correction received by the helicopter's GPS unit minimized the relative positional uncertainty to +/- 15 feet (5 meters). The position was processed and directed into the steering indicator, which was used by the pilot to guide the aircraft along a predetermined set of flight lines.

4.3 Data Recording

The signals produced through interaction of gamma rays with the NaI(Tl) detectors are digitized and sorted in the REDAR acquisition system to produce second-by-second records which contain the number of gamma rays detected at each specific gamma ray energy. This record is called a spectrum. As every radioactive material, natural or man-made, has its own unique set of gamma rays, a spectrum can be used to identify and separate the sources of the detected gamma radiation.

The REDAR, which produces the gamma spectra described above, is a multi-processor data acquisition and real-time analysis system custom designed by the RSL to operate in the severe environments associated with platforms such as helicopters, fixed-wing aircraft, and various ground-based vehicles. The system displays radiation and positional information in real time to the operator via video displays and multiple LED readouts. Archival gamma-ray spectra, aircraft position, meteorological parameters, real-time clock and other data reference information (survey area names, specific flight lines, labels) are recorded at one-second intervals on digital data storage devices for postflight analysis on a ground-based minicomputer system. The digitally recorded data are archived at the RSL in Las Vegas, Nevada.

4.4 Data Verification and Analysis System

A Radiation and Environmental Data Analysis Computer (REDAC) was located at each base of operation. Different bases of operation were chosen for the different survey regions. Depending on the location, different REDAC configurations were used either a 1) mobile laboratory, based on a large Airstream Recreational Vehicle (Figure 4), or 2) portable system, set up in a motel room.

Figure 4. Mobile Data Laboratory.

A standard REDAC system has a Data General MV computer, SCSI disk subsystem for mass storage, numerous tape drives for data transfer and archiving, a 36-inch-wide plotter for data mapping, a laser printer, and two IBM personal computers for terminal emulation.

The REDAC uses an extensive software library developed by the RSL for analysis of REDAR data. The library utilizes industry standard operating systems and programming languages to support custom application software specifically designed by the RSL to perform gamma-ray spectral analysis, flight path recovery, parameter cross-timing, calibration, presentation of acquired/processed data, and conversion of processed/analyzed data to standard Geographic Information System (GIS)-compatible data files. The system provides full-function analysis (data qualification, parameter examination and correction, spectral analysis and interpretation, spectral plotting, contour mapping, etc.) of data acquired and recorded by the REDAR. Documentation for both industry standard software and custom applications software is archived at the RSL in Las Vegas, Nevada.

Prior to and immediately following each flight, extensive diagnostic processes, tailored to the specific survey and system characteristics, were used to evaluate data acquired from the REDAR system to verify proper operation of the system and validate operating procedures. These processes are designated as “preflight” and “postflight.”

For the preflight sequence, the calibrated flight-ready system is run for 5 minutes at a stationary ground location. By taking static data, one produces data sets that are easily evaluated by statistical means for proper values and for acceptable data variability. The preflight data file is read into the analysis system where pre-programmed validation analyses are automatically performed for every appropriate acquisition parameter. For the Navajo surveys, the evaluated parameters were position (differential GPS), radar altitude, outside air temperature, absolute pressure, gamma count rate, gamma spectral information, labels, and “on-tops” (specific event markers). Results of the preflight evaluation are produced both as Pass/Fail printed information and as second-by-second parameter plots. Results are reviewed by the data analyst and the mission manager. If the acquisition system fails a critical test in the preflight, the flight will be postponed until the equipment malfunction is corrected. Hardcopies of the preflight procedures and results are permanently retained in the data books archived at the RSL.

For the postflight sequence, the entire data set acquired during the flight (2-3 hours) is read into the analysis system. A pre-programmed validation process (similar but not identical to the preflight process) is automatically run on the flight data. The same parameters are evaluated in the postflight as in the preflight but the emphasis is somewhat different. Each parameter is tested for validity. In addition, the parameters must also be evaluated in relation to the intended mission (for example, good data taken in the wrong location does not satisfy mission requirements). In addition to parameter evaluation, postflights are also designed to derive data (such as isotope extraction coefficients) to be used in further analysis Results are reviewed and data are archived as with the preflight.

5.0 Data Analysis

Gross count and excess bismuth data were derived from the measured gamma spectral information.

Gross count measures total terrestrial gamma activity, without considering its source, much like a hand-held Geiger counter. Aerial gross count data documents the wide range of radioactivity present even in areas not associated with uranium mining activities.

The excess bismuth extraction shows only those areas where uranium concentrations are out of balance with the other naturally occurring radioisotopes (potassium and thorium). The excess bismuth parameter thus identifies areas of interest which are rich in uranium due to natural deposition or because human intervention has occurred.

Products of the gross count and excess bismuth analyses done in the field and at the RSL include contour maps, spectral data, summary tables, and GIS-compatible data files. All these files are archived at the RSL. Following EPA direction, only GIS .gen contour vector files were delivered to EPA and their subcontractors.

Detailed information for Gross Count and Excess Bismuth extractions follows.

5.1 Aerial Gross Count Data

From recorded spectral information, all gamma events of energy 38 keV through 3026 keV are summed to create the observed aerial gross counts per second.

Converting observed aerial count rate to local exposure rate requires consideration of 1) location-dependent factors, and 2) location-independent factors. The location-dependent factors include radon background, meteorological conditions, cosmic activity, and second-by-second elevation of the aircraft above the terrain. The location-independent factors are functions of the aircraft, detector size and configuration, and properties of the acquisition system.

Prior to field deployment, many measurements were made with the different helicopter systems in the Las Vegas area over land surfaces whose radiation properties have been carefully measured on the ground. Aerial measurements over these land surfaces were meticulously corrected for the location-dependent parameters present at the time of the calibration flights to derive the location-independent conversion parameters for each aircraft. Observed count rates are adjusted in the field for second-by-second altitude, meteorological conditions, radon contributions, cosmic activity, and aircraft backgrounds before applying the location-independent conversion parameters. Precise relative measurements for each survey area are assured by conducting flights over a standard test line at the beginning and end of each flight and by normalizing residual flight-to-flight differences.

The aerial count rate-to-surface exposure rate factor assumes a uniformly distributed source covering an area large compared with the field of view (footprint) of the detector. For sources of spatial extent smaller than the detector footprint, observed aerial values may differ appreciably from values measured at ground level (see Section 6).

5.2 Excess Individual Isotope Activity

Relative contributions of the natural radioisotopes to the total background are stable over large geographical areas. This results in a spectral shape that remains essentially constant over large count rate variations. This property allows one to measure the integral count rate in a reference energy region (e.g., from energy c through energy d) and multiply it by an appropriate constant to estimate the integral count rate that should appear in any other energy region (e.g., from energy a through b). One may then detect an excess count rate that appears in an energy region of interest by a simple relation:

EXCESS(a thru b) = MEASURED(a thru b)-ESTIMATED(a thru b)

Because the shape of the normal spectrum is relatively constant,

ESTIMATED(a thru b) = K * MEASURED(c thru d)

One may then write the equation for excess activity in terms of all measured quantities:

EXCESS(a thru b) = MEASURED(a thru b) - K * MEASURED(c thru d)

The most likely value of EXCESS within any large survey area will be zero. The value for K is then determined as the statistically most likely value of MEASURED(a thru b) divided by MEASURED(c thru d).

To account for different meteorological conditions and other factors, K is determined for each flight. A single flight includes takeoff, survey activity, and return to the operations base. Typical flight duration varies from 1½ hours to 3 hours depending upon helicopter loading, weather, survey terrain, and other considerations.

Bismuth 214, of the uranium family, was selected as the indicator of choice because of a gamma-ray photopeak at 1760 keV which is 1) prominent in the spectrum, 2) fairly high in energy, and 3) in a portion of the gamma spectrum which is not complicated by competing gamma peaks. Energy limits (in keV) for the bismuth 214 excess activity extraction were a=1574, b=1946, c=2342, and d=2882.

Because measured radiological data are statistical by nature, second-by-second values of excess bismuth observed in background areas are not each zero but are statistically distributed about zero. For the Navajo excess bismuth extraction, the most likely value of excess bismuth activity (background) was zero with a measured standard deviation (sigma) of +/- 20 counts per second (cps). To virtually eliminate false indications of excess bismuth caused by background statistical variations, minimum reportable activity (MRA) in this document was set to 80 cps (4 sigma). This level corresponds to approximately 3.5 uR/h.

6.0 Spatial Considerations

An airborne detector system, flown at 150-foot (46-meter) altitude over a point radiation source, will observe ½ the maximum activity at a horizontal distance of 150 feet (46 meters) prior to passing over the source, maximum activity directly over the source, and ½ the maximum activity at 150 feet (46 meters) after the source passing. By convention, the horizontal distance between the ½ maximum points is the diameter of the circular detector "footprint." The description of the exact surface-to-air transport mechanism is not within the scope of this document, but the bottom line is that the aerial system records the average surface activity over the extent of the footprint.

Standard ground-based environmental exposure rate measurements are taken at 3 feet (1 meter) above ground level. The footprint of these measurements is about 6 feet (1.8 meters) in diameter. By convention, the RSL aerial measurements are normalized to this standard. Occasionally, non-standard measurements are made with instruments within 2 inches (5 centimeters) of ground level (footprint approximately 4 inches [10 centimeters] in diameter) when one is trying to find the "hottest" area. If ground activity varies significantly over any of these footprints, activity will not agree among the three referenced measurements. It is not unusual to have orders of magnitude differences between such measurements. Therefore, it is very important to consider effects.

When the spatial extent of excess ground level activity (source) is appreciably less than the detector footprint, the average activity seen by the detector is weighted heavily by the large relative contribution of normal activity surrounding the source. This creates an underestimation of the peak source activity. Bull's-eye rings, which appear spatially centered on the location of a small source, do not indicate contamination on the ground but essentially are a spatial picture of the detector footprint. A familiar analogy is that of a campfire - the campfire exists only at a small fixed location, its effect can be felt some distance away, and the effect diminishes with distance from the fire.

Table 1 is useful for understanding spatial effects. The relationships are accurate only if the detector footprint and the ground deposition pattern are of Gaussian shape. This criterion is not exactly met, but the relationships are close enough to provide one with considerable insight into interpretation of the aerial data.

> For ground depositions of FWHM (Full Width at Half Maximum amplitude) from 10 to 100 feet (3 to 30 meters), the aerial FWHM changes only from 300 to 316 feet (91 to 96 meters). Such measured widths are really indistinguishable from each other and from the detector footprint within the positional uncertainty of the aerial measurement. Over this indistinguishable width range, the aerial-to-ground peak activity factor changes from 10 to more than 900. In this situation, aerial and ground measurements cannot be expected to be in agreement.
>
> Given that one cannot tell the difference between a ground area of 10-foot (3-meter) extent and 100-foot (30-meter) extent, it also follows that one cannot tell the difference between a

uniform deposition of 100-foot (30-meter) extent and a similar-size area made up of many smaller areas. Such might well be the case where several small debris piles are in close proximity on the ground. At the other extreme, for uniform ground depositions of FWHM 1000 feet (300 meters) or greater, the aerial and surface measurements will be in good agreement.

Risk from radiation exposure is a complex mixture of activity levels, region of occupancy, and time of occupancy. A large-footprint aerial measurement, while not completely sufficient for risk evaluations, has tremendous utility in targeting areas for further work. For the Navajo survey activities, the MRA for excess bismuth was approximately 3.5 µR/h. While 3.5 µR/h excess ground exposure would not generally be considered a risk, the level identifies areas that are either naturally rich in uranium or have had man-made activities that concentrated uranium. For example, the small level of 3.5 µR/h, estimated from aerial data, could represent an actual 3,150 µR/h if all activity were contained in a 10-foot (3-meter)-diameter area such as a small hogan built of uranium tailings. Therefore, one should carefully evaluate all areas reaching this MRA threshhold.

Table 1. Spatial Relationships for Aerial and Ground Correlation*

S Surface Deposition Pattern (FWHM in Feet)	**A** Aerial Pattern Seen from Altitude = 150' (FWHM in Feet)	**M** Multiplier to Obtain Ground Activity from Aerial Activity Estimate	**E** Exposure at Ground Level That Looks Like 3.5 µR/h from Aerial Platform Data (µR/h)
10	300.2	901	3,150
30	301.5	101	350
100	316.2	10.0	35
300	424.3	2.00	7.0
1000	1044.0	1.09	3.8
3000	3015.0	1.01	3.5

* Note: Spatial relationships which accurately correlate ground and aerial activity are very complex and are beyond the scope of this document. The relationships presented here are first order approximations useful for providing insight. The relationships should not be used to attempt aerial-to-ground corrections.

Definitions

S = **S**urface deposition pattern FWHM amplitude

A = **A**pparent deposition pattern FWHM when viewed from 150 feet (46 meters) above ground level

D = **D**etector footprint FWHM at 150 feet (46 meters) above ground level = 300 feet (91 meters)

M = **M**ultiplier to obtain ground activity from aerial activity estimate

E = **E**xposure level on the ground that looks like 3.5 µR/h (minimum reported excess bismuth value) at 150 feet (46 meters) above the ground

Relations used to generate Table 1

$A = SQRT(S^2 + D^2) = SQRT(S^2 + 300^2)$

$M = (A/S)^2$

$E = M * 3.5$ µR/h

7.0 Aerial Survey Results

This section shows typical products which can be produced from the data acquired by RSL. Such maps, without the USGS overlay, were produced for all 41 survey areas as part of the quality control process. Because the primary product requested by EPA was GIS-formatted .gen files to be used by other contractors, final overlay maps were not produced by the RSL for all surveyed areas.

The reader is referred to the document:

Abandoned Uranium Mines Project
Arizona, New Mexico, Utah – Navajo Lands
1994-2000
Project Atlas

The document presents data from all the surveyed areas in various GIS formats and is available from:

U.S. EPA Region 9
Superfund Records Center
95 Hawthorne Street, Suite 403 S
San Francisco, CA 94105-1985

7.1 Sample Flight Area

The area selected as a data sample is the Cameron Flight Area taken from the Cameron/Tuba City Region (see Figure 1). The RSL field-chosen name was Cameron E. The survey was conducted during the period September 25, 1997 through October 3, 1997. The area covered 166.7 square miles (431.8 square kilometers) and was irregular in shape. The area was bounded on the west by longitude –111.4690 degrees (111 deg, 28 min, 8.4 sec West), on the east by longitude –111.2532 degrees (111 deg, 15 min, 11.5 sec West), on the south by latitude +35.6260 degrees (35 deg, 37 min, 33.6 sec North), and on the north by latitude +35.9686 degrees (35 deg, 58 min, 7.0 sec North).

The average gross exposure rate was determined to be 8.3 µR/h (standard deviation 2.4 µR/h) with a minimum of 2.4 µR/h and a maximum of 66.7 µR/h. There were 110,803 one-second spectra acquired in this flight area by the acquisition system. Of these measurements, 2734 indicated excess bismuth activity greater than 80 cps (approximately 3.5 µR/h). The samples indicating excess bismuth represent approximately 2.5% (or 2638 acres [10.7 square kilometers]) of the total area of the Cameron flight area.

The data were collected by the B-412 helicopter with twelve 2- x 4- x 16-inch Na(Tl) detectors flown at 150 feet (46 meters) above the terrain at a line spacing of 300 feet (91 meters).

Note: The information presented in the preceding narrative for the Cameron Survey Area is presented in concise spreadsheet form for all 41 flight areas in Table 3.

7.2 Typical Terrestrial Exposure Rate Map

The terrestrial exposure rate plot (Figure 5) includes contributions from all natural terrestrial contributors (potassium, uranium, thorium) and possible man-made contributors. Aircraft, airborne radon, and cosmic contributors have been removed.

7.3 Typical Excess Bismuth Activity Plot

The excess bismuth plot (Figure 6) shows bismuth activity in excess of that expected from a normal distribution of natural contributors. Excess bismuth 214 activity indicates high uranium activity due either to previous mining activity or to high natural uranium activity. Only ground-truth activities can completely determine which case applies to a specific area.

7.4 Typical Spectral Plots

Spectral plots are shown in Figure 7. Figure 7a is typical of normal background areas. Figure 7b is typical of survey areas which show excess bismuth activity. Figure 7c is an overlay of Figures 7a and 7b, which illustrates the large difference between a typical background spectral sum and a spectral sum which has excess bismuth. Figure 7d is the net spectrum produced when the background spectrum (Figure 7a) is subtracted from the excess bismuth spectrum (Figure 7b).

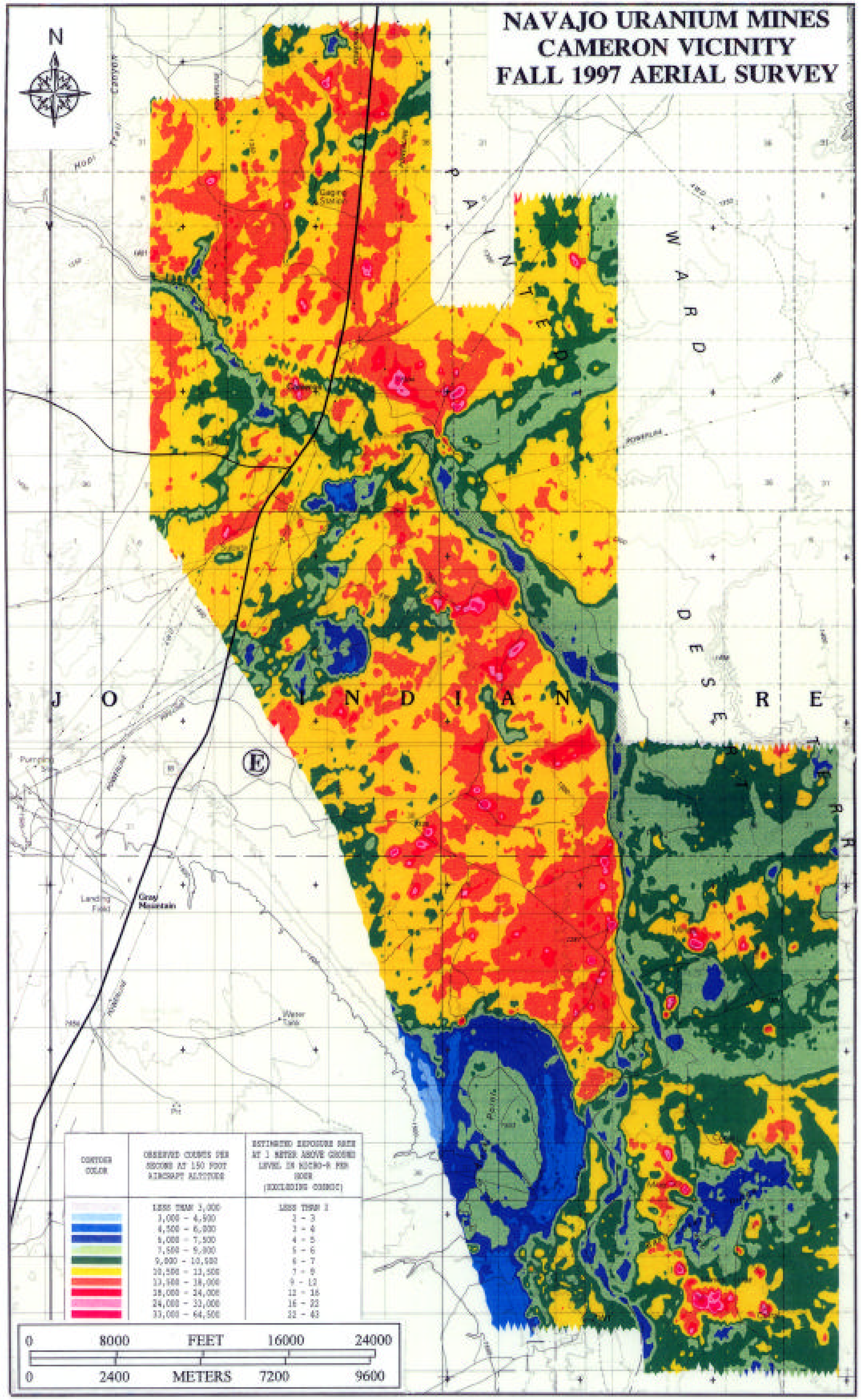

Figure 5. Typical Terrestrial Exposure Rate Plot.

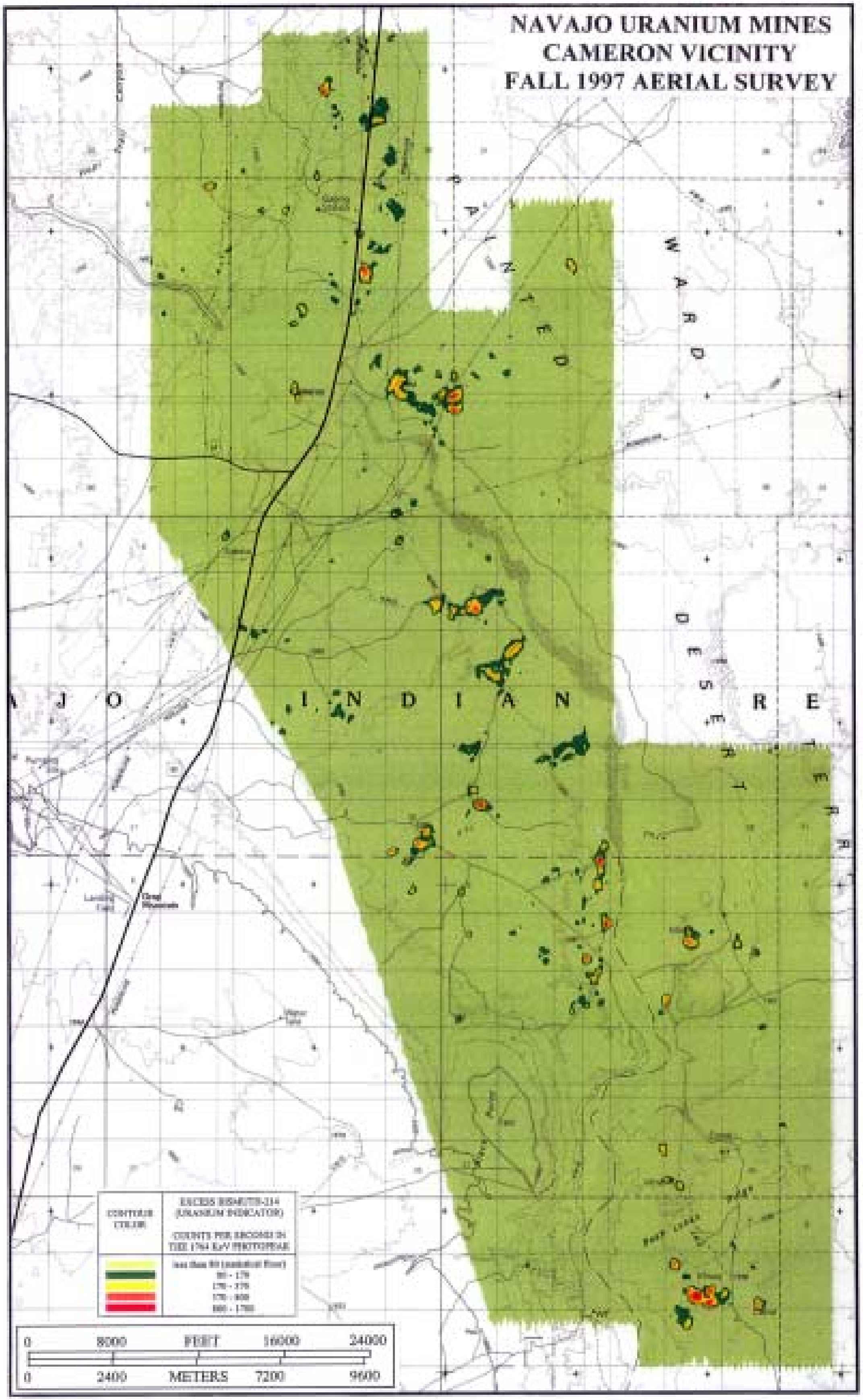

Figure 6. Typical Excess Bismuth Plot

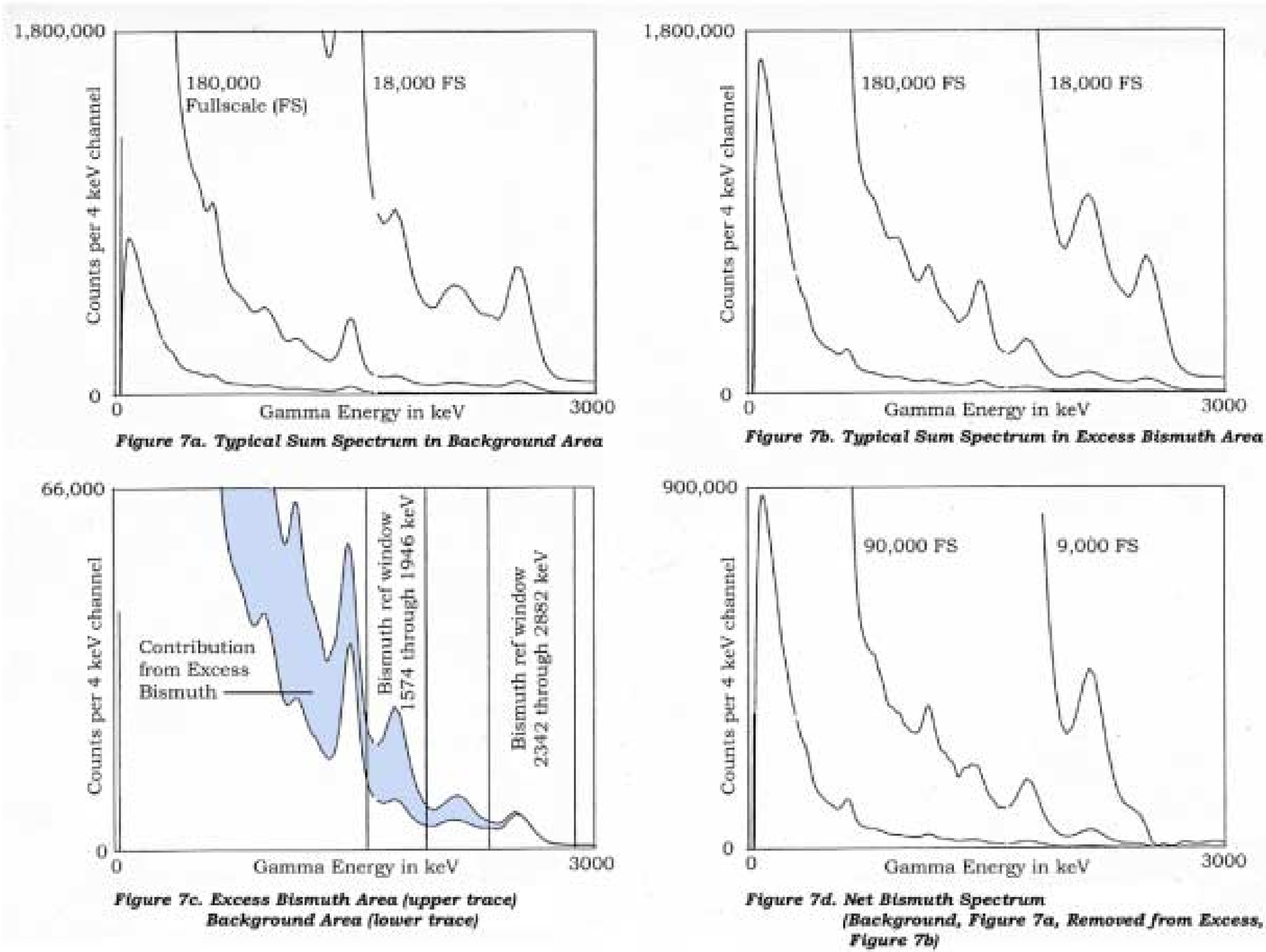

Figure 7. Typical Spectra for Navajo Abandoned Uranium Mines Surveys

7.5 Navajo Abandoned Uranium Mines Summary Information

Table 2 presents a project overview.

Table 2. Summary of Navajo Survey

Survey Parameter	
Overall survey period	Oct 1994–Oct 1999
Total number of areas surveyed	41
Total analyzed gamma spectra	771,964
Total area surveyed	1144.3 mi^2 (2963 km^2) (or 732,160 acres)
Area showing excess bismuth/uranium	15.0 mi^2 (39 km^2) (or 9600 acres) (1.3 percent)

Table 3 gives a detailed summary for all areas.

The following parameters are tabulated in Table 3.

Area Name – The name in this column is the final USEPA geographical designation.
Sub-Area Name – The name in this column is the final USEPA survey area designation.
Original Survey Name – Survey area name used during all field operations. All archived data at RSL have these designations.
Survey Start – Date the individual survey area began
Survey End – Date the individual survey area was completed
Survey Area – Total square miles covered in the individual survey area
Survey Shape –Shape of the individual survey (either rectangular or irregular)
Longitude Min – Extreme minimum longitude (westernmost boundary) within the individual survey
Longitude Max – Extreme maximum longitude (easternmost boundary) within the individual survey
Latitude Min – Extreme minimum latitude (southernmost boundary) within the individual survey
Latitude Max – Extreme maximum latitude (northernmost boundary) within the individual survey
Terrestrial Exposure Rate in µR/h (average) – Average exposure rate for the individual survey area
Terrestrial Exposure Rate in µR/h (deviation) – Standard deviation of the average exposure rate for the individual survey area
Terrestrial Exposure Rate in µR/h (minimum) – Minimum exposure rate found in the individual survey area
Terrestrial Exposure Rate in µR/h (maximum) – Maximum exposure rate found in the individual survey area
Total Number of Survey Samples – Total number of 1-second aerial sampled points for which full gamma spectral data were acquired for the individual survey area
Excess bismuth greater than 80 cps, approximately 3.5 µR/h (number of samples) Total number of 1-second bismuth-extracted values which exceeded the MRA level for the individual survey area
Excess bismuth greater than 80 cps, approximately 3.5 µR/h (approximate acres) Total number of acres which had bismuth extracted values which exceeded the statistically significant level for the individual survey area
Notes – Reference information relating to helicopter, detector configuration, and survey line spacing

1 = BO-105 helicopter with eight 2- x 4- x 16-inch Na(Tl) gamma detectors
2 = B-412 helicopter with twelve 2- x 4- x 16-inch Na(Tl) gamma detectors
3 = 250-foot (76-meter) survey line spacing
4 = 300-foot (91-meter) survey line spacing

Table 3. Navajo Abandoned Uranium Mines Summary Information

Area Name	Sub Area Name	Original Survey Name	Survey Start End	Survey Area (sq miles)	Survey Shape	Longitude Min	Longitude Max	Latitude Min	Latitude Max	Terrestrial Exposure Rate in uR/hr Does not include cosmic values of 5.1 @ 4000 ft to 9.7 @ 9000 ft elevation				Total # Survey Samples	Excess Bismuth Greater than 80 cps (Approx 3.5 uR/hr)		Notes
										avg	dev	min	max		# of samples	Approx acres	
Bidahochi	Dilcon	Winslow C	05/17/98 05/18/98	18.58	irregular	-110.3669	-110.2077	35.2856	35.3353	6.48	0.84	3.73	10.61	12,004	5	5.0	2,4
	Indian Wells	Winslow A	05/18/98 06/06/98	248.68	irregular	-110.2238	-109.8235	35.3132	35.6470	7.63	1.57	3.93	49.77	157,299	1,916	1938.6	2,4
	Teesto	Winslow B	05/13/98 05/18/98	75.42	irregular	-110.4133	-110.2057	35.3863	35.6080	6.77	1.46	3.68	24.13	47,990	376	378.2	2,4
	Twin Buttes	Winslow K	05/18/98 06/06/98	5.09	rectangle	-109.9448	-109.9034	35.3049	35.3363	5.93	1.11	3.84	8.86	3,232	0	0.0	2,4
	Winslow A	Winslow D	06/06/98	14.47	irregular	-110.5841	-110.4869	35.0831	35.1455	6.34	1.46	3.98	16.05	9,212	4	4.0	2,4
	Winslow B	Winslow H	06/07/98	5.28	rectangle	-110.6221	-110.5816	35.0080	35.0418	4.77	0.84	3.31	7.18	3,435	0	0.0	2,4
	Winslow C	Winslow G	06/06/98 06/07/98	5.21	rectangle	-110.7078	-110.6751	35.0774	35.1114	6.37	0.53	4.45	8.26	3,423	0	0.0	2,4
Cameron	Bodaway East	Cameron D	09/23/97 09/25/97	60.52	irregular	-111.4872	-111.3350	35.9989	36.1818	9.21	3.04	2.40	47.00	40,868	2,732	2589.3	2,4
	Bodaway West	Cameron F	09/10/97	7.48	irregular	-111.6657	-111.5922	35.9886	36.0278	5.65	1.69	2.42	11.70	5,203	8	7.4	2,4
	Cameron	Cameron E	09/25/97 10/03/97	166.72	irregular	-111.4690	-111.2532	35.6260	35.9686	8.26	2.41	2.43	66.66	110,803	2,734	2632.8	2,4
	Cedar Wash	Cameron G	09/09/97 09/10/97	3.58	rectangle	-111.7802	-111.7434	35.5197	35.5469	5.68	1.16	2.54	9.50	2,595	0	0.0	2,4
	Coalmine Chapter	Cameron I	09/11/97	7.52	rectangle	-111.0713	-111.0008	35.9684	36.0194	4.56	0.58	3.32	7.77	4,984	0	0.0	2.4
	Coalmine Mesa A	Cameron B	09/10/97	3.80	rectangle	-111.1991	-111.1626	35.8530	35.8806	4.75	2.23	2.30	11.22	2,658	0	0.0	2.4
	Coalmine Mesa B	Cameron A	09/23/97 09/24/97	3.69	rectangle	-111.1594	-111.1248	35.7380	35.7660	6.90	1.01	4.69	10.19	2,678	0	0.0	2,4
	Coalmine Mesa C	Cameron C	09/11/97 09/23/97	12.88	irregular	-111.2296	-111.1437	35.5160	35.5756	6.43	1.04	2.06	15.33	8,768	6	5.6	2,4
	Tuba City	Cameron H	09/11/97 09/12/97	24.78	rectangle	-111.1771	-111.0490	36.1055	36.1957	3.42	1.30	1.57	10.22	16,339	58	56.3	2,4

Key for notes: 1 = BO105 helicopter with 8(2x4x16) gamma detectors, 2 = B412 helicopter with 12(2x4x16) gamma detectors, 3 = 250 foot line space, 4 = 300 foot line space

Table 3. Navajo Abandoned Uranium Mines Summary Information (continued)

Area Name	Sub Area Name	Original Survey Name	Survey Start End	Survey Area (sq miles)	Survey Shape	Longitude Min	Longitude Max	Latitude Min	Latitude Max	Terrestrial Exposure Rate in uR/hr Does not include cosmic values of 5.1 @ 4000 ft to 9.7 @ 9000 ft elevation				Total # Survey Samples	Excess Bismuth Greater than 80 cps (Approx 3.5 uR/hr)		Notes
										avg	dev	min	max		# of samples	Approx acres	
Central	Black Mesa East	Chinle CE	10/10/98 05/25/99	72.56	irregular	-109.9569	-109.7990	36.1759	36.3956	9.03	1.86	3.31	30.51	47,475	236	230.8	2,4
	Chilchin-bito	Chinle A	05/24/99	11.53	irregular	-109.9792	-109.9058	36.4454	36.4880	6.96	1.81	3.70	22.45	6,553	377	424.5	2,4
	Oraibi Wash	Chinle D	05/24/99 05/25/99	4.02	rectangle	-110.2420	-110.2071	36.2334	36.2641	10.02	1.12	7.24	15.97	2,859	0	0.0	2,4
Chinle	Chinle	Chinle F	05/25/99 05/26/99	15.00	irregular	-109.5180	-109.4195	36.1625	36.2240	6.74	1.03	3.49	16.37	10,278	47	43.9	2,4
	Fort Defiance	Chinle I	05/19/99 05/21/99	4.51	rectangle	-109.0784	-109.0420	35.7782	35.8116	5.76	0.89	3.48	8.82	3,243	0	0.0	2,4
	Nazlini East	Chinle G	05/22/99	19.92	irregular	-109.3939	-109.2878	35.9039	36.0116	6.15	0.94	2.27	10.86	13,617	0	0.0	2,4
	Nazlini West	Chinle H	05/21/99 05/22/99	7.11	rectangle	-109.4875	-109.4336	35.8642	35.8999	6.84	1.28	1.59	14.66	4,857	29	27.2	2,4
	Kinlichee	Chinle J	05/21/99	4.81	rectangle	-109.3853	-109.3479	35.7760	35.8110	6.93	1.69	3.17	17.51	3,340	4	3.7	2,4
Four Corners	Cove Mesa	Cove Mesa	10/25/94 10/26/94	20.11	irregular	-109.1877	-109.0862	36.5778	36.6613	5.58	1.2	3.47	52.69	18,499	65	45.2	1,3
	Lukachu-kai	Lukachu-kai	10/14/99 10/20/99	42.29	irregular	-109.3206	-109.1884	36.4706	36.5756	6.89	1.7	3.23	34.68	27,623	202	197.9	1,4
	Red Valley	Beclabito	10/22/94 10/25/94	33.04	rectangle	-109.0695	-108.9968	36.7005	36.8203	5.37	2.38	2.69	41.52	30,156	292	204.8	1,3
	Red Valley S	Red Valley S	10/15/99 10/18/99	13.50	rectangle	-109.0577	-108.9893	36.6639	36.7156	5.36	1.27	2.92	42.23	9,756	81	71.7	1,4
	Round Rock	Chinle B	05/25/99	4.35	rectangle	-109.4675	-109.4314	36.4227	36.4545	5.45	1.39	2.55	13.22	2,998	1	0.9	2,4
	Sanostee	Sanostee	10/13/99 10/14/99	21.27	irregular	-109.0500	-108.9713	36.3638	36.4547	7.1	3.02	3.08	82.62	15,440	81	71.4	1,4
	Tsetah Wash	Rattle-snake	10/20/94 10/22/94	16.18	irregular	-109.3119	-109.2389	36.8665	36.9275	5.27	1.19	3.54	38.62	15,048	100	68.8	1,3

Key for notes: 1 = BO105 helicopter with 8(2x4x16) gamma detectors, 2 = B412 helicopter with 12(2x4x16) gamma detectors, 3 = 250 foot line space, 4 = 300 foot line space

Table 3. Navajo Abandoned Uranium Mines Summary Information (continued)

Area Name	Sub Area Name	Original Survey Name	Survey Start End	Survey Area (sq miles)	Survey Shape	Longitude Min	Longitude Max	Latitude Min	Latitude Max	Terrestrial Exposure Rate in uR/hr Does not include cosmic values of 5.1 @ 4000 ft to 9.7 @ 9000 ft elevation				Total # Survey Samples	Excess Bismuth Greater than 80 cps (Approx 3.5 uR/hr)		Notes
										avg	dev	min	max		# of samples	Approx acres	
Monument Valley	Agathla Peak	Monument Valley I	09/04/97	2.59	rectangle	-110.2301	-110.2004	36.8177	36.8416	10.19	4.72	4.08	24.25	1,804	0	0.0	2,4
	Baby Rocks	Monument Valley F	08/27/97	3.97	rectangle	-110.0678	-110.0297	36.7228	36.7521	3.65	0.57	2.65	6.79	2,711	0	0.0	2,4
	Cane Valley	Monument Valley G	09/03/97	21.94	irregular	-109.9050	-109.8235	36.9083	37.0214	4.16	1.87	1.74	32	14,999	312	292.1	2,4
	Denne-hotso	Monument Valley H	09/03/97 09/04/97	8.77	irregular	-109.8091	-109.7597	36.9118	36.9679	3.91	0.77	2.5	7.14	5,971	0	0.0	2,4
	Double Arch Cnyn	Monument Valley E	09/04/97	9.55	irregular	-110.0804	-110.0236	36.8398	36.9181	3.63	1.1	1.57	12.4	6,493	0	0.0	2,4
	Mexican Hat	Monument Valley K	09/05/97	4.61	rectangle	-109.9003	-109.8440	37.1147	37.1600	6.06	1.07	2.79	10.19	3,180	6	5.6	2,4
	Monument Valley Prk	Monument Valley D	08/26/97 08/27/97	8.51	irregular	-110.1331	-110.0730	36.9372	36.9848	4.68	1.44	1.98	13.06	5,953	11	10.1	2,4
	Oljato	Monument Valley BC	08/28/97 09/02/97	113.59	irregular	-110.4480	-110.1980	36.8670	37.0698	4.4	1.57	1.66	57.95	76,290	266	253.5	2,4
	Shonto	Monument Valley A	09/05/97	14.01	irregular	-110.5326	-110.4488	36.9326	37.0157	5.44	1.69	2.44	12.51	9,376	0	0.0	2,4
	Wetherill Mesa	Monument Valley J	09/05/97	2.88	irregular	-110.1388	-110.1199	36.8774	36.9268	4.46	0.95	2.48	8.53	1,954	0	0.0	2,4

Key for notes: 1 = BO105 helicopter with 8(2x4x16) gamma detectors, 2 = B412 helicopter with 12(2x4x16) gamma detectors, 3 = 250 foot line space, 4 = 300 foot line space

8.0 Summary

The aerial survey and subsequent processing characterized the overall radioactivity levels and excess bismuth 214 activity (indicator of uranium ore deposits and/or uranium mines) within the surveyed areas. A total of 772,000 aerial gamma spectra and associated position parameters were obtained and analyzed during the multi-year operation. The survey determined that only 15 square miles (39 square kilometers) of the 1,144 square miles (2,963 square kilometers) surveyed (approximately 1.3 %) had excess bismuth indications above the minimum reportable activity, thus reducing the area requiring further investigation by a nominal factor of 76.

Radiation contour data files, produced by RSL, were converted to GIS-compatible digital files and provided to EPA and EPA contractors for inclusion in numerous reports and graphics products.

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