REMOTE SENSING LABORATORY
Operated by Bechtel Nevada for
the U.S. Department of Energy

DOE/NV/11718--546
March 2001

AN AERIAL RADIOLOGICAL SURVEY OF THE SANDIA NATIONAL LABORATORIES/ NEW MEXICO AND SURROUNDING AREAS

ALBUQUERQUE, NEW MEXICO

Thane J. Hendricks
David L. Prout
Bechtel Nevada
Las Vegas, Nevada

DATE OF SURVEY — APRIL 23 TO MAY 3, 2000

DISCLAIMER

Available for sale to the public from–

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Phone: 800.553.6847
Fax: 703.605.6900
Email: orders@ntis.fedworld.gov
Online ordering: http://www.ntis.gov/ordering.htm

Available electronically at http://www.doe.gov.bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from–

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Phone: 865.576.8401
Fax: 865.576.5728
E-mail: reports@adonis.osti.gov

REMOTE SENSING LABORATORY
Operated by Bechtel Nevada for
the U.S. Department of Energy

DOE/NV/11718--546
March 2001

AN AERIAL RADIOLOGICAL SURVEY OF THE SANDIA NATIONAL LABORATORIES/ NEW MEXICO AND SURROUNDING AREAS

ALBUQUERQUE, NEW MEXICO

DATE OF SURVEY: APRIL 23 TO MAY 3, 2000

Thane J. Hendricks
David L. Prout
Project Scientists

Reviewed by

Paul P. Guss
AMS Project Engineer

Clifton M. Bluitt, Manager
Radiation Science Section

This Document is UNCLASSIFIED

David P. Colton
Derivative Classifier

Prepared for the U.S. Department of Energy, Nevada Operations Office
Work performed under Contract Number DE-AC08-96NV11718

ABSTRACT

A team from the U.S. Department of Energy's Remote Sensing Laboratory conducted an aerial radiological survey of the area surrounding the Sandia National Laboratories/ New Mexico and Kirtland Air Force Base in Albuquerque, New Mexico, during the months of April and May 2000. The survey team measured the terrestrial gamma radiation at the site to determine the levels of natural and man-made radiation. The current survey includes the areas covered by a previous survey that was performed in 1993.

The results of the aerial survey show a background exposure rate that varies between 5 and 18 microRoentgens per hour (μR/h) plus an approximate 6 μR/h contribution from cosmic rays. The major radioactive isotopes found in this survey were potassium-40, thallium-208, bismuth-214, and actinium-228, which are all naturally occurring isotopes, and cobalt-60, cesium-137, and excess amounts of thallium-208 and actinium-228, which are due to human activity in the survey area. In regions away from the man-made activity, the exposure rates inferred from this survey agree well with the exposure rates inferred from the 1993 survey.

In addition to the aerial measurements, a series of ground-based pressurized ion chamber (PIC) measurements were acquired at four sites within the survey area. These ground-based PIC measurements ranged from 5.4 to 9.5 μR/h and were 13 to 21% lower than the inferred aerial exposure-rate results.

CONTENTS

Sections

Figures

Tables

Appendices

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

cps	counts per second
keV	kiloelectronvolts (a unit of gamma-ray energy)
μR/h	microRoentgens per hour (a unit of exposure rate)
mR/yr	milliRoentgens per year
mrem/yr	millirems per year
^{228}Ac	actinium-228
^{241}Am	americium-241
^{214}Bi	bismuth-214
^{134}Cs	cesium-134
^{137}Cs	cesium-137
^{60}Co	cobalt-60
^{40}K	potassium-40
^{234m}Pa	protactinium-234m
^{226}Ra	radium-226
^{208}Tl	thallium-208
^{210}Tl	thallium-210
^{228}Th	thorium-228
^{232}Th	thorium-232
^{238}U	uranium-238
ADC	analog-to-digital converter
AGL	above ground level
AMS	Aerial Measuring System
BN	Bechtel Nevada
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRR	Demolition Range Road
FS	full scale
GC	gross count
INWS	Interservice Nuclear Weapons School
LRRI	Lovelace Respiratory Research Institute
MAN	Manzano area
MCA	multichannel analyzer
MMGC	man-made gross count
MSL	mean sea level
NaI(T*l*)	thallium-activated sodium iodide gamma-ray scintillation detector
PIC	pressurized ionization chamber
RDGPS	Real-Time Differential Global Positioning System
REDAR V	Radiation and Environmental Data Acquisition and Recorder, Version V
RMWMF	Radioactive and Mixed Waste Management Facility
RSL	Remote Sensing Laboratory
SNL/NM	Sandia National Laboratories/New Mexico
TA	Technical Area
TS	Training Site
USGS	U.S. Geological Survey

1.0 INTRODUCTION

The U.S. Department of Energy's (DOE) Remote Sensing Laboratory (RSL) maintains the Aerial Measuring System (AMS), which is an aerial radiological surveillance system. The RSL, managed under contract by Bechtel Nevada (BN), maintains a fully functional AMS at Nellis Air Force Base in Las Vegas, Nevada, and at Andrews Air Force Base near Washington, D.C.

In 1958 the U.S. Atomic Energy Commission, a predecessor of the DOE, began a program to map the terrestrial gamma radiation environment in and around facilities which produce, use, or store radioactive materials. As part of this ongoing program, BN routinely conducts aerial surveys for the DOE and other government agencies. The aerial surveys provide data that assist in effective environmental management at nuclear facilities. The surveys, if performed at the appropriate times, can also provide information on the radiation profile before, during, and after a facility is operating using radioactive materials.

During the months of April and May 2000, a team from the RSL conducted an aerial radiological survey of the area surrounding the Sandia National Laboratories/New Mexico (SNL/NM) and Kirtland Air Force Base in Albuquerque, New Mexico. A previous radiological survey of SNL/NM and surrounding area, conducted by EG&G Energy Measurements, Inc. in April 1993, used a helicopter flying at a nominal altitude of 46 meters (150 feet), ground speed of 36 meters/second (70 knots), with a line spacing of approximately 76 meters (250 feet)[1]. The present survey used these same parameters. The DOE requested this follow-up survey to assess the impact of the last seven years of operation. This survey includes nearly the same area as that covered in 1993. Unlike the survey performed in 1993, no soil samples were taken for analysis, but surface gamma rate measurements were made with a pressurized ionization chamber (PIC). A radiological survey was also performed in 1981[2]; a detailed comparison of the 1993 survey and the 1981 survey is given in Reference 1.

2.0 SURVEY SITE DESCRIPTION

The survey covers an area of roughly 139 square kilometers (50 square miles), which includes most of the SNL/NM, the Lovelace Respiratory Research Institute (LRRI), and Kirtland Air Force Base. The survey site consists of land owned by DOE and used by the various contractor agencies, land withdrawn from the U.S. Forest Service and controlled by DOE, or land owned by the U.S. Department of Defense (DoD). Figure 1, page 6, shows the survey area along with contour levels of gross count exposure rate, which will be described later. The elevation of the survey area varies from 1615 meters (5300 feet) above mean sea level (MSL) on the western side of the region to about 2133 meters above MSL (6900 feet) at the highest peak of the Manzano area, a small mountain range. The Manzano area, located just east of the center of the survey site, is easily distinguished; the road encircling the range appears as a tan oval on the map.

The SNL/NM is a nuclear ordnance laboratory, whose primary purpose is to provide the interface between the military delivery systems and the nuclear weapons developed by both Los Alamos National Laboratory and Lawrence Livermore National Laboratory. Principal activities at SNL/NM include the testing of major non-nuclear weapon components; development of the arming and firing systems; and the quality control, quality assurance, and safety of the delivery systems. Components developed by SNL/NM undergo tests involving mechanical shock, vibration, electrical pulses, temperature and moisture variations, and radiation fluxes. SNL/NM is located in several Technical Areas on the western half of the survey area and a number of other locations spread around the eastern portion of the survey area.

The LRRI, which was formerly called the Inhalation Toxicology Research Institute, is known for its research into almost all areas of inhalation toxicology and other fields associated with the respiratory tract. LRRI is situated near the center of the southern boundary of the survey area. The LRRI facility consists of a main complex of about two dozen buildings for research and kennels, a waste treatment facility located approximately 30 meters (100 feet) southeast of the main complex, another waste treatment facility about 30 meters (100 feet) west of the main complex, and a group of lagoons 60-300 meters (200-1000 feet) west of the main complex. Some of the radioactive isotopes used in their studies include cesium-134 (^{134}Cs), cesium-137 (^{137}Cs), radium-226 (^{226}Ra), thorium-228 (^{228}Th), and americium-241 (^{241}Am).

Kirtland Air Force Base and the city of Albuquerque share the land around the airport. On recent maps, most of the land covered in this survey is identified as Kirtland Air Force Base, a DoD agency, even though the DOE owns the land and buildings used by most or all of its contractors in this area. Part of the survey covers land identified as Cibola National Forest, but this land has been withdrawn from the U.S. Forest Service and is controlled by DOE for use by its contractors. Since the land is used by DOE contractors, it was included in this survey.

3.0 SURVEY EQUIPMENT AND PROCEDURES

The area was surveyed by flying a series of parallel flight lines in a north-south direction. The small mountain range in the eastern portion of the survey area is aligned nearly north-south. Flying along the length of the range rather than across the width minimized the number of times the helicopter had to climb and descend the mountain, thus allowing the helicopter to remain near the desired survey altitude. Appendix A provides a summary of the survey parameters.

The following paragraphs present a short description of the data collection procedures used for this survey. For interested readers, Appendix B presents a more-detailed description of the survey procedures.

3.1 Aerial Measuring System

A Bell-412 helicopter was used in this survey. The helicopter flew a nominal altitude of 46 meters (150 feet) above ground level (AGL) over most of the survey area. A radar altimeter system continuously monitored and provided feedback to the pilot of the helicopter's altitude. In the eastern portion of the survey area, where the terrain contains mountains and canyons, the helicopter could not follow the rapid changes in the elevation of the terrain and instead flew more gentle rises and falls over obstacles in its path. At 46 meters (150 feet) AGL, the optimum line spacing is 76 meters (250 feet), which provides 100 percent coverage of the area surveyed.

The position of the helicopter was established by using two systems: a real-time differential global positioning system (RDGPS) and a radar altimeter. The helicopter was equipped with two detector pods mounted on the sides. Each of the detector pods carried six 2- x 4- x 16-inch rectangular, thallium-activated sodium iodide, NaI(Tl), gamma-ray scintillation detectors. The signals from the individual detectors, matched in amplitude and then combined within a summing amplifier, were fed into an analog-to-digital converter/multichannel analyzer (ADC/MCA). The ADC/MCA is one of the components of the Radiation and Environmental Data Acquisition and Recorder system, Model V (REDAR V). Typical data collected include four 1024-channel gamma energy spectra, ambient air temperature, absolute barometric pressure, and aircraft altitude and position. All data are acquired in one-second increments and stored to hard disk drives.

3.2 Survey Procedures

The collected data consist of position, atmospheric information, and a gamma energy spectrum. Many factors, including radiation from sources of interest, radiation from sources of no interest, and electrical noise, contribute to form the total gamma energy spectrum. These components can be summarized as the five terms in the following equation:

$$\begin{pmatrix} \text{Measured} \\ \text{Gamma} \\ \text{Energy} \\ \text{Spectrum} \end{pmatrix} = \begin{matrix} \text{Naturally Occurring Terrestrial Radionuclides} \\ + \text{Man - Made Radionuclides} \\ + \text{Airborne Radon} \\ + \text{Cosmic Rays} \\ + \text{Equipment Contributions} \end{matrix} \tag{1}$$

The naturally occurring radionuclides, airborne radon, and cosmic ray contributions to the equation are discussed in more detail later in Section 4.0, *Natural Background Radiation*. The man-made radionuclides produced through actions by man are generally the components of the radiation field of most interest. Typical man-made radionuclides include cobalt-60 (^{60}Co) and ^{137}Cs. The final term in this equation represents all sources of noise ranging from electrical noise spikes in the electronics to radiation sources in the body of the aircraft.

Since the detectors measure the radiation field at the altitude of the helicopter, a correction must be applied for the attenuation of the gamma ray intensities through the air to obtain an exposure rate at 1 meter (3.3 feet) AGL. One factor that strongly affects the measurement is the presence of liquid water between the radiation source and the detectors. Changes in the relative humidity of the air (water vapor) are not of concern here since the gamma-ray absorption for even 100% relative humidity differs little from that for dry air. However, changes in the amount of water in the top several centimeters of the soil can introduce major discrepancies. For this reason, no data are collected immediately after rainstorms. There was no precipitation during the period of this survey.

3.3 Ground-Based Measurements

Just after the aerial survey, pressurized ion chamber (PIC) measurements were performed on the ground at four selected sites. The main purpose of the *in situ* measurements is to provide an independent check on the exposure rate values inferred from the aerial measurements. Since the field-of-view of the airborne detector is very large, the sites chosen for the ground-based measurements were selected to be within fairly uniform background radiation areas and far from any obvious anomalies.

For the *in situ* measurements, a Reuter-Stokes PIC at 1 meter (3.3 feet) AGL was used to measure the incident radiation from an area roughly 18 meters (60 feet) in diameter. Since variations in the elevation of the terrain will shield some of the radiation from the detector, the survey locations were chosen to be relatively flat over these distances.

4.0 NATURAL BACKGROUND RADIATION

Natural background radiation originates from several different sources. Natural terrestrial isotopes, airborne radon gas, and cosmic rays are the three sources generally considered to make up the natural background radiation field.

Long-lived radionuclides present in the earth's crust are usually the largest source of background terrestrial radiation. Naturally occurring isotopes found in the soil and bedrock consist mainly of radionuclides from the uranium (U) and Th decay chains, and radioactive potassium (^{40}K). The most prominent natural isotopes usually seen in aerial spectra are ^{40}K (0.012% of natural potassium), thallium-208 (^{208}Tl) and actinium (^{228}Ac) (decay products in the ^{232}Th chain), and bismuth-214 (^{214}Bi), a decay product in the ^{238}U chain. Although it is considered a man-made radionuclide, a measurable amount of ^{137}Cs is found (initially as a surface deposition and then migrating several centimeters into the soil) throughout the world as a result of the atmospheric testing of nuclear weapons. These naturally occurring isotopes typically contribute 1-15 micro-Roentgens per hour (μR/h) to the background radiation field[3].

Radon, a noble gas, is a member of both the U and Th decay chains. After being created in the soil from its parent isotope, radon can diffuse through the soil and become airborne. While the isotopes of radon have relatively short half-lives, their decay products may become attached to dust particles in the atmosphere and contribute to the airborne radiation field until the dust eventually settles to the ground. The contribution of radon and its decay products to the background radiation field depends on several factors, including the concentration of U and Th isotopes in the soil, the permeability of the soil, and the meteorological conditions at the time of the measurement. Typically, airborne radon contributes 1-10% of the natural background radiation level.

Cosmic rays entering the earth's atmosphere are a third source of background radiation. High-energy cosmic rays, principally protons, alpha particles, and some heavier nuclei, interact predominantly with atoms in the upper atmosphere to produce showers of secondary radiation. The contribution of cosmic rays to the background radiation field varies with altitude and geomagnetic latitude. The earth's magnetic field traps some of the cosmic rays, so a larger fraction of them reaches the poles than the equator. In regions of the continental United States, values range from 3.3 μR/h at sea level in Florida to 12 μR/h at an altitude of 3000 meters in Colorado[4].

5.0 DATA REDUCTION PROCEDURES

Several methods of data processing were used to view the survey data. The Gross Count (GC) or terrestrial exposure-rate method was used to convert the measured counts per second (cps) data to an exposure rate in μR/h at a height of 1 meter (3.3 feet) AGL. The results are shown as a gamma exposure rate contour map superimposed on a U.S. Geological Survey (USGS) topographic map or aerial photograph of the survey area, acquired on April 6, 2000. With this display, large-scale variations of the radiation field within the whole survey area may be seen easily.

However, variations in the total radiation field are not always of most interest. The second method employed was the Man-Made Gross Count (MMGC) method. The MMGC method was used to determine locations of the non-naturally occurring gamma emitters. The MMGC is the portion of the gamma energy spectrum that is directly attributed to the gamma rays produced by man-made radionuclides. A third data processing method was employed to search the gamma energy spectral data. This method assumes that the observed count rate from a specific isotope can be determined from the sum of the counts in the gamma energy source window of that isotope, minus a scaled background contribution. Appendix C explains these three methods in more detail.

6.0 RESULTS

6.1 Gamma Exposure Rate Contour

The gross count data (in counts per second [cps]) is converted into an exposure rate (in μR/h) by applying a conversion factor that was determined from a documented, land-based, calibration test line located near Lake Mohave, Nevada. The applicability of the conversion factor assumes a uniformly distributed radiation source covering an area that is large when compared to the field-of-view of the detection system. For the data collected over a region containing only naturally occurring radionuclides in approximately the same abundances as the calibration test line, this GC-to-exposure-rate conversion is a good approximation. In regions where there are man-made radionuclides present or the composition of the natural radionuclides changes significantly from the calibration test line, this approximation will not produce an accurate exposure rate value. However, for most of the survey area, the exposure rate display is a very useful representation.

The gamma exposure rates inferred from the aerial data are shown in Figure 1 as a series of contour lines superimposed on an aerial photograph of the SNL/NM area. In Figure 2 the gamma exposure rates are shown as a color-filled contour map superimposed onto a USGS topographic map of the survey area. It should be noted that the contributions from both airborne radon and cosmic rays have been removed from the depicted exposure results.

The cosmic ray contribution, which is not included in the contour levels shown, varies from 6 μR/h near the airport (1600-meter [5250-foot] elevation) to 6.5 μR/h in the southeast corner of the survey area (1830-meter [6000-foot] elevation) and is even higher over the mountainous areas. The large-scale variations in exposure tend to follow the geologic terrain and are principally changes in the natural radioactivity of the soil. Most of the smaller-sized, elevated radiation areas are caused by man-made activities.

FIGURE 1. GAMMA EXPOSURE RATE CONTOUR. Contour lines are presented for positional information only.
0 4000 FEET 12000 16000
0 1200 METERS 3600 4800
LOCATION DIAGRAM
CO
AZ
NM
Sandia National Laboratories/New Mexico
TX
N
Date of Photo: April 6, 2000
Survey Date: April-May, 2000

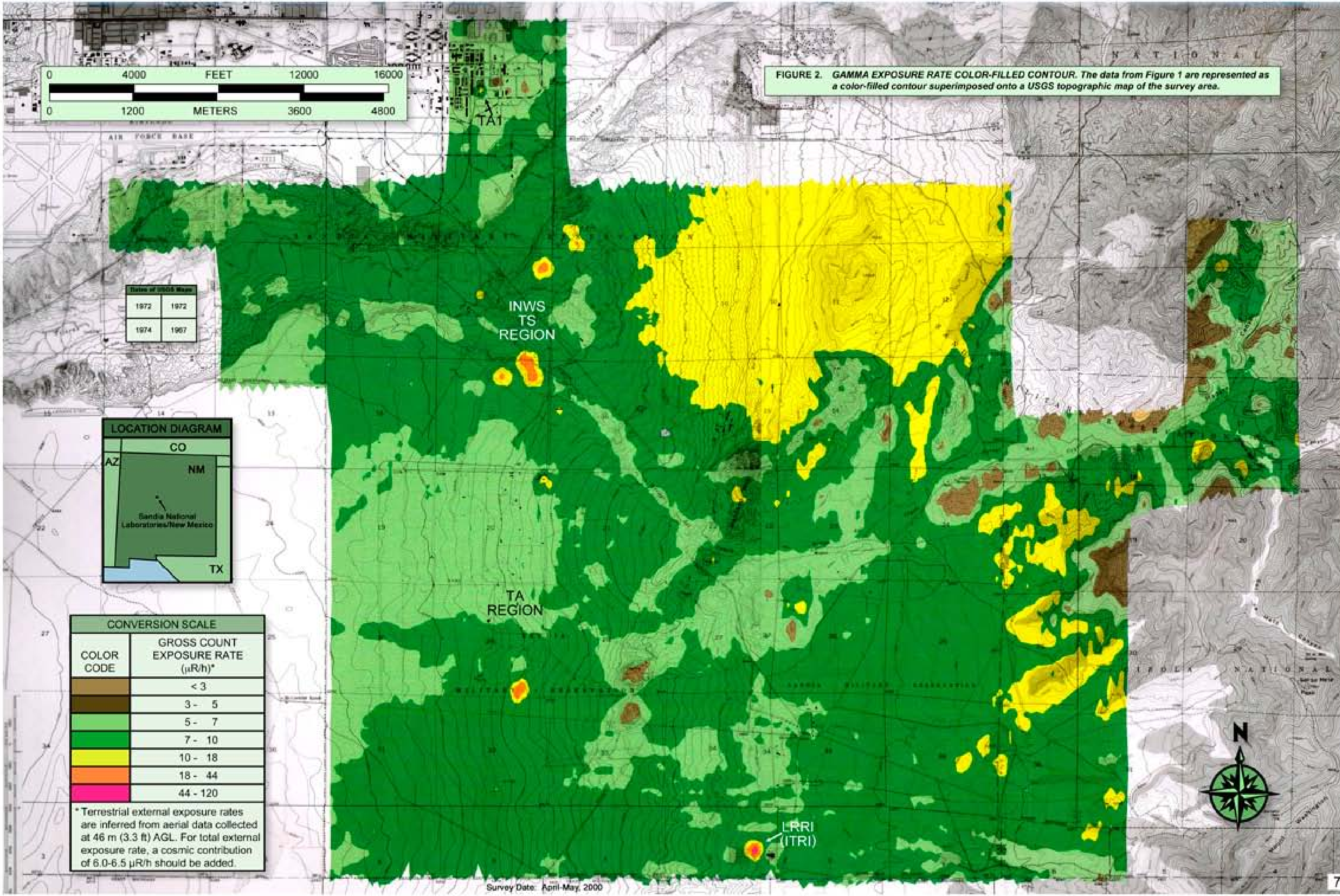

FIGURE 2. *GAMMA EXPOSURE RATE COLOR-FILLED CONTOUR. The data from Figure 1 are represented as a color-filled contour superimposed onto a USGS topographic map of the survey area.*

6.2 Man-Made Gross Count Contour

The GC-derived exposure rates are not always the most informative presentation of the data. The MMGC method emphasizes the portion of the gamma energy spectrum that is most sensitive to the gamma rays produced by man-made radionuclides (see Appendix C). Hence, the MMGC method was used to analyze the data to search for the man-made radionuclides.

The results of the MMGC analyses are presented as a contour map superimposed onto an aerial photograph of the survey area in Figure 3 and onto a USGS topographic map of the survey area in Figure 4. The levels of man-made activity are shown in cps and are representative of the intensity of the detected radioactivity. For ease of discussion, a short, descriptive label, keyed to an organization or a geographic feature in the location, is used to identify each location of anomalous radioactivity. The gamma energy spectrum for each region of elevated MMGC activity was examined to ascertain which radionuclides are present. The resulting spectral analyses are discussed in Section 6.4. Note that in an area where the aircraft's altitude changes significantly from the planned altitude and/or in an area that exhibits extremely excess concentrations of natural K, U or Th, the MMGC algorithm may generate a set of false-positive or false-negative anomalies in 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.

6.3 Excess Thorium Contour

In the GC color-filled contour, Figure 2, a prominent anomaly is seen in the LRRI region. Within this same region, the MMGC color-filled contour, Figure 4, shows a ring of high count rate inside of which is a region of slightly lower count rate. This effect occurs in areas where the concentrations of the naturally occurring radionuclides (K, U, Th) are higher than normal. Since it was known that this region and the Interservice Nuclear Weapons School (INWS) Training Sites had previously contained excess thorium, a search was conducted over the entire survey area for regions of excess thorium (^{232}Th) concentrations. The ^{208}Tl gamma ray (a decay product of ^{232}Th) at an energy of 2614 kiloelectronvolts (keV) was used to search for areas of enhanced thorium since it is much more distinctive and free from interference in comparison to the ^{232}Th gamma ray at 59 keV.

The window algorithm relies on determining a ratio between the counts in the ^{208}Tl photopeak at 2614 keV and the counts in a ^{214}Bi photopeak (from the ^{238}U decay chain) at 1764 keV in a background region of the survey area. This ratio is used to locate regions where the Tl (or Th) concentration differs markedly from the Bi concentration. Since the half-lives of the decay products in the chain are all less than six years, this technique is fine for searching for elevated thorium concentrations which are older than 10-15 years. After this length of time, all of the members of the decay chain are in equilibrium and a search using a member near the end of the thallium chain does bear some relationship to the presence and quantity of the parent thorium radionuclide. Figures 5 and 6 show the regions of excess thorium. In these two figures, as opposed to the GC and MMGC contours, the INWS Training Sites, (TS1-TS6) appear as well-defined locations. The region with the largest deviation from the general sitewide values is near the LRRI, which coincides with the prominent anomaly on the GC contour (Figure 2). In addition to the INWS and LRRI sites, several low-level areas appear to contain slightly excess concentrations of ^{232}Th in the Manzano area and the hills and canyons on the eastern edge of the survey region.

FIGURE 3. ***MAN-MADE GROSS COUNT CONTOUR. Contour lines are presented for positional information only.***

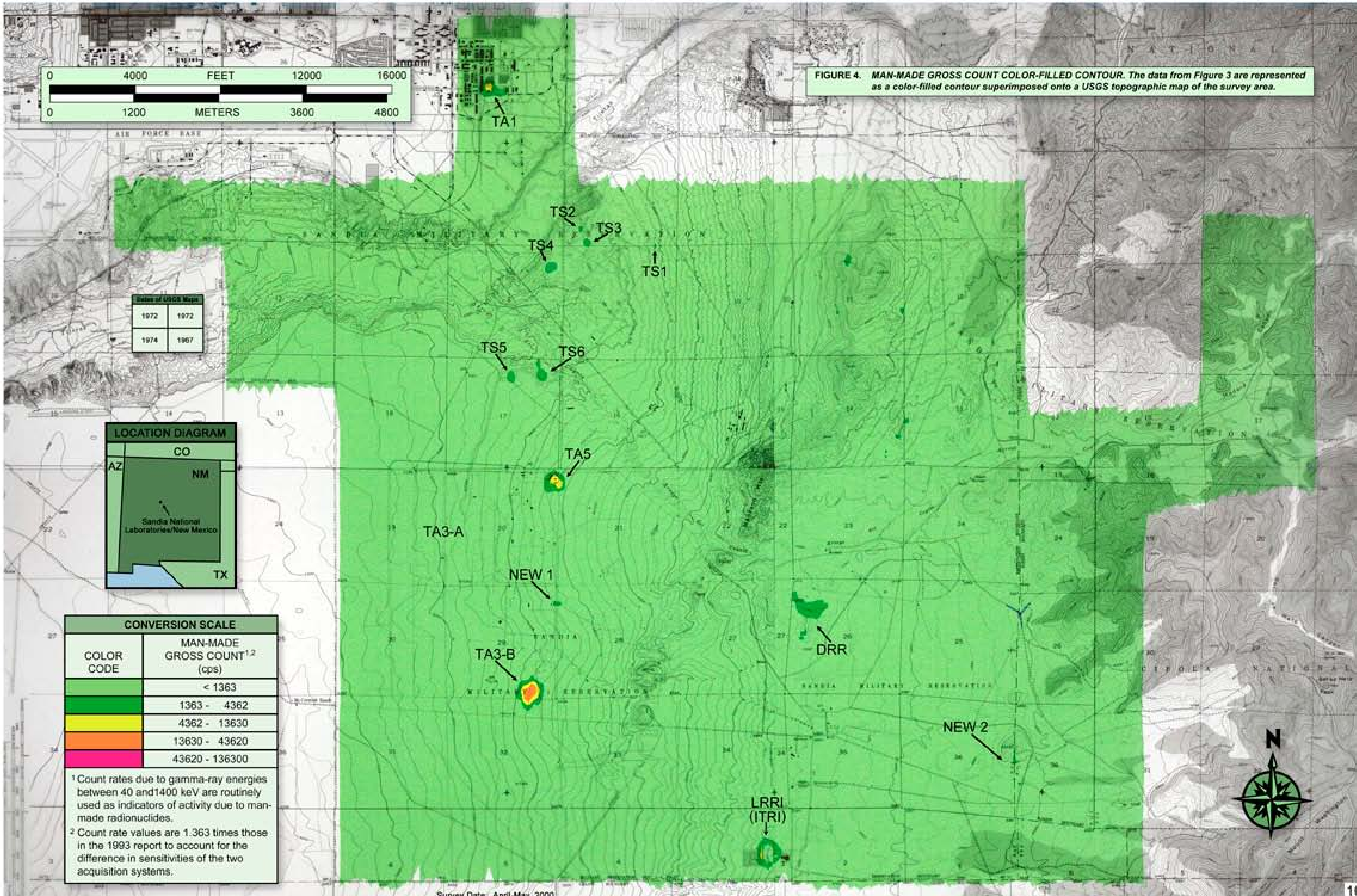

FIGURE 4. ***MAN-MADE GROSS COUNT COLOR-FILLED CONTOUR. The data from Figure 3 are represented as a color-filled contour superimposed onto a USGS topographic map of the survey area.***

CONVERSION SCALE

COLOR CODE	MAN-MADE GROSS COUNT[1,2] (cps)
(light green)	< 1363
(dark green)	1363 - 4362
(yellow)	4362 - 13630
(orange)	13630 - 43620
(magenta)	43620 - 136300

[1] Count rates due to gamma-ray energies between 40 and1400 keV are routinely used as indicators of activity due to man-made radionuclides.

[2] Count rate values are 1.363 times those in the 1993 report to account for the difference in sensitivities of the two acquisition systems.

FIGURE 5. *EXCESS THORIUM CONTOUR. Contour lines are presented for positional information only.*

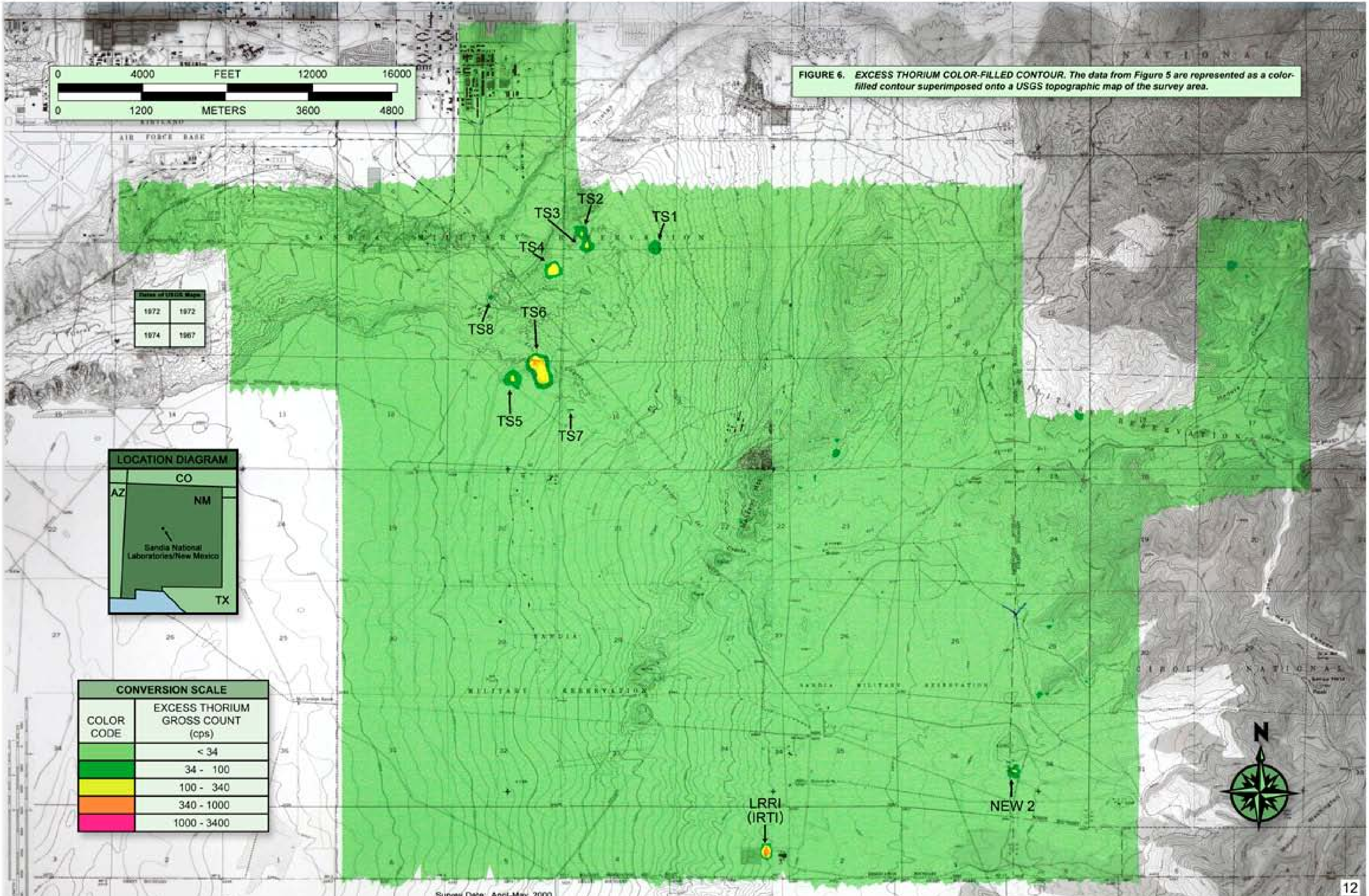

FIGURE 6. *EXCESS THORIUM COLOR-FILLED CONTOUR. The data from Figure 5 are represented as a color-filled contour superimposed onto a USGS topographic map of the survey area.*

CONVERSION SCALE

COLOR CODE	EXCESS THORIUM GROSS COUNT (cps)
(light green)	< 34
(dark green)	34 - 100
(yellow)	100 - 340
(orange)	340 - 1000
(magenta)	1000 - 3400

Each region of man-made activity is associated with a unique name, which identifies it for later analysis. The apparent elevated activity in the Manzano area may be caused by changes in the natural radionuclides or by errors introduced by the rapidly changing altitude while surveying this area. Other man-made radiation regions are known by site personnel.

6.4 Gamma Energy Spectral Analysis

The ^{238}U and ^{232}Th decay chains and ^{40}K produce the majority of the gamma activity within the survey area. For each area where a significantly elevated count rate was observed, a gamma energy spectrum was created both for the anomaly and for a region next to the anomaly. In most cases, the spectrum from the region near the anomaly should be a good representation of the natural background for the region that includes the anomaly. For all regions of the survey area, the background spectra were quite similar. The constant spectral shape indicates that the inferred exposure rates shown in Figures 1 and 2 are internally consistent. Very few gamma rays with energies between 3000 keV and 4000 keV were recorded by the detector system. Hence, to make the spectra more readable, the few gamma rays observed above 3000 keV will not be displayed.

Appendix C describes the process for creating the net (or background-subtracted) gamma energy spectra shown in this section. A net gamma energy spectrum is the resultant spectrum when the background component has been removed. This technique is good for identifying which radionuclides are present but is not necessarily the best way to determine the quantity of the particular radionuclide present.

Using the contour maps made for the MMGC and the thorium extraction procedures, the anomalies were classified into five regions. Two regions are found on the MMGC contour map. The first, labeled Technical Area 1 (TA1), is in the extreme northern part of the survey area; a second region, in the west central area, has anomalies labeled Technical Area 3 (TA3) and Technical Area 5 (TA5) (the labeling is adopted from the 1993 survey). A third region, labeled Demolition Range Road (DRR), is only seen on the MMGC contour and not on the thorium contour. The fourth region, labeled TS1-TS6, is made up of anomalies in the north central area. The fifth region, labeled LRRI, is in the extreme southern part of the survey area. The boxes on Figure 7 indicate the regions where spectra were extracted and where ground measurements were made. On a facing page, Figure 8 displays the net gamma energy spectra for each of the boxed regions. A summary of all of the detected man-made sources is shown in Table 1. Figure 9, entitled *Typical Background Spectrum from Technical Area 3 (TA3)*, is representative of the background spectra taken throughout the survey region. This background spectrum exhibits photopeaks from the major naturally occurring radionuclides: ^{40}K, ^{208}Tl, possibly ^{228}Ac from the thorium decay chain, and ^{214}Bi from the uranium decay chain.

6.4.1 Technical Area 3 (TA3) and Technical Area 5 (TA5)

Spectra labeled TA3-B and TA5 in Figure 8 represent the gamma net energy spectra for two of the four MMGC anomalies identified in Figure 4. The area labeled NEW 1 is the Low Dose Gamma Irradiation Facility, Building 6631, that began operation around 1998. The net spectrum from the region has no discernable peaks and an elevated count rate only in the low-energy portion of the spectrum, very likely caused by scattered photons from some well-shielded ^{137}Cs sources. No MMGC anomaly was observed in this region during the 1993 survey.

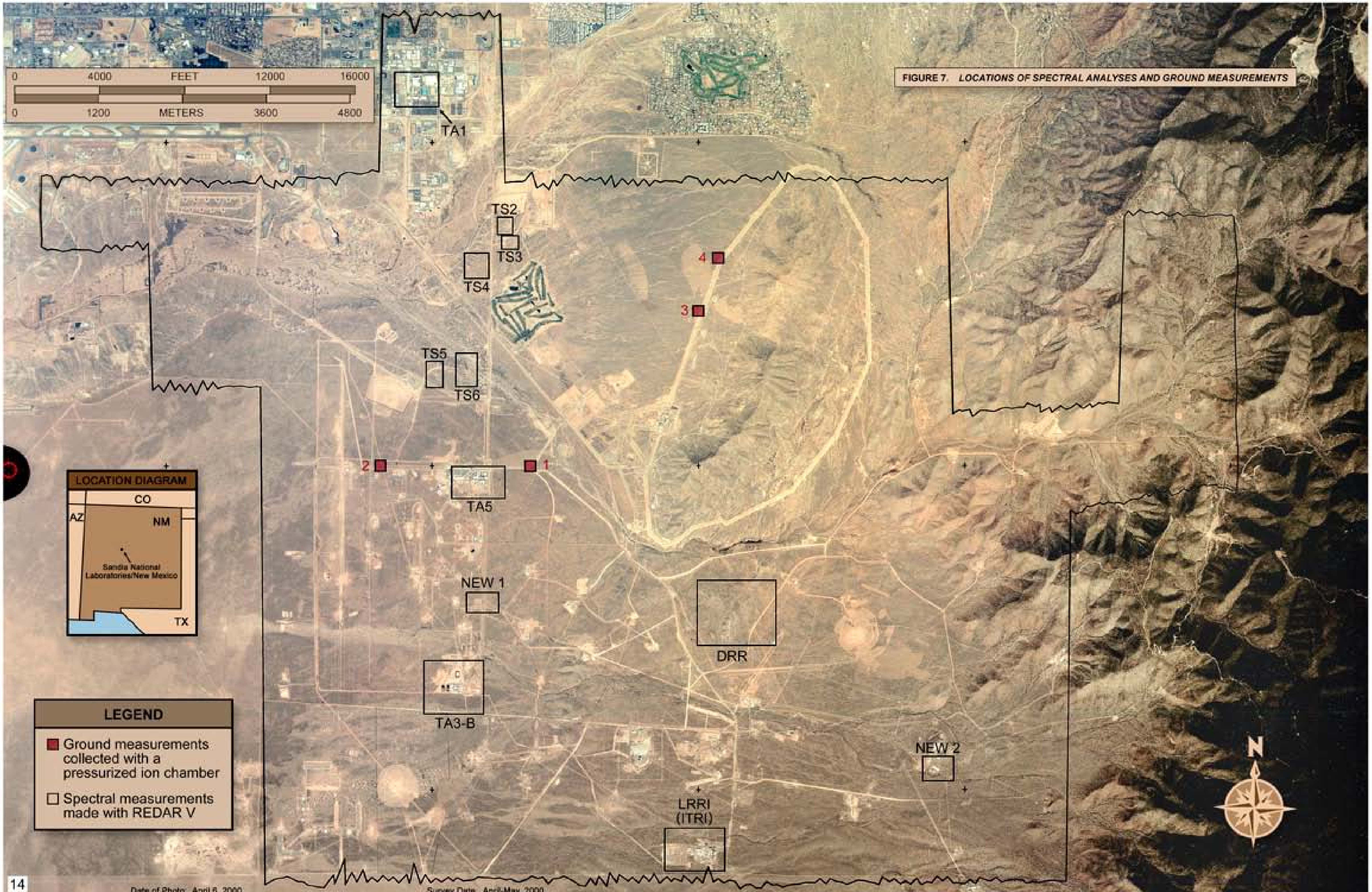

FIGURE 7. *LOCATIONS OF SPECTRAL ANALYSES AND GROUND MEASUREMENTS*

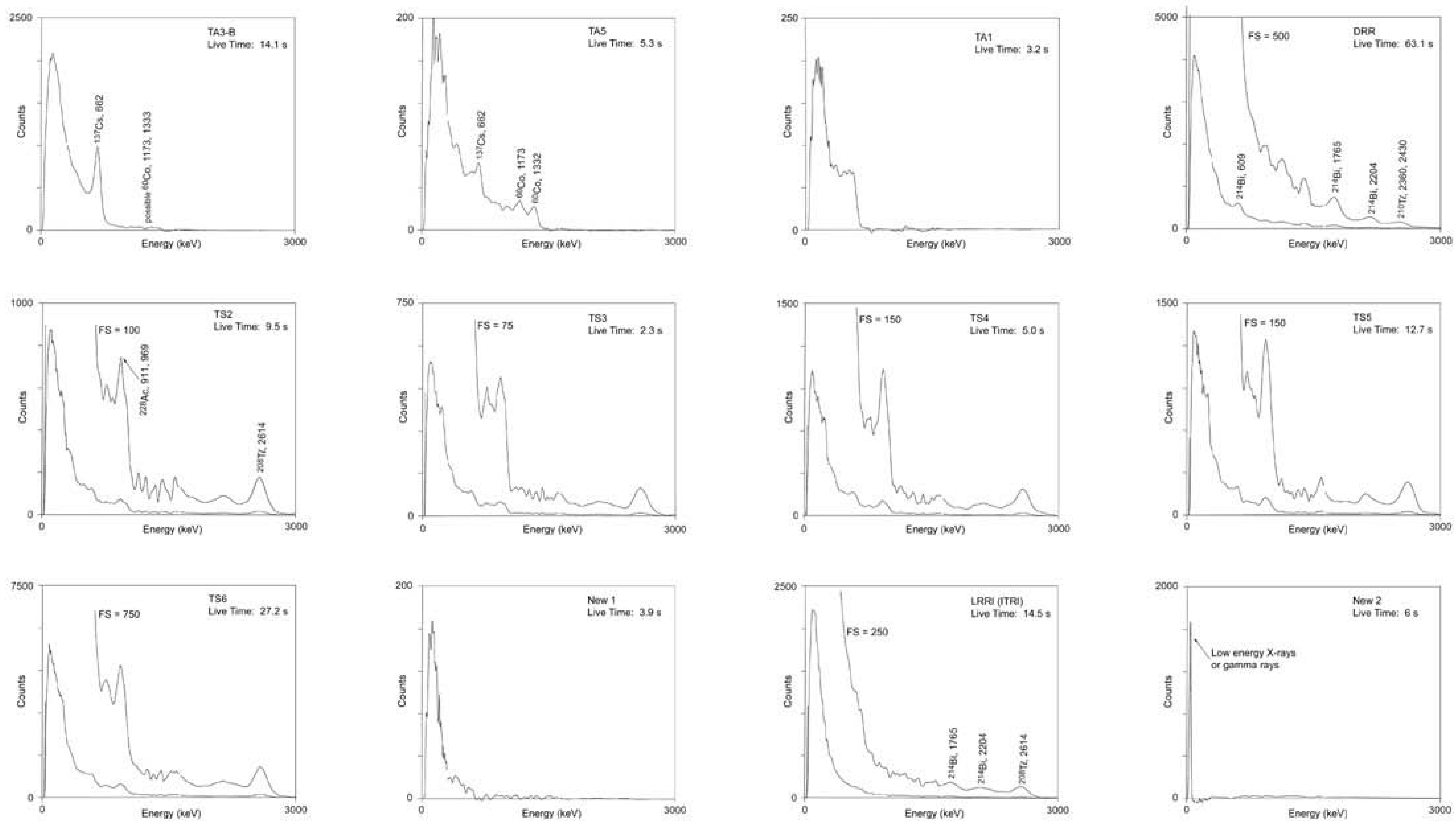

FIGURE 8. ***NET SPECTRA FROM AREAS SHOWN IN FIGURE 7. The net spectra were formed by subtracting a background spectrum from a high-activity spectrum generated from the areas labeled in Figure 7.***

Table 1. Summary of Man-Made Detected Sources

Site ID	Site Description	Isotopes Identified
TA3-B	RMWMF	^{137}Cs, ^{60}Co
TA5	Reactor	^{137}Cs, ^{60}Co
LRRI	LRRI	^{208}Tl, ^{214}Bi
TS	All INWS Training Sites	^{208}Tl, ^{228}Ac
DRR	DRR area	^{210}Tl, ^{214}Bi
TA1	Technical Area 1 buildings	Possible ^{137}Cs source (heavily shielded)
NEW 2	Southwest corner	Possible low-energy X-ray or gamma ray source

The areas labeled TA3-A and TA3-B have undergone some changes since the previous report. In 1993, significant activity was seen at TA3-A from radioactive and mixed waste stored aboveground (it was closed as a landfill in 1989). That waste was moved in 1995-1996 to the Radioactive and Mixed Waste Management Facility (RMWMF) in TA3-B, Building 6920 and immediate area. In the present survey, no significant activity was found in TA3-A.

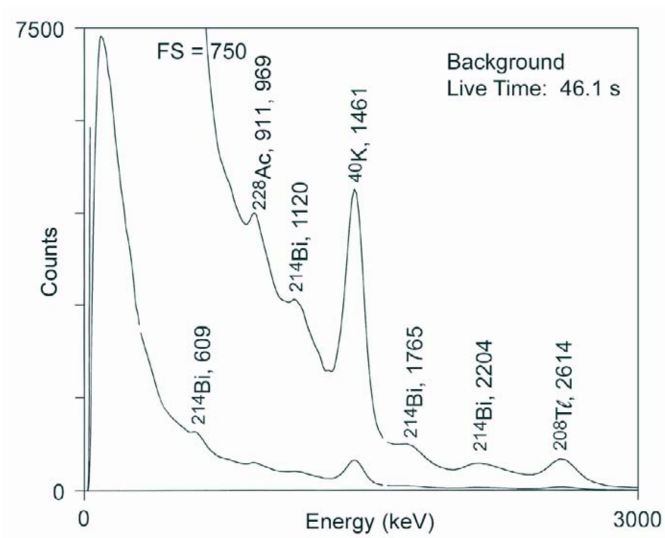

Figure 9. Typical Background Spectrum from Technical Area 3 (TA3).

Significant activity was found in TA3-B where there is storage of materials for the TA5 reactor and radioactive and mixed waste at the RMWMF. The material previously stored at the Storage and Salvage Yard, identified as TA3-B in the 1993 report, has been gone since about 1995. TA3-B shows a very strong ^{137}Cs peak. There is also a hint of double peaks at energies that would be consistent with the presence of small quantities of ^{60}Co.

The spectrum of the nuclear reactor site at TA5 exhibits a strong ^{137}Cs peak and evidence of ^{60}Co consistent with many of the spectra seen over nuclear reactors.

6.4.2 Technical Area 1 (TA1)

The MMGC anomaly depicted in TA1 corresponds to the buildings where radiation sources are used. The spectrum shown in Figure 8 shows no obvious peaks, only an increase in the low-energy portion of the gamma spectrum. The plateau and sharp dropoff of the spectrum at 600 keV is characteristic of a source with a single photopeak that has been smeared by multiple scattering of the gamma rays. It is probable that the buildings provided sufficient shielding so that no identifiable photopeaks were present. In order to obtain a good extraction of the spectral shape for this region, the background spectrum was taken from a region corresponding to the annulus surrounding the contour with the highest count rate in the anomaly. Although this background spectrum will contain some gamma rays scattered from the source, it gives a closer representation of the background contributing in the high-activity region by accounting for attenuation of the natural background gamma rays through the building containing the source. Note also that the count rates are quite low. There are multiple laboratories in this area of TA-1 that contain large, but well-shielded, radioactive sources.

6.4.3 Manzano Area (MAN) and Demolition Range Road (DRR)

No known man-made activities are found in these areas. No anomalies were detected in the Manzano area. This contrasts with the 1993 survey in which several apparent anomalies were displayed on the MMGC contour. For the analysis of the year 2000 survey, an algorithm was employed to account for altitude variations in the coefficient (K_{mm}) used in the MMGC method. The altitude spiral data were used to determine the altitude variation of K_{mm}. This method was not used in the 1993 survey and accounts for the differences in MMGC values between the two surveys in this region.

The man-made anomaly near DRR, the only recognizable landmark in the area, appears to be an enrichment in ^{238}U decay products. The peaks in this spectrum appear to belong to excess amounts of ^{214}Bi and thallium-210 (^{210}Tl). The background spectrum is completely dominated by the isotopes seen in other regions of this survey. The spectrum from this region is similar to that extracted for this area from the 1993 survey.

6.4.4 Lovelace Respiratory Research Institute (LRRI) (formerly known as ITRI)

Figure 8 shows the LRRI net gamma energy spectra for the excess thorium anomalous region identified in Figure 6. The spectrum clearly shows the presence of excess ^{208}Tl from the ^{228}Th decay chain and excess ^{214}Bi from the ^{226}Ra decay chain. The 1993 survey expected to find both ^{228}Th and ^{226}Ra in the area. The ^{137}Cs isotope that was seen in the 1993 survey was not detected in the 2000 survey.

6.4.5 Interservice Nuclear Weapons School (INWS)

As part of the INWS training program, INWS maintains eight training sites located roughly in the north-central region of the survey area. These sites are used to train military personnel responding to emergencies involving the transportation of nuclear materials. The sites consist of wrecked aircraft and ground vehicles seeded with a natural thorium-dioxide ($^{232}ThO_2$) slurry. Additional radioactive materials have been added to these sites at different times over the past 30+ years. This area is indicated on the Th contour by labels TS1-TS6. Sites TS7 and TS8 are small, low-intensity areas that are nearly invisible in the present survey.

The background spectrum from near these eight training sites looks very similar to the TA3 and LRRI background spectra. The method for generating these net spectra is designed to optimize the identification of the radionuclides and may not preserve a proper relationship for the quantity of a given radionuclide between different spectra.

The only definitive radionuclide identified in these spectra is the 2614-keV photopeak from ^{208}Tl. The other gamma rays that should be present from the ^{232}Th decay chain, which appear in all the spectra to varying degrees, are the 583-keV ^{208}Tl photopeak and the 911- and 969-keV ^{228}Ac photopeaks. The ^{228}Ac photopeaks are merged into a single peak.

6.5 Ground-Based Measurements

As discussed earlier, a series of ground-based PIC measurements was performed to check the validity and integrity of the aerial data. Table 2 shows the exposure rates, which were measured *in situ* by a PIC and inferred from the 2000 aerial data. The PIC sample location numbers in the table corresponded with the small numbered red boxes shown in Figure 7. The PIC exposure rates range from 5.4 to 9.5 μR/h. The inferred 2000 aerial exposure rate data ranged from 6.7 to 11.7 μR/h.

Table 2. Comparison of Exposure Rates from Aerial and Ground Measurements

			Exposure Rate[a] (μR/h at 1 meter AGL)	
Area	**Latitude**	**Longitude**	**PIC[b]**	**Aerial[c]**
1	35.00006	106.52641	6.05∓0.92	6.97∓0.12
2	35.00011	106.54990	5.35∓0.92	6.73∓0.04
3	35.02001	106.50011	9.50∓0.71	11.71∓0.10
4	35.02686	106.49697	9.15∓0.71	11.70∓0.10

(a) Reported error represents a one standard deviation statistical counting error.
(b) Measurements were acquired using a counting interval of approximately 240 seconds at a detector height of 1 meter (3.3 feet) using a Reuter-Stokes PIC.
(c) Cosmic-ray contribution has been excluded and the natural radon contribution has been removed.

7.0 COMPARISON OF 1993 AND 2000 SURVEYS

The 1993 and 2000 surveys compared well. From the exposure rate contour and color-filled plots, one can see that the surveys yield nearly identical results over the majority of the survey area. However, a few areas do show significant changes over the past seven years. All of these occur where present or past man-made activity was substantial. The most prominent change occurred in what was designated TA3-A (Mixed Waste Landfill) in the 1993 report. Previously, this region contained high activity, part of which was generated from ^{137}Cs. The area is now indistinguishable from background since the waste was moved to the RMWMF in TA3-B. The MMGC contours for the 2000 survey show two new regions of activity. The first, labeled NEW 1 in the TA region, is the Low Dose Gamma Irradiation Facility that began operation in 1998. The region has relatively lower man-made count rates compared to the other man-made regions. The net gamma energy spectral analysis of the region shows elevated low-energy count rates without any distinguishable peaks. The second region is located in the southeast corner of the survey area and labeled NEW 2. This area has been identified as the Starfire Optical Range operated by the Air Force Research Laboratory. The spectral analysis reveals a strong spike at low energy (approximately 35 keV). This spike was seen over the same area on adjacent flight lines, indicating that the spike is generated by a radioactive source or by continuous high-intensity radiofrequency emissions.

The two regions designated TS7 and TS8 were active in the 1993 survey but were not detected in the 2000 survey. These areas were quite weak in the 1993 survey (1 to 3.2×10^3 cps) and could have dropped below the 2000 survey's minimum detectable limit during the intervening years.

Other differences between the two surveys were relatively minor and are revealed in the analysis of the spectra for the TA3 and TA5 regions. Both areas showed evidence of ^{137}Cs and ^{60}Co, but they were in much different relative abundances compared to the 1993 survey. The ^{60}Co peaks relative to the ^{137}Cs peak were much stronger in the 1993 survey. Table 3 gives a comparison of the highest MMGC levels for the major regions in the 1993 and 2000 surveys.

8.0 CONCLUSIONS

An aerial radiological survey was conducted over the Sandia National Laboratories/New Mexico, Lovelace Respiratory Research Institute, and Kirtland Air Force Base during April and May 2000. The 2000 aerial survey re-flew areas that had been surveyed in 1993. Comparison of the two surveys showed that the background radiation levels were very similar, ranging from 5 to 18 μR/h. In regions of man-made radioactivity, the differences between the two surveys are relatively small. The areas of major difference appear to be associated with the movement of radioactive waste and the use of radioisotopes at a new facility. The data from the aerial survey were compared with a set of ground-based PIC exposure rate measurements. Results from the comparison showed that the PIC results were within 13% to 21% of the inferred 2000 aerial exposure rate data.

Evidence of non-naturally occurring (man-made) radionuclides was detected within the survey area. All of the locations have been identified as known radiological working areas.

Table 3. Man-Made Gross Count Contour Level Comparison
The average count rate over the anomalies was compared between the 1993 and 2000 surveys.

Count Rate (10^3 cps)		
2000	**1993**	**1993 Identification Designators**
ND[1]	3.2-10	LRRI3 (LRRI SE waste building)
ND	3.2-10	LRRI2 (LRRI NW waste building)
3.2-10	10-32	LRRI1
1-3.2	1-3.2	DRR
<1	32-100	TA3-A (Mixed Waste Landfill)
10-32	3.2-10	TA3-B (RMWMF)
3.2-10	3.2-10	TA5 (reactor)
1-3.2	3.2-10	TS6 (INWS Training Site #6)
1-3.2	3.2-10	TS5 (INWS Training Site #5)
1-3.2	3.2-10	TS4 (INWS Training Site #4)
1-3.2	1-3.2	TS3 (INWS Training Site #3)
3.2-10	1- 3.2	TA1-B (Building 867)

[1]ND – not detected

AERIAL SURVEY PARAMETERS AND RESULTS

Parameters

Survey Site:	Sandia National Laboratories/New Mexico and surrounding areas
Survey Dates:	April 23-May 3, 2000
Nominal Site Elevation:	1600-2100 meters (5300-6900 feet) mean sea level
Survey Altitude:	46 meters (150 feet)
Line Spacing:	76 meters (250 feet) along north-south lines
Aircraft Speed:	70 knots (36 meters/second)
Survey Coverage:	approximately 130 $kilometers^2$ (50 $miles^2$)
Line Direction:	North-South
Base of Operation:	Ross Aviation at the Albuquerque International Airport/ Kirtland Air Force Base
Aircraft:	Bell-412 helicopter (tail number ND411DE)
Navigation System:	Omni-Star 3000L RDGPS (Space-Based)
Detector Arrays:	Twelve 2- x 4- x 16-inch NaI(Tl) logs
Acquisition System:	REDAR V

Results

Cosmic Ray Contribution:	6.0-6.5 μR/h (depending on elevation)
Air Attenuation Coefficient:	0.00515 m^{-1} (0.001570 $feet^{-1}$)

Data Processing Items:

- Gamma Exposure-Rate (Gross Count) Contour
- Man-Made Gross Count Contour
- Excess Thorium Contour
- Individual Net Gamma-Ray Energy Spectra

Conversion Factors

1 foot = 0.3048 m
1 μR/h = 8.76 mR/yr = 8.37 mrem/yr
1 μR/h = 1336 cps at survey altitude of 46 meters (150 feet) AGL

Figure A-1 Bell-412 Helicopter with Detector Pods. **The white detector pods, mounted on the sides, each contain six detectors.**

SURVEY PROCEDURES

The body of the report gave an overview of the process employed to collect the data for this survey. This appendix presents details of that process for those readers interested in a more precise description.

B.1 Helicopter Positioning

The position of the helicopter was established using two systems: a real-time differential global positioning system (RDGPS) and a radar altimeter. The RDGPS is an OmniStar 3000L (space-based L-band) navigational system that provides continuous positional informational accurate to 3 meters (10 feet) using a minimum of 4 of the 24 Global Positioning System satellites orbiting the earth at a very high altitude. 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%.

B.2 Gamma Ray Data Collection

The helicopter has two detector pods mounted on the sides. Each of the two detector pods carries six 2- x 4- x 16-inch rectangular, thallium-activated sodium iodide, NaI(Tl), gamma-ray scintillation detectors, totaling 12 log detectors. When a gamma ray interacts with the NaI(Tl) crystal, the crystal creates a flash of light whose intensity is proportional to the amount of energy deposited in the crystal. This light flash is converted into a pulse of electrons, which is amplified and shaped by a photomultiplier tube attached to the crystal. The voltage pulses from the individual detectors, matched in amplitude and combined with summing amplifiers, feed into a 1024-channel analog-to-digital converter (ADC) with its gain adjusted to provide a resolution of 4 keV per channel. However, when the gamma data are collected and recorded every second, there are very few counts in many of the channels, especially the higher-energy channels. To facilitate the output of the one-second duration spectra onto disk every second and still preserve most of the useful energy information, the Radiation and Environmental Data Acquisition and Recorder system, Model V (REDAR V) selectively compresses the data according to Table B-1. The low-energy data (below 300 keV) are not compressed at all, the middle energies (300-1620 keV) are compressed slightly with three channels merged into one channel, and the high energies (1620 keV and up) are compressed the most with nine channels summed together into one output channel.

Table B-1. REDAR V Spectral Data Compression
To facilitate the data storage onto hard disk drives, the energy spectrum is compressed.

Input Channel (at 4 keV/channel)	Energy Range (keV)	Output Channel	Output ΔE (keV/channel)
0-75	0-302	0-75	4
76-405	302-1622	76-185	12
406-1017	1622-4070	186-253	36
1018-1023	4070 and up	254	
		255	value set to 0

In addition to the 12 rectangular detector logs discussed above, the output from one of the detectors is also routed into a separate ADC. This separate, parallel data acquisition path provides coverage for higher-intensity radiation fields. If the count rate in the ADC that is processing the pulses from all 12 detectors gets too high, pulse pileup will shift the energy of subsequent pulses and distort the shapes of the photopeaks in the spectra (rendering the data nearly useless). When this occurs, data analysis is shifted to the data from the single detector.

The gains of the preamplifiers and summing circuit amplifiers are carefully matched before the equipment goes into the field. They are checked before each flight to ensure that any gain shift of an individual amplifier is small enough to be ignored.

As with all radiation detection systems, there is a counting rate at which the performance of the system begins to deteriorate. With the present system, pulse pileup problems begin to produce noticeable distortions in the energy spectrum when the count rate exceeds approximately 50,000 counts per second (cps). Routing the output of a single detector into its own ADC extends the detectable range by a factor of 12 (since the pileup problems will not appear until the output of this single detector reaches the 50,000-cps limit).

The REDAR V is a portable, real-time, Unix-based multiple-processor data acquisition and analysis system capable of operating in severe environments. The REDAR V runs multiple, dedicated processors and operating systems including four 4096-channel multichannel analyzers, 16 analog inputs and 6 serial input/output ports that can gather a multitude of data. The typical data that are collected include 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.

B.3 Data Processing

Data processing was initiated in the field using a computer analysis laboratory installed in a mobile van located near the survey area. Data were examined before leaving the area, and a preliminary analysis was completed to ensure that the raw data were satisfactory. The same type of computer analysis laboratory system was used to complete the data analysis process at the Remote Sensing Laboratory in Las Vegas, Nevada.

Standard techniques for analyzing the survey data were used: 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 (^{137}Cs and ^{60}Co) were determined through differences between total counts in appropriate gamma energy spectral windows (Appendix C).

DATA ANALYSIS PROCEDURES

The body of the report gave an overview of the process employed to analyze the data for this survey. This appendix presents details of that process for those readers interested in a more precise description.

There are several methods of data processing that may be employed to view the data. The most obvious is the Gross Count (GC) or terrestrial exposure rate method, which is a simple integration of all gamma rays detected at each location. The GC Method calculates the exposure rate for each sample and presents the results as a series of equal exposure rate contours on a map or photograph of the survey area. With this display, variations in the whole radiation field may be easily seen.

However, variations in the total radiation field are not always of most interest. Often what is important is changes in isotopic concentrations (variations in the energy composition of the field) or the ability to track a single radioactive isotope throughout the survey area. The Man-Made Gross Count (MMGC) method is another integral-based analysis method. It locates regions in which the energy content of the gamma ray spectrum deviates significantly from that of the natural background spectrum.

A third data processing method often applied to the data looks for a specific isotope throughout the survey area. This method relies on mapping the observed count rate in a narrow energy window minus a suitably chosen background window to show how that isotope is distributed throughout the survey area.

C.1 Gross Count (GC) Method

For the purposes of this survey, the gross count of a gamma ray energy spectrum is the integrated count rate in the energy range from 38 keV to 3026 keV. The lower energy limit is the effective lowest energy that the airborne detector systems can reliably record. In these surveys, almost no gamma rays of interest have energies above the upper energy limit. The exact energy values depend on how the spectral data are compressed and stored on tape (see Appendix B).

$$E_G = \frac{(C_G - B)}{1336} e^{\mu\,(H - 150)} \qquad \text{(C-1)}$$

where

- μ = the gamma-ray air attenuation coefficient (0.001570 feet^{-1})
- B = background count rate at the survey altitude (cps)
- C_G = total terrestrial or gross count rate at the survey altitude (cps)
- E_G = the gamma ray exposure rate microRoentgens per hour (μR/h) extrapolated to 1 meter (3.3 feet) AGL
- H = the aircraft height above the ground during the measurement (feet)

The factor in parenthesis (C_G-B) is the net count rate (from terrestrial sources) for each one-second data sample, where C_G changes each second and B is determined from flying a common test line at the beginning and end of each flight. B is a measure of the cosmic-ray, radon, and equipment/ aircraft contributions to the radiation field at the flight altitude. The exponential factor corrects this net count rate for variations in altitude. For example, if the aircraft is momentarily too high, this factor raises the net count rate to what it would have been if the aircraft had been at the desired survey altitude of 46 meters (150 feet).

The factor of 1336 in the denominator is the conversion from counts per second, measured at an altitude of 46 meters (150 feet), to μR/h measured at 1 meter (3.3 feet) above the ground. This conversion factor was determined from a documented, land-based, calibration test line located near Lake Mohave, Nevada. The conversion factor assumes a uniformly distributed radiation source over an area large compared to the field-of-view of the detector and one which has an energy distribution similar to that of natural background.

C.2 Man-Made Gross Count (MMGC) Method

The Gross Count Method maps the variations in the total radiation field. This is not always the most useful presentation of the data. Changes in the GC data may indicate the presence of man-made radionuclides or they may simply indicate changes in the radionuclide abundances caused by changes in the types of rocks. Similar changes in the GC data may be caused by an abrupt change in the vegetation coverage. Generally, for purely background radiation, the shape (energy distribution) of the gamma-ray energy spectrum is fairly constant and variations in the GC data can be represented by scaling the energy spectrum measured at one location to fit the new location.

The Man-Made Gross Count (MMGC) Method is a means of identifying regions in the survey area where the shape of the energy spectrum deviates significantly from the shape of the background spectrum. The MMGC is very sensitive to small changes in the abundance of man-made isotopes while being very insensitive to large changes in the abundance of natural isotopes.

The technique relies on two basic characteristics. First, the energies of naturally occurring isotopes occur throughout the energy range in which the system is designed to observe (0-4000 keV). Second, considering the man-made isotopes that have half-lives long enough to be dispersed from their creation site and then be seen by an aerial survey, man-made isotopes generally have gamma ray energies limited to less than about 1400 keV. This energy is approximately midway between the 1330-keV peak of cobalt-60, a commonly observed man-made isotope, and the 1460-keV peak of potassium-40, a common, naturally occurring isotope.

This situation can be exploited by measuring the gamma ray spectrum in a background region known to contain only naturally occurring isotopes. This background region provides a ratio of the low-energy-to-high-energy count rate, which will be applied to succeeding measurements to find the gamma ray spectrum attributable to activity by man-made isotopes in the area. This process is good at locating regions of man-made isotopes, but it can also find false-positive regions which deviate from the originally measured background spectrum, simply because they have different relative abundances of the naturally occurring radioactive isotopes embedded in their rock formations. Usually, the number of regions identified by the MMGC method is small enough that the gamma energy spectrum for each region can be inspected and a judgement of which isotopes are present be made easily.

Using a gamma energy spectrum from an area known to contain only naturally occurring radioactive isotopes, the ratio of the number of counts in the spectrum below a cutoff energy to those above that energy is defined as K_{MM}. Equation C-2 shows this ratio, where the cutoff energy (1394 keV) is determined by details of how the spectrum is compressed and stored (see Appendix B). Almost no gamma rays are observed beyond the thallium-208 peak at 2614 keV, so an arbitrary upper limit of 3000 keV (shifted up to 3026 keV to match the energy of a particular spectral channel number) is chosen as the end of the high-energy range.

$$K_{MM} = \frac{\sum_{E=38}^{1394} c(E)}{\sum_{E=1394}^{3026} c(E)} \qquad \text{(C-2)}$$

where

- $c(E)$ = energy spectrum containing the number of gamma-rays collected at the given energy, E, per second.
- K_{MM} = the ratio of the low-energy counts to high-energy counts in the background (naturally occurring radionuclides) spectrum

This ratio, although nearly constant over the entire survey area, is adjusted flight by flight to compensate for minor differences due to airborne radon, equipment setup, and changes in the geology. The MMGC rate represents the integrated counts observed below the cutoff energy minus the integrated counts expected below the cutoff energy. The MMGC rate (C_{MM}) is given in Equation C-3:

$$C_{MM} = \sum_{E=38}^{1394} c(E) - K_{MM} \sum_{E=1394}^{3026} c(E) \qquad \text{(C-3)}$$

where the other terms in the equation were defined above. In regions where there are no man-made isotopes, this equation reduces to statistical fluctuations about zero. In past studies, the MMGC method described has been shown to be sensitive to low levels of man-made radiation (<1 μR/h) even in the presence of large variations in the natural background. In practice, this algorithm is a general search tool to locate regions of anomalous radioactivity.

C.3 Gamma Energy Spectral Analysis

The MMGC algorithm is very general and is sensitive to any change in the low-energy portion of the spectrum. It cannot tell us what causes the change — whether a true man-made isotope is present in this region, whether the increased low-energy gamma rays are caused by naturally occurring isotopes whose gamma rays underwent more inelastic scatterings before reaching the detectors (thus distorting the energy profile of the spectrum), or whether the isotopic composition of the background spectrum in this region of the survey is significantly different from where K_{MM} was determined (for example, granite versus limestone). Once a region appears in the man-made contours, the gamma energy spectrum is searched for individual isotopes. An analysis of the gamma energy spectrum will determine what isotopes are present in the spectrum and will determine which of the three scenarios above caused the MMGC deviation.

Generally, the large background field (due to the naturally occurring isotopes) is not of interest, only the spectrum due to the man-made isotopes. Unfortunately, the number of counts at any given energy is so small as to make the identification of a particular isotope very difficult. To increase the number of counts in the spectrum (and thus produce better statistics), the spectra from neighboring locations are combined to produce a single spectrum showing the radiation measured over some larger area.

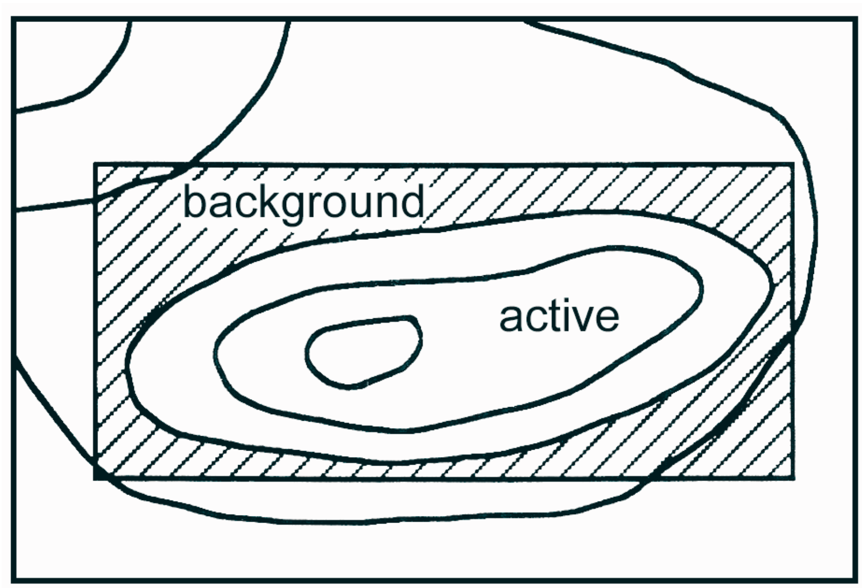

Figure C-1. Defining Active and Background Regions around Radiation Anomalies. **For the area shown, the active region consists of all survey spectra within the rectangle and enclosed by the outer contour line. The background region consists of all spectra outside the outer contour line but inside the rectangle.**

Figure C-1 shows how the net spectra shown throughout this report are created. The high activity area is divided into an active and a background region. The contour levels used to define the active and background regions are usually determined by the MMGC levels since the man-made activity regions are usually the ones under investigation when creating these spectra. (The active and background boundaries may be defined by any means; GC contour levels or simple rectangular boxes may also be used.) The active region of the box consists of the spectra contained in the area bounded by the outer contour level. The background region of the box consists of the spectra residing inside the rectangular box but outside the outer contour level. This partitioning ensures that the background spectrum is representative of the geology near the anomaly, but there will be <u>some</u> contribution of man-made radioactivity in the background region. The net spectrum is the result of subtracting the background spectrum, normalized by the ratio of the active spectrum's live-time to the background spectrum's live-time, from the active spectrum.

$$c_{Net}(E) = c_{Active}(E) - \frac{T_{Active}}{T_{Bkg}} c_{Bkg}(E) \qquad \text{(C-4)}$$

where

$c_{Active}(E)$ = the counts in the active energy spectrum at the energy E
$c_{Bkg}(E)$ = the counts in the background energy spectrum at the energy E
$c_{Net}(E)$ = the counts in the net energy spectrum at the energy E
T_{Active} = the total live-time for the spectrum comprised of all active-region spectra
T_{Bkg} = the total live-time for the spectrum comprised of all background-region spectra

This technique produces a net spectrum, which has very little contribution from the naturally occurring radionuclides in the region and makes the identification of the remaining isotopes fairly easy. Its one major drawback is that it does not necessarily produce a true indication of the strength of the isotopes seen in the net spectrum. That is, comparing the intensity of an isotope in one net spectrum with the intensity of that same isotope in another spectrum may not be very meaningful.

C.4 Isotopic Extraction Algorithms

The algorithm employed in the search for a particular isotope is quite similar to the MMGC method. The major difference is that instead of using the full gamma ray energy spectrum, only two or three small pieces of it are used. The two-window algorithm is the simplest of several window algorithms in use. It employs a narrow, primary window centered on the energy of the specific isotope's photopeak. A second window, located at higher energies, assumes that the background counts in the primary window are proportional to the counts recorded in the second window. The background window may abut the primary window or it may be separated from it in energy. The proportionality factor is determined in a region of the survey that does not contain any of the specific isotope, so that the number of counts in the primary window is directly related to the number of counts in the background window. The equation for the two-window algorithm is:

$$C_{2\text{-Window}} = \sum_{E=E_1}^{E_2} c(E) - K_2 \sum_{E=E_3}^{E_4} c(E) \qquad \text{(C-5)}$$

where

$C_{2\text{-Window}}$ = the net counts in the primary window
$c(E)$ = the counts in the gamma ray energy spectrum at the energy E
E_n = the limiting energies of the windows ($E_1<E_2\leq E_3<E_4$)
K_2 = the ratio of the counts in the primary window to the counts in the background window in a clean region of the survey area

If the principle source of background gamma rays in the primary window is from scattered gamma rays from photopeaks at higher energies, this is a good assumption. If there are isotopes other than the one of interest with photopeaks in the primary window, then this algorithm will fail. For example, protactinium-234m is a member of the uranium-238 decay chain and actinium-228 is a member of the thorium-232 decay chain. Both of these radionuclides occur naturally and both have several gamma rays in the 910-970 keV range. Attempting to map the distribution of one radionuclide using a window in this energy range produces very marginal results since it is very difficult to determine whether changes in the count rate are caused by fluctuations in the isotope of interest or by fluctuations in the concentration of the other isotope.

If a region free of the specific isotope (clean region) cannot be found or if the composition of the other isotopes changes drastically in the clean region, then a simple multiplicative factor will not relate the counts in the primary window to the counts in the background window. To ease this problem, the three-window algorithm employs a background window on each side of the primary window. (The two background windows generally abut the primary window in energy.) This algorithm assumes that, for any spectrum, the number of background counts in the primary window is linearly related to the counts in the two background windows. The equation for the three-window algorithm is:

$$C_{3\text{-Window}} = \sum_{E=E_2}^{E_3} c(E) - K_3 \left(\sum_{E=E_1}^{E_2} c(E) + \sum_{E=E_3}^{E_4} c(E) \right) \qquad \text{(C-6)}$$

where

$C_{3\text{-Window}}$ = the net counts in the primary window
$c(E)$ = the counts in the gamma ray energy spectrum at the energy E
E_n = the limiting energies of the windows ($E_1<E_2<E_3<E_4$)
K_3 = the ratio of the counts in the primary window to the counts in the two background windows in a clean region of the survey area

The three-window algorithm is also very useful in extracting low-energy photopeak counts where the shape of the Compton-scatter contributions from other isotopes is changing significantly. The three-window algorithm is commonly used to extract the counts in the cesium-137 photopeak.

REFERENCES

1. Riedhauser, S.R., *An Aerial Radiological Survey of the Sandia National Laboratories and Surrounding Area*, Report No. EGG-11265-1030, EG&G/EM, Las Vegas, Nevada, June 1994.

2. Boyns, P.K., *An Aerial Radiological Survey of the United States Department of Energy's Sandia National Laboratories and Inhalation Toxicology Research Institute*, Report No. EGG-1183-1779, EG&G/EM, Las Vegas, Nevada, May 1982.

3. Lindeken, C.L., *et al.*, "Geographical Variations in Environmental Radiation Background in the United States," *Proceedings of the Second International Symposium on the Natural Radiation Environment, August 7-11, 1972, Houston, Texas: Vol. 1*, National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, 1972, pp 317-332.

4. Klement, A.W., *et al.*, *Estimate of Ionizing Radiation Doses in the United States 1960-2000*, U.S. EPA Report ORP/CSD72-1, U.S. Environmental Protection Agency, Washington, D.C., August 1972.

DISTRIBUTION

DOE/DP

J.W. Cook III, Lt. Col.	(1)

DOE/NSIC

R. S. Scott	(1)

DOE/NV

S.P. Curtis	(1)

DOE/AL

S.D. Lacy	(10)

SNL/NM

H.D. Oldewage	(10)

BN

C.M. Bluitt	RSL-N	(1)
N.F. Cochrane	RSL-N	(1)
P.P. Guss	RSL-N	(1)
T.J. Hendricks	RSL-N	(1)
S.D. Liedle	LVAO	(1)
T.G. Moser	RSL-A	(1)
D. L. Prout	RSL-N	(1)
H.J. Saxton	LVAO	(1)
A.J. Will	RSL-N	(1)

OSTI electronic copy (1)

RESOURCE CENTERS

Public Reading Facility	(1)
RSL- Andrews	(1)
RSL-Nellis	(30)
TIRC	(1)