



United State Environmental Protection Agency

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## **Aerial Radiological Surveys Ambrosia Lake Uranium Mines Ambrosia, NM**

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## Executive Summary

From August 22 through August 25, 2011, the EPA Aerial Spectrophotometric Environmental Collection Technology (ASPECT) program conducted aerial surveys of nearly 22,000 acres of land near Ambrosia Lake, New Mexico. This area of New Mexico was extensively mined for Uranium ore from the 1950s until the 1980s. The aerial survey was conducted to determine if residual contamination was present in areas exceeding natural background concentrations. In addition, nearly 375 aerial and oblique photographs were taken.

Roughly 11,000 one-second spectra were collected and analyzed for total count rate, exposure rate, and uranium concentration. Radiological analysis results indicate the following:

- Approximately 20 distinct areas had exposure levels that exceeded 20 microRoentgens per hour ( $\mu\text{R/h}$ ).
- Approximately 1,700 acres of land exceeded 5 picoCuries per gram (pCi/g) of equivalent Uranium (as measured by the gamma emission from Bismuth-214).
- Exposure rates were measured as high as 435  $\mu\text{R/hr}$  and equivalent uranium concentrations as high as 350 pCi/g during this survey.

The terrestrial background exposure rate in areas not associated with elevated readings on the site ranged between 5 to 10  $\mu\text{R/h}$ . These estimates exclude cosmic radiation which is estimated to be about 7.4  $\mu\text{R/h}$  based on the altitude of about 7000 feet. Areas associated with elevated radiation levels ranged from 20  $\mu\text{R/h}$  to 435  $\mu\text{R/h}$ .

Approximately 300 downward looking aerial and 75 oblique aerial photographs were taken over the entire survey area. These photos are meant to record the actual conditions of the site at the time of the survey and may indicate differences from the standard Google Earth images. These are available for viewing in the Google Earth application.

## Acronyms and Abbreviations

AGL	above ground level
ASPECT	Airborne Spectral Photometric Environmental Collection Technology
Bi	bismuth
Ci	Curie
cps	counts per second
EPA	Environmental Protection Agency
eU	Equivalent Uranium based on $^{214}\text{Bi}$ region of interest
FOV	Field of view
ft	feet
FT-IR	Fourier Transform Infrared detector
FWHM	full width at half maximum
g	gram
GEM	Gamma Emergency Mapper
GPS	Global Positioning System
IR	Infrared
K	potassium
MeV	Mega electron volts
NaI(Tl)	sodium iodide thallium drifted detector
NORM	Naturally Occurring Radioactive Material
pCi	picocurie ( $10^{-12}$ Curies)
R	Roentgen
Ra	radium
Rn	radon
TENORM	technologically enhanced naturally occurring radioactive material
Th	thorium
Tl	thallium
U	uranium
$\mu\text{R/hr}$	microRoentgen per hour ( $10^{-6}$ R/hr)

## 1.0 Introduction

The purpose of the radiological survey was to identify areas of elevated surface uranium contamination. While subsurface concentrations of gamma-emitting isotopes can be detected by the instrumentation, self-shielding of the ground limits its effective detection to a depth of about 30 centimeters.<sup>1</sup>

## 2.0 Background and Survey Area Descriptions

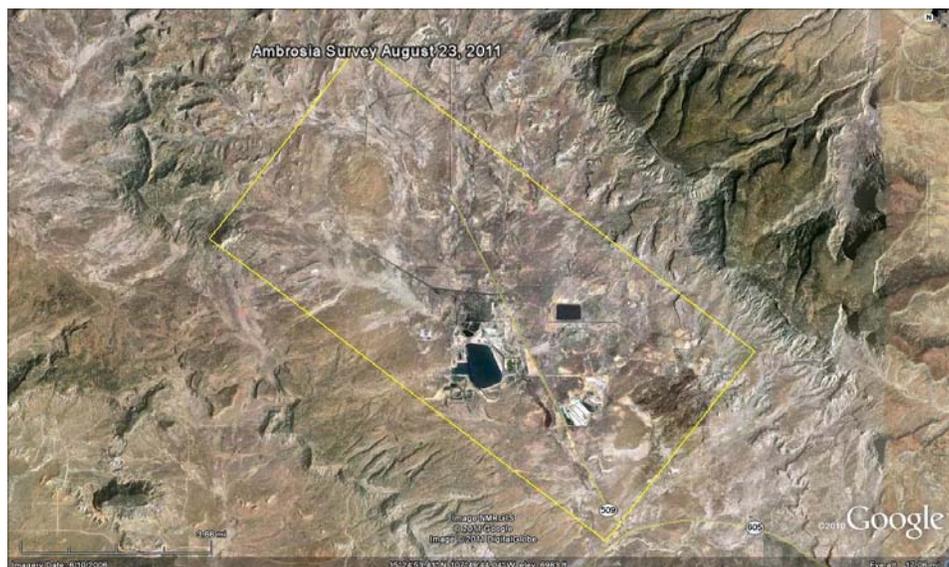
The Grants Mineral Belt is located in Cibola and McKinley counties of New Mexico, near the town of Grants. This area was the site of extensive uranium mining from 1950-until the early 1980's. During this time the economy of the region changed from agriculture to uranium mining and uranium ore processing. Most uranium mining stopped in the recession of 1982-1983.

In 2007, EPA Region 9 began a project in coordination with the Navajo Nation to investigate residences on the Navajo Indian Reservation located in parts of Arizona, New Mexico, and Utah for radioactive contamination caused by uranium mining on the reservation. In 2009, EPA Region 6 initiated a similar project to investigate radioactive contamination in and around residences near uranium mining and ore processing areas outside of the Navajo Reservation in the Ambrosia Lake and Laguna sub-districts of the Grants Mineral Belt area of northwestern New Mexico. These areas will include non-Navajo lands adjacent to the eastern boundary of the Navajo Reservation with public and/or private ownership as well as lands within the Laguna Pueblo.

The Ambrosia survey area was located approximately 15 miles north of Grants, New Mexico and 100 miles west of Santa Fe. The survey area comprised of approximately 22,000 acres and include the former Ambrosia Lake Mill, the Rio Algom Mill, and 27 legacy Uranium mines.

Image 1 below depicts the area of the aerial survey conducted for this report.

**Image 1: Survey boundaries for radiological Ambrosia survey.**



### 3.0 Flight Parameters



The ASPECT aircraft used the following flight procedures for data collection on August 23<sup>rd</sup> and 25<sup>th</sup>, 2011:

Altitude above the ground level (AGL):

- 300 feet for radiological survey
- 5,000 feet for photography

Target Speed: 100 knots (115 mph)

Line Spacing:

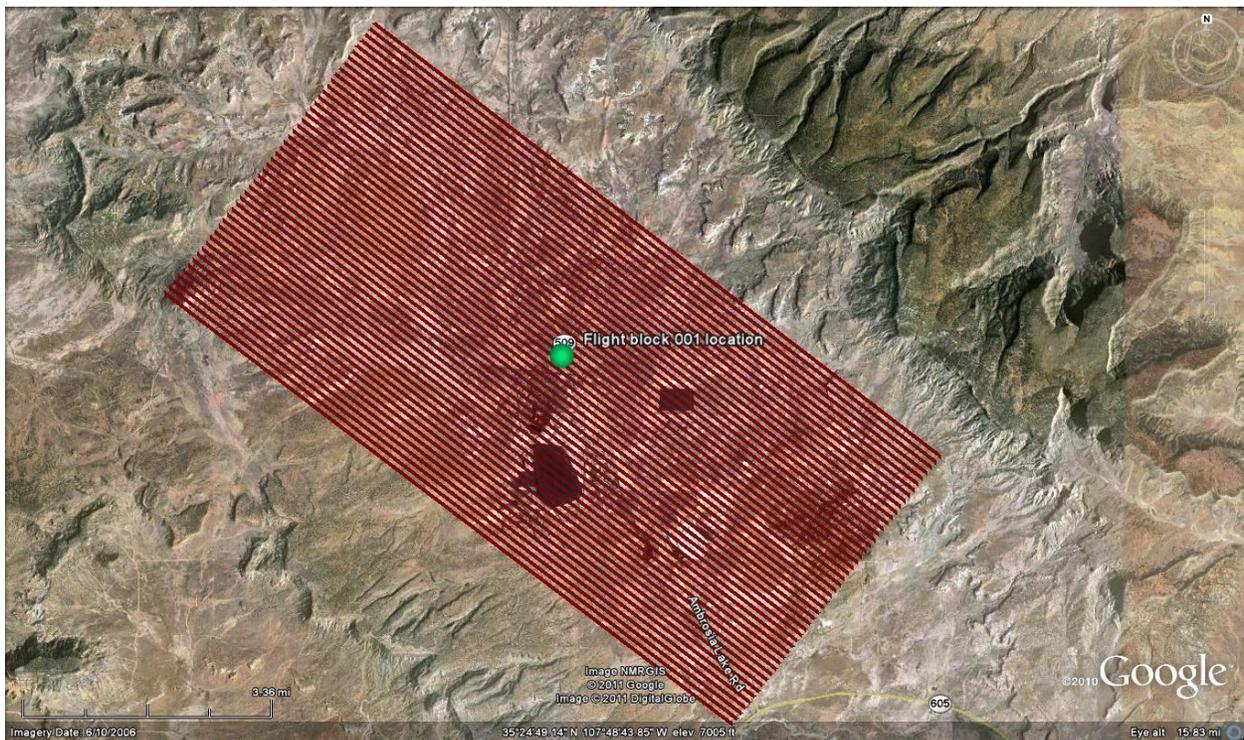
- 500 feet for radiological survey
- 3,000 feet for photographic survey

Data collection frequency:

1 per second for radiological survey

The survey area contained 49 flight lines spaced 500 feet apart and are depicted below.

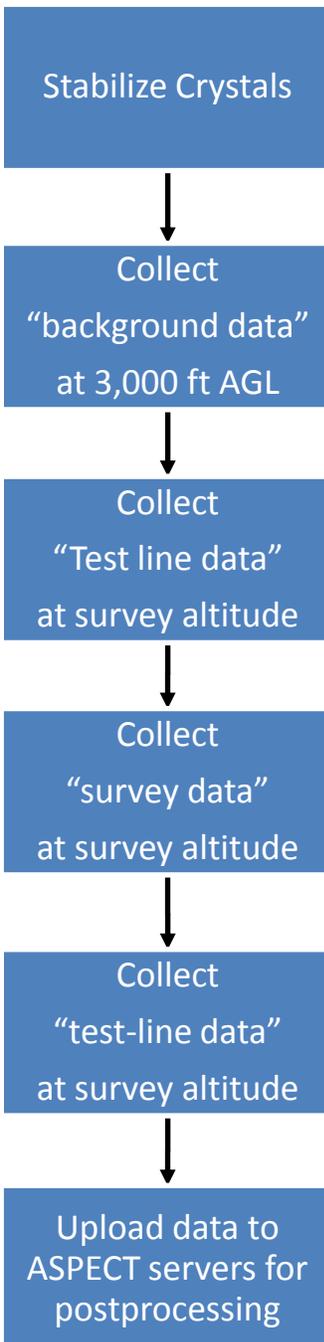
**Image 2:** Flight lines for the August 23 radiological survey.



## 4.0 Data Analysis

A unique feature of the ASPECT chemical and radiological technologies includes the ability to process spectral data automatically in the aircraft with a full reach back link to the program QA/QC program. As data is generated in the aircraft using the pattern recognition software, a support data package is extracted by the reach back team and independently reviewed as a confirmation to data generated on the aircraft.

Radiological spectral data are collected every second along with GPS coordinates and other data.



These data are subject to quality checks within the Radiation Solutions internal processing algorithms (e.g. gain stabilization) to ensure a good signal. If no problems are detected, a green indicator light notifies the user that all systems are good. A yellow light indicates a gain stabilization issue with a particular crystal. This can be fixed by waiting for another automatic gain stabilization process to occur or the user can disable the particular crystal via the RadAssist Software application. A red light indicates another problem and would delay the survey until it can be resolved. If any errors are encountered with a specific crystal during the collection process, an error message is generated and the data associated with that crystal are removed from further analyses.

The data collection process used for this survey consisted of powering up the crystals and initiating the automated gain stabilization process. This process uses naturally occurring radioelements of potassium, uranium, and thorium to ensure proper spectral data collection.

The “background data” include radiation contributions from radon, cosmic, and aircraft sources. It does not include terrestrial radiation. Ideally, these data are collected over water at the survey altitude but when a large body of water does not exist, research has shown that an acceptable alternative is to collect data 3,000 ft above the ground (AGL).<sup>1</sup> At this altitude atmospheric attenuation reduces the terrestrial radiation to a negligible level but is still low enough that cosmic radiation is not significant.

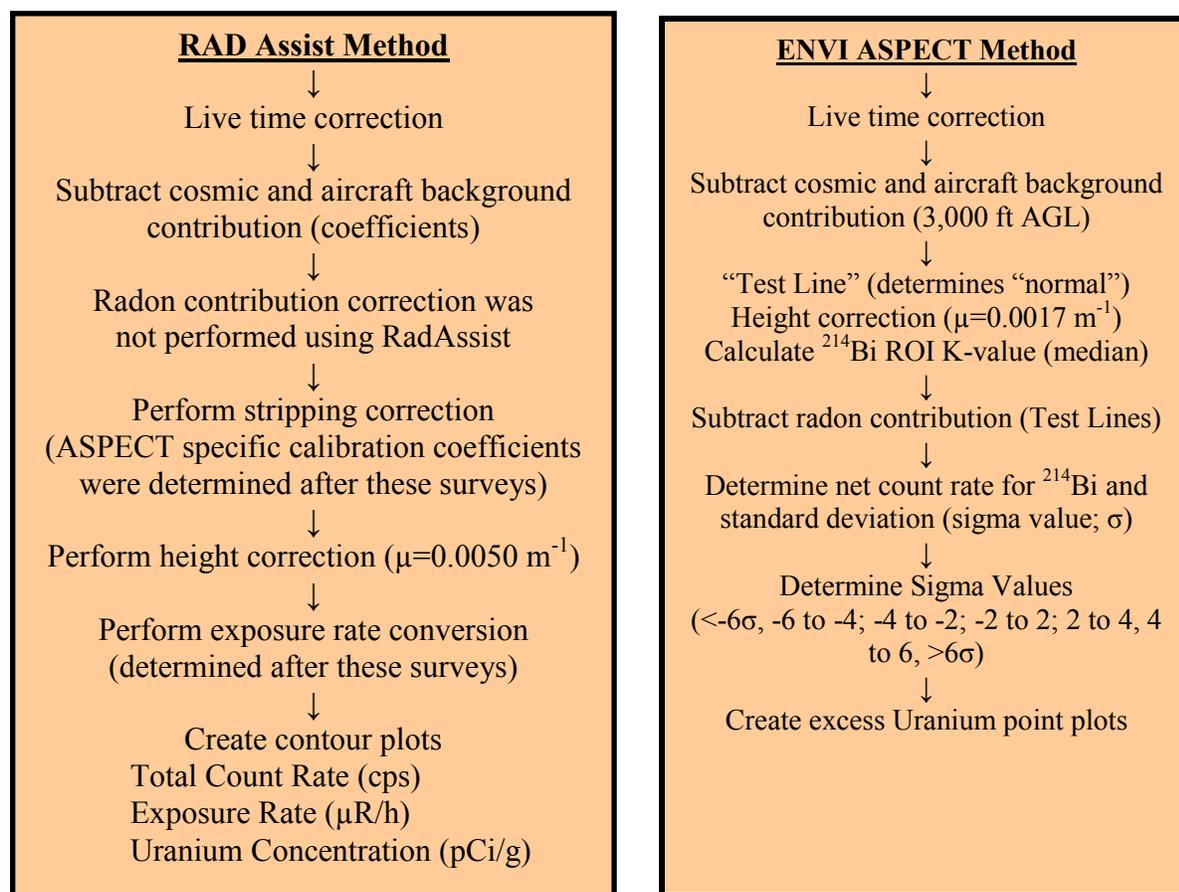
A “test line” is flown at survey altitude (300 feet AGL) near the survey area that is not expected to contain any elevated concentrations of NORM or man-made radionuclides. A second line is flown at the conclusion of the survey. If the difference between these lines exceeds 10 percent, then the survey data are corrected using a time-dependent linear interpolation correction factor.

Two software packages were used to generate products for this survey. The first was RadAssist Version 3.18.2.0 ([Radiation Solutions, Inc.](#), 386 Watline Avenue, Mississauga, Ontario, Canada) which produced contour plots of:

- (1) **total count rate** (counts per second),
- (2) **exposure rate** (microRoentgen per hour),
- (3) **concentration contours for uranium** (pCi/g).

The second software package was ENVI<sup>®</sup> Version 4.8; ASPECT Version 8.6.8.0, Build 1107221901 (ITT Visual Information Solutions, Boulder, CO) which produced:

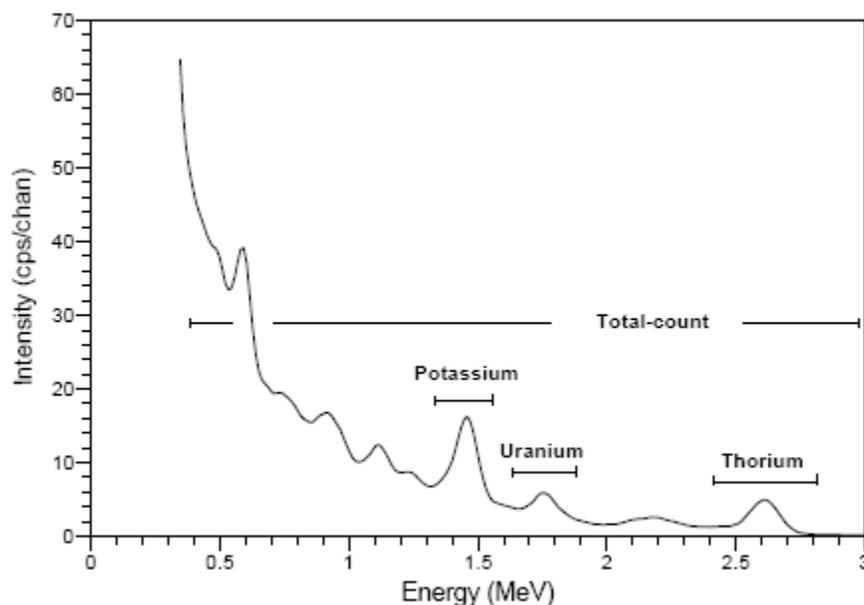
- (4) **excess uranium** sigma point plots showing locations where <sup>214</sup>Bi was out of balance with the surrounding environment.



Total count rate products illustrate gamma activity from all terrestrial sources after subtracting the “background data” contributions from radon, cosmic and aircraft sources. They can be used to assess the wide range of radioactivity present in the environment. The RadAssist calibration coefficients were determined based on methodology published by the International Atomic Energy Agency.<sup>3</sup> Radon was accounted for by using the ENVI code and DOE AMS algorithms by flying various test lines at the respective survey locations.

Excess uranium sigma points were determined using an algorithm published by the IAEA and incorporated into the ENVI software program. This algorithm is based on the assumption that natural background radioisotope contributions are stable over large geographical areas. This will

result in a spectral shape that remains essentially constant over large count rate variations (Figure 1).



**Figure 1:** Typical airborne gamma ray spectrum showing positions of the conventional energy windows. *Adapted from IAEA-TECDOC-1363.*

To determine excess eU count rate, the region-of-interest around  $^{214}\text{Bi}$  (labeled uranium above, 1659 keV to 1860 keV) is compared to the region-of-interest (ROI) represented by nearly the entire spectrum, called the Total Count ROI (36 keV to 3,027 keV).<sup>\*</sup> The count rate ratio between these windows (e.g., Uranium ROI / Total Count Rate ROI) is relatively constant and is referred to as the “K” value. The actual windows (ROIs) used in this survey are shown in Appendix III. A K-value was determined from the “test line” data collected before and after each survey. The median K-value (e.g., most common K-value) was used in the algorithm to determine excess uranium.

$$\mathbf{K\text{-value}} = \frac{\text{Count rate in } \mathbf{target} \text{ region-of-interest}}{\text{Count rate in “Total Count” region-of-interest}}$$

Excess activity can be estimated using the following formula:

$$\text{Excess eU activity} = \mathbf{Measured} \text{ eU activity} - \mathbf{Estimated} \text{ eU activity}$$

Where:

**Measured** eU activity = the measured count rate within the eU ROI during the survey

**Estimated** eU activity = **K-value** \* measured count rate in Total Count ROI during the survey

<sup>\*</sup> The Total Count ROI is an arbitrary selection. Recent discussions among Radiation Solutions, DOE AMS, and EPA ASPECT have resulted in a recommended Total Count ROI of channels 9 to 937 (30 keV to 2,814 keV).



## 5.0 Results

### 5.1 Radiological Results

ASPECT collected radiological and photographic information over the Ambrosia Lake area from August 23-25, 2011. This survey covered nearly 22,000 acres of land consisting of about 11,000 data points. Radiological products included contour plots for total count rate, exposure rate, and uranium concentration (Images 3 to 5) and excess uranium sigma plots, which represent the number of standard deviations from background (Image 6). The table below contains the estimated areas of the survey based on exposure rate in steps of 5  $\mu\text{R/hr}$ .

Table 1. Exposure Rate Data

Exposure Rate Range ( $\mu\text{R/hr}$ )	Percent of Total Area	Approximate Acreage
< 5	3.2%	684
5 to 10	74.6%	16,178
10 to 15	10.3%	2,235
15 to 20	3.9%	854
20 to 25*	2.6%	554
25 to 30*	1.9%	403
30 to 35*	1.1%	238
35 to 40*	0.6%	124
40 to 45*	0.4%	81
> 45*	1.6%	343
Totals	100.0%	21,694

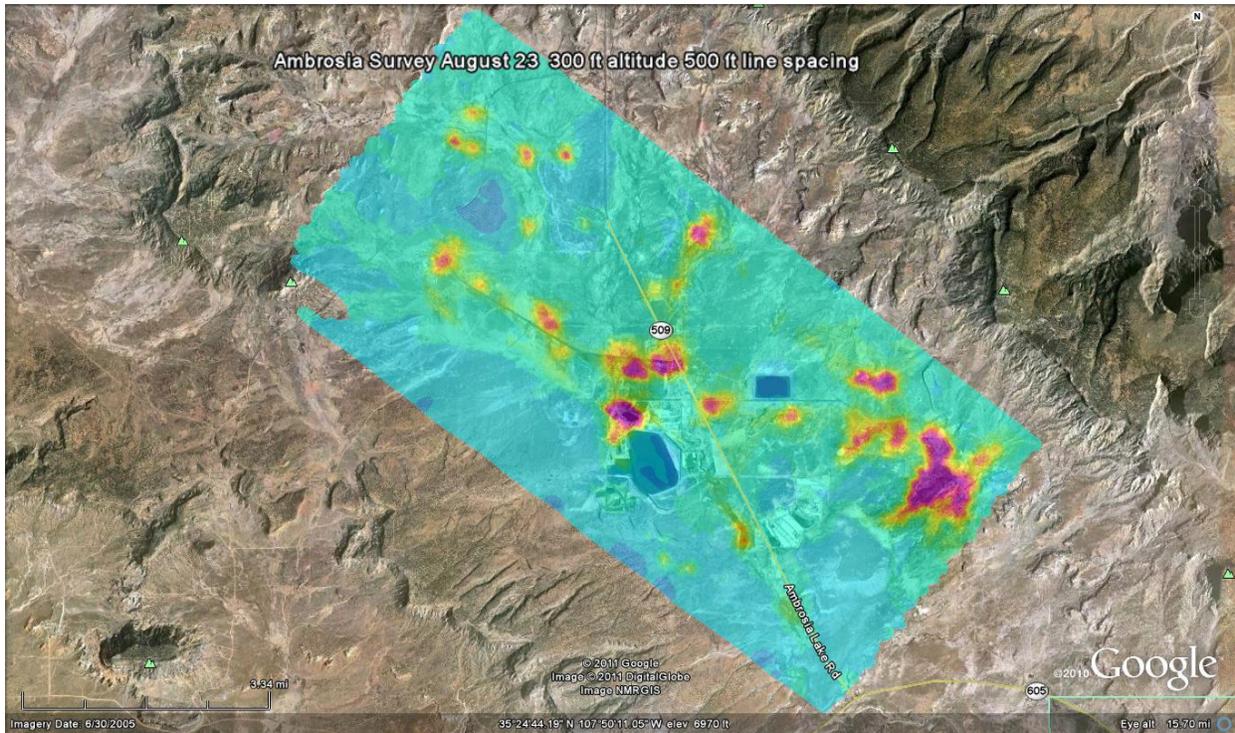
\* These exposure rates correspond to equivalent uranium concentrations greater than 5 pCi/g.

Multiple areas were identified that exceed 5 pCi/g eU. The largest of these areas was near the southeast edge of the survey area. The area of highest uranium concentration was located in the area of possible mine water discharges associated with the legacy Kerr McGee Sections 35 and 36 Uranium mines. Approximately 20 distinct areas were identified as having exposure rates greater than 20  $\mu\text{R/hr}$ .

By visual analysis of the contour plots, it appears that the areas exceeding 5 pCi/g eU correspond approximately to those areas with exposure rates of greater than 20  $\mu\text{R/hr}$ . This indicates that approximately 1,700 acres of the nearly 22,000 acres surveyed (about 8% of the area) exceed 5 pCi/g eU.

Since uranium is a naturally occurring radionuclide and is ubiquitous in nature, special analysis is required in order to determine whether the uranium or its decay products are greater than the naturally occurring uranium/radium concentrations. The analysis used is referred to as a sigma plot as discussed in section 4. Areas on a sigma plot with values greater than 4 are very likely to contain uranium or its decay products in concentrations greater than background, while values greater than 6 sigma almost certainly indicate above background levels for uranium and its decay products. Of the 11,000 data points collected in this survey, 53 were greater than 4 sigma (standard deviations) from the mean value and an additional 42 points were greater than 6 sigma from the mean.

**Image 3: Exposure Rate Contour  
Ambrosia Survey  
August 23, 2011**



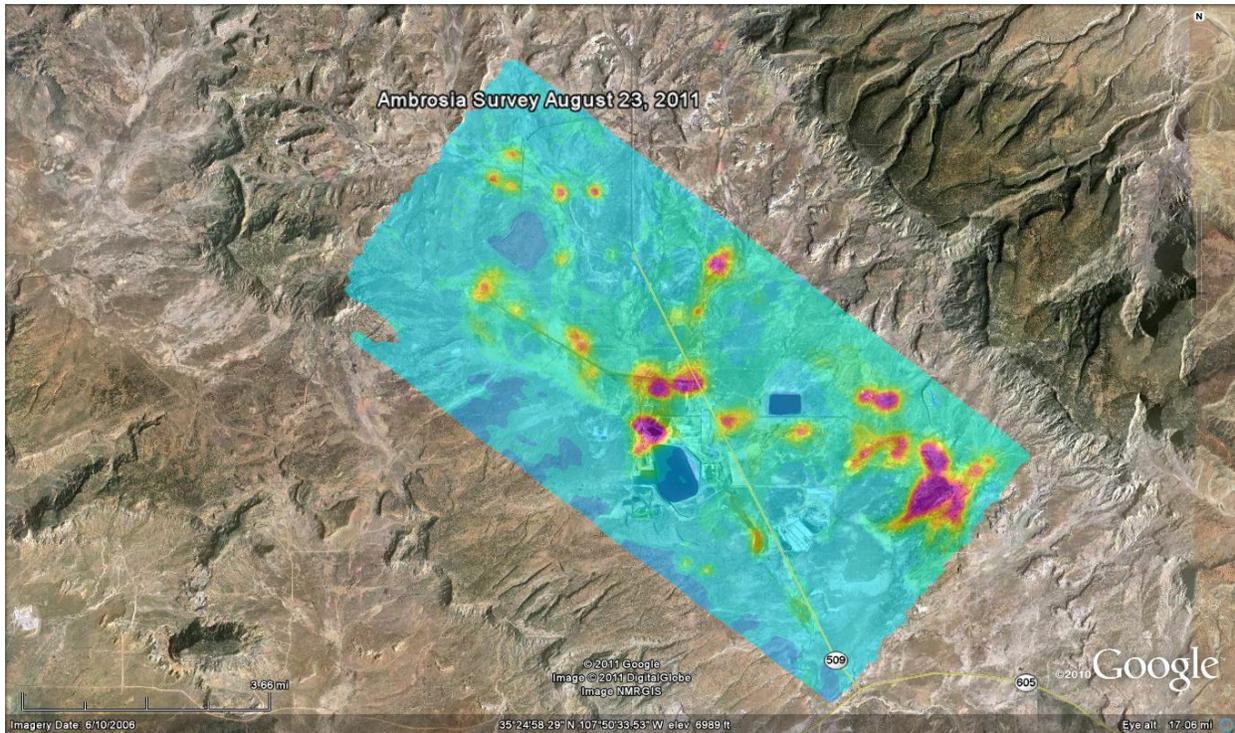
Parameter Exposure Rate (microR/hr)	
<span style="color: blue;">■</span>	< 5.0000
<span style="color: cyan;">■</span>	5.0000 : 10.000
<span style="color: green;">■</span>	10.000 : 15.000
<span style="color: lightgreen;">■</span>	15.000 : 20.000
<span style="color: yellow;">■</span>	20.000 : 25.000
<span style="color: orange;">■</span>	25.000 : 30.000
<span style="color: red;">■</span>	30.000 : 35.000
<span style="color: magenta;">■</span>	35.000 : 40.000
<span style="color: purple;">■</span>	40.000 : 45.000
<span style="color: darkpurple;">■</span>	> 45.000



<u>Flight Parameters</u>
300 ft altitude
500 ft line spacing
110 knots
1 second acquisition time

**This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.**

**Image 4: Total Count Rate Contour  
Ambrosia Survey  
August 23, 2011**



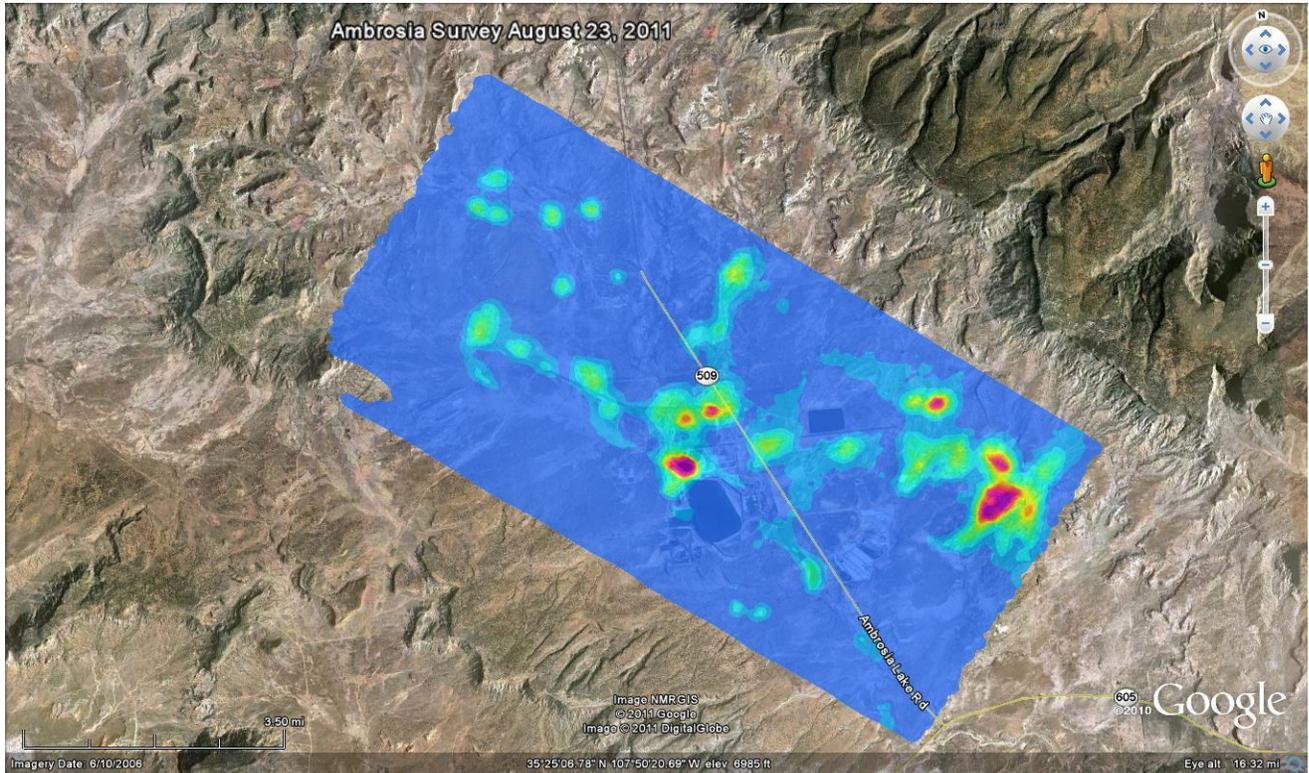
Parameter: Total Counts (cps)	
	< 5500.0
	5500.0 : 11000.
	11000. : 16500.
	16500. : 22000.
	22000. : 27500.
	27500. : 33000.
	33000. : 38500.
	38500. : 44000.
	44000. : 49500.
	> 49500.



<u>Flight Parameters</u>
500 ft altitude
250-500 ft line spacing
110 knots
1 second acquisition time

**This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.**

**Image 5: Equivalent Uranium Concentration Contour  
Ambrosia Survey  
August 23, 2011**



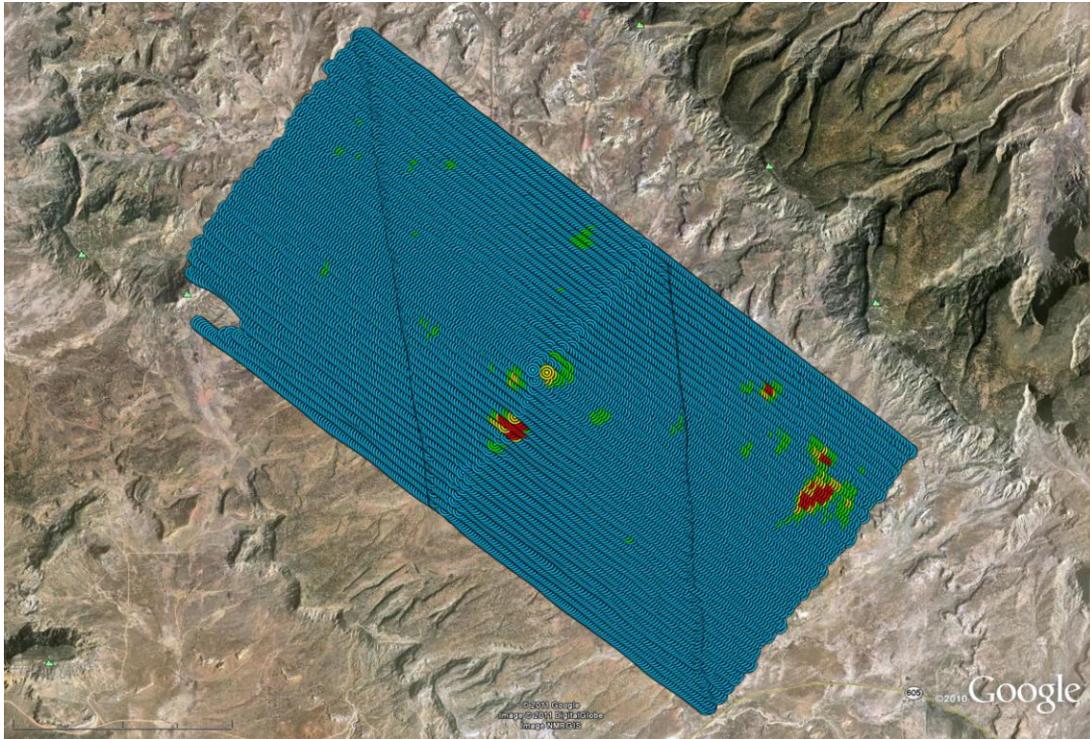
Parameter	eU concentration (pCi/g)	
	< 5,000	
	5,000 : 10,000	
	10,000 : 15,000	
	15,000 : 20,000	
	20,000 : 25,000	> 45,000
	25,000 : 30,000	
	30,000 : 35,000	
	35,000 : 40,000	
	40,000 : 45,000	



<p><b><u>Flight Parameters</u></b></p> <p>300 ft altitude                      500 ft line spacing                      110 knots                      1 /second acquisition</p>
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**This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.**

**Image 6: Excess Uranium Sigma Plot  
Ambrosia Survey  
August 23, 2011**



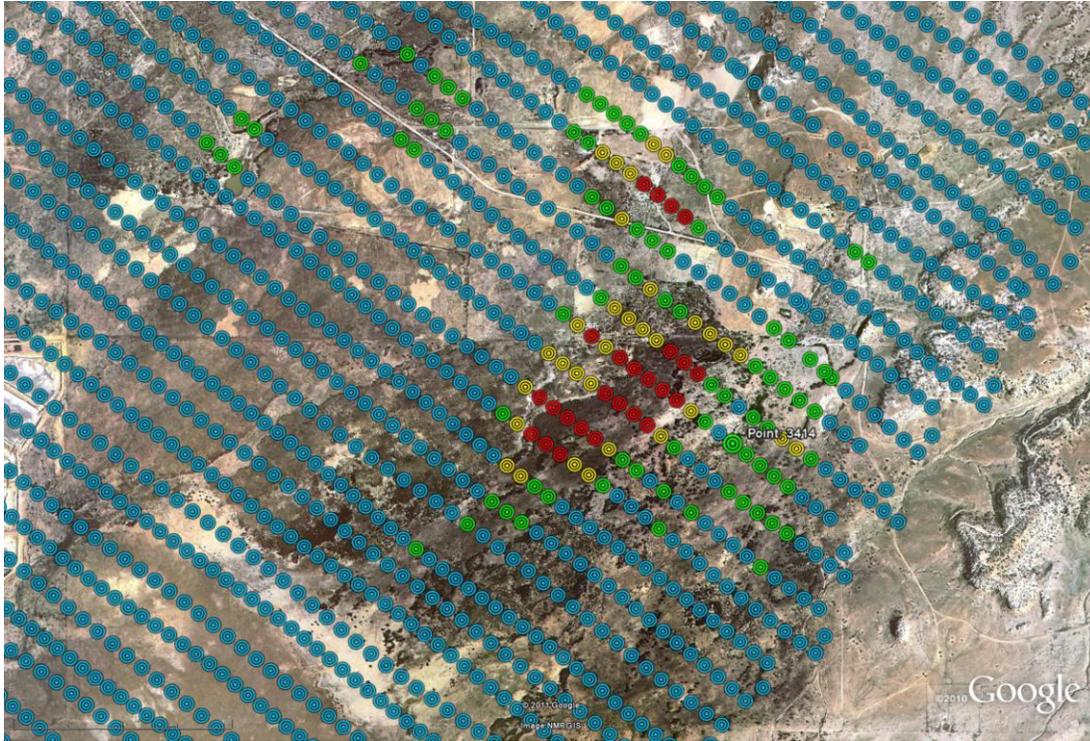
Sigma Values (Excess Bismuth-214)					
	Less than -6.0		-2.0 to +2.0		Greater than +6.0
	-6.0 to -4.0		+2.0 to +4.0		
	-4.0 to -2.0		+4.0 to +6.0		



<u>Flight Parameters</u>
300 ft altitude
500 ft line spacing
110 knots
1 second acquisition time

**This image should not be used independently to assess potential health risks.  
Additional information is necessary to make appropriate health-related decisions.**

**Image 7 - Excess Uranium Sigma Plot  
Ambrosia Survey  
August 23, 2011**



Sigma Values (Excess Bismuth-214)					
	Less than -6.0		-2.0 to +2.0		Greater than +6.0
	-6.0 to -4.0		+2.0 to +4.0		
	-4.0 to -2.0		+4.0 to +6.0		



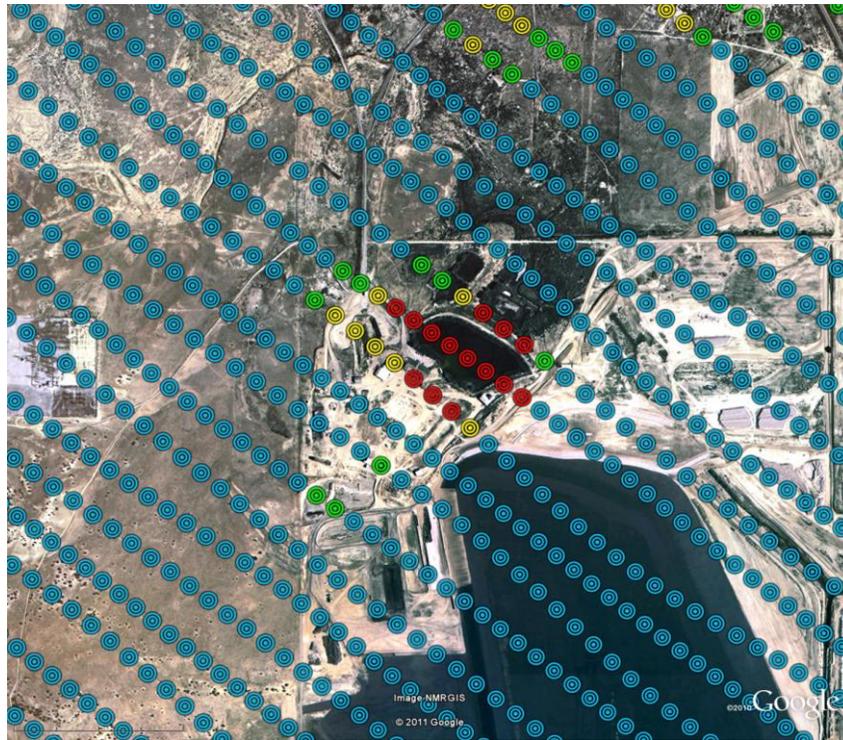
ASPECT Program

<u>Flight Parameters</u>
300 ft altitude
500 ft line spacing
110 knots
1 second acquisition time

The highest measurements in this area for equivalent uranium concentration and exposure rate were 118 pCi/g and 192  $\mu$ R/h respectively. The maximum concentration and exposure rate measured throughout the entire survey area are shown in Image 9.

**This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.**

**Image 9 - Excess Uranium Sigma Plot  
Ambrosia Survey  
August 23, 2011**



Sigma Values (Excess Bismuth-214)		
	Less than -6.0	
	-6.0 to -4.0	
	-4.0 to -2.0	
	Greater than +6.0	



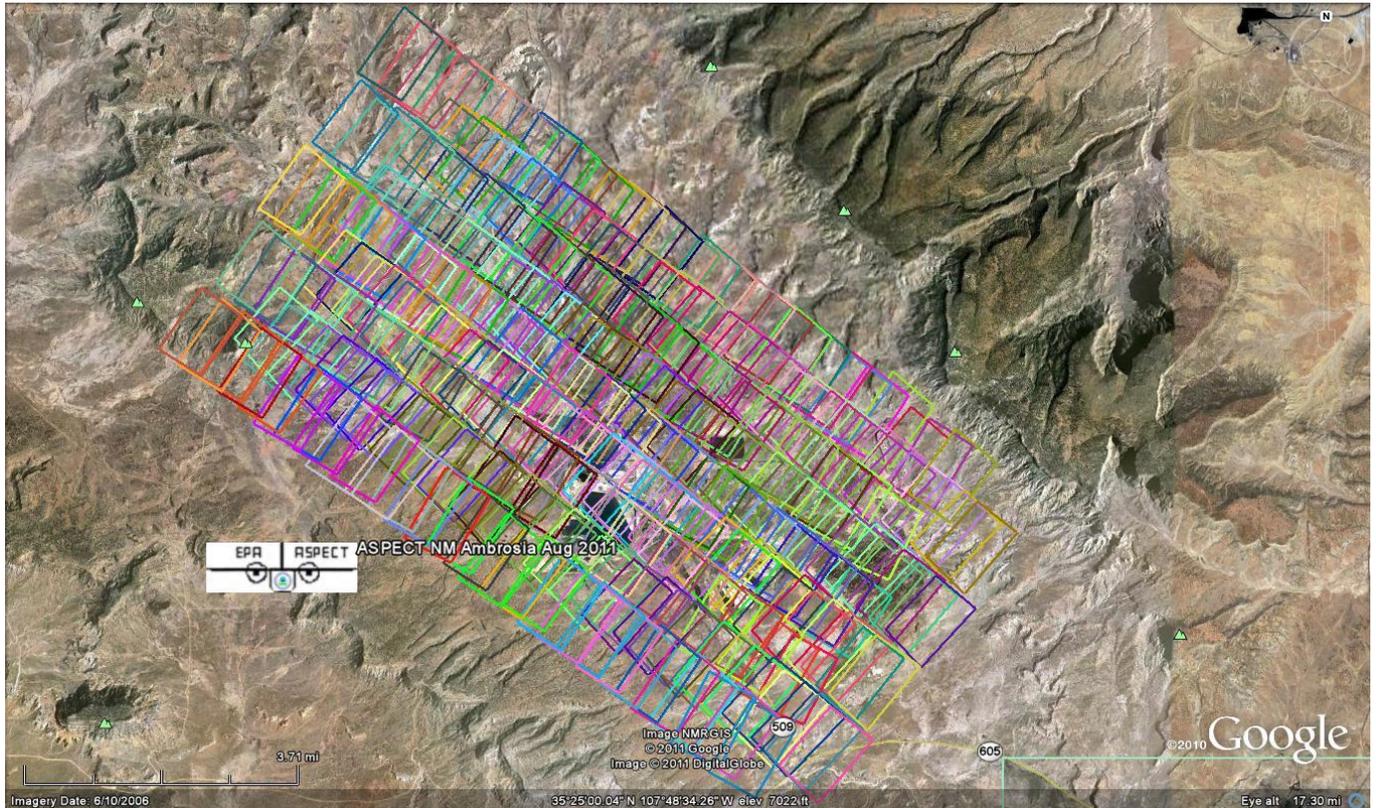
<u>Flight Parameters</u>
300 ft altitude
500 ft line spacing
110 knots
1 second acquisition time

The maximum equivalent uranium concentration (350 pCi/g) and exposure rate (435  $\mu$ R/h) were measured directly over the area containing red data points.

**4.2 Photographic Results**

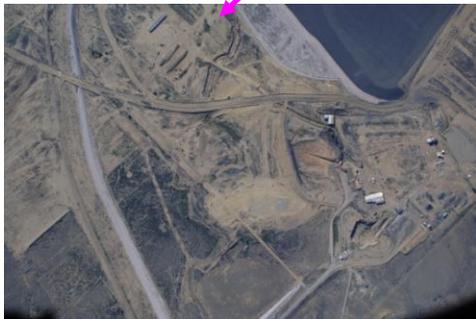
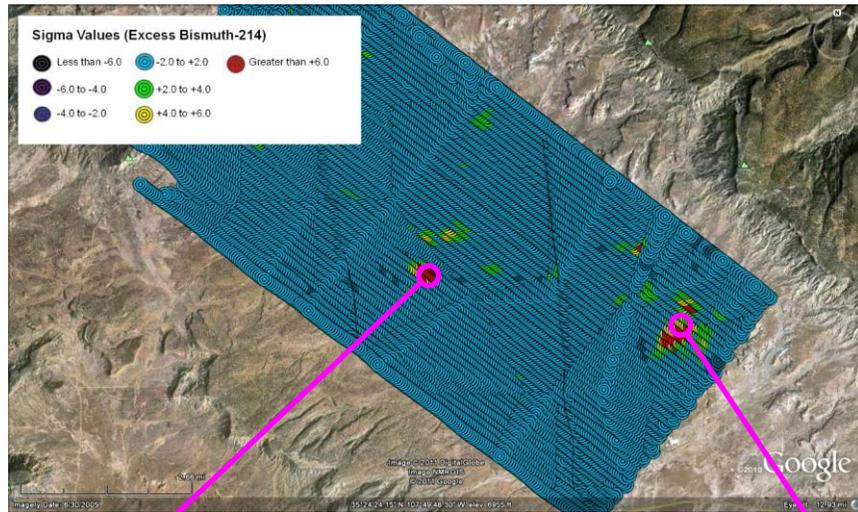
Approximately 300 high resolution digital aerial photographs were taken over the entire survey area (as depicted in Image 10). These photographs have been geo- and ortho-rectified for geospatial applications and are available to view within Google Earth. Each aerial photo provides coverage of about 355 acres with a pixel resolution of about 12 inches. Image 11 is representative of the images that were collected during the survey. Access to the photographic imagery is available by contacting Lisa Price, Region 6.

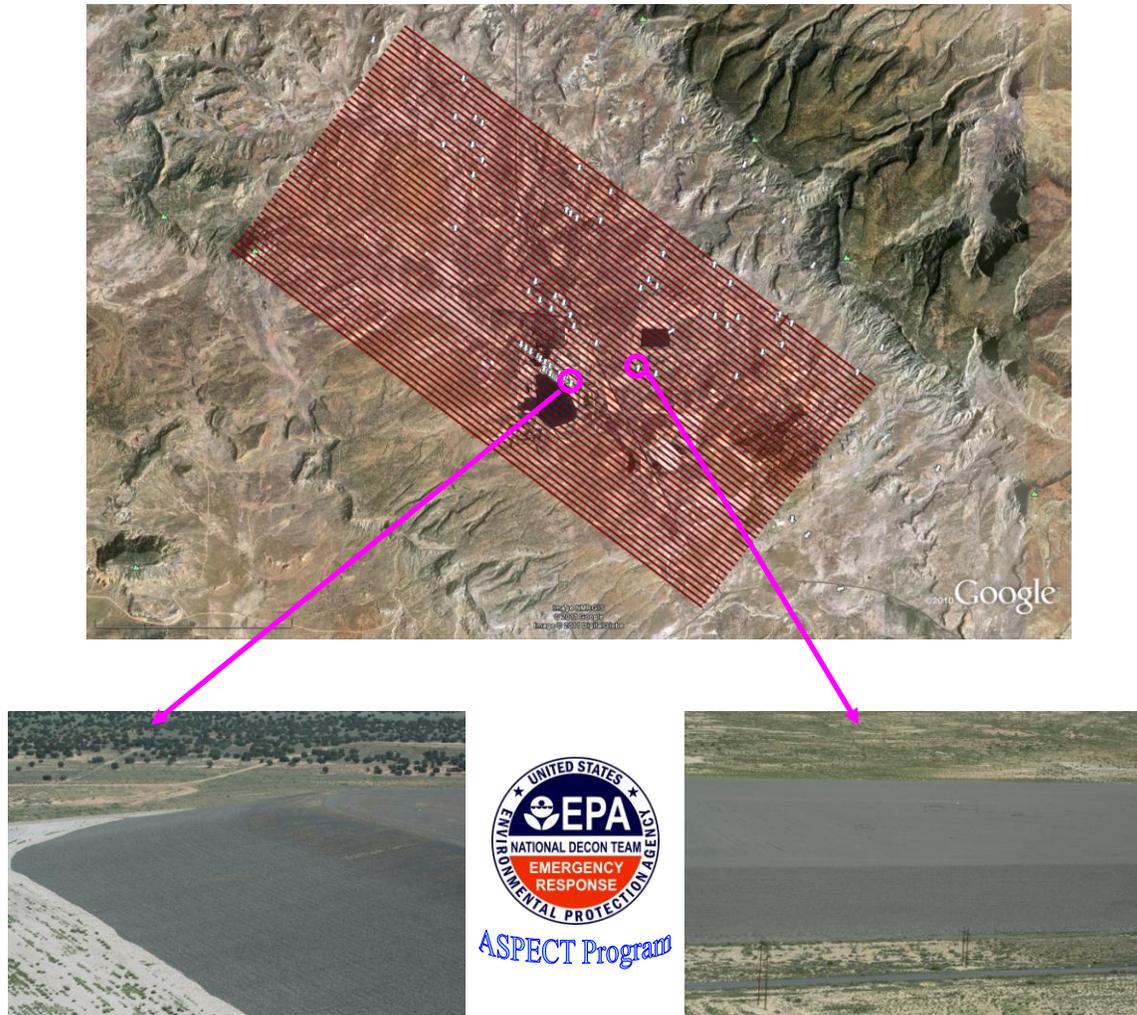
**Image 10 – Digital Photo Outlines  
Ambrosia Survey  
August 23, 2011**



The above image indicates the location of the nearly 300 downward looking digital photographs taken by the ASPECT aircraft on August 25, 2011. In addition, nearly 75 oblique photographs of various features were also taken. Oblique and downward looking photographs can all be viewed in the Google Earth software.

Image 11: Digital Images Ambrosia, New Mexico



**Image 12 - Oblique Photo Tracks****Ambrosia Survey  
August 23, 2011**

About 75 oblique photographs were taken over the entire survey area. They have been geo-located for incorporation into Google Earth or other geospatial software applications. Oblique photographs were taken out the right side of the plane at an angle consistent with the direction of the white arrows. The oblique photographs shown here are of the Rio Algom Mill (left) and the former Ambrosia Lake Mill (right). Access to the photos is available by contacting Lisa Price, Region 6.

## Appendix I

### ***Discussion about radiological uncertainties associated with airborne systems.***

Ideally the airborne radiation measurements would be proportional to the average surface concentrations of radioactive materials (mainly NORM). However, there are several factors that can interfere with this relationship causing the results to be over- or under-estimated, as described below. Additionally, two other sections discuss how data are interpreted and airborne measurement data are compared to surface measurements.

#### ***Background radiation***

Airborne gamma-spectroscopy systems measure radiation originating from terrestrial, radon, aircraft, and cosmic sources. To obtain only the terrestrial contribution, all other sources need to be accounted for (subtracted from the total counts), especially for this survey where small differences are important. Radon gas is mobile and can escape from rocks and soil and accumulate in the lower atmosphere. Radon concentrations vary from day to day, with time of day, with weather conditions (e.g., inversions and stability class), and with altitude. It is the largest contributor among background radiation and its daughter product,  $^{214}\text{Bi}$ , is used to estimate radium and uranium concentration in the soil. Radon is accounted for in the processing algorithm by flying specific test lines before and after each survey and comparing the results. Cosmic and aircraft radiation (e.g., instrument panels and metals containing small amounts of NORM) also provide a small contribution to the total counts. These are accounted for in the processing algorithm by flying a “high-altitude” or “water-” test line and subtracting these contributions for the survey data.

#### ***Secular Equilibrium Assumption***

Secular equilibrium is assumed in order to estimate thorium concentrations from one of its daughter products,  $^{214}\text{Bi}$ . Secular equilibrium exists when the activity of a daughter product equals that of its parent radionuclide. This can only occur if the half-life of the daughter product is much shorter than its parent and the daughter product stays with its parent in the environment. In this case, the measurement of  $^{214}\text{Bi}$  gamma emission is used to estimate the concentration of its parent radionuclide if one assumes all the intermediate radionuclides stay with each other. However,  $^{222}\text{Rn}$  is a noble gas with a half-life of 3.8 day and may degas from soils and rocks fissures due to changes in weather conditions. Due to the relatively long half-life and the combined effect of radon gas mobility and environmental “chemical” migration, it is not certain whether the secular equilibrium assumption is reasonable. In addition, human intervention in this natural chain of events may have caused an increased uncertainty in uranium concentration estimates.

#### ***Atmospheric Temperature and Pressure***

The density of air is a function of atmospheric temperature and pressure. Density increases with cooler temperatures and higher pressures, causing a reduction in detection of gamma-rays. This reduction in gamma-ray detection is called attenuation and it is also a function of the gamma-ray energy. Higher energy gamma-rays are more likely to reach the detectors than lower energy gamma-rays. For example, 50% of the  $^{214}\text{Bi}$  1.76 MeV gamma-rays will reach the detector at an

altitude of 300 ft whereas only 44% of the  $^{40}\text{K}$  1.46 MeV gamma-rays will reach the detector.\* Temperature and pressure changes contribute little to the overall uncertainties associated with airborne detection systems as compared to other factors.

### ***Soil moisture and Precipitation***

Soil moisture can be a significant source of error in gamma ray surveying. A 10% increase in soil moisture will decrease the total count rate by about the same amount due to absorption of the gamma rays by the water. Snow cover will cause an overall reduction in the total count rate because it also attenuates (shields) the gamma rays from reaching the detector. About 4 inches of fresh snow is equivalent to about 33 feet of air. There was no significant precipitation during this survey.

### ***Topography and vegetation cover***

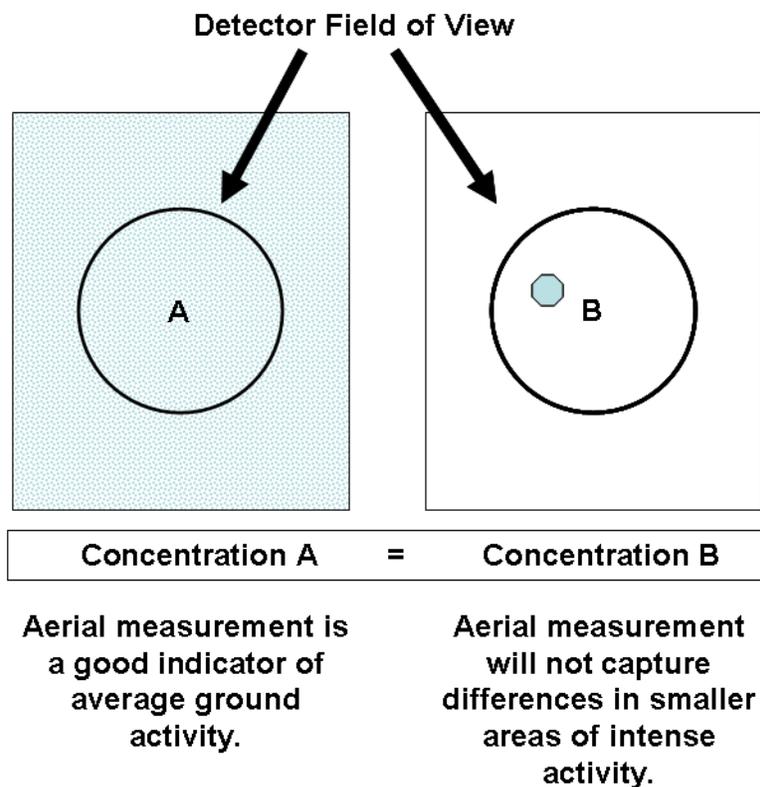
Topographic effect can be severe for both airborne and ground surveying. Both airborne and ground-based detection systems are calibrated for an infinite plane source which is referred to as  $2\pi$  geometry (or flat a surface). If the surface has mesas, cliffs, valleys, and large height fluctuations, then the calibration assumptions are not met and care must be exercised in the interpretation of the data. Vegetation can affect the radiation detected from an airborne platform in two ways: (1) the biomass can absorb and scatter the radiation in the same way as snow leading to a reduced signal, or (2) it can increase the signal if the biomass concentrated radionuclides found in the soil nutrients.

### ***Spatial Considerations***

Standard ground-based environmental measurements are taken 3 ft above the ground with a field of view of about 30 ft<sup>2</sup>. The ASPECT collected data at about 300 ft above the ground with an effective field of view of about 6.5 acres. These aerial measurements provide **an average surface activity over the effective field of view**. If the ground activity varies significantly over the field of view, then the results from ground- and aerial-based systems may not agree. It is not unusual to have differences as much as several orders of magnitude depending on the survey altitude and the size and intensity of the source material. For example, in the figures below, if the "A" circle represents the detector field of view and the surrounding area had no significant differences in surface activity, a 300 ft aerial measured could correlate to a ground-based exposure rate of 3.5  $\mu\text{R}/\text{h}$ . However, if all the activity was contained in a small area such as a single small structure containing thorium tailings (represented by the blue dot within the field of view of "B"), a 300 ft aerial measurement may still provide the same exposure rate measurement but the actual ground-based measurements could be as high as 3,150  $\mu\text{R}/\text{h}$ .

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\* Attenuation coefficients of  $0.0077\text{m}^{-1}$  for 1.76 MeV and  $0.0064\text{m}^{-1}$  for 1.46 MeV.



**Illustration of aerial measurement capabilities and interpretation of the results**

### ***Comparing ground samples and airborne measurements***

Aerial measurements are correlated to ground concentrations through a set of calibration coefficients. The ASPECT calibration coefficients for exposure-rate, potassium, uranium, and thorium concentrations were derived from a well characterized “calibration” strip of land near Las Vegas, Nevada. *In-situ* gamma spectroscopy and pressurized ionization chambers measurements were used to characterize the area. One must exercise caution when using a laboratory to analyze soil samples to verify or validate aerial measurements because differences will occur. In addition to local variations in radionuclide concentrations, which are likely to be the most significant issue, differences may arise due to laboratory processing. Laboratory processing typically includes drying, sieving and milling. These processes remove soil moisture, rocks and vegetation, and will disrupt the equilibrium state of the decay chains due to liberation of the noble gas radon. Thus reliance on  $^{208}\text{Tl}$  and  $^{214}\text{Bi}$  as indicators of  $^{232}\text{Th}$  and  $^{238}\text{U}$  (as is assumed for aerial surveying) is made more complex. In addition, aerial surveys cannot remove the effects of vegetation on gamma flux. Intercomparisons must minimize these differences and recognize the effects of differences that cannot be eliminated.

### ***Geo-Spatial Accuracy***

All aerial measurements collected by the ASPECT aircraft are geo-coded using latitude and longitude. The position of the aircraft at any point in time is established by interpolating between positional data points of a non-differential global positioning system and referencing the relevant position to the time that the measurement was made. Time of observation is derived from the aircraft computer network which is synchronized from a master GPS receiver and has a

maximum error of 1 second\*. Timing events based on the network running the Windows-based operating system and the sensor timing triggers have a time resolution of 50 milliseconds, so the controlling error in timing is the network time. If this maximum timing error is coupled to the typical ground velocity of 55 meter/sec of the aircraft, an instantaneous error of 55 meters is possible due to timing. In addition, geo-positional accuracy is dependent on the instantaneous precision of the non-differential GPS system which is typically better than 30 meters for any given observation. This results in an absolute maximum instantaneous error of about 80 meters in the direction of travel.

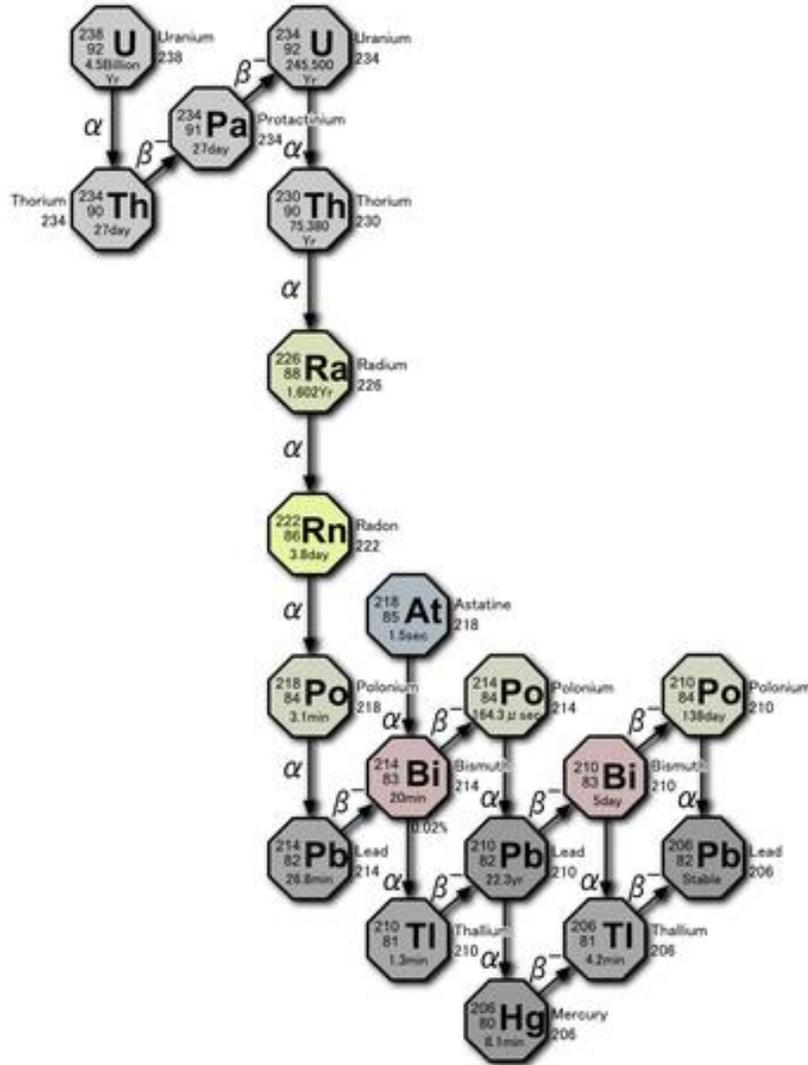
For measurements dependent on aircraft attitude (photographs, IR images) three additional errors are relevant and include the error of the inertial navigation unit (INU), the systemic errors associated with sensor to INU mounting, and altitude errors above ground. Angular errors associated with the INU are less than 0.5 degrees of arc. Mounting error is minimized using detailed bore alignment of all sensors on the aircraft base plate and is less than 0.5 degrees of arc. If the maximum error is assumed then an error of 1.0 degree of arc will result. At an altitude of 150 meters (about 500 feet) this error translates to about 10 meters. Altitude above ground is derived from the difference in the height above the geoid (taken from the GPS) from the ground elevation derived from a 30 meter digital elevation model. If an error of the model is assumed to be 10 meters and the GPS shows a typical maximum error of 10 meters, this results in an altitude maximum error of 20 meters in altitude error. If this error is combined with attitude and the instantaneous GPS positional error (assuming no internal receiver compensation due to forward motion) then an error of about 50 meters will result. The maximum forecasted error that should result from the aircraft flying straight and level is +/- 130 meters in the direction of travel and +/- 50 meters perpendicular to the direction of travel. Statistical evaluation of collected ASPECT data has shown that typical errors of +/- 22 meters in both the direction of and perpendicular to travel are typical. Maximum errors of +/- 98 meters have been observed during high turbulence conditions.

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\* The ASPECT network is synchronized to the master GPS time at system start-up. If the observed network/GPS time difference exceeds 1 sec. at any time after synchronization, the network clock is reset.

## Appendix II

### Uranium 238 decay series



## Appendix III

### Calibration Parameters

RadAssist calibration parameters for Ambrosia Survey on August 23, 2011.

**Calibration Parameters**
✕

ROI	Active	Only Up	Name	Start Ch	End Ch	Det.Bg	Cosmic	Alt. Beta	Sens.Coef
01	YES		TotCount	137	937	14.55	1.0085	0.00702	1
02	YES		Tot Count (...)	9	937	41.961	3.9698	0.00665	1
03	YES		Potassium	457	523	6.831	0.0541	0.00915	5.30216
04	YES		Uranium (Bi-...)	553	620	0.8849	0.0442	0.00803	12.89833
05	YES		Thorium(Tl-2...)	803	937	-0.8314	0.0505	0.00689	21.91768
06	YES		Cs-137	200	240	3.0329	0.1001	0	1
07	YES		Co-60	364	472	3.5458	0.1083	0	1
08	YES		Man-Made L...	16	465	42.487	3.5095	0	1
09	YES		Man-Made H...	466	937	0.0265	0.2592	0	1
10	YES		Cosmic	1000	1000	0	0	0	1

Calibration Coefficients Matrix

*	TotCount	Tot Coun...	Potassium	Uranium (...)	Thorium(...)	Cs-137	Co-60	Man-Mad...
TotCount	1	0	0	0	0	0	0	0
Tot Coun...	0	1	0	0	0	0	0	0
Potassium	0	0	1	1.04984	0.7131	0	0	0
Uranium (...)	0	0	-0.00767	1	0.51735	0	0	0
Thorium(Tl...	0	0	-0.0011	0.04125	1	0	0	0
Cs-137	0	0	0	0	0	1	0	0
Co-60	0	0	0	0	0	0	1	0
Man-Made...	0	0	0	0	0	0	0	1
Man-Made...	0	0	0	0	0	0	0	0
Cosmic	0	0	0	0	0	0	0	0

**Dose Rate computation**

Dose Calibration Factor

Dose Altitude Beta

Scale to # xtals

**Height Correction**

Enable Height Correction      Meters per unit of Altitude

Reference Altitude       Altitude field       Fixed Altitude

This screen-shot from the RadAssist Program shows the calibration coefficients used in the determination of eUranium concentrations for this report.

## Appendix IV

### **Background Radiation**

Naturally occurring radioactive material (NORM) originates from cosmic radiation, cosmogenic radioactivity, and primordial radioactive elements that were created at the beginning of the earth. Cosmic radiation consists of very high energy particles from extraterrestrial sources such as the sun (mainly alpha particles and protons) and galactic radiation (mainly electrons and protons). Its intensity increases with altitude, doubling about every 6,000 ft, and with increasing latitude north and south of the equator. The cosmic radiation level at sea level is about 3.2  $\mu\text{R/h}$  and nearly twice this level in locations such as Denver, CO.

Cosmogenic radioactivity results from cosmic radiation interacting with the earth's upper atmosphere. Since this is an ongoing process, a steady state has been established whereby cosmogenic radionuclides (e.g.,  $^3\text{H}$  and  $^{14}\text{C}$ ) are decaying at the same rate as they are produced. These sources of radioactivity were not a focus of this survey and were not included in the processing algorithms.

Primordial radioactive elements found in significant concentrations in the crustal material of the earth are potassium, uranium and thorium. Potassium is one of the most abundant elements in the Earth's crust (2.4% by mass). One out of every 10,000 potassium atoms is radioactive potassium-40 ( $^{40}\text{K}$ ) with a half-life (the time it takes to decay to one half the original amount) of 1.3 billion years. For every 100  $^{40}\text{K}$  atoms that decay, 11 become Argon-40 ( $^{40}\text{Ar}$ ) and emit a 1.46 MeV gamma-ray.

Uranium is ubiquitous in the natural environment and is found in soil at various concentrations with an average of about 1.2 pCi/g. Natural uranium consists of three isotopes with about 99.3% being uranium-238 ( $^{238}\text{U}$ ), about 0.7% being uranium-235 ( $^{235}\text{U}$ ), and a trace amount being uranium-234 ( $^{234}\text{U}$ ). The tenth daughter product of  $^{238}\text{U}$ , bismuth-214 ( $^{214}\text{Bi}$ ), is used to estimate the presence of radium and uranium by its 1.76 MeV gamma-ray emission.

Thorium-232 is the parent radionuclide of one of the 4 primordial decay chains. It is about four times more abundant in nature than uranium and also decays through a series of daughter products to a stable form of lead. The thorium content of rocks ranges between 0.9 pCi/g and 3.6 pCi/g with an average concentration of about 1.3 pCi/g.<sup>2</sup> The ninth daughter product, thallium-208 ( $^{208}\text{Tl}$ ), is used to estimate the presence of thorium by its 2.61 MeV gamma-ray emission.

Technologically enhanced naturally occurring radioactive material (TENORM) is NORM processed in such a manner that its concentration has been increased. TENORM is associated with various industries including energy production, water filtration, fertilizer production, mining and metals production. Concentrations of radionuclides in TENORM are often orders of magnitude greater than the naturally occurring concentrations. This survey was designed to identify areas where the TENORM concentrations were significantly higher than the natural background concentrations due to the mining and processing of uranium ore.

## Appendix V: ASPECT Instrumentation

### ***Survey Instrumentation***

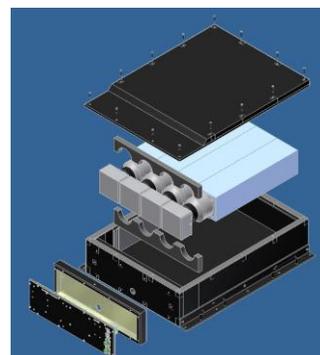
The ASPECT aircraft is a twin engine, high wing AeroCommander 680FL capable of cruising speeds ranging from about 100 knots (115 mph) to 200 knots (230 mph) (Image 2). It is based in Waxahachie, Texas and operated by two pilots and one technician. A suite of chemical, radiological, and photographic detection technology is mounted within the airframe making it the only aircraft in the nation with remote chemical and radiological detection capabilities.

### ***Radiation Detectors***

The radiological detection technology consisted of two RSX-4 Units ([Radiation Solutions, Inc.](#), 386 Watline Avenue, Mississauga, Ontario, Canada) (Image 9). Each unit was equipped with four 2"x4"x16" thallium-activated sodium iodide (NaI[Tl]) scintillation crystals for a total of 8 NaI[Tl] (16.8 L) crystals.

Detector packs for airborne spectroscopy typically consist of clusters of NaI[Tl] crystals because they are relatively inexpensive compared to other scintillation crystals. In addition, NaI crystals have high sensitivity with acceptable spectral resolution (approximately seven percent full width at half maximum (FWHM)\* at 662 keV), and are easy to maintain.

The Radiation Solutions RSX-4 unit was specifically designed for airborne detection and measurement of low-level gamma radiation from both naturally occurring and man-made sources. It uses advanced digital signal processing and software techniques to produce spectral data equivalent to laboratory quality. The unit is a fully integrated system that includes an individual high resolution (1,024 channel) advanced digital spectrometer for each detector. A high level of self diagnostics and performance verification routines such as auto gain stabilization are implemented with an automatic error notification capability, assuring that the resulting maps and products are of high quality and accuracy.



**Image 13:** RSX-4 unit showing four detector locations. The ASPECT was equipped with 6 NaI[Tl] and 2 LaBr<sub>3</sub>:Ce scintillating detectors.

The ASPECT program calibrates its radiological instrumentation according to the International Atomic Energy Agency specifications.<sup>3</sup>

### Chemical Sensors



**Image 14:** View of chemical sensors: high speed infrared spectrometer, lower left corner; infrared line scanner is out of view behind the line scanner.

The chemical sensors installed in the aircraft detect the difference in infrared spectral absorption or emission of a chemical vapor. The first sensor is a model RS-800, multi-spectral IR-Line Scanner (Raytheon TI Systems, McKinney, TX) (Image 4). It is a multi-spectral high spatial resolution infrared imager that provides two-dimensional images. Data analysis methods allow the operator to process the images containing various spectral wavelengths into images that indicate the presence of a particular chemical species.

The second sensor is a modified model MR254/AB (ABB, Quebec, Quebec City, Canada). It is a high throughput Fourier Transform Infrared Spectrometer (FT-IR) that collects higher spectral resolution of the infrared signature from a specific plume location. The instrument is capable of collecting spectral signatures with a resolution selectable between 0.5 to 32 wave-numbers.

The principle of measurement involves the detection, identification, and quantification of a chemical vapor species using passive infrared spectroscopy. Most vapor compounds have unique absorption spectral bands at specific frequencies in the infrared spectral region. Careful monitoring of the change in

total infrared radiance levels leads to concentration estimations for a particular vapor species.

### Camera

The ASPECT aircraft uses a high resolution digital camera to collect visible aerial images. The camera consists of a Nikon D2X SLR camera body with a fixed focus (infinity) 24mm F1.2 Nikor lens. The camera sensor has 12.5 million pixels (12.2 Mpixels viewable) giving a pixel count of 4288 x 2848 in a 3:2 image ratio. An effective ground coverage area of 885 x 590 meters is obtained when operated from the standard altitude of 850 meters.

Image ortho-rectification, which corrects for optical distortion and geometric distortion due to the three dimensional differences in the image, is accomplished using an inertial navigation unit (pitch, roll, and heading) coupled with a dedicated 5 Hz global positioning system (GPS). Aircraft altitude above ground is computed using the difference between the indicated GPS altitude and a 30 meter digital elevation model (DEM). Full ortho-rectification is computed using a camera model (lens and focal plane geometric model) and pixel specific elevation geometry derived from the digital elevation model to minimize edge and elevation distortion. Documented geo-location accuracy is better than 49 meters.

Radiological spectral data are collected every second along with GPS coordinates and other data reference information. These data are subject to quality checks within the Radiation Solutions internal processing algorithms (e.g. gain stabilization) to ensure a good signal. If any errors are encountered with a specific crystal during the collection process, an error message is generated and the data associated with that crystal are removed from further analyses.

Prior to the survey, the RSX-4 units go through a series of internal checks. If no problems are detected, a green indicator light notifies the user that all systems are good. A yellow light indicates a gain stabilization issue with a particular crystal. This can be fixed by waiting for another automatic gain stabilization process to occur or the user can disable the particular crystal via the RadAssist Software application. A red light indicates another problem and would delay the survey until it can be resolved.

## References

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- <sup>1</sup> Bristow Q., Airborne  $\gamma$ -ray spectrometry in Uranium Exploration. Principles and Current Practice. International Journal of Applied Radiation and Isotopes. Vol. 34. No. 1. Pp 199-229, 1983.
- <sup>2</sup> Eisenbud, M. Environmental Radioactivity: From Natural, Industrial, and Military Sources. 3<sup>rd</sup> Edition. Academic Press, Inc., New York, NY. 1987.
- <sup>3</sup> International Atomic Energy Agency [2003]. Guidelines for radioelement mapping using gamma ray spectrometry data. Technical Report Series No. 1363. IAEA, Vienna.