United States Environmental Protection Agency

Office of Emergency Management
Consequence Management Advisory Team
Erlanger, Kentucky 41018

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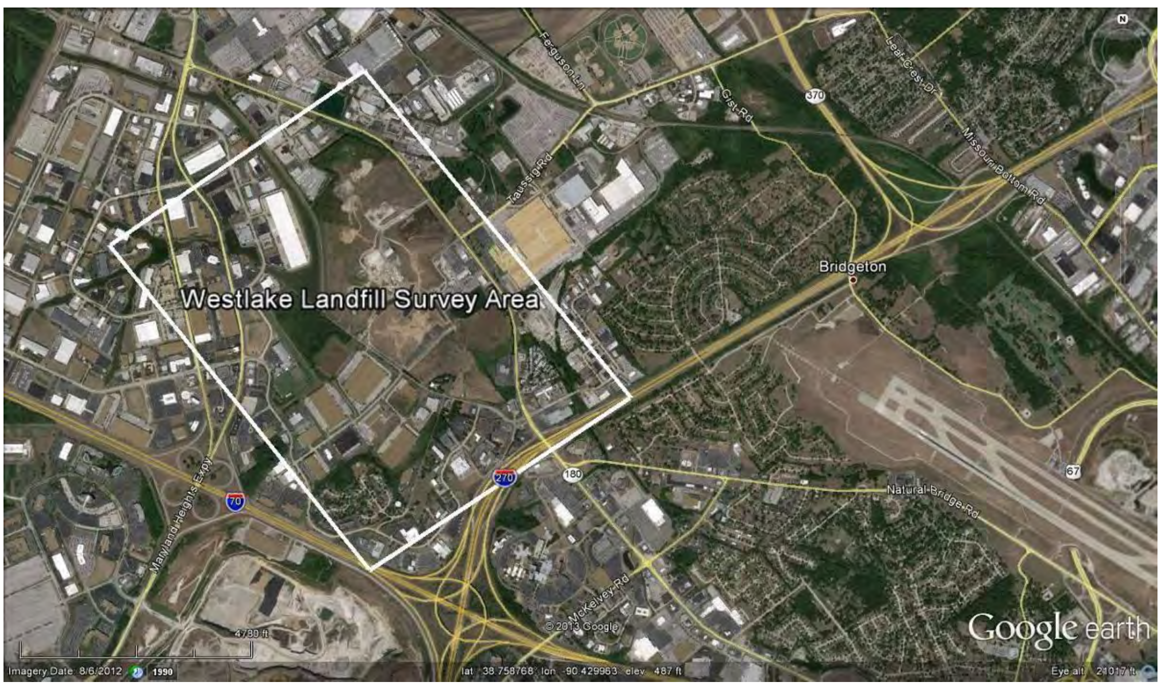
Radiological and Infrared Survey of West Lake Landfill Bridgeton, Missouri



Airborne Spectral Photometric Environmental Collection Technology (ASPECT)

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Executive Summary

The United States Environmental Protection Agency (EPA), Office of Emergency Management (OEM), Chemical Biological Radiological and Nuclear (CBRN) Consequence Management Advisory Team (CMAT) manages the Airborne Spectral Photometric Environmental Collection Technology (ASPECT) Program. This program provides scientific and technical support nationwide to characterize the environment using airborne technologies for environmental assessments, homeland security events, and emergency responses.

In January 2013, EPA Region 7 requested that the ASPECT Program conduct radiological and infrared surveys over the West Lake Landfill in Bridgeton, Missouri. The surveys were conducted on March 8, 2013, between 10:00 a.m.-12:00 noon. The West Lake Landfill is a Superfund site that was placed on the Superfund National Priorities List (NPL) in 1990. The site is known to contain leached barium sulfate residue from uranium ore processing activities.

The purpose of the radiological survey was to identify areas of elevated gamma radiation in Operable Unit 1 as compared to normal background levels. The purpose of the infrared survey was to identify any heat signatures associated with the ongoing subsurface smoldering event in one of the non-radiological cells in Operable Unit 2, and to help delineate the extent of this event. EPA chose to use the ASPECT airplane for this survey due to access issues on the site that prevented ground-based scanning, specifically the heavy vegetation on parts of the landfill. The responsible parties at the site conducted a ground-based radiation survey as part of the Operable Unit 1 Remedial Investigation and EPA chose to refresh the radiation survey and reconfirm its results. The ASPECT radiological survey confirmed the previous data showing surface gamma emissions above background levels in a portion of Area 2 of Operable Unit 1, but this area above background levels is within the fenced area of the site and is inaccessible to the public, so it does not pose a public health risk. The results are consistent with previous studies indicating that the radiological wastes remain in the previously identified areas of Operable Unit 1, Areas 1 and 2.

RADIOLOGICAL

About 800 gamma radiation measurements were collected and only 10 indicated excess uranium or uranium decay products. The ASPECT measures gamma radiation from Bismuth-214 which is the ninth decay product in the Uranium-238 decay chain because Uranium-238 is not a strong gamma emitter. In this survey, Bismuth-214 most likely indicates the presence of Radium-226 (the fifth decay product of Uranium-238) rather than Uranium-238 since the original uranium ore was chemically separated from the rest of its decay products. The separation process invalidates a key assumption in the algorithms used to estimate equivalent uranium concentrations from the gamma radiation data; therefore, throughout this report "equivalent radium" will be reported instead of equivalent uranium.

All of the gamma radiation measurements that were significantly higher than background were detected at 20 contiguous acres within Operable Unit 1, Area 2.

INFRARED

Since the ASPECT airplane can also collect infrared imagery, EPA chose to use these capabilities in an effort to assist MDNR in assessing the extent of the subsurface smoldering event in the Former Active Sanitary Landfill cell. The infrared surveys covered about 600 acres of the West Lake Landfill and surrounding areas. Two infrared imagery passes over the landfill generated four multi-spectral data sets. The data were converted to Celsius thermal units and contoured for ease of interpretation. These thermal contour images did not reveal any obvious subterranean heat signatures. In the area of the subsurface smoldering event in the Former Active Sanitary Landfill cell in Operable Unit 2, all temperature differences observed were due to surface features such as the black plastic cover placed there by the facility. Due to limitations of the sensitivity of the infrared imager on the ASPECT airplane, the data did not show any temperature differences that could be attributed to the subsurface smoldering event. This is due in part to the depth of the subsurface smoldering event (ranging from approximately 40 to 160 feet below the surface, based on data reported to MDNR).

Acronyms and Abbreviations

AEC	Atomic Energy Commission
AGL	above ground level
AOC	administrative order on consent
ASPECT	Airborne Spectral Photometric Environmental Collection Technology
Bi	bismuth
CBRN	Chemical Biological Radiological Nuclear
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CMAT	Consequence Management Advisory Team
cps	counts per second
DOE	Department of Energy
ENVI	Environment for Visualizing Images
EPA	Environmental Protection Agency
eRa	Equivalent Radium based on ^{214}Bi region of interest
eTh	Equivalent Thorium based on ^{208}Tl region of interest
eU	Equivalent Uranium based on ^{214}Bi region of interest
FOV	Field of view
FS	feasibility study
ft	feet
FUSRAP	Formerly Utilized Sites Remedial Action Program
GPS	Global Positioning System
Hz	hertz
IAEA	International Atomic Energy Agency
INU	inertial navigation unit
K	potassium
KeV	kilo electron volts
MeV	Mega electron volts
MDNR	Missouri Department of Natural Resources
MSW	municipal solid waste
NaI(Tl)	sodium iodide thallium drifted detector
NCP	national contingency plan
NCRP	National Council on Radiation Protection
NORM	Naturally Occurring Radioactive Material
NPL	National Priorities List
NRC	Nuclear Regulatory Commission
OEM	Office of Emergency Management
OU	operable unit
pCi/g	picocuries per gram
PRP	potentially responsible party
QA	quality assurance
QC	quality control
Ra	radium
RI	remedial investigation
Rn	radon
ROD	record of decision

ROI	region of interest
SLAPS	St. Louis Airport Sites
Th	thorium
Tl	thallium
U	uranium
μR/h	microRoentgen per hour
USACE	United States Army Corps of Engineers

1.0 Introduction

The EPA initiated the Airborne Spectral Photometric Environmental Collection Technology (ASPECT) Program shortly after 9/11. Its primary focus was the detection of chemicals using an infrared line scanner coupled with a Fourier transform infrared spectrometer mounted within an Aero Commander 680 twin-engine airplane. In 2008, ASPECT significantly upgraded the radiological detector system to improve its airborne gamma-screening and mapping capabilities. In 2012, a neutron detection system was installed. Currently, ASPECT is the only program in the United States with a 24/7/365 operational platform that conducts remote sensing for hazardous chemicals, gamma/neutron emitters, and aerial imaging. It has deployed to more than 130 incidents involving emergency responses, homeland security events, and environmental characterizations.

Up to a four member crew, two pilots and two technicians, operate the airplane. A scientific support staff provides additional assessment and product development commensurate with the site-specific needs.

In January 2013, EPA Region 7 requested that the ASPECT Program conduct radiological and infrared surveys over the West Lake Landfill located in Bridgeton, Missouri. The surveys were conducted on March 8, 2013.

The purpose of the radiological survey was to identify areas of elevated radiation contamination as compared to normal background concentrations.* ASPECT uses multiple algorithms to produce a variety of products for decision makers. One algorithm requires measurements to be collected over an unaffected area to establish a local background. This area was located near Cora Island, northeast of the survey areas. These measurements were used to determine the statistical significance for any excess eRa and the results are represented in a product called a “sigma plot.” One sigma represents one standard deviation from expected background levels. 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 or 12 inches (Bristol, 1983).

The purpose of the infrared survey was to screen the area to aid in identifying any surface thermal signatures resulting from the ongoing subsurface smoldering event in one of the Operable Unit 2 cells or heat of reaction associated with the landfill.

* A “normal background” area was selected by the ASPECT subject matter experts to be an area northeast of the site where no known contaminants exist.

2.0 Description of the West Lake Landfill Survey Area

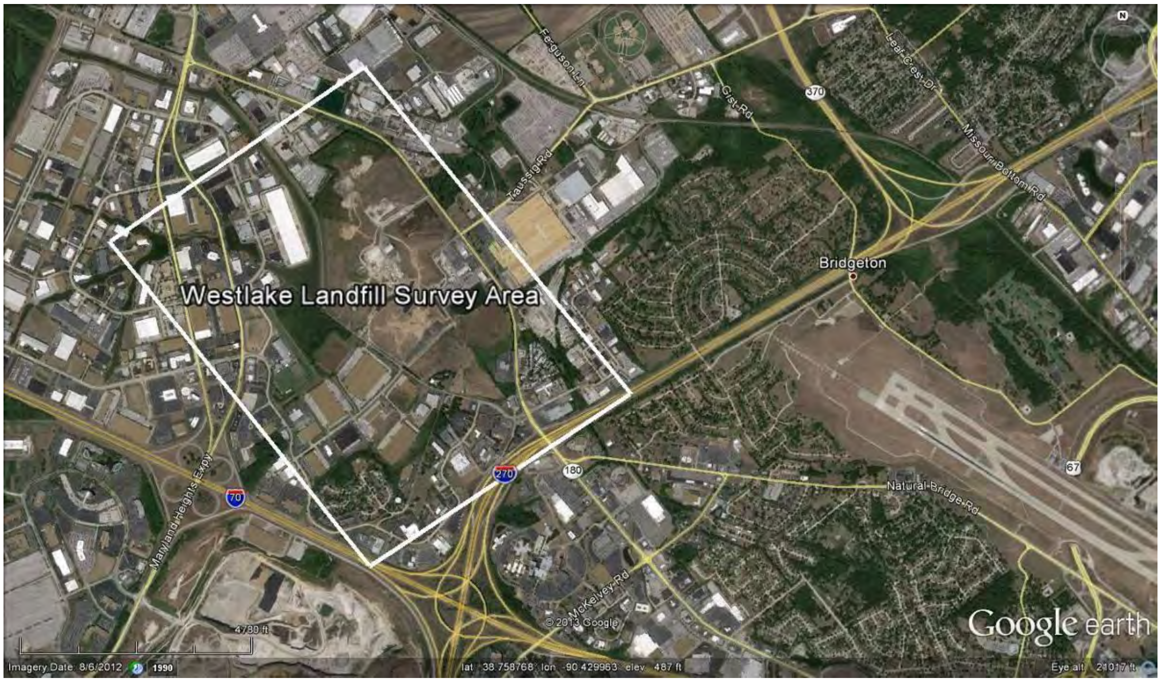


Figure 1: West Lake Landfill Survey Area covers about 1,400 acres (2.25 square miles).

The West Lake Landfill Site covers 200 acres in Bridgeton, St. Louis County, Missouri, about 16 miles northwest of downtown St. Louis (Figure 1). The site consists of the Bridgeton Sanitary Landfill (Former Active Sanitary Landfill) and several inactive areas with sanitary and demolition fills that have been closed. The Bridgeton Landfill is located at 13570 St. Charles Rock Road.

Other facilities which are not subject to this response action are located on the 200-acre parcel including concrete and asphalt batch plants, a solid waste transfer station, and an automobile repair shop.

The site was used agriculturally until a limestone quarrying and crushing operation began in 1939. The quarrying operation continued until 1988 and resulted in the formation of two quarry pits. Beginning in the early 1950s, portions of the quarried areas and adjacent areas were used for landfilling municipal solid waste (MSW), industrial solid wastes and construction/demolition debris. These operations were not subject to state permits because they occurred prior to the formation of the Missouri Department of Natural Resources (MDNR) in 1974. Two landfill areas were radiologically contaminated in 1973 when they received soil mixed with leached barium sulfate residues.

The leached barium sulfate residues, containing traces of uranium, thorium, and their long-lived decay products, were some of the uranium ore processing residues initially stored by the Atomic Energy Commission (AEC) on a 21.7-acre tract of land in a then undeveloped area of north St. Louis County, now known as the St. Louis Airport Site

(SLAPS), which is part of the St. Louis Formerly Utilized Sites Remedial Action Program (FUSRAP) managed by the U.S. Army Corps of Engineers (USACE).

In 1966 and 1967, the remaining residues from SLAPS were purchased by a private company for mineral recovery and placed in storage at a nearby facility on Latty Avenue under an AEC license. Most of the residues were shipped to Canon City, Colorado, for reprocessing except for the leached barium sulfate residues, which were the least valuable in terms of mineral content, i.e., most of the uranium and radium was removed in previous precipitation steps. Reportedly, 8,700 tons of leached barium sulfate residues were mixed with approximately 39,000 tons of soil and then transported to the site. According to the landfill operator, the soil was used as cover for municipal refuse in routine landfill operations. The data collected during the Remedial Investigation (RI) are consistent with this account.

The quarry pits were used for permitted solid waste landfill operations beginning in 1979. In August 2005, the Bridgeton Sanitary Landfill (Former Active Sanitary Landfill) stopped receiving waste pursuant to a restrictive covenant with the Lambert - St. Louis Airport to reduce the potential for birds interfering with airport operations.

EPA placed the site on the Superfund National Priorities List (NPL) in 1990. In 1993, EPA entered into an Administrative Order on Consent (AOC) with the potentially responsible parties (PRPs) for performance of the Operable Unit (OU) 1 RI/Feasibility Study (FS). Pursuant to the requirements of that order, the PRPs submitted for EPA's review and approval an RI which detailed the findings of extensive sampling and analysis on the area of OU 1 and the surrounding area. Following the RI, the PRPs submitted for EPA's review and approval an FS which evaluated the various remedial alternatives for OU 1 consistent with the requirements of the AOC, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the National Contingency Plan (NCP).

The site is divided into the following areas:

• OU 1 Area 1 – This area was part of the landfill operations conducted prior to state regulation. Approximately 10 acres are impacted by radionuclides at depths ranging down to 15 feet. The radionuclides are in soil material that is intermixed with the overall landfill matrix consisting of municipal refuse.

• OU 1 Area 2 – This area was also part of the unregulated landfill operations conducted prior to 1974. Approximately 30 acres are impacted by radionuclides at depths generally ranging down to 12 feet, with some localized occurrences that are deeper. The radionuclides are in soil material that is intermixed with the overall landfill matrix consisting mostly of construction and demolition debris.

• Buffer Zone/Crossroad Property – This property—also known as the Ford Property—lies on the western edge of OU 1 Area 2 and became surficially contaminated when erosion of soil from the landfill berm resulted in transport of radiologically contaminated soils from Area 2 onto the adjacent property.

• Closed Demolition Landfill – This area is located on the southeast side of Radiological Area 2. This landfill received demolition debris. It received none of the radiologically contaminated soil. It operated under a permit with the State and was closed in 1995.

• Inactive Sanitary Landfill – This landfill is located south of Radiological Area 2 and was part of the unregulated landfill operations conducted prior to 1974. The landfill contains sanitary wastes and a variety of other solid wastes and demolition debris. It received none of the radiologically contaminated soil.

• Former Active Sanitary Landfill – This municipal solid waste landfill—known as the Bridgeton Landfill—is located on the south and east portions of the site. The landfill is subject to a State permit issued in 1974. This landfill received none of the radiologically contaminated soil. This landfill ceased operation in 2005 and is the cell that is currently experiencing a subsurface smoldering event.

The site has been divided into two OUs (Figure 7). OU 1 consists of Radiological Area 1 and Radiological Area 2 (Areas 1 and 2) and the Buffer Zone/Crossroad Property. OU 2 consists of the other landfill areas that are not impacted by radionuclides, i.e., the Closed Demolition Landfill, the Inactive Sanitary Landfill, and the Former Active Sanitary Landfill (US EPA, Record of Decision for West Lake Landfill Site, Bridgeton Missouri, Operable Unit 1, May 2008).

3.0 Natural Sources of Background Radiation

Naturally occurring radioactivity originates from cosmic radiation, cosmogenic radioactivity, and primordial radioactive elements that were created at the beginning of the earth about 4.5 billion years ago. 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) and contributes to the total radiation exposure on earth. The intensity of cosmic radiation 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 μR/h and nearly twice this level in locations such as Denver, Colorado. (Grasty, et al., 1984).

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}H and ^{14}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}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}K atoms that decay, 11 become Argon-40 (^{40}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}U), about 0.7% being uranium-235 (^{235}U), and a trace amount being uranium-234 (^{234}U). Thorium-230 and Radium-226, as decay products of Uranium-238, would be expected to have the same activity concentrations as background Uranium-238 except that in some instances, changes in soil chemistry may cause one species to migrate with the groundwater and disrupt the local equilibrium so that the concentrations of Ra-226 and Th-230 may differ slightly from the U-238 concentration. The ninth decay product of Uranium-238 is Bismuth-214 which is used to estimate the uranium present since it is relatively easy to detect. Bismuth-214 has a very short half-life relative to Ra-226, Th-230 or U-238; therefore it can be used to infer the presence of Ra-226, Th-230, and U-238 for airborne applications. When it is used to estimate these isotopes, the precursor designator ”e” (which means equivalent) is used to identify that a decay product was used to estimate the Ra-226, Th-230, or U-238 levels and is reported as eRa, eTh, and eU accordingly. See Appendix 1 for the Uranium decay chain.

Thorium-232 is the parent radionuclide of one of the four primordial decay chains. It is about four times more abundant in nature than uranium and also decays through a series of decay products to a stable form of lead. Thorium-232 is not part of the Uranium decay chain. 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 (Eisenbud, 1987). The ninth decay product, thallium-208 (^{208}Tl), is used to estimate the presence of thorium by its 2.61 MeV gamma-ray emission.

All these primordial radionuclides are present in varied concentrations in building materials which make-up part of our naturally occurring radioactive background (Table 1) (NCRP, 1987). Other radiation sources that contribute to our external radiation include nuclear fallout and man-made radiation such as medical and industrial uses of radiation or radioactive sources.

Table 1: Average concentrations of uranium and thorium in some building materials

Material	Uranium-238 (pCi/g)	Thorium-232 (pCi/g)
Granite	1.7	0.22
Sandstone	0.2	0.19
Cement	1.2	0.57
Limestone concrete	0.8	0.23
Sandstone concrete	0.3	0.23
Wallboard	0.4	0.32
By-product gypsum	5.0	1.78
Natural gypsum	0.4	0.2
Wood	-	-
Clay brick	3	1.2

4.0 Survey Equipment and Data Collection Procedures

4.1 Radiation Detectors

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

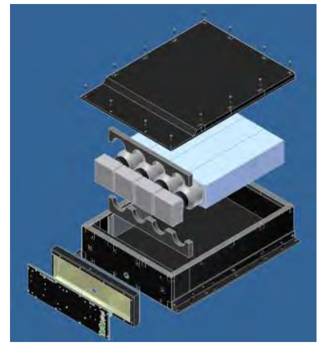


Figure 2: RSX4 unit showing four detector locations.

The Radiation Solutions RSX-4 unit was used during this survey for airborne detection and measurement of low-level gamma radiation from both naturally occurring and man-made sources. It can also be used for ground-based measurements. These units use 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.

4.2 Infrared Sensor

Figure 3 - View of infrared sensors: high speed infrared spectrometer, lower left corner; infrared line scanner is out of view behind the line scanner

There are two infrared sensors installed in the airplane to detect the difference in infrared spectral absorption or emission on the surface. The first sensor is a model RS-800, multi-spectral IR-Line Scanner (Raytheon TI Systems, McKinney, TX) (Figure 3). 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 subtle temperature differences.
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 any heat source. The instrument is capable of collecting spectral signatures with a resolution selectable between 0.5 to 32 wave-numbers and was used to assess infrared heat signatures over the West Lake Landfill.

4.3 Flight Parameters

The ASPECT airplane used the following flight procedures for data collection on March 8, 2013:

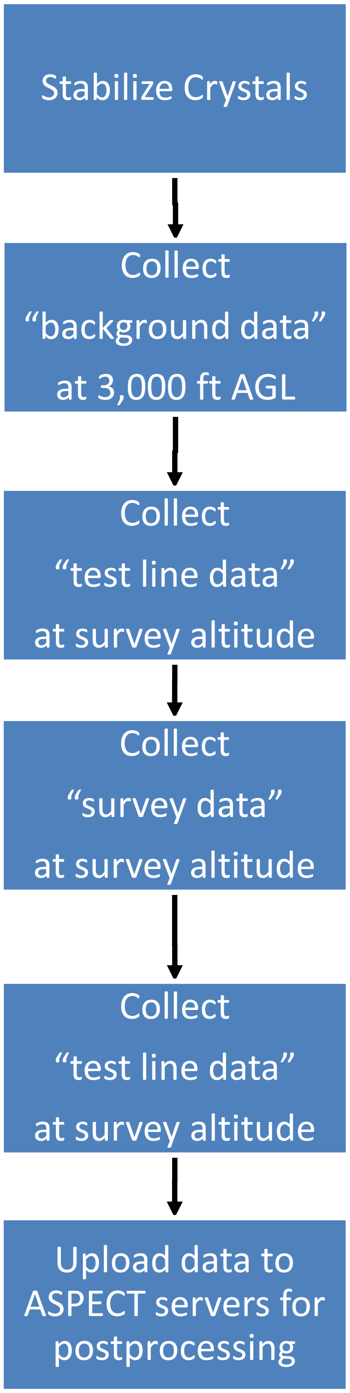
Altitude above ground level (AGL):	500 feet for radiological survey 2,800 feet for infrared and photographic survey
Target Speed:	110 knots (125 mph)
Line Spacing:	400 feet for radiological survey 1,500 feet for infrared and photographic survey
Data collection frequency:	1 Hz for radiological survey 60 Hz for infrared survey

Figure 4: Flight lines radiological survey over West Lake Landfill site.

For environmental radiation surveys using a fixed-wing airplane, the flying height above ground level has been more or less standardized at 400 feet (IAEA 1991, 2003). ASPECT target height for this survey was 500 feet to permit safer flying conditions. Aerial and ground-based surveys collected over phosphate mines in central Florida provided evidence that the increased altitude flight parameters have no significant effect on the airplane sensitivity or resolution for environmental surveys (Cardarelli et al., 2011a, 2011b).

5.0 Data Analyses

A unique feature of the ASPECT chemical and radiological technologies includes the ability to process spectral data automatically in the airplane with a full reach back link to the quality assurance/quality control (QA/QC) program. While data are generated in the airplane using automated algorithms, a support data package is extracted by the reach back team and independently reviewed for scientific validity and confirmation. The following sections detail the analyses completed for this survey.



5.1 Radiological

Aerial gamma spectroscopy analyses have several distinctive considerations that must be addressed in order to obtain accurate and meaningful products. Due to the unique interactions of gamma rays with matter, special techniques are used to process the data. For a uranium/radium survey, care must be taken to account for the background levels of uranium/radium. This process was described in Section 3. The ASPECT measures gamma radiation from Bismuth-214 which is the ninth decay product in the Uranium-238 decay chain because Uranium-238 is not a strong gamma emitter. In this survey, Bismuth-214 most likely indicates the presence of Radium-226 (the fifth decay product of Uranium-238) rather than Uranium-238 since the original uranium ore was chemically separated from the rest of its decay products. The separation process invalidates a key assumption in the algorithms used to estimate equivalent uranium concentrations; therefore, throughout this report “equivalent radium” will be reported instead of equivalent uranium.

Several environmental factors, such as moisture, may significantly affect the detector response. Specifically, precipitation disturbs the equilibrium of the uranium decay chain and soil moisture actually shields some of the gamma rays and prevents them from reaching the detectors. There are several similar considerations that are discussed in Appendix II.

In the days leading up to the survey, the St. Louis area had received significant snowfall. During the survey, the snowfall had melted, but the ground was likely fairly saturated. This additional moisture in the ground would serve as a partial shield and reduce the intensity of radiation reaching the detectors. A 10 percent increase in soil moisture would decrease the total count rate by about 10 percent. The higher than average energy from Bismuth-214 would be slightly less affected, because soil moisture affects the detection of lower-energy gamma rays more than higher-energy gamma rays.

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. When powered up, the crystals go through an automated gain stabilization process. The process uses naturally occurring radioelements of potassium, uranium, and thorium to ensure proper spectral data collection. 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.

The “background data” in this context includes radiation contributions from radon, cosmic, and airplane sources. These are unwanted contributions to the radiation measurements and must be subtracted from the raw measurements to properly estimate radiation contributions from terrestrial sources only. 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 at 3,000 ft AGL (Bristow, 1983). 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” in this context is flown at survey altitude near the survey area. The line is not expected to contain any known elevated concentrations of naturally occurring radioactive material (NORM) or man-made radionuclides. For this survey, an area near Cora Island, northeast of the site, was used for this purpose. Hence, this test line serves as the natural background area (after the radon, cosmic, and airplane sources are subtracted) which the survey data is compared to determine if any statistical anomalies occur within the survey area.

The calibration coefficients were determined based on methodology published by the International Atomic Energy Agency (IAEA, 2003).

One of the possible software programs available to the ASPECT team for processing radiological data is the Environment for Visualizing Images (ENVI) code. For this survey, ENVI® Version 5.0; ASPECT Version 9.1.1.2, Build 1302282009 (Exelis Visual

Information Solutions, Boulder, CO) was used to produce **excess eRa** sigma point plots showing locations where ^{214}Bi was out of balance with the surrounding environment. The process is depicted below.

<u>ENVI ASPECT Method</u>
↓
Live time correction
↓
Subtract cosmic and airplane background contribution (3,000 ft AGL)
↓
"Test line" (determines "normal")
Height correction (μ=0.0018 m-1
)
Calculate ^{214}Bi ROI K-value (median)
↓
Subtract radon contribution (Test lines)
↓
Determine net count rate for ^{214}Bi and standard deviation (sigma value; σ)
↓
Determine Sigma Values
(<-6σ, -6 to -4; -4 to -2; -2 to 2; 2 to 4, 4 to 6, >6σ)
↓
Create excess eRadium sigma plots

The excess eRa sigma plots are used to help determine whether the detected radiation associated with the Bi-214 is consistent with areas known not to contain any elevated radiation signatures, e.g. a background area. Because the uranium/radium concentration will vary slightly from point to point, a statistical analysis is used to help make this determination. The first step of this process is to determine the background variation. This is done by measuring an area that is close to the site but not contaminated by the site or containing any similar contaminants from other sources. All of the site measurements are then compared to make sure they are within the range of the background data. Points that are noticeably different from the background points are likely to be of man-made origin. Excess eRa sigma points were determined using an algorithm 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.

ASPECT used the ENVI code analysis wherein a background "test" line is flown with similar characteristics in an area physically close to the survey location but not affected by the contamination. This background is used to compare the readings by statistical methods. For this survey the area was near Cora Island just northeast of the site.

To determine excess radium count rate, the region-of-interest (ROI) around ^{214}Bi (1659 keV to 1860 keV) is compared to the ROI represented by nearly the entire spectrum, called the Total Count ROI (36 keV to 3,027 keV). 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. 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 eRa.

$$\textbf{K-value} = \frac{\text{Count rate in } \textbf{\textit{target}} \text{ region-of-interest}}{\text{Count rate in "Total Count" region-of-interest}}$$

Excess activity can be estimated using the following formula:

Excess eRa activity = **Measured** eRa activity – **Estimated** eRa activity

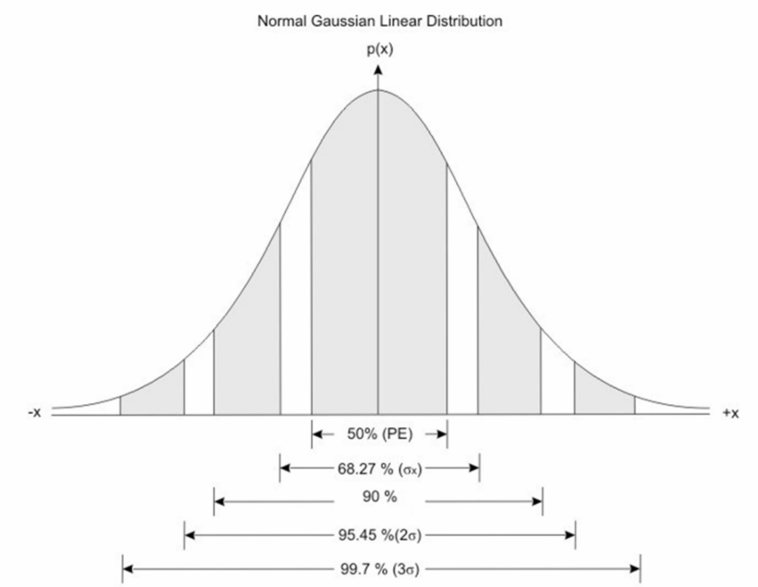
Where:
Measured eRa activity = the measured count rate within the eRa ROI during the survey

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

The equation for excess activity becomes:

EXCESS eRa = Measured eRa ROI – (K * Measured Total Counts ROI)

The most likely value of net "excess eRa" should be zero, and since radiological disintegrations are randomly occurring events, the second-by-second "excess eRa" results are statistically distributed about the mean in a normal Gaussian distribution (Figure 5).



Standard deviation (σ, sigma) represents the spread of the data about the mean. In this survey, the mean value (net "eRa") was zero.

1 σ = 68.27% of the data
2 σ = 95.45% of the data
3 σ = 99.73% of the data
4 σ = 99.99366% of the data
5 σ = 99.99994% of the data
6 σ = 99.999999% of the data

Figure 5: Normal Gaussian distribution and associated confidence intervals.

Every measurement was scored according to its "sigma" value and color coded according to the ranges in Figure 6. The color code and range were arbitrarily selected to limit the risk of false positives to 1 in about 15,800,000 samples (greater than or less than 6 sigma).

Figure 6: Standard Deviation Legend for Excess eRadium

5.2. Infrared

The ASPECT RS-800 multi-spectral line scanner is used to generate high spectral and spatial resolution long wave energy data displayed as a standard imagery product. Thermal imaging is produced by converting the measured radiance energy of each data point by solving for the surface temperature (T) of the emitting object using the Stephan-Boltzmann equation:

$$R = \sigma T^4$$

R = radiance (watts per (square meter * steradian * Wavenumber)) of the emitting surface
σ = emissivity (ranging from 0 to 1.0 and material dependent) of the surface
T = temperature (degrees Kelvin) of the emitting surface.

To fully utilize the relationship between the emitted radiance and the temperature of the emitting surface, an accurate measurement of radiance must be conducted and an emissivity must be known or assumed. The ASPECT RS-800 permits fully radiometrically calibrated radiance to be measured by using two flanking blackbody calibration units which calibrate each scanned line of the image at a rate of 60 times per second. Since the unit is multi-spectral, a channel optimized for sulfur hexafluoride (centered on 947 Wavenumber) is used as the long wave thermal channel since the infrared detector typically has the highest response in this spectral region. For a thermal survey of grass covered areas, an emissivity of 0.85 is used. By rearranging the Stephan-Boltzmann equation, the temperature can be extracted:

$$T = (R/\sigma)^{1/4}$$

This relationship permits the temperature for each image pixel (0.5 X 0.5 meter) to be plotted and contoured. Based on the precision and accuracy of the blackbody units and the overall sensitivity of the infrared channel used, the RS-800 can discern thermal differences of about 0.2 degree Celsius from adjacent pixels.

6.0 Results

This survey was conducted on March 8, 2013, and covered over 2.25 square miles of land and consisted of about 800 radiological data points and two infrared multi-spectral images.

6.1 Radiological Results

Radiological products included eRa sigma plots, which represent the number of standard deviations from a normal background (Figures 8, 9 and 10).

All of the elevated radiation measurements were detected during the West Lake Landfill survey at or over 20 contiguous acres associated with Operable Unit 1, Area 2 (Figure 8). This suggests that the surface soil contains waste residues from uranium ore processing.

All other areas throughout the West Lake Landfill Survey did not register a significant deviation from background.

Figure 7: West Lake Landfill sub-area designations. Highest eRa measurements were obtained over Operable Unit 1 Area 2.

6.1.1 eRa Sigma Plots

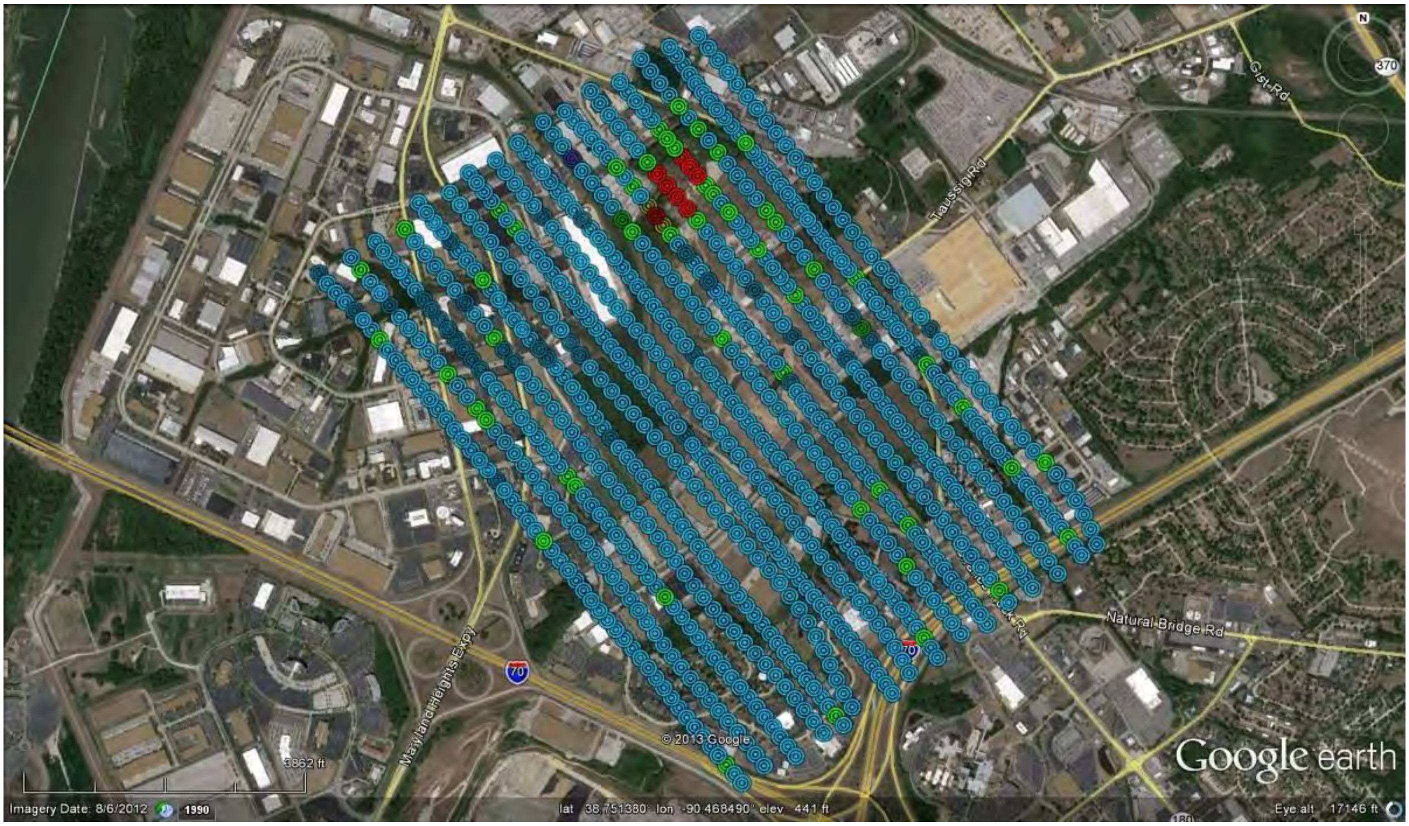
Since uranium (and radium) is a naturally occurring radionuclide and is ubiquitous in nature, a statistical analysis was conducted to determine the significance of any deviation from naturally occurring background levels. The analysis is referred to as a sigma plot and is discussed in Section 5. Areas on a sigma plot with values greater than 4 sigma (standard deviations) 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 or its decay products.

Table 2 summarizes the sigma plot results for excess eRa for the area surveyed over West Lake Landfill. Of the 804 data points collected, two were within 4 to 6 sigma and an additional eight were greater than 6 sigma. Over 92 percent of the area surveyed was below the 2 sigma threshold. Less than 7 percent of the surveyed area fell between 2 and 4 sigma, while the areas between 4 and 6 sigma and those above 6 sigma combined were 1.25 percent of the total. Data above the 6 sigma threshold were centered over Operable Unit 1 Area 2 (Figure 10).

Table 2: Statistical data for eRa results

Flt. Block	Area	# Data	< 2 Sigma	> 2 Sigma	>4 Sigma	>6 Sigma
1	West Lake Landfill	804	741	53	2	8
			92.2%	6.6%	0.25%	1%

Figure 8: Excess eRadium Sigma Plot
West Lake Landfill Survey
March 8, 2013



Flight Parameters

500 ft altitude
400 ft line spacing
110 knots
1 second acquisition time

The area associated with eRa sigma points exceeding 6 sigma is associated with Operable Unit 1, Area 2. Since the waste in the West Lake Landfill is known to contain uranium ore processing residues, it is likely that the elevated measurements are from radium or other uranium decay products rather than uranium itself.

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

Figure 9: Area 1 Excess eRadium Sigma Plot
West Lake Landfill Survey
March 8, 2013

Sigma Values (Excess Bismuth-214)

- Less than -6.0
- -6.0 to -4.0
- -4.0 to -2.0
- -2.0 to +2.0
- +2.0 to +4.0
- +4.0 to +6.0
- Greater than +6.0

Flight Parameters

500 ft altitude
400 ft line spacing
110 knots
1 second acquisition time

A close up of Operable Unit 1 Area 1. No points exceeding 6 sigma were detected in this area.

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

Figure 10: Area 2 Excess eRadium Sigma Plot
West Lake Landfill Survey
March 8, 2013

Flight Parameters

500 ft altitude
400 ft line spacing
110 knots
1 second acquisition time

Operable Unit 1, Area 2. Since the waste in the West Lake Landfill is known to contain uranium ore processing residues, it is likely that the elevated measurements are from radium or other uranium decay products rather than uranium itself.

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

6.2 Infrared Results

Infrared imagery provides high resolution thermal data that can provide useful information to assess environmental conditions. At the West Lake landfill, Operable Unit 2 is known to have a subsurface smoldering event in the Former Active Sanitary Landfill cell. Two infrared images from the West Lake Landfill area (Figures 11 and 12) were evaluated for thermal signatures for the purpose of identifying any indication of subsurface heat generation and for the potential to delineate the extent of the subsurface smoldering event.

The infrared energy data in each image was converted to thermal units and contours added to assist interpretation. The contour levels began at 10 degrees Celsius and increment by 2 degrees each contour up to a maximum of 30 degrees. This represents the thermal range expected for the surface features in the landfill areas. The resulting images (Figures 13 and 14) were reviewed and no anomalous heat signatures that could be attributed to the subsurface smoldering event were identified. The warmest areas shown on the thermal figures (orange, red and white colors) correlate to obvious surface features, such as black plastic cover material or structures, and the more subtle thermal differences can be attributed to differential heating due to sun angle and soil type.

Figure 11: Infrared Image of the Eastern Portion of the West Lake Landfill Survey March 8, 2013

Figure 12: Infrared Image of the Western Portion of the West Lake Landfill Survey March 8, 2013

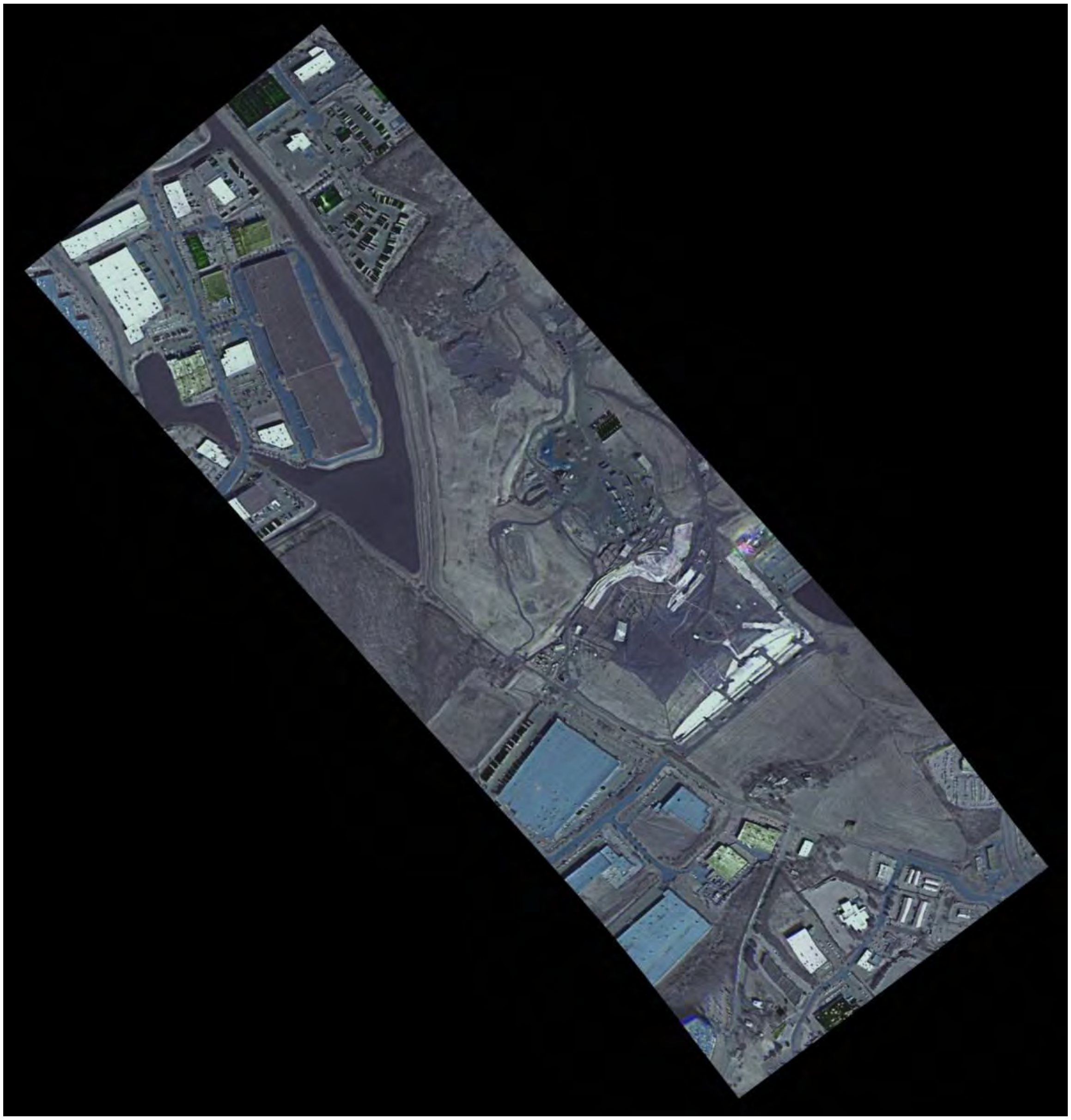
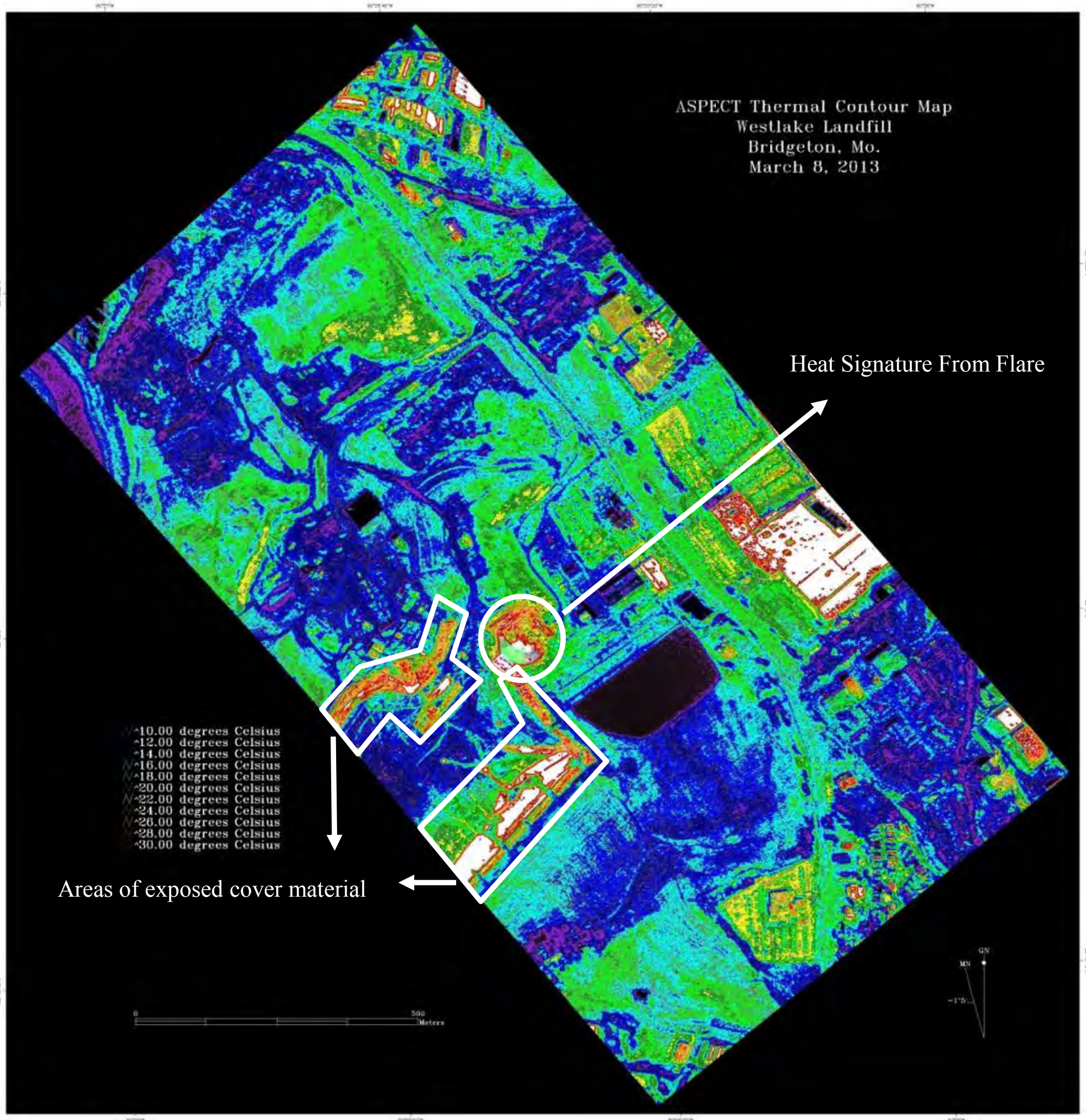
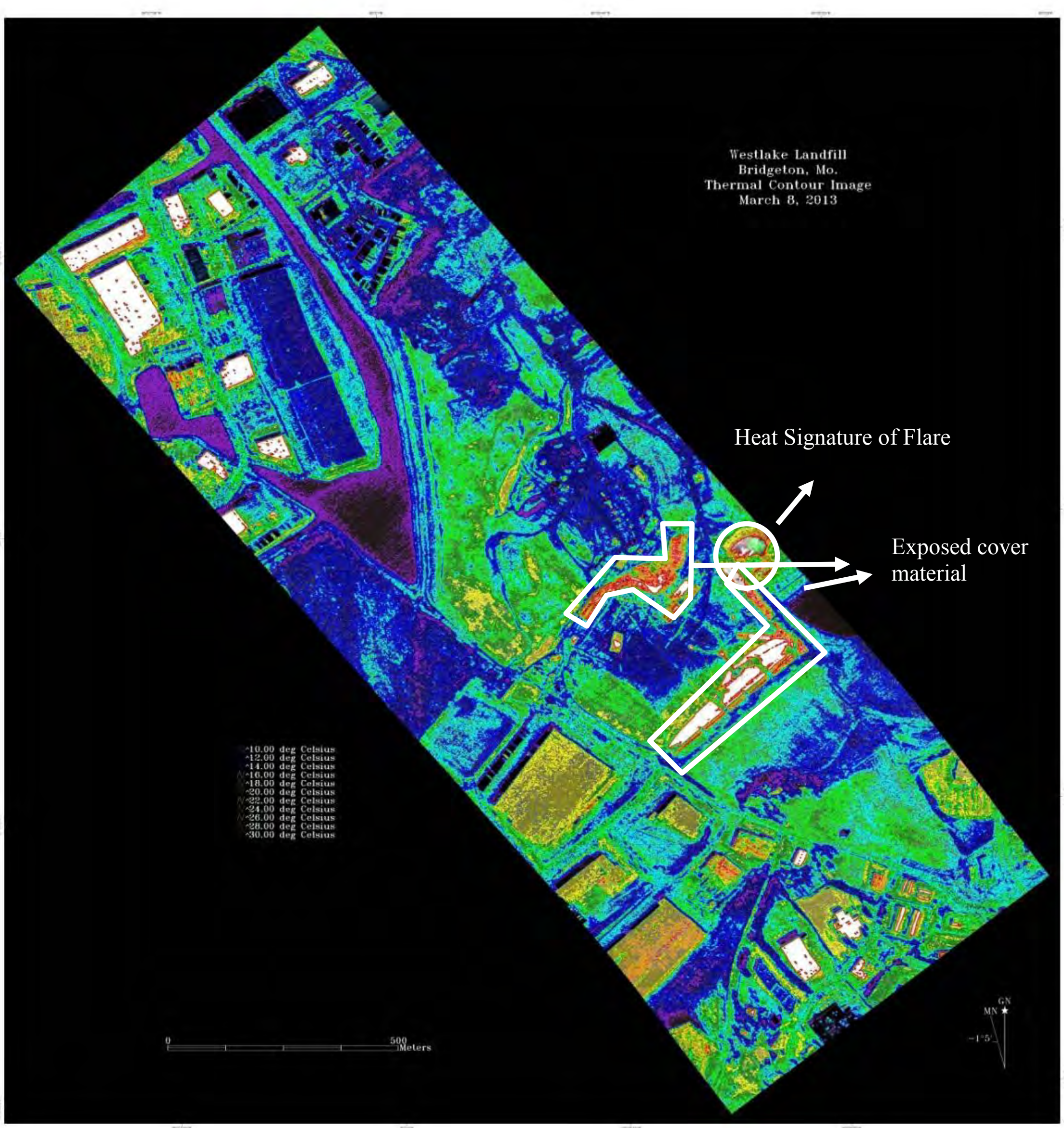


Figure 13: Thermal Contouring Image of the Eastern Portion of the West Lake Landfill Survey March 8, 2013



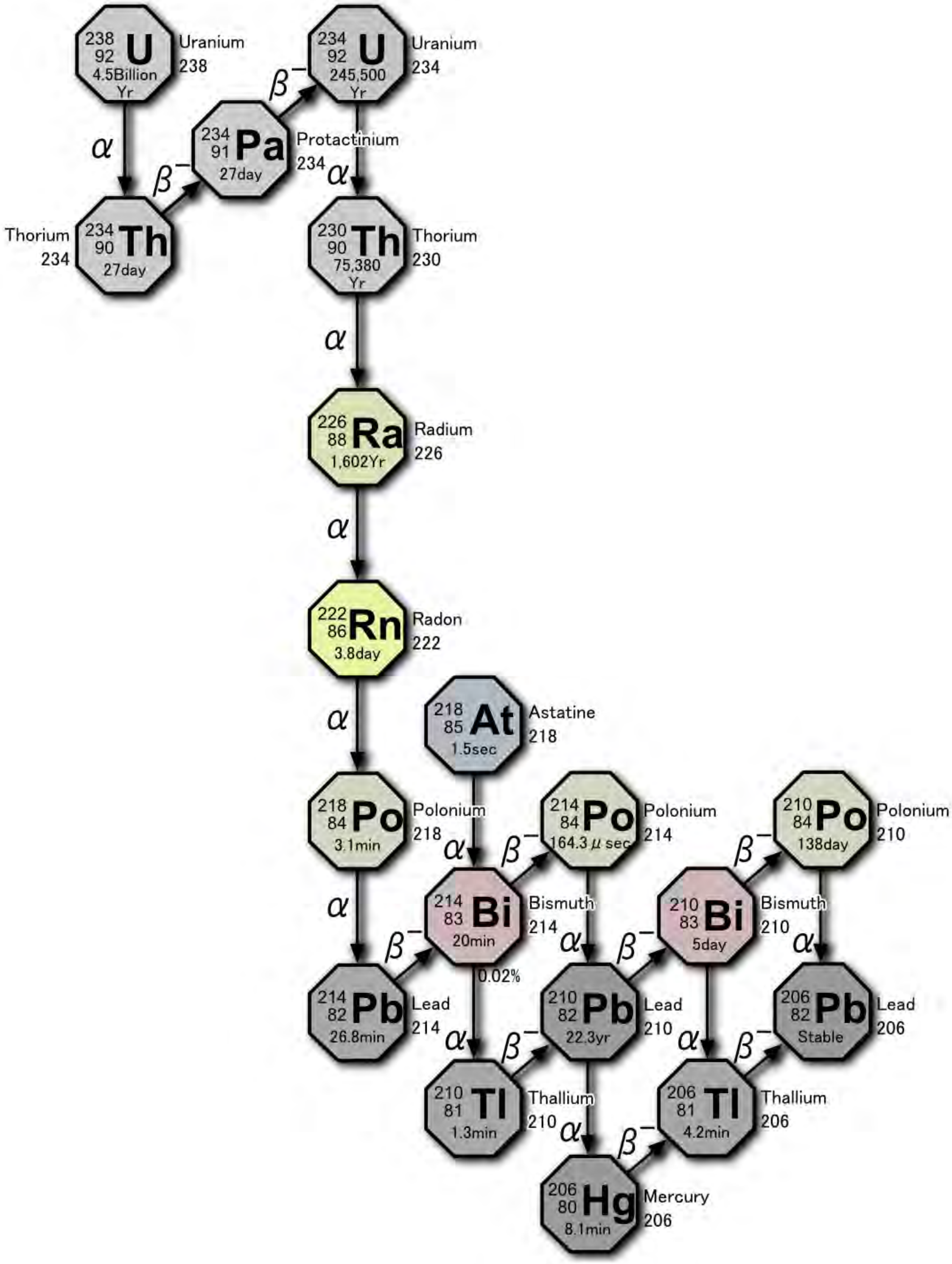
The flare referenced in this figure is the device the landfill owner uses to burn off methane and other gases collected from the landfill.

Figure 14: Thermal Contouring Image of the Western Portion of the West Lake Landfill Survey March 8, 2013



These images were collected in the late morning when the sun was striking the site and heating up the surface materials, including large areas of black plastic cover material the facility has been placing on the surface of the Former Active Sanitary Landfill cell. On this figure, the exposed cover material, a high emissivity material, in the Former Active Sanitary Landfill area clearly stands out as white with tightly spaced reddish contours surrounding it. This is the anticipated signature from that type surface cover material. Other higher thermal signatures of the Former Active Sanitary Landfill unit are consistent with the known surface features at the site. The remaining signatures across the rest of the landfill were consistent with slight differences in the emissivity of the surface materials found in those areas and differential solar heating due to the sun angle. This infrared data set from the landfill area does not provide the information needed to delineate the subsurface smoldering event.

Appendix I : Uranium Decay Chain



Appendix II
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 in this Appendix discuss how airborne data should be interpreted and compared to ground-based surface measurements.

Background radiation

Airborne gamma-spectroscopy systems measure radiation originating from terrestrial, radon, airplane, 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 decay product, ^{214}Bi, is used to estimate radium and uranium concentration in the soil. Radon is normally accounted for in the processing algorithm by flying specific test lines before and after each survey and comparing the results. Cosmic and airplane 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 or uranium concentrations from one of its decay products, ^{208}Tl or ^{214}Bi respectively. Secular equilibrium exists when the activity of a decay product equals that of its parent radionuclide. This can only occur if the half-life of the decay product is much shorter than its parent and the decay product stays with its parent in the environment. In this case, the measurement of ^{214}Bi gamma emission is used to estimate the concentration of its parent radionuclide, uranium, if one assumes all the intermediate radionuclides stay with each other. However, ^{222}Rn is a noble gas with a half-life of 3.8 days and may de-gas from soils and rock fissures due to changes in weather conditions. Due to the relatively long half-life (compared to ^{214}Bi) 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. This becomes more complex with uranium ore waste materials, where the uranium has been extracted and the resulting waste materials contain mostly uranium decay products, e.g. radium. In this situation, the eRa concentration would be a better estimate for radium concentration rather than uranium concentrations, as is the case in this survey.

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}Bi 1.76 MeV gamma-rays will reach the detector at an altitude of 300 ft whereas only 44% of the ^{40}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. Despite the nominal correction, the ASPECT program accounts for temperature and pressure effects.

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; however, the ground was likely saturated from recent snow melt.

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 2π geometry (a flat 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 are present in the leaves or surfaces of the vegetation.

Spatial Considerations

Ground-based environmental measurements are usually taken 3 ft above the ground with a field of view of about 30 ft^2. The ASPECT collected data at about 500 ft above the ground with an effective field of view of about 10 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

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

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 500 ft aerial measured could correlate to a ground-based exposure-rate of 3.5 μR/h. However, if all the activity was contained in a small area such as a single small structure containing uranium waste materials (represented by the blue dot within the field of view of "B"), a 500 ft aerial measurement may still provide the same exposure-rate measurement but the actual ground-based measurements could be as high as 3,150 μR/h.

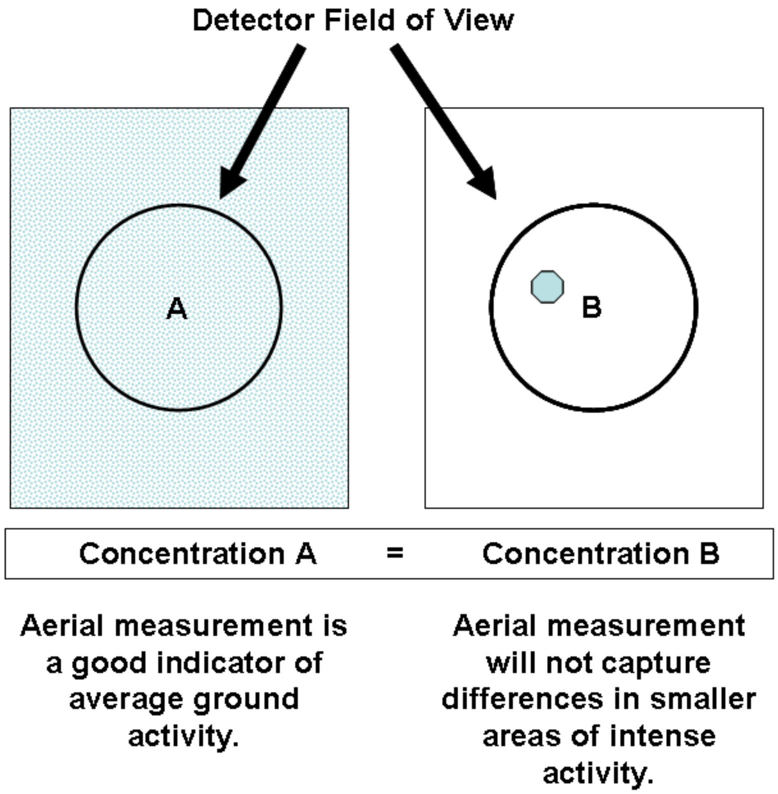


Illustration of aerial measurement capabilities and interpretation of the results

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}Tl and ^{214}Bi as indicators of ^{232}Th and ^{238}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 airplane are geo-coded using latitude and longitude. The position of the airplane at any 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 airplane computer network which is synchronized from a master GPS receiver and has a maximum error of one 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 airplane, 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 airplane altitude (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 airplane 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 altitude 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 airplane 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.

* 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.

References

BRISTOW, Q. (1983). Airborne γ-ray spectrometry in Uranium Exploration. Principles and Current Practice. International Journal of Applied Radiation and Isotopes **34**(1), 199-229.

CARDARELLI, J., THOMAS, M., and CURRY, T. (2011). Environmental Protection Agency airborne detection capabilities. Health Physics Society Midyear Meeting: Radiation Measurements. Charleston, South Carolina, February 8, 2011. (page 27) Abstract available at http://www.hps.org/documents/2011_midyear_final_program.pdf Accessed on 10 April 2013.

CARDARELLI, J., THOMAS, M., CURRY, T., KUDARAUSKAS, P., and KAPPELMAN, D. (2011). Aerial and Ground Radiological Surveys: Phosphate Mines in January 2011. US EPA. Available at http://epa.gov/region4/superfund/images/nplmedia/pdfs/coroiflrt2011.pdf Accessed on 12 March 2013.

EISENBUD, M., (1987). Environmental Radioactivity; From Natural, Industrial, and Military Sources. 3rd Edition. Academic Press, Inc., New York, NY.

GRASTY, R.L., CARDSON, J.M. CHARBONNEAU, B.W., HOLMAN, P.B., (1984). Natural Background Radiation in Canada, Geol. Surv. Can. Bull. 360.

IAEA (1991). International Atomic Energy Agency. *Airborne Gamma Ray Spectrometer Surveying*. Technical Report Series No. 323. (International Atomic Energy Agency, Vienna).

IAEA (2003). International Atomic Energy Agency. *Guidelines for radioelement mapping using gamma ray spectrometry data.* Technical Document 1363. IAEA, Vienna. Available at http://www-pub.iaea.org/mtcd/publications/pdf/te_1363_web.pdf. Accessed on 12 March 2013.

NCRP (1987). National Council on Radiation Protection and Measurements. *Exposure of the Population in the United States and Canada from Natural Background Radiation.* NCRP Report 94 (National Council on Radiation Protection and Measurements, Bethesda, Maryland).