Bechtel Nevada
REMOTE SENSING LABORATORY
OPERATED BY BECHTEL NEVADA
FOR THE U.S. DEPARTMENT OF ENERGY

DOE/NV/11718--218
OCTOBER 1998

AN *IN SITU* RADIOLOGICAL SURVEY CONDUCTED DURING REMEDIATION ACTIVITIES AT THE CLEAN SLATE 1 SITE

TONOPAH TEST RANGE
TONOPAH, NEVADA

Steven R. Riedhauser
Bechtel Nevada
Las Vegas, Nevada

DATE OF SURVEY: APRIL 28 TO JUNE 19, 1997

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

Abstract

A team from the Remote Sensing Laboratory, operated by Bechtel Nevada for the U.S. Department of Energy, conducted a series of radiological measurements at the Clean Slate 1 site on the Tonopah Test Range, which is located southeast of Tonopah, Nevada. The team performed a series of gamma radiation measurements during April 28–June 19, 1997, while the remediation work, which was also conducted by Bechtel Nevada, was in progress.

During the expedition, one set of radiation measurements were used to assess whether sufficient soil had been removed during the excavation work. If the measured activity was not below the remediation level, an additional layer of soil was removed. A second set of measurements were used to monitor the soil-packaging operation. As the excavated soil was loaded into trailers for transportation to the disposal site, a detector measured the amount of ^{241}Am passing into the trailer. This measurement was used in generating the necessary transportation and disposal site paperwork. The third set of measurements were produced by the Kiwi detector platform and used to characterize the distribution of transuranic contamination (measuring the americium activity levels and inferring the plutonium activity levels) remaining at the site. Several plots compare the 1997 post-remediation data with the 1996 characterization data.

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List of Acronyms and Abbreviations

NOTE: The names, symbols, and other nomenclature of chemicals mentioned in this report are listed in Appendix B.

AGL	above ground level
^{241}Am	americium-241
BN	Bechtel Nevada
CADD	corrective action decision document
CAIP	corrective action investigation plan
Ci	curie (a unit of activity equal to 3.7×10^{10} disintegrations per second)
cm	centimeter
^{137}Cs	cesium-137
DASA	Defense Atomic Support Agency
DOE	Department of Energy
FIDLER	field instrument for detection of low-energy radiation
ft	feet
g	gram
GC	gross count
GPS	global positioning system
GZ	ground zero
IT	International Technology Corporation
keV	kiloelectron volt
kg	kilogram
km	kilometer
lb	pound
m	meter
mm	millimeter
MCA	multichannel analyzer
MSL	mean sea level
m/s	meters per second
µR/h	microroentgen per hour (a unit of exposure rate)
mph	miles per hour
NaI	sodium iodide
nCi/g	nanocuries per gram (a unit of activity concentration)
NIST	National Institute of Standards and Technology
NTS	Nevada Test Site
pCi/g	picocuries per gram (a unit of activity concentration)
Pu	plutonium
REDAR IV	Radiation and Environmental Data Acquisition and Recorder, Version IV
RSL	Remote Sensing Laboratory
TTR	Tonopah Test Range

1.0 Introduction

The U.S. Department of Energy (DOE) maintains the Remote Sensing Laboratory (RSL), which provides several systems for measuring terrestrial radiation. In addition to the aerial radiological surveillance systems mounted in either helicopters or airplanes, the RSL has several systems for collecting ground-based measurements. RSL is operated by Bechtel Nevada (BN) under contract to the DOE, with bases of operation at the Nellis Air Force Base in Las Vegas, Nevada, and at the Andrews Air Force Base near Washington, D.C.

The three Clean Slate sites are situated on Cactus Flat (an arid plain) on the Tonopah Test Range (TTR) and are located approximately 60 km southeast of Tonopah, Nevada. The elevation at the Clean Slate sites is approximately 1640 m. The area is comprised mostly of sandy soil with a thin surface layer of small gravel and is covered with small shrubs and some grass.

The Clean Slate 1 test involved a high-explosive detonation near an array of mock devices containing 1.365 kg of plutonium and 52 kg of depleted uranium.[1] This test was one in a series designed to study the dispersal of transuranic elements from a weapons accident for conditions of open storage, storage in a Defense Atomic Support Agency (DASA) igloo covered with 0.6 m of earth, and storage in a DASA igloo covered with 2.4 m of earth. Clean Slate 1 was the test for open storage, conducted on a 6.4-m^2 slab of concrete. The test was conducted at 4:17 am on May 25, 1963. After the test, the concrete pad was broken into small pieces and buried in a pit near ground zero (GZ). Soil from near the GZ was pushed on top of this area to create a mound about 1 m high.

The five-sided fence surrounding the Clean Slate 1 site formed the radiation exclusion zone of approximately 0.24 km^2 (59.3 acres). This fence was established several years after the test, and the boundary was based on the gamma radiation levels measured by a set of FIDLER (field instrument for the detection of low-energy radiation) detectors.

The RSL performed aerial surveys of the three Clean Slate sites using helicopter-mounted sodium iodide (NaI) detectors in February 1977 and October 1993. The 1977 survey[2] was conducted at a 30-m altitude using a line spacing of 61 m. The 1993 survey[3] was also conducted at an altitude of 30 m, but a line spacing of 46 m was used. At this altitude, the ground area that was measured each second from the helicopter system is similar in size to the areas where the proposed remediation levels would be averaged. The 1993 survey indicated that the areas having an average level of contamination above 200 pCi/g total transuranic material were contained inside the fences at each site. The 1993 aerial survey used a total plutonium-to-americium (total Pu:^{241}Am) ratio of 10:1 based on measurements[4] from soil samples collected and analyzed by the Sandia National Laboratories. However, these samples were collected outside the exclusion fence at the Clean Slate 2 site, and all samples produced rather low activities. The large uncertainties (as well as the scatter in the ratio values) produced an average ratio value that was considered too small for the current work.

The 1977 survey data are a little more perplexing and only a qualitative comparison with the 1993 survey will be discussed in this report. A qualitative comparison of the positions of various contour levels indicates a multiplicative difference between the activity levels of the two surveys at each site. At Clean Slate 1, the 1977 survey showed activities about 30–40 times greater than the activities of the 1993 survey. At Clean Slate 2, the 1977 survey showed activities about 25–30 times greater than those of the 1993 survey. At Clean Slate 3, the 1977 survey showed activities about 10 times greater than those of the 1993 survey. At the Double Tracks site, the 1977 survey showed activities about 20 times greater

than those of the 1993 survey. The cause of this discrepancy appears to be the factors used in converting from count rate to activity in the soil. A precise cause of the problem could not be determined since the detector arrays used in 1977 are no longer available to verity the characterization measurements used in the calculations.

In parallel with the 1993 aerial survey, a series of ground-based *in situ* measurements made with Ge detectors mounted on tripods were taken at each of the three Clean Slate sites.[5] These measurements were made in one or two lines across the plume just outside the fenced area farthest from the GZ. Measured at 1 m above the ground with a typical footprint of 6–8 m and spaced 15 m apart, these measurements agreed qualitatively with the 1993 aerial results. A rigorous comparison was not possible since the variations in activity, seen with the tripod measurements within a single aerial footprint, are significant (commonly as much as a factor of 2). This variation in activity makes the data from these ground-based measurements extremely limited. The very discrete distribution of plutonium particles, observed at the Double Tracks site and reported[6] in detail, was also observed at the Clean Slate 1 site.

In the spring of 1996, the RSL participated in the Clean Slate 1 site characterization initiated by the International Technology Corporation (IT). The site characterization was described in the DOE-issued corrective action investigation plan (CAIP)[7] and corrective action decision document (CADD).[8] The CADD report described the nature and extent of the radioactive contamination so that corrective action options could be evaluated. The techniques used during the characterization were very similar to the techniques employed during the Double Tracks characterization.[6,9] Based on the results of the Clean Slate 1 characterization, BN remediated the site during the summer of 1997. Much of the background material for this report is contained in the previous characterization reports, although some of the more important material is retained so that having those reports is not necessary to understand this report. Details of the remediation plan and the work performed at Clean Slate 1 can be found in the corrective action plan[10] and closure report.

The remediation work involved (a) excavating soil above a certain contamination level and collecting the soil in a stockpile (requiring about 10 days), (b) loading the soil into trailers (requiring about three weeks), (c) transporting the soil to the Nevada Test Site (NTS) for disposal at the Radioactive Waste Management Site in Area 3 (performed concurrently with the trailer-loading operation), and (d) conducting a final radiation survey (requiring about three days) to ensure that the proper areas had been remediated. The remediation levels were specified as soil having a total transuranic activity of more than "200 pCi/g averaged over a 100-×100-m area" or more than "600 pCi/g averaged over a 10-×10-m area". However, all areas having an activity over 200 pCi/g averaged over a 10-×10-m area were remediated.

2.0 Natural Background Radiation

Many factors—radiation from sources of interest to the current investigation, radiation from sources not of immediate interest, and electrical noise—contribute to the total measured gamma-ray energy spectrum. These components can be summarized as the five terms in the following equation:

$$\begin{bmatrix} \text{Measured} \\ \text{Radiation} \\ \text{Spectrum} \end{bmatrix} = \begin{bmatrix} \text{Natural Terrestrial Radionuclides} \\ + \text{ Man - Made Radionuclides} \\ + \text{ Airborne Radon} \\ + \text{ Cosmic Rays} \\ + \text{ Equipment Contributions} \end{bmatrix} \quad (1)$$

The term "natural background radiation" is generally considered to comprise three of the terms included in the previous equation: namely, natural terrestrial radionuclides, airborne radon gas and its daughter products, and cosmic rays. The man-made radionuclides (such as ^{60}Co and ^{137}Cs), produced through actions of man, are generally the components of the radiation field of most interest. The final term in this equation—equipment contributions—represents all sources of "noise" in the final spectrum, ranging from electrical noise in the electronics used to process the detector signals to radiation sources inherent in the detectors and other measuring equipment.

Long-lived radionuclides present in the earth's crust are usually the largest source of background radiation. Naturally occurring isotopes found in the soil and bedrock consist mainly of radionuclides from the uranium and thorium decay chains and radioactive potassium. The most prominent natural isotopes usually seen in spectra are ^{40}K (0.012 percent of natural potassium), ^{208}Tl and ^{228}Ac (daughters in the ^{232}Th chain), and ^{214}Bi (a daughter in the ^{238}U chain). Although it is considered a man-made radionuclide, a measurable amount of ^{137}Cs is found throughout the world (initially as a surface deposition and then, over time, migrating several centimeters into the soil) as a result of the atmospheric testing of nuclear weapons. These naturally occurring isotopes typically contribute 1–15 μR/h to the background radiation field.[11]

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

Cosmic rays entering the earth's atmosphere are a third source of background radiation. High-energy cosmic rays (principally protons, alpha particles, and some heavier nuclei) interact predominantly with atoms in the upper atmosphere to produce showers of secondary radiation (neutrons, electrons, gamma rays, and X-rays). The contribution of cosmic rays to the background radiation field varies with elevation above mean sea level (MSL) and with geomagnetic latitude. The earth's magnetic field deflects some of the cosmic rays and traps some of the secondary radiation, so a larger fraction of

the radiation reaches the ground near the poles than near the equator. Within the continental United States, the exposure rate ranges from 3.3 μR/h at sea level to 12 μR/h at an elevation of 3,000 m.[12] For domestic surveys, the dependence on geomagnetic latitude is small, and the elevation of the survey is the predominant determinant of the cosmic-ray flux.

3.0 General Considerations for Detecting Gamma Rays

Each radioactive isotope encountered in the environment emits one or more of the following types of radiation when it decays: alpha particles, beta particles, gamma rays, or X-rays. More importantly, these decay products have a specific energy (or specific set of energies) that helps to identify the parent isotope. The mix of plutonium isotopes (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu) that are present at the site decay either by the emission of an alpha particle (which is impossible to detect more than a few centimeters away) or by the emission of a very low-energy beta particle (which is also very difficult to detect). In addition to these particles, plutonium emits some low-energy X-rays and, at a very low rate, some gamma rays. Nearly all systems used to search for plutonium rely on detecting the 60-keV gamma ray emitted by the decay of ^{241}Am, which is the initial product in the decay of ^{241}Pu. These gamma rays are relatively easy to detect even from aerial detection systems 30–50 m above the ground and are significantly more abundant than the gamma rays emitted directly from the plutonium decays. Calculations based on historical information (the initial abundances of the plutonium isotope) can be used then to predict the current abundances of the various plutonium isotopes.

Two different types of detectors are used to detect gamma radiation. The NaI detectors (used in the ground-based Kiwi system and the aerial platforms) can be used with large surface areas and volumes, which allow the detectors to efficiently collect most of the incident gamma rays. However, the energy resolution of NaI detectors is relatively poor, so the ability to identity specific gamma-ray energies and, therefore, specific isotopes is limited to areas containing only a few isotopes. The Ge detectors (used on a mast-mounted detector system and on the tripods) are much smaller than the NaI detectors. Consequently, the Ge detectors collect gamma rays at a much slower rate, but the Ge detectors have the advantage of high-energy resolution, which makes isotopic identification relatively easy even in areas containing many isotopes. The higher-energy resolution is also very useful when contributions from very small photopeaks must be analyzed in the midst of a relatively large background count rate.

In the preceding discussion pertaining to the identification of isotopes from the measured gamma-ray energies, it is assumed that all of the initial gamma-ray energy is collected by the detector. This is often not the case. Many of the gamma rays emitted by an isotope will be scattered (by soil or air or inside the detector) and lose some of their energy, breaking the correlation between a specific energy and a specific isotope. This process is known as Compton scattering and creates a smoothly varying background within the energy spectrum. Statistical fluctuations, due to this Compton background, increase the uncertainty in how many gamma rays of a specific energy were detected. Thus the uncertainty in the amount of an isotope present during a measurement increases with the increase in the Compton background.

Unlike alpha and beta particles, gamma rays can travel large distances through the atmosphere. With a detector suspended 1 m above a perfectly flat ground, 50 percent of the detected 60-keV ^{241}Am gamma rays will originate from more than 6 m away. Typical ground roughness effects will decrease this far-field effect significantly, but a measurement made at this height still is not very localized. When a measurement must be made of a well-defined area on the ground, a collimator must be used to shield the detector from gamma rays emitted from areas outside the desired area. Generally, this shielding requires the use of a large quantity of very dense material. For 60-keV gamma rays, however, the collimation can be accomplished using approximately 3 mm of lead.

4.0 Kiwi Data Reduction Procedures

Several methods of processing the Kiwi data can be employed. The gross count-rate (GC) algorithm calculates the total counts from all gamma rays detected during each 1-second sample and presents the results as a series of colored, count-rate ranges (often superimposed on a map or photograph of the survey area). With this display, large-scale variations of the radiation field within the whole survey area may be easily seen. Since the Clean Slate sites are relatively small and there are no major geological variations within the sites, the GC plot is quite flat—except in areas containing transuranic (plutonium and americium) contamination. The GC algorithm was used principally to provide a picture of the overall radiation field in the survey area. An example of this plot is given in the CADD report.

At the Clean Slate sites, the major contaminant is plutonium (and its gamma-ray emitting daughter, americium). With this knowledge, the count rate in the ^{241}Am photopeak can be plotted versus position, and a more sensitive plot of the contamination can be made from the isotopic count rate. The isotopic stripping of the ^{241}Am photopeak from the gamma-ray spectra was the beginning step in producing the enclosed data maps.

4.1 Isotopic Extraction Algorithms

In general, the gamma rays emitted by radioisotopes have very precise, well-defined energies. If the gamma rays could be measured ideally, the energy spectrum would consist of tall, very narrow photopeaks centered at the total energy of the gamma ray. (Some of the peaks would be riding on top of the slowly varying distribution of Compton-scattered gamma rays from other isotopes, but the peaks would be narrow.) However, the detector and associated electronics used to measure the gamma rays have energy resolutions that broaden the photopeak distribution. The spectrum actually recorded by the measuring system will have broader, Gaussian-shaped peaks with widths equal to the resolution of the detection system.

The total number of counts contained in the Gaussian-shaped photopeak can be obtained by summing all of the counts within ΔE of the gamma-ray energy, E. The magnitude of ΔE will determine how many of the total counts are summed. If $\Delta E = 3\sigma$, where σ is the standard deviation of the Gaussian distribution, then 99.7 percent of the total photopeak counts will be included in the sum. This is not an unreasonable assumption for Ge detectors, which have very narrow-peak shapes. However, if the standard deviation for the system is large as is the case for NaI detectors, then the distributions from different photopeaks can overlap significantly. This interference between peaks can be minimized by decreasing ΔE, with the knowledge that not all counts will be included in the sum. A correction factor, determined in a region free of conflicting peaks, can be found to relate the number of counts in the range $E \pm \Delta E$ to the total counts in the peak.

The 3-window algorithm (Figure 1) is the principal calculational tool for assessing the quantity of ^{241}Am present in the spectral data. The algorithm employs a background window on each side of the photopeak window. The two background windows abut the photopeak window in energy. This algorithm assumes that the number of background counts in the photopeak window is linearly related to the counts in the two background windows. The 3-window algorithm is also very useful in extracting low-energy photopeak counts where the shape of the Compton-scattered background from other isotopes is changing significantly.

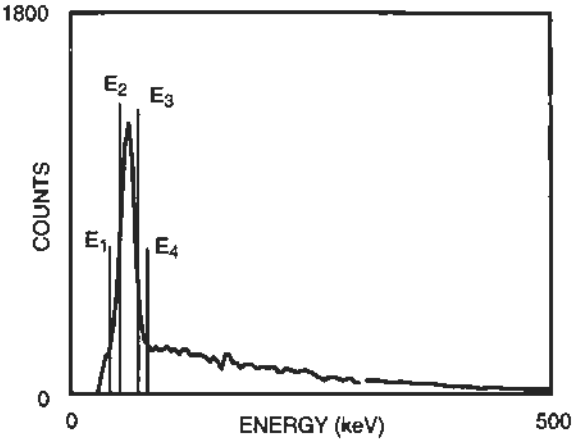

FIGURE 1. ***THREE-WINDOW ALGORITHM APPLIED TO A TYPICAL SPECTRUM. The 3-window algorithm uses a central window containing the photo-peak of interest and two background windows to determine the net spectral counts.***

$$c_{3-Window} = \sum_{E=E_2}^{E_3} c(E) - K_3 \left[\sum_{E=E_1}^{E_2} c(E) + \sum_{E=E_3}^{E_4} c(E) \right] \tag{2}$$

with

$$K_3 = \frac{\sum_{E=E_2}^{E_3} c_{bkg}(E)}{\sum_{E=E_1}^{E_2} c_{bkg}(E) + \sum_{E=E_3}^{E_4} c_{bkg}(E)} \tag{3}$$

where

$c_{3\text{-}Window}$ = net counts from the 3-window algorithm

$c(E)$ = counts in the gamma-ray energy spectrum at the energy E

E_n = energies of the window limits ($E_1<E_2<E_3<E_4$)

K_3 = ratio of the counts in the photopeak window to the counts in the two background windows in a "background" region of the survey

$c_{bkg}(E)$ = counts in the gamma-ray energy spectrum at the energy E in a "background" region of the survey

The proportionality factor, K_3, was determined in a region of the survey that did not contain any of the specific isotope so that the photopeak window contained only background counts and, therefore, was directly related to the number of counts in the background windows.

4.2 Data Gridding

To produce the Kiwi data plots in this report, the data were collected into a 10-m grid. Since (a) the data were collected second-by-second, (b) the speed of the vehicle was not constant, and (c) the

actual "flight" lines sometimes covered the same ground, gridding was necessary. Because the interest in the data was predominantly to determine the ^{241}Am activity over square areas of 10-m and 100-m sizes, the gridding did not significantly degrade the spatial resolution of the data.

Once the grid was constructed, the windowed data—corrected for live-time—from individual spectra having positions that lie inside a grid cell were summed, and an average count rate was calculated for the center of the grid.

$$\frac{c_g(x_c, y_c)}{T_{Live,g}} = \frac{1}{N} \sum_{i=1}^{N} \frac{c_{3-Window}(x_i, y_i)}{T_{Live,i}} \tag{4}$$

where

$c_g(x_c, y_c)$ = number of counts in the gamma-ray window at the center of the grid cell at location (x_c, y_c)

$T_{Live,g}$ = live time associated with the measurement at the center of the grid cell; equal to the sum of the $T_{Live,i}$

N = number of data samples contained within the grid cell

$T_{Live,i}$ = live time of the ith measurement

$c_{3\text{-}Window}(x_i, y_i)$ = number of counts in the gamma-ray window from the spectrum collected at location (x_i, y_i)

In this equation, the individual spectral counts are converted into count rates and averaged to produce the count rate at the center of the grid cell. The uncertainty in the gridded data (σ_g) is roughly $1/N^{1/2}$ times the uncertainty of an original measurement (σ). Thus gridding increases the accuracy of the measurement at the expense of decreasing the spatial resolution. On average, about ten Kiwi measurements are collected in a given grid cell, resulting in an uncertainty of the grid cell activity, which is about one-third the uncertainty of an individual measurement.

It should be noted that by shifting the position of the grid relative to the measured radiation data (or relative to some other fixed positions such as the fence posts), a different set of Kiwi measurements will be collected in a grid cell. In the CADD report, other data collected from the Clean Slate 1 site indicated that the radioactive material was distributed predominantly in discrete clusters. Since the activity changes rapidly over distances of a few meters in some regions of the survey, the inclusion or exclusion of one Kiwi measurement in a grid cell could produce a significant change in the average result. This is the predominant reason behind the differences in the April 1996 data presented in the CADD report versus the same data presented in this report.

4.3 Converting Count Rate to Activity in the Soil

The conversion from the count rate measured by a detector system to the activity of the isotope in the soil depends on several factors involving the radiation source, the intervening material, and the detection system. These factors include (a) the distribution of the isotope in or on the soil, (b) the energy of the gamma ray emitted by the isotope, (c) the ground roughness, (d) the amount of moisture in the soil, (e) the air density, (f) the distance of the detector from the source, (g) the sensitivity of the detector

system to the incident radiation, (h) the geometry of the detector–source arrangement including the use of collimators, and (i) the amount of background radiation present (principally cosmic rays, vehicle and equipment background, and airborne radon).

The soil activity concentrations deduced from the Kiwi system count rates are based on a simple multiplicative factor relating the count rate to the activity concentration measured by a collimated Ge tripod system. For the characterization data (April 1996), the Kiwi was parked over an area inside the fence at the Clean Slate 3 site, and the count rate was measured for several minutes. The activity in this same area was also recorded in a series of Ge tripod system measurements. The Ge measurements showed a variation in the activity of a factor of 2 from one end of the area to the other end.

The Kiwi conversion factor thus depends on the conversion factor calculated for the Ge tripod systems. These detector systems have been characterized using a well-defined, accurate method for many years. The conversion from count rate to activity for the Ge tripod systems is briefly outlined in the following paragraphs as a summary of work given in several previous reports (for example, the work by Reiman[13]) that are generally based on the assumptions and derivations in the work by Beck *et al.*[14] This material was presented in the Clean Slate 1 CADD report;[8] therefore, only the highlights will be presented here.

The conversion factors are determined by combining a laboratory measurement of the detector's efficiency to a given gamma-ray energy with a theoretical calculation of the gamma-ray flux arriving at the detector as a function of source distribution in the soil. One of the most important components in the conversion factor calculation is the distribution of the isotope in the soil. For the plutonium and americium dispersed over 30 years ago at this site, an exponential distribution is assumed.

$$S(z) = S_{E0} e^{-z/z_0} \tag{5}$$

where

$S(z)$ = activity concentration of the isotope at the depth z (pCi/cm^3)

S_{E0} = activity concentration of the isotope at the surface of the soil (pCi/cm^3)

z_0 = exponential relaxation distance

The value of z_0 is usually poorly known and is highly dependent on the actual soil conditions. Since the chemical properties of an element determine how quickly the element can migrate through the soil, the value of z_0 is also generally different for each isotope that is present. (For example, ^{137}Cs migrates through the soil faster than ^{241}Am; therefore, ^{137}Cs would be expected to have the larger z_0.) In addition, soil disturbance (farming, construction, etc.) will affect the relaxation distance. Variations in z_0 can produce significant changes in the average or total activity measured as well as the activity concentration.

The number of photopeak counts registered by the detector depends on the flux of gamma rays at the location of the detector and a quantity that is designated as the effective detector area. Since the probability of a gamma ray depositing its full energy in the detector depends on the dimensions and orientation of the detector and energy of the gamma-ray, the effective area is not easily calculated. Instead, the effective area is measured in the laboratory and expressed as a zero-degree value, A_0, multiplied by a function, $R(\theta)$, which contains all of the angular dependence. The effective area is measured at ten-degree intervals, and logarithmic interpolation is applied between the measured values.

The measured photopeak count rate can be expressed as an integral over the factors for (a) the source activity in the soil, (b) the detector's effective area, (c) the distance from the source to the detector, and (d) the attenuation of the gamma rays by the intervening material (air and soil). Figure 2 presents a visual representation of the detector–source geometry.

$$C_p = \int_0^{\infty} \int_0^{\infty} \frac{0.037 \beta S(z) \quad A_0 R(\theta)}{4\pi d^2} e^{-\left(\frac{\mu}{\rho}\right)_a \rho_a d_a} e^{-\left(\frac{\mu}{\rho}\right)_s \rho_s d_s} 2\pi r dr dz \qquad (6)$$

where

C_p = net photopeak count rate (counts/s)
0.037 = a conversion factor (decays/second per pCi)
b = branching ratio (number of gamma rays of the photopeak energy emitted per decay)
$S(z)$ = activity concentration of the isotope at the depth z (pCi/cm^3)
A_0 = effective area of the detector at zero degrees (cm^2)
$R(\theta)$ = angular response of the detector at the angle θ
d = $d_a + d_s$, the distance from the source element to the detector (cm)
$(\mu/\rho)_{a,s}$ = air or soil mass attenuation coefficient (cm^2/g)
$\rho_{a,s}$ = air or soil density (g/cm^3)

Substituting the exponentially distributed activity and changing the integration variables results in the following expression for the conversion factor, F_E, which relates the measured photopeak count rate, C_p, to the unknown activity per unit volume at the surface, S_{E0}.

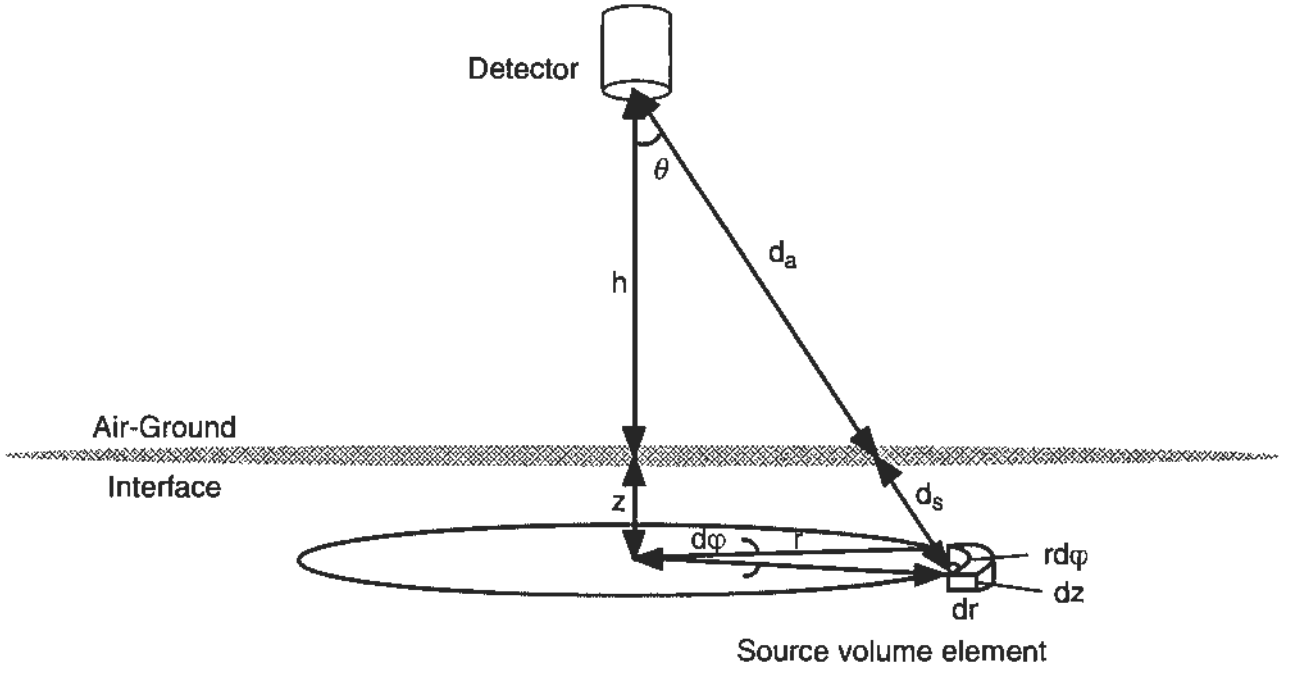

FIGURE 2. ***GEOMETRY FOR RADIATION MEASUREMENTS. The detector–soil elemental geometry applies to both aerial and gamma-ray spectroscopic measurements. The count rate in the detector is an integration of the gamma-ray flux from all of the individual source elements.***

$$\frac{1}{F_E} = \frac{C_p}{S_{E0}} = \frac{0.037\beta A_0}{2} \int_0^{\pi/2} \frac{R(\theta) \tan\theta \, e^{-\left(\frac{\mu}{\rho}\right)_a \rho_a h \sec\theta}}{\frac{1}{z_0} + \left(\frac{\mu}{\rho}\right)_s \rho_s \sec\theta} \, d\theta \tag{7}$$

In this equation, the detector parameters, A_0 and $R(\theta)$, are empirically determined for a given detector system using standard calibration sources. The branching ratio and the mass attenuation coefficients for air and typical soils can be found in standard reference tables. An average soil density of 1.5 g/cm^3 is assumed unless an actual measured value is available. The air density is calculated from measurements of temperature and barometric pressure. The detector height, h, is measured and the exponential relaxation length, z_0, is either measured or assumed from the analysis of similar locations.

The conversion factor relates a measured photopeak net count rate, expressed in units of counts per second, to source activity at the soil surface expressed in units of pCi/cm^3. The activity per unit volume can be converted to activity per unit mass by dividing by the soil density. It should be emphasized that the activity concentration previously discussed is the concentration at the soil surface for the exponential distribution.

5.0 Measurements and Results

5.1 Excavation Measurements

In the excavation plan for the site, an attempt was made to minimize the amount of soil that was excavated; therefore, the plan stipulated that 2- to 3-cm-deep cuts should be made with a grader across most of the contaminated areas. The terrain around the Clean Slate 1 site was not perfectly flat as each clump of shrubs harbored a small mound of soil. Since the terrain was uneven during the first cut with the grader, it was not always possible to remove the planned depth of soil. In some places, the grader removed more soil and in others it removed less soil. After each cut, FIDLER detectors were used to locate the remaining spots that required further excavation.

The FIDLER detectors were "calibrated" by making several measurements over an area at the site with a relatively constant ^{241}Am activity level. The count rate in the detector and the activity level from the site characterization data were used to determine the count rate corresponding to the action level of 200 pCi/g total transuranic material. Spots that measured above this count-rate level were outlined with spray paint. A second pass was made with the grader to remove another layer of soil from these small areas. Follow-up measurements indicated the activity was then below the action level.

Similar to the operation at the Double Tracks site in 1996, a four-wheel-drive vehicle (Chevrolet Suburban, Figure 3) with a collimated Ge detector suspended on a mast 7.5 m above ground level (AGL) was used at selected locations to confirm that the residual activity was below the action level. The collimated detector views a circular area having a radius of approximately 13 m for the 60-keV ^{241}Am gamma ray. Ten-minute measurements were made at each location producing sufficient statistics to

FIGURE 3. *SUBURBAN VEHICLE WITH Ge DETECTOR ON MAST. The detector on the end of the mast can be extended up to 7.5 m above the ground.*

accurately determine if the remaining activity was below the cleanup criteria. The detector was characterized before taken into the field so that an activity value could be computed within a couple minutes after each measurement. Not all of the excavated area was measured using this system. The final verification would be performed with the Kiwi system. The mast-mounted Ge detector system was used to confirm that the FIDLER detectors were adequate in locating remaining pockets of contamination.

While the FIDLER detectors were adequate in determining the areas requiring additional excavation, a drawback to their use was the need to translate the "large-area" average activity levels to much "smaller-area" averages. The cleanup levels were set at "200 pCi/g over a 100-$\times$100-m area" and "600 pCi/g over a 10-$\times$10-m area". The mast-mounted Ge detector views an area about 13 m in radius (equivalent to a 23-$\times$23-m area). General use of the Ge detector data brought the 200 pCi/g action level down to this 23-$\times$23-m area. The FIDLER detectors typically view only a 10- to 30-m^2 area, which is highly dependent on surface roughness. Unless the operator mentally averages the FIDLER readings while walking over the excavated areas, "small" areas may be needlessly excavated.

5.2 Activity Measurements at the Conveyor Belt

The excavated soil was packaged prior to being shipped for disposal at the Area 3 Radioactive Waste Management Site on the NTS. Unlike the Double Tracks remediation effort,[15,16] the Clean Slate 1 remediation effort relied on soil "packages" equivalent to the size of the trailers used to transport the soil to the NTS. For this project, soil was loaded into plastic liners that fit inside the trailer bed. Two liners (front and back) were loaded into each trailer. When full, the liner flaps were folded over the soil and tied together, making a closed package. For the operation, nine packages (trailers) were loaded with soil each day and transported to the NTS. For the whole period, 5.3×10^6 kg (11.7×10^6 lb) of soil were excavated, packaged, and disposed of at the NTS. Assuming a soil density of 1.28 g/cm^3 (80. lb/ft^3), a total of 4140 m^3 (146,000 ft^3) of soil was shipped from the Clean Slate 1 site. The use of two tractors having different capacities to pull the trailers resulted in transporting two different typical soil masses in the trailers. The closure report provides more details on this part of the operation.

The activity of each package was measured to satisfy transportation and disposal requirements. To perform this operation, a rectangular NaI log detector (5 cm thick by 10 cm wide by 40 cm long) was packaged inside a small plastic case that was positioned about 8 cm above a conveyor belt. The detector response was characterized using an ^{241}Am source with a National Institute of Standards and Technology (NIST)-traceable activity to relate the measured count rate to a soil activity.

As the soil on the conveyor belt passed by the detector, some of the ^{241}Am 60-keV gamma rays were collected. A Davidson portable multichannel analyzer (MCA) processed and stored the detector's signals. When the package was full, the net counts in the 60-keV photopeak and the detection time were calculated by a routine in the MCA. A scale on the conveyor belt measured the mass of the moving soil and integrated this measurement to obtain the mass of the package. The total activity of the package and the activity per gram were calculated in a spreadsheet program where the initial documentation was produced. Further documentation was generated by a radiation technician who surveyed the exterior of the package, checking for any removable contamination. The final transportation and disposal documents were created from these initial documents before the trucks moved the soil from the TTR.

Conservative limits were placed on this system. The limit on activity for the disposal of soil at the disposal site was 100 nCi/g. Since the plastic liners had not been rigorously tested, they were only classified to handle radioactive material with a specific activity less than 5.4 nCi/g. None of the 216 packages

were rejected for exceeding the 5.4 nCi/g activity limit. The package activities ranged from 0.35 nCi/g to 1.69 nCi/g, with an average of 1.06 nCi/g. A total of 5.65 Ci (about 56 g) of plutonium and americium were shipped from the site. The uncertainty in an activity measured by this system was dependent on many factors, most of them related to the distribution of the activity within the soil stream. However, if realistic assumptions are used (for example, the activity was distributed throughout the soil stream), the activity of any package could be determined with a reasonably small uncertainty.

5.3 Kiwi Verification Survey

The Kiwi system (Figure 4) was equipped by mounting the detectors and data collection system from RSL's standard aerial system on a Chevrolet Suburban vehicle (thus the name of a flightless bird). Six NaI logs were housed in pods mounted on an angle-iron frame attached to the vehicle in place of the rear bumper. Signals from these detectors were fed into a Radiation and Environmental Data Acquisition and Recorder, Version IV, (REDAR IV) data acquisition system bolted to the floor inside the Suburban. The radiation signals were processed by the REDAR IV and stored as 1-second spectra on magnetic tape. For the characterization work, precision positioning information was obtained by merging data from a Trimble global positioning system (GPS) (antenna was mounted above the detectors) and a John Chance Omnistar positional correction system (antenna was mounted on the roof of the Kiwi). The Omnistar control center acquired data from a network of precisely located GPS ground stations, computed corrections for all visible GPS satellites, and relayed correctional information to subscribers through a dedicated satellite transponder. The Omnistar corrections received by the Kiwi produced positional data with an uncertainty of less than $\pm$ 1 m versus $\pm$ 100 m for an autonomous GPS receiver.

FIGURE 4. *KIWI VEHICLE. Six NaI logs in the three pods on the rear of the Suburban vehicle detect gamma rays from americium directly beneath and slightly to the side of the pods. Shielding on the sides of the detectors limits the field of view to less than a meter to either side of the pods. The two antennas collect normal GPS signals from the satellite constellation and correctional signals from the John Chance Omnistar system.*

remediation work, a more compact GPS system from LandStar was used with similar positional uncertainties.

A cadmium sheet shielded the Kiwi detectors on the back, top, and sides while the end-mounted photomultiplier tubes and the vehicle chassis provided shielding to the front of the detectors. This shielding was more than adequate for attenuating the 60-keV gamma rays of ^{241}Am but did not significantly affect the higher-energy radiation from the natural radioisotopes. The shielding produces a well-defined footprint for making assessments of the americium concentration in a given volume of soil. Thus the ^{241}Am footprint of the stationary Kiwi system was about 3 m wide and 1.2 m long. With the Kiwi traveling at 2.2 m/s (5 mph), the footprint for each 1-second measurement was about 3 m wide by 3.4 m long. The speed of the Kiwi traveling over the Clean Slate 1 terrain was not constant and was usually less than 2 m/s, resulting in consecutive, 1-second spectra and in measuring some of the same area along the direction of travel.

The Kiwi measured the locations of the corner fence posts and made three loops outside the fence. The fence-post positions tied the survey positional data to the physical world. The radiation data collected outside the fence was used to ensure that the activity levels (represented by the contours) that appeared to end at or near the fence actually continued to decrease outside the fence.

The characterization (April 1996) and post-remediation (June 1997) results of the Kiwi survey are displayed in Figures 5 and 6. Figure 5 presents the total transuranic activity levels as averages over 10-m grid cells. During data analysis, approximately 10 Kiwi measurements were averaged into one 10-m square grid cell. This presentation is most useful in getting a rough estimate of the area at each level of contamination. The ^{241}Am activity was calculated from each spectrum by extracting the net counts in a window around the 60-keV photopeak as previously described. The total transuranic activity was calculated from the ^{241}Am activity by multiplying by the transuranic to ^{241}Am ratio of 16:1, described in Section B.5.3 of the CADD report.[8] Figure 6 presents both the characterization and verification activity levels as contour levels drawn from the data contained in the 10-m grid cells. This presentation provides an easier-to-decipher picture of the plume area as well as more details of the isolated hot spots.

Note that the eastern fence (toward the top of the figures) actually has a slight curvature that is not depicted in these figures. This curvature explains why there appears to be more data outside the fence on the eastern side as compared to the western side. The eastern fence curvature is sufficient that all of the light-green areas (over 200 pCi/g) reside inside the fenced region. Labels designate the locations of the base camp, decontamination area, conveyor system, and the stockpile of topsoil, which was being saved for the revegetation work. During the remediation effort, the truck entrance and exit ports were located at the ends of the base camp. The Kiwi traced a path around the excavated area inside the fence, and this area is outlined by the curve superimposed on the data. The total area inside this curve is about 40,000 m^2 (9.9 acres).

These figures represent a comparison of the site in April 1996 before any remediation work and June 1997 when the remediation at the site was complete but before any revegetation work had begun. The revegetation work at Clean Slate 1 has been delayed indefinitely. Therefore, the third data set (as generated for Double Tracks just after the final soil-disturbing operations and before seed planting) does not yet exist for the Clean Slate 1 site.

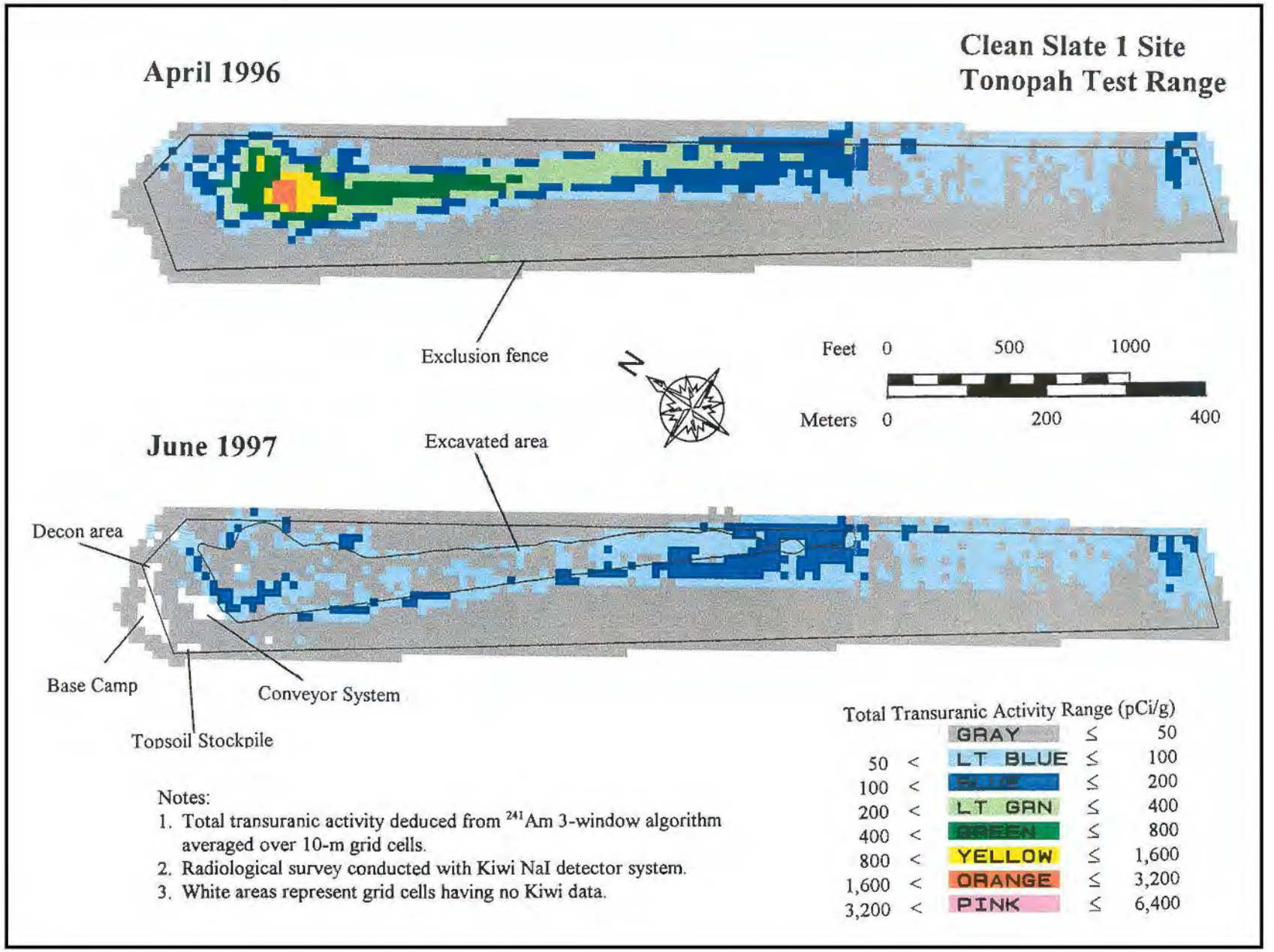

FIGURE 5. *TRANSURANIC ACTIVITIES MEASURED WITH THE KIWI BEFORE AND AFTER EXCAVATION (GRID). The total transuranic activity from April 1996 and June 1997 is based on the measured ^{241}Am counts and collected into 10-mm (33-ft) grid cell averages. The data are presented as squares centered on the grid loci. Several locations of interest are labeled.*

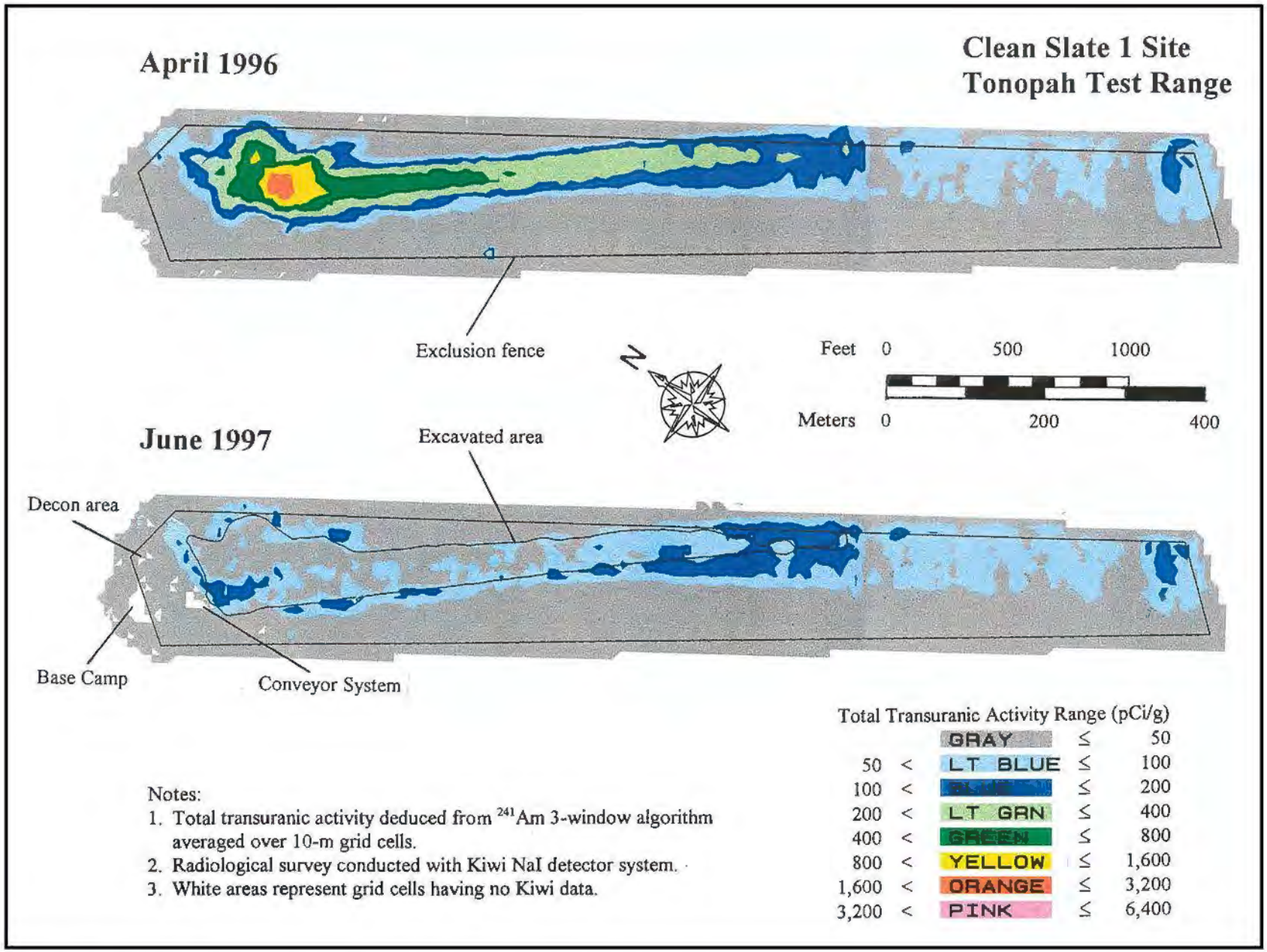

FIGURE 6. *TRANSURANIC ACTIVITIES MEASURED WITH THE KIWI BEFORE AND AFTER EXCAVATION (CONTOUR). The total transuranic activity from April 1996 and June 1997 is based on the measured ^{241}Am counts and collected into 10-mm (33-ft) grid cell averages. The gridded data are then contoured to produce this plot. Several locations of interest are labeled.*

6.0 Summary

A series of gamma radiation measurements were conducted during the remediation activities at the Clean Slate 1 site located at Cactus Flat on the TTR. The radioactivity levels of the ^{241}Am contamination measured after the remediation work in June 1997 were compared to the same measurements made during the site characterization work in April 1996.

During the remediation work at the Clean Slate 1 site, soil was removed from areas that exceeded the cleanup criteria of "200 pCi/g transuranic activity over a 100-$\times$100-m area" or "600 pCi/g over a 10-$\times$10-m area." The June 1997 plot showed no 10-$\times$10-m areas above the 200 pCi/g level.

Appendix A
Survey Parameters

Survey Site:	Clean Slate 1 Tonopah Test Range near Tonopah, Nevada
Survey Dates:	April 28 to June 19, 1997 (remediation)
Nominal Site Elevation:	1640 m (5,380 ft) MSL
Survey Altitude:	0.75 m (30 in) Kiwi (NaI) System
Line Spacing:	3 m (10 ft)
Line Direction:	Varied
Survey Coverage:	Approximately 0.24 km^2 (59.3 acres)
Base of Operation:	Tonopah Test Range, Nevada
Positioning System:	Landstar Differential GPS
Detector Arrays:	Six 2-×4-×16-in NaI Detectors
Acquisition System:	REDAR IV

Appendix B
Chemical Elements

The radioactive isotopes described in this document are designated using the current version of nuclear physics and chemistry nomenclature. The symbol designating the chemical element is usually an abbreviation of the element's name, but sometimes the symbol is derived from the Latin name of the element. The mass number of the isotope is added as a superscript preceding the symbol. For example, the radioisotope americium-241 is designated as ^{241}Am and cesium-137 is ^{137}Cs.

The following two pages list the elements ordered either by their atomic number (the number of protons in their nucleus) or alphabetized by their symbol (to facilitate finding an element discussed in the text).

CHEMICAL ELEMENTS LISTED BY ATOMIC NUMBER

Z	Sym	Element	Z	Sym	Element	Z	Sym	Element
1	H	Hydrogen	36	Kr	Krypton	70	Yb	Ytterbium
2	He	Helium	37	Rb	Rubidium	71	Lu	Lutetium
3	Li	Lithium	38	Sr	Strontium	72	Hf	Hafnium
4	Be	Beryllium	39	Y	Yttrium	73	Ta	Tantalum
5	B	Boron				74	W	Tungsten
6	C	Carbon	40	Zr	Zirconium	75	Re	Rhenium
7	N	Nitrogen	41	Nb	Niobium	76	Os	Osmium
8	O	Oxygen	42	Mo	Molybdenum	77	Ir	Iridium
9	F	Fluorine	43	Tc	Technetium	78	Pt	Platinum
			44	Ru	Ruthenium	79	Au	Gold
10	Ne	Neon	45	Rh	Rhodium			
11	Na	Sodium	46	Pd	Palladium	80	Hg	Mercury
12	Mg	Magnesium	47	Ag	Silver	81	Tl	Thallium
13	Al	Aluminum	48	Cd	Cadmium	82	Pb	Lead
14	Si	Silicon	49	In	Indium	83	Bi	Bismuth
15	P	Phosphorus				84	Po	Polonium
16	S	Sulfur	50	Sn	Tin	85	At	Astatine
17	Cl	Chlorine	51	Sb	Antimony	86	Rn	Radon
18	Ar	Argon	52	Te	Tellurium	87	Fr	Francium
19	K	Potassium	53	I	Iodine	88	Ra	Radium
			54	Xe	Xenon	89	Ac	Actinium
20	Ca	Calcium	55	Cs	Cesium			
21	Sc	Scandium	56	Ba	Barium	90	Th	Thorium
22	Ti	Titanium	57	La	Lanthanum	91	Pa	Protoactinium
23	V	Vanadium	58	Ce	Cerium	92	U	Uranium
24	Cr	Chromium	59	Pr	Praseodymium	93	Np	Neptunium
25	Mn	Manganese				94	Pu	Plutonium
26	Fe	Iron	60	Nd	Neodymium	95	Am	Americium
27	Co	Cobalt	61	Pm	Promethium	96	Cm	Curium
28	Ni	Nickel	62	Sm	Samarium	97	Bk	Berkelium
29	Cu	Copper	63	Eu	Europium	98	Cf	Californium
			64	Gd	Gadolinium	99	Es	Einsteinium
30	Zn	Zinc	65	Tb	Terbium			
31	Ga	Gallium	66	Dy	Dysprosium	100	Fm	Fermium
32	Ge	Germanium	67	Ho	Holmium	101	Md	Mendelevium
33	As	Arsenic	68	Er	Erbium	102	No	Nobelium
34	Se	Selenium	69	Tm	Thulium	103	Lr	Lawrencium
35	Br	Bromine						

CHEMICAL ELEMENTS LISTED BY SYMBOL

Z	Sym	Element
89	Ac	Actinium
47	Ag	Silver
13	Al	Aluminum
95	Am	Americium
18	Ar	Argon
33	As	Arsenic
85	At	Astatine
79	Au	Gold
5	B	Boron
56	Ba	Barium
4	Be	Beryllium
83	Bi	Bismuth
97	Bk	Berkelium
35	Br	Bromine
6	C	Carbon
20	Ca	Calcium
48	Cd	Cadmium
58	Ce	Cerium
98	Cf	Californium
17	Cl	Chlorine
96	Cm	Curium
27	Co	Cobalt
24	Cr	Chromium
55	Cs	Cesium
29	Cu	Copper
66	Dy	Dysprosium
68	Er	Erbium
99	Es	Einsteinium
63	Eu	Europium
9	F	Fluorine
26	Fe	Iron
100	Fm	Fermium
87	Fr	Francium
31	Ga	Gallium
64	Gd	Gadolinium
32	Ge	Germanium
1	H	Hydrogen
2	He	Helium
72	Hf	Hafnium
80	Hg	Mercury
67	Ho	Holmium
53	I	Iodine
49	In	Indium
77	Ir	Iridium
19	K	Potassium
36	Kr	Krypton
57	La	Lanthanum
3	Li	Lithium
71	Lu	Lutetium
103	Lr	Lawrencium
101	Md	Mendelevium
12	Mg	Magnesium
25	Mn	Manganese
42	Mo	Molybdenum
7	N	Nitrogen
11	Na	Sodium
41	Nb	Niobium
60	Nd	Neodymium
10	Ne	Neon
28	Ni	Nickel
102	No	Nobelium
93	Np	Neptunium
8	O	Oxygen
76	Os	Osmium
15	P	Phosphorus
91	Pa	Protoactinium
82	Pb	Lead
46	Pd	Palladium
61	Pm	Promethium
84	Po	Polonium
59	Pr	Praseodymium
78	Pt	Platinum
94	Pu	Plutonium
88	Ra	Radium
37	Rb	Rubidium
75	Re	Rhenium
45	Rh	Rhodium
86	Rn	Radon
44	Ru	Ruthenium
16	S	Sulfur
51	Sb	Antimony
21	Sc	Scandium
34	Se	Selenium
14	Si	Silicon
62	Sm	Samarium
50	Sn	Tin
38	Sr	Strontium
73	Ta	Tantalum
65	Tb	Terbium
43	Tc	Technetium
52	Te	Tellurium
90	Th	Thorium
22	Ti	Titanium
81	Tl	Thallium
69	Tm	Thulium
92	U	Uranium
23	V	Vanadium
74	W	Tungsten
54	Xe	Xenon
39	Y	Yttrium
70	Yb	Ytterbium
30	Zn	Zinc
40	Zr	Zirconium

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DATE OF REPORT: OCTOBER 1998