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AN IN SITU SURVEY OF CLEAN SLATE 1, 2, AND 3

TONOPAH TEST RANGE, CENTRAL NEVADA

DATE OF SURVEY: SEPTEMBER-NOVEMBER 1993

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Abstract

A ground-based *in situ* radiological survey was conducted downwind of the Clean Slate 1, 2, and 3 nuclear safety test sites at the Tonopah Test Tange in central Nevada from September through November 1993. The purpose of the study was to corroborate the americium-241 (^{241}Am) soil concentrations that were derived from the aerial radiological survey of the Clean Slate areas, which was conducted from August through October 1993. The presence of ^{241}Am was detected at 140 of the 190 locations, with unrecoverable or lost data accounting for fifteen (15) of the sampling points. Good agreement was obtained between the aerial and *in situ* results.

1.0 INTRODUCTION

A ground-based *in situ* radiological survey was conducted downwind of the Clean Slate 1, 2, 3 nuclear safety test sites at the Tonopah Test Range (TTR) in central Nevada from September through November 1993. The purpose of the study was to corroborate the americium-241 (^{241}Am) soil concentrations that were derived from the aerial radiological survey of the Clean Slate areas, which was conducted from August through October 1993. Other radiological surveys have been conducted at the TTR.^{1,2,3}

This survey was conducted at the request of the United States Department of Energy, Nevada Operations Office, (DOE/NV) by the Remote Sensing Laboratory (RSL) operated by EG&G Energy Measurements, Inc. (EG&G/EM). One of the main functions of RSL is to maintain and manage an aerial surveillance program called the Aerial Measurement Systems (AMS). Since its inception in 1958, AMS has continued a nationwide effort to document baseline radiological conditions at nuclear energy-related sites.

2.0 SITE DESCRIPTION

The Clean Slate sites are located on Cactus Flats at the Tonopah Test Range in central Nevada, about 70 km southeast by road from Tonopah. The TTR is part of the Nellis Air Force Bombing and Gunnery Range. All of the sites are within the boundaries of the TTR.

The sites have been isolated from human use since 1963. Appropriate special permission and security clearances are required to visit the areas. The land is arid, sandy, covered with low-growing shrubs and grasses, and without trees.

Locations of the Clean Slate sites are shown in Figure 1, from the aerial gamma survey report.⁴ Exclusion fences are shown in green; outlines of plutonium contamination (> 25 pCi/g) found at each site are shown in red.

An explosive device was detonated at each location in close proximity to an assembly of plutonium and/or uranium. The area containing ground zero (GZ) and the higher concentrations of fallout is enclosed within a barbed wire fence with prominent radiation hazard warning signs posted. The exact locations of GZ and detonation dates for each event are indicated in Table 1.

3.0 SURVEY OPERATIONS

The object of the *in situ* radiological survey was to corroborate the aerial data collected during the same time period.

Table 1. Event Locations and Dates

Event Name	GZ Coordinate	Detonation Date
Clean Slate 1	N37 42' 30.92" W116 39' 25.09"	May 25, 1963
Clean Slate 2	N37 42' 30.40" W116 36' 48.58"	May 31, 1963
Clean Slate 3	N37 45' 33.22" W116 40' 48.88"	June 9, 1963

A total of one hundred ninety (190) High Purity Germanium (HPGe) measurement locations were examined using portable HPGe detection systems at a height of 1m above ground level (AGL). Gamma radiation data were collected as an energy spectrum over a 10 to 1,500 keV energy range. The original spectra were stored on magnetic cassette tape following each measurement.

Measurement locations were spaced 15m (50 ft) apart along two parallel lines outside the fenced boundary in the downwind direction. One line was 15m (50 ft) from the fence; the second was 30m (100 ft) from the fence. The measurement locations were parallel to the the exclusion fence, except for Clean Slate 1, where they were set at about 30 degrees with respect to the fence. Each site was staked with flags positioned and numbered to make a return to any measured location possible. Figure 2 shows a measurement team using the equipment during a training exercise.

At each of the Clean Slate sites, a control point was established. This point was remeasured on succeeding days as a quality measure. The ^{241}Am counts were recorded daily. All were within the 2σ counting statistics.

Measurement data (spectra) were acquired, using a 900-second, live-time sampling interval, at the locations shown in Figures 3, 4, and 5. After the completion of the live-time sampling interval, the HPGe detector was moved to a predetermined location by a two-person crew. The detector field of view was determined to be approximately 10 m (33 ft), adequate overlap for the 50-ft spacing to ensure coverage of the entire area along the lines.

At the completion of the *in situ* survey, the gamma spectral data were archived on floppy diskettes and the data were analyzed using the Nuclear Material Analysis program (NUMAL) developed at RSL. NUMAL produced the results in the form of radionuclide net counts and soil concentrations.

4.0 GROUND-BASED MEASUREMENT EQUIPMENT

Each portable HPGe detection system consisted of an ORTEC HPGe, N-type, coaxial detector; a Davidson multichannel, pulse-height analyzer (MCA); and a one-meter-high tripod. Postprocessing of the gamma spectral data was performed on a portable laptop computer.

For personal radiation protection, the survey team members wore totes and gloves; further protective measures were deemed unnecessary. Plastic was wrapped around the legs of the tripods. At the end of each day, Radiation Protection Technologists, in accordance with standard REECO monitoring and decontamination procedures, confirmed that none of the crew members, nor any of the equipment had been contaminated.

4.1 High Purity Germanium N-type Coaxial Detectors

Three ORTEC HPGe, N-type, coaxial detectors, Model GMX Series, were used to collect the gamma energy spectral data. Each detector was equipped with a beryllium endcap window and a 1.2-liter liquid nitrogen dewar.

The operational characteristics and configuration for each detector, series number 29-TN40044, 29-TN30453A, and 29-TN20327 were respectively:

Nominal total active area:	189cm ²	192cm ²	213cm ²
Relative photopeak efficiency at 1,332-keV (⁶⁰ Co):	62%	68.8%	80%
Energy resolution (Full Width Half Maximum) at 60-keV ²⁴¹ Am:	0.9 keV for all detectors		

Collimators were not used.

Detector height was approximately 94 cm AGL.

4.2 Davidson Portable Multichannel Analyzer

The output signal from the HPGe detector was fed via coaxial cable to a Davidson portable multichannel (4,096 channels), pulse-height analyzer (MCA), model 2056-4K-A, which was positioned during the measurement on top of the tripod beside the dewar.

The MCA has the capability to acquire, display, and perform preliminary data analysis on the acquired gamma energy spectra. The acquired spectral data were then stored on mini data cassettes for later retrieval. Also, the MCA has the ability to transmit the data digitally via an EIA RS-232C serial port. This option was used to transfer the data to the laptop computer at the completion of the survey.

All detectors were calibrated daily using ^{241}Am and cesium-137 (^{137}Cs) radioactive sources. The MCA electronics were adjusted until the photopeak energies of the point sources appeared in preselected channels. Prior to deployment, both systems were characterized using radioactive sources that were traceable to the National Institute of Standards and Technology (NIST).

4.3 Computer Processing

Postprocessing of the gamma special data in the field was conducted on a portable laptop computer.

5.0 IN SITU DATA ANALYSIS

5.1 Photopeak Extraction and Counting Error

The gamma ray spectral data acquired by the detection systems were analyzed during field operations with the MCA's CALCULATE command function to verify that the equipment was functioning properly. NUMAL was used to compute photopeak areas and identify gamma emitters from peak locations upon returning from the field. The NUMAL program identifies photopeaks present and their computed count rate uncertainties, which represents one standard deviation counting rate error.

Since plutonium is a very weak gamma ray emitter, the 59.5-keV ^{241}Am gamma ray is used as a practical measure of plutonium contamination. ^{241}Am is a daughter of plutonium-241 (^{241}Pu), one of the constituents of weapons-grade plutonium. The factors contributing to the derived standard error are presented in Appendix A.

5.2 Minimum Detectable Activity and Soil Concentration Conversion Factors

The derivation of the soil concentration estimate from the observed photopeak net count rate was based on the one-meter methodology developed by Beck, *et al.*⁵ Details for the calculation of conversion factors may be found in Appendix B.

The minimum detectable activity (MDA) is the minimum activity of a radionuclide that must be present before it can be detected with certainty. This value is a function of the gamma ray energy, the distribution of the source within the soil matrix, the detector-to-source geometry, the radionuclide photopeak background counting rates, the measurement's live-time counting interval, and the analysis methodology.

For typical radioactive fallout distribution patterns, the distribution of a gamma emitter in the soil over a period of time can generally be approximated as an exponential vertical distribution of concentration:

$$C(z) = C_v^o e^{-\alpha z} \quad (1)$$

where

$C(z)$	=	activity per unit volume at depth, z
C_v^o	=	activity per unit volume at the surface, $(\gamma/\text{sec})/\text{cm}^3$
α	=	reciprocal of the relaxation depth, cm^{-1}
z	=	source distribution depth in the soil, cm

In general terms, the relationship between the observed photopeak net count rate and the flux of gamma rays emanating above a smooth air-ground interface plane caused by a monoenergetic gamma emitter distributed in the soil can be written as:

$$\frac{\langle CR \rangle}{S_v^o} = \frac{A_o}{2} \int_{\theta=0}^{\frac{\pi}{2}} R(\theta) \tan \theta \frac{e^{-(\mu/\rho)_a \rho_a h \sec \theta}}{\alpha + (\frac{\mu}{\rho})_s \rho_s \sec \theta} d\theta \quad (2)$$

where

$\langle CR \rangle$	=	photopeak net area count rate, counts per seconds (cps)
$A_o R(\theta)$	=	detector effective area (cm^2) for the total absorption in the detector as a function of angle of incidence upon the detector at a single gamma ray energy
θ	=	angle between the source and the detector, where $\theta = 0$ implies the source is directly below the detector, degrees
μ_a, μ_s	=	air and soil mass attenuation coefficients for the monoenergetic gamma energy, cm^2/g
ρ_a, ρ_s	=	air and soil density, g/cm^3

The detector effective area, A_o , represents the detector's capability or efficiency in detecting the specific gamma ray. In practice, the effective area is measured with known point radiation sources of different energies that are traceable to the NIST. Since the effective area varies as a function of the gamma ray angle incident to the detector face, the angular response, $R(\theta)$, of the detector was also measured with known point radiation sources.

Using the effective area and angular response measurement results, a set of conversion factors for the ^{241}Am and ^{239}Pu radionuclides was then derived; the values are listed in Table 2.

**Table 2. HPGe DETECTOR MINIMUM DETECTABLE ²⁴¹Am ACTIVITY AND
CONVERSION FACTORS**

HPGe Detector Serial Number	29-TN40044	29-TN30453A	29-TN20327
LIVE-TIME SAMPLING INTERVAL	900 seconds	900 seconds	900 seconds
60-keV ²⁴¹ Am (pCi/g)	0.3 pCi/g	0.4 pCi/g	0.4 pCi/g
60-keV ²⁴¹ Am (nCi/m ²)	88.1 nCi/m ²		
CONVERSION FACTOR	0.7170 pCi/g/cps 66.6 nCi/m ² /cps	0.872 pCi/g/cps 63.0 nCi/m ² /cps	0.872 pCi/g/cps 63.0 nCi/m ² /cps

The assumptions used to derive the values in Table 2 are:

The detectors were positioned 94 cm (3.0 ft) AGL.

No shielding material covered the soil.

A soil moisture content of 10 percent.

A soil density of 1.5 g/cm³.

A source relaxation depth in the soil of 3.0 cm (1.2 in) and a soil sample depth of 3.0 cm.

The ²⁴¹Am soil concentration conversion factors for both detection systems depend on the reciprocal of the relaxation depth, α , and the source distribution depth in the soil, z . In the above model, the values for α and z are less well known or least controllable, and are highly dependent upon the actual soil conditions. Therefore, the conversion factors are uncertain.

5.3 ²³⁹Pu/²⁴¹Am Ratio

Americium-241 is a decay product of ²⁴¹Pu; thus, the presence of the ²⁴¹Am infers the presence of ²⁴¹Pu, which is associated with weapons-grade Pu. The plutonium-to-amerium ratios are used to determine the relative abundance of the one radionuclide to the other. The values are obtained through radiochemical analysis of the soils samples to establish an average.

Soil samples were collected in accordance with the activity-specific Environmental, Safety, and Health Standard Operation Procedures for Sandia National Laboratory (SNL). Eighty soil

samples were collected at the TTR. All samples were analyzed for gross alpha, gross beta, total uranium (U_{tot}), percent moisture, and by gamma spectroscopy. These results were used to establish the ratio of $^{239, 240}\text{Pu}$ to ^{241}Am . The completed results are on file with SNL Department 7725 Records Center.

All data collected indicated the presence of Pu. The concentrations generally decrease with an increased distance from the Clean Slate 2 GZ. A $^{239, 240}\text{Pu}$ -to- ^{241}Am value of ten (10) was obtained and should be applied to convert the reported ^{241}Am values to $^{239, 240}\text{Pu}$.

6.0 RESULTS

The HPGe-estimated concentrations for ^{241}Am are reported in the attached table and range from 0.3 to 16.1 pCi/g. The presence of ^{241}Am was detected at 140 of the 190 locations, with unrecoverable or lost data accounting for fifteen (15) of the sampling points. Measured americium activity and Nevada Coordinates for each measured point are shown in Tables 3, 4A, 4B, 4C, 4D, 5A, 5B. Measurement locations are shown in Figures 3, 4, and 5.

Measurements were averaged in groups of four prior to comparison with the aerial data. Averaged values were plotted over the aerial survey contour maps for comparison. Good agreement between the aerial and *in situ* results was obtained; Figures 9, 10, and 11 show the comparisons. The *in situ* measurements indicate greater local variability, as would be expected from the order of magnitude difference in the aerial and *in situ* detector footprints.

TABLE 3

Americium-241 Concentrations, Clean Slate 1

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1072985	502244	MDA
2	1073014	502285	0.4 ± 0.1
3	1073042	502326	MDA
4	1073071	502367	MDA
5	1073100	502408	MDA
6	1073128	502449	MDA
7	1073157	502490	MDA
8	1073186	502531	MDA
9	1073214	502572	MDA
10	1073243	502613	MDA
11	1073272	502654	MDA
12	1073300	502695	MDA
13	1073329	502736	MDA
14	1073357	502777	MDA
15	1073386	502818	MDA
16	1073415	502859	MDA
17	1073444	502900	No Result
18	1073473	502941	2.6 ± 0.2
19	1073501	502982	4.1 ± 0.2
20	1073530	503023	6.7 ± 0.3
21	1073558	503064	7.6 ± 0.3
22	1073588	503105	5.2 ± 0.2

23	1073616	503142	8.2 ± 0.3
24	1073644	503187	7.7 ± 0.3
25	1073674	503228	5.9 ± 0.3
26	1073702	503269	4.6 ± 0.2
27	1073731	503310	3.4 ± 0.2
28	1073760	503351	2.9 ± 0.2
29	1073788	503392	1.6 ± 0.2
30	1073817	503433	MDA
31	1073846	503474	MDA
32	1073875	503515	MDA
33	1073903	503556	MDA
34	1073932	503597	MDA
35	1073961	503638	MDA
36	1073989	503679	MDA
37	1074018	503720	MDA
38	1074046	503761	MDA
39	1074075	503801	MDA
40	1074104	503841	MDA
41	1074132	503882	MDA
42	1074161	503923	MDA
43	1074189	503964	MDA
44	1074217	504005	MDA

^aRepresents average activity in a 3-cm-deep soil sample.

^bMDA implies count rate below minimum detectable activity.

^cUncertainties represent the standard error.

TABLE 4A

**Americium-241 Concentrations, Clean Slate 2
(North, East/West Line)**

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1094179	516408	4.8 ± 0.2
2	1094181	516458	5.9 ± 0.2
3	1094184	516508	6.4 ± 0.2
4	1094186	516558	7.4 ± 0.3
5	1094189	516608	9.4 ± 0.3
6	1094192	516658	10.6 ± 0.4
7	1094194	516708	13.2 ± 0.5
8	1094197	516758	10.8 ± 0.4
9	1094199	516808	10.6 ± 0.4
10	1094202	516858	10.6 ± 0.4
11	1094205	516908	10.3 ± 0.4
12	1094207	516958	10.0 ± 0.4
13	1094209	517008	11.5 ± 0.4
14	1094212	517058	11.7 ± 0.4
15	1094215	517108	7.2 ± 0.3
16	1094218	517158	8.1 ± 0.3
17	1094220	517208	8.0 ± 0.3
18	1094223	517253	14.8 ± 0.5
19	1094225	517308	16.1 ± 0.6
20	1094228	517358	MDA

^aRepresents average activity in a 3-cm-deep soil sample.

^bMDA implies count rate below minimum detectable activity.

^cUncertainties represent the standard error.

TABLE 4B

**Americium-241 Concentrations, Clean Slate 2
(South, East/West Line)**

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1094129	516408	4.6 ± 0.2
2	1094131	516458	5.4 ± 0.2
3	1094134	516508	6.1 ± 0.2
4	1094136	516558	5.6 ± 0.2
5	1094139	516608	6.5 ± 0.2
6	1094142	516658	8.5 ± 0.3
7	1094144	516708	6.9 ± 0.2
8	1094147	516758	10.5 ± 0.4
9	1094149	516808	11.7 ± 0.4
10	1094152	516858	MDA
11	1094155	516908	9.8 ± 0.3
12	1094157	516958	11.7 ± 0.4
13	1094160	517008	10.0 ± 0.4
14	1094162	517058	11.2 ± 0.4
15	1094165	517108	4.9 ± 0.2
16	1094168	517158	5.8 ± 0.2
17	1094170	517208	7.2 ± 0.3
18	1094173	517258	13.7 ± 0.5
19	1074175	517308	13.0 ± 0.5
20	1094178	517358	13.6 ± 0.5

^aRepresents average activity in a 3-cm-deep soil sample.

^bMDA implies count rate below minimum detectable activity.

^cUncertainties represent the standard error.

TABLE 4C

**Americium-241 Concentrations, Clean Slate 2
(Northern, SW/NE Line)**

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1094004	517258	7.9 ± 0.3
2	1094048	517283	6.8 ± 0.2
3	1094091	517308	8.9 ± 0.3
4	1094135	517333	13.2 ± 0.5
5	1094178	517358	13.3 ± 0.5
6	1094221	517383	13.7 ± 0.5
7	1094265	517408	18.6 ± 0.6
8	1094308	517433	12.7 ± 0.4
9	1094351	517458	13.7 ± 0.5
10	1094395	517483	16.1 ± 0.6
11	1094438	517508	14.7 ± 0.5
12	1094481	517533	14.6 ± 0.5
13	1094524	517558	24.2 ± 0.8
14	1094568	517583	17.7 ± 0.6
15	1094611	517608	MDA
16	1094654	517633	13.0 ± 0.5
17	1094698	517658	12.7 ± 0.4
18	1094741	517683	12.1 ± 0.4
19	1094784	517708	15.5 ± 0.5
20	1094828	517733	8.8 ± 0.3
21	1094871	517758	2.6 ± 0.1
22	1094914	517783	3.1 ± 0.1
23	1094957	517808	1.9 ± 0.1

^aRepresents average activity in a 3-cm-deep soil sample.

^bMDA implies count rate below minimum detectable activity.

^cUncertainties represent the standard error.

TABLE 4D

**Americium-241 Concentrations, Clean Slate 2
(Southern, SW/NE Line)**

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1093904	517253	9.3 ± 0.3
2	1093948	517283	9.1 ± 0.3
3	1093991	517308	7.7 ± 0.3
4	1094035	517333	11.5 ± 0.4
5	1094078	517358	11.1 ± 0.4
6	1094121	517383	8.8 ± 0.3
7	1094164	517408	9.6 ± 0.3
8	1094208	517433	9.1 ± 0.3
9	1094251	517458	10.0 ± 0.4
10	1094295	517483	12.1 ± 0.4
11	1094338	517508	15.7 ± 0.5
12	1094381	517533	17.6 ± 0.6
13	1094424	517558	12.6 ± 0.4
14	1094468	517583	30.2 ± 1.0
15	1094511	517608	15.6 ± 0.5
16	1094554	517633	14.6 ± 0.5
17	1094598	517658	17.9 ± 0.6
18	1094640	517683	14.0 ± 0.5
19	1094684	517708	13.6 ± 0.5
20	1094728	517733	6.6 ± 0.2
21	1094771	517758	4.7 ± 0.2
22	1094814	517783	3.1 ± 0.1
23	1094857	517808	1.9 ± 0.1

^aRepresents average activity in a 3-cm-deep soil sample.

^bUncertainties represent the standard error.

TABLE 5A

**Americium-241 Concentrations, Clean Slate 3
(North, East/West Line)**

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1086069	504099	3.8 ± 0.1
2	1086097	504140	4.4 ± 0.2
3	1086125	504181	5.1 ± 0.2
4	1086153	504223	5.2 ± 0.2
5	1086181	504264	5.3 ± 0.2
6	1086209	504305	4.3 ± 0.2
7	1086237	504347	4.3 ± 0.2
8	1086265	504389	5.4 ± 0.2
9	1086293	504430	6.6 ± 0.2
10	1086321	504472	6.7 ± 0.2
11	1086349	504518	6.7 ± 0.2
12	1086377	504554	7.1 ± 0.3
13	1086405	504596	MDA
14	1086432	504637	6.5 ± 0.2
15	1086461	504678	6.4 ± 0.2
16	1086489	504720	6.1 ± 0.2
17	1086517	504761	5.5 ± 0.2
18	1086544	504803	4.9 ± 0.2
19	1086573	504845	4.7 ± 0.2
20	1086600	504886	3.1 ± 0.1
21	1086629	504927	2.7 ± 0.1

22	1086656	504968	0.4 ± 0.1
23	1086684	505010	1.5 ± 0.1
24	1086712	504051	1.2 ± 0.1
25	1086740	504093	1.0 ± 0.1
26	1086768	504134	MDA
27	1086796	504176	MDA
28	1086824	504217	MDA
29	1086852	504259	0.7 ± 0.1
30	1086880	505300	MDA

^aRepresents average activity in a 3-cm-deep soil sample.

^bMDA implies count rate below minimum detectable activity.

^cUncertainties represent the standard error.

TABLE 5B

**Americium-241 Concentrations, Clean Slate 3
(South, East/West Line)**

Map No.	Nevada Coordinates		²⁴¹ Am Concentration ^{a,b,c} (pCi/g)
	North (ft)	East (ft)	
1	1086037	504137	4.1 ± 0.2
2	1086065	504179	4.7 ± 0.2
3	1086093	504220	5.3 ± 0.2
4	1086121	504262	5.7 ± 0.2
5	1086149	504303	6.1 ± 0.2
6	1086177	504345	5.7 ± 0.2
7	1086205	504386	5.6 ± 0.2
8	1086233	504428	5.1 ± 0.2
9	1086261	504469	0.4 ± 0.1
10	1086289	504511	4.7 ± 0.2
11	1086317	504552	4.8 ± 0.2
12	1086345	504593	4.7 ± 0.2
13	1086373	504635	0.6 ± 0.2
14	1086401	504676	0.4 ± 0.1
15	1086429	504718	5.1 ± 0.2
16	1086457	504759	5.3 ± 0.2
17	1086484	504800	5.2 ± 0.2
18	1086513	504842	3.9 ± 0.1
19	1086541	504884	1.5 ± 0.1
20	1086569	504925	1.5 ± 0.1
21	1086596	505967	1.0 ± 0.1

22	1086624	504007	0.8 ± 0.1
23	1086652	504049	MDA
24	1086680	504090	MDA
25	1086708	504132	MDA
26	1086736	504173	MDA
27	1086764	504215	0.6 ± 0.1
28	1086792	504257	0.9 ± 0.1
29	1086820	504298	MDA
30	1086848	505339	MDA

^aRepresents average activity in a 3cm deep soil sample.

^bMDA implies count rate below minimum detectable activity.

^cUncertainties represent the standard error.

TTR DATA REPORT

APPENDIX A

STANDARD ERROR CALCULATION AND CORRECTIONS

The net area counts reported by the NUMAL program or the Davidson multichannel CALCULATION command function were corrected for the system dead time using the nonparalysable counter dead-time correction factor of:

$$N = \langle CR \rangle / (1 - \langle CR \rangle * \tau) \quad (A1)$$

where

$$\begin{aligned} N &= \text{true photopeak net count rate, counts/seconds} \\ \langle CR \rangle &= \text{observed photopeak net count rate, counts/seconds} \\ \tau &= \text{detection system dead time, seconds} \end{aligned}$$

The system dead time is the amount or percent of time that the system is occupied and cannot process any new counts. The fraction of time when the detection systems were insensitive to receiving new counts ranges from 1 to 3 percent. The system dead-time rates were measured using the two-source measurement method for a nonparalysable counter and the two-point radiation sources, that had been used, were traceable to the National Institute of Standards and Technology (NIST). The measured system dead-time rate for the two HPGe detection systems was 253 and 189 microseconds, respectively.

The standard error reported for the estimated soil concentrations was calculated using Equation A2 and included as sources of error only the observed photopeak counting rate error, the background counting rate error (σ_b), the system dead-time correction, and the soil concentration conversion factor correction (σ_{CF}):

$$\sigma_{conc} = \sqrt{\left(\frac{1}{1 - \langle CR \rangle * \tau}\right)^4 * \frac{\langle CR \rangle}{LT} + \sigma_b^2 + \sigma_{CF}^2} \quad (A2)$$

where

$$LT = \text{measurement live-time counting interval, seconds}$$

APPENDIX B

THE THEORY OF IN SITU MEASUREMENT AND THE DEVELOPMENT OF CONVERSION FACTORS FROM POINT SOURCES

In general terms, the relationship between the observed photopeak net count rate and the flux of gamma rays emanating above a smooth air-ground interface caused by a monoenergetic gamma emitter distributed in the soil can be written as:

$$\langle CR \rangle = \int_0^\infty \int_0^\infty \frac{S_V * A}{4\pi D^2} e^{-\alpha z} e^{-\mu_a \rho_a r_a} e^{-\mu_s \rho_s r_s} 2\pi dx dz \quad (B1)$$

where

$\langle CR \rangle$	=	photopeak net area count rate, counts per seconds (cps)
S_V	=	activity per unit volume at the surface, (γ/sec)/cm ³
A	=	detector effective area for the total absorption in the detector as a function of gamma ray energy and angle of incidence upon the detector, cm ²
D	=	$r_a + r_s$; Detector-to-source distance in air and the soil combined, cm
α	=	reciprocal of the relaxation depth, cm ⁻¹
z	=	source distribution depth in the soil, cm
$\mu_a \mu_s$	=	air and soil mass attenuation coefficients for the monoenergetic gamma energy, cm ² /g
$\rho_a \rho_s$	=	air and soil density, g/cm ³

For typical radioactive fallout distribution patterns, the distribution of a gamma emitter in the soil over a period of time can generally be approximated by an exponential vertical distribution of concentration, namely $e^{-\alpha z}$, as shown in Equation B1. This implies that the representative volume of soil at a gamma energy relaxation depth of $1/\alpha$ is assumed to contain approximately 63 percent of the source's total activity. At relaxation depths of $2/\alpha$ and $3/\alpha$, respectively, the representative volume of soil is assumed to contain approximately 86 percent and 95 percent of the total activity.

The detector effective area, A , represents the detector's capability or efficiency in detecting the specific gamma ray. In practice, the effective area is measured with known point radiation sources of different energies that are traceable to the NIST. The effective area, in general, varies as a function of the gamma ray angle incident to the detector face and can be written:

$$A = A_0 * R(\theta) \quad (B2)$$

where

$$\begin{aligned} A_0 &= \text{detector effective area for a unit flux perpendicular to the ground surface (zero degrees), cm}^2 \\ R(\theta) &= \text{ratio of the detector response at an angle } \theta \text{ to its response at } \theta = \text{zero degrees} \end{aligned}$$

The angular response, $R(\theta)$, is also measured with known point radiation sources that are traceable to the NIST.

Rewriting Equation B1 in terms of θ and z , and combining Equation B2 leads to an expression which relates the measured photopeak count rate to the source activity where the conversion factor can be expressed in units of cps/(γ/cm^3 -sec).

$$\frac{\langle CR \rangle}{S_V^0} = \frac{A_0}{2} \int_{\theta=0}^{\frac{\pi}{2}} R(\theta) \tan \theta \frac{e^{-(\mu/\rho)_a \rho_a h \sec \theta}}{\alpha + (\frac{\mu}{\rho})_s \rho_s z \sec \theta} d\theta \quad (B3)$$

For a specific isotope, the conversion factor can be changed to units of cps/(pCi/cm³) by converting gamma per disintegrations into pCi (3.7E-02 $\gamma/\text{pCi-sec}$). Multiplying the expression in Equation B3 by the soil density (g/cm³), the conversion factor can be given in units of cps/(pCi/g).

The average radionuclide concentration in the top z cm in the soil, the source distribution expression can be written as:

$$S_V^z = \frac{1}{z} \int_0^z S_V^0 * e^{-\alpha z} dz = \frac{S_V^0}{\alpha z} * (1 - e^{-\alpha z}) \quad (B4)$$

for an exponentially distributed gamma emitter. Substituting Equation B4 into Equation B3, dividing by the soil density, and taking the inverse, the conversion factor can be expressed in units of (pCi/g)/cps. This conversion factor has the utility of being able to compare the HPGe *in situ* results with the results of soil samples collected at a depth of 0 to z cm.

A more detailed explanation concerning the theory of deriving the minimum detectable activities and soil concentration conversion factors from point radiation sources can be found in the literature.^{5,6}

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EXCLUSION FENCE
DETECTABLE AMERICIUM
SURVEY BOUNDARY

CLEAN SLATE 3

CLEAN SLATE 2

Landing Strips

CLEAN SLATE 1

Landing Strips

C A C T U S

FIGURE 1. In Situ Measurement Locations at Clean Slates 1, 2, and 3. Area exclusion fences are shown in green, the aerial survey boundary in blue and the minimum ^{241}Am detection levels in red.

FIGURE 2. High Purity Germanium Detector System

FIGURE 3. In Situ Measurement Locations, Clean Slate 1

FIGURE 4. In Situ Measurement Locations, Clean Slate 2

FIGURE 5. In Situ Measurement Locations, Clean Slate 3

FIGURE 6. Aerial and In Situ ^{239}Pu Estimates, Clean Slate 1

FIGURE 7. Aerial and In Situ ^{239}Pu Estimates, Clean Slate 2

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AN *IN SITU* SURVEY OF
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