POWERTECH (USA) INC.

August 19, 2013

Mr. Ronald Burrows
Office of Federal and State Materials and Uranium Recovery Licensing Branch
Division of Waste Management and Environmental Protection
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Re: Dewey-Burdock Project Additional Statistical Analysis of Radium-226 Soil Sampling Data and Gamma Measurements, Draft Materials License No. SUA-1600, License Condition 12.11

Dear Mr. Burrows:

Enclosed please find Powertech (USA) Inc.'s report with additional statistical analysis of radium-226 soil sampling data and gamma measurements for the Dewey-Burdock Project.

The additional analysis was completed to comply with Draft Materials License Number SUA-1600, License Condition 12.11. If NRC's comments upon review require, Powertech will revise and resubmit the report.

Powertech (USA) Inc. appreciates NRC's consideration and respectfully requests review by mid-September to permit field work, should it be required, to occur beginning in late September.

Please do not hesitate to contact me with questions at (303) 790-7528.

Sincerely,

Richard Blubaugh
Vice President, Environmental Health and Safety Resources

Enc. Additional Statistical Analysis of Radium-226 Soil Sampling Data and Gamma Measurements

POWERTECH (USA) INC.

Dewey-Burdock Project

Fall River and Custer Counties
South Dakota

ADDITIONAL STATISTICAL ANALYSIS OF RADIUM-226 SOIL SAMPLING DATA AND GAMMA MEASUREMENTS

Supplement to TR Appendix 2.9-A Baseline Radiological Report
Draft Materials License No. SUA-1600, License Condition 12.11

Prepared for
U.S. Nuclear Regulatory Commission
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August 2013

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1.0 Introduction

Draft U.S. Nuclear Regulatory Commission (NRC) Source and Byproduct Materials License Number SUA-1600, License Condition (LC) 12.11 requires Powertech (USA) Inc. (Powertech) to perform additional statistical analysis of soil sampling data and gamma measurements to establish sufficient statistical relationships as follows:

> *No later than 30 days prior to construction, the licensee will provide additional statistical analysis of the soil sampling data and gamma measurements to establish sufficient statistical relationships. If such relationships are not sufficient for use at the site, additional procedures or data shall be submitted to the NRC staff for review and written verification.*

The NRC Safety Evaluation Report for the Dewey-Burdock Project (NRC, 2013) provides the following rationale for the condition:

> *Instead of using the R^2 value the applicant directly compared model predictions to the data by examining the median and quartiles. The applicant concluded that the median and quartiles predicted by Equation 2 are very close to the median and quartiles of the data and are much closer than the median and quartiles of Equation 1 (Powertech, 2011a). However, the staff finds that the applicant has not provided sufficient justifications to validate the methodology used to exclude the outliers to establish the correlation between GPS based direct gamma measurement and the results obtained from soil samples. Also, the applicant is required to explain why the predicted median and quartiles using [Equation 2] is not merely by coincidence. Therefore, the staff included a condition in the Dewey-Burdock license that addresses the need for additional statistical analysis of the soil sample data and gamma measurements.* (p. 70)

> *… staff determines that the applicant has not provided sufficient justifications to validate the methodology used to exclude the outliers to establish the correlation between the direct gamma measurements (i.e., measurements with various gamma probes) versus the results obtained from soil samples. Also, the applicant must explain the basis for its predicted median and quartile values using Equation 2.* (p. 71)

This document presents additional statistical analysis of soil sampling data and gamma measurements to satisfy draft LC 12.11.

2.0 Correlation Objective

The objective of developing a sufficient statistical relationship between radium-226 soil results and gamma measurements is to provide an equation for predicting radium-226 concentrations in surface soils based on field gamma measurements. A coefficient of determination, denoted R^2, is calculated to assess how well the statistical equation predicts expected values so that the closer R^2 is to 1, the closer the equation predicts observed values.

3.0 Summary of Work Completed to Date

In September 2007, 80 surface soil samples were collected and analyzed for radium-226. At each sampling location, one-minute integrated direct radiation readings were measured using a portable Ludlum 44-10/2221 sodium iodide gamma detector. Field methodologies and location rationale are described in the following documents:

- Appendix 2.9-A Baseline Radiological Report of the Dewey-Burdock Project Application for NRC Uranium Recovery License, Custer and Fall River Counties, South Dakota, Technical Report (TR) (Powertech, 2009), and

- Dewey-Burdock Project Application for NRC Uranium Recovery License, Fall River and Custer Counties, South Dakota, Technical Report RAI Responses (Powertech, 2011).

A review of TR Appendix 2.9-A Table 4-1 (Powertech, 2009) identified minor data entry errors. Applicable portions of the corrected table are provided as Table 1. Supporting field data are provided in Appendix A. Laboratory reports and sampling locations are provided in Appendix 2.9-A of the TR (Powertech, 2009).

Using all 80 data points, the following linear regression equation with an R^2 of 0.75 resulted:

$y = 0.0002x - 0.87$ (Equation 1) (Powertech, 2009)

where: y = predicted radium-226 concentration in picocuries per gram (pCi/g)
x = gamma measurements in counts per minute (cpm)

Table 1. Summary of One-Minute Gamma Measurements and Radium-226 Soil Sampling Data Ordered from Highest to Lowest Gamma Measurement

Obs. No.	Surface Soil Sample ID	Date	One-Minute Gamma Measurement (cpm)	Radium-226 (pCi/g)
1	SMA-B29	9/28/2007	231,041	29
2	SMA-B27	9/28/2007	130,293	40
3	SMA-B30	9/28/2007	89,139	34
4	SMA-B26	9/28/2007	73,243	11
5	SMA-B28	9/29/2007	39,061	6.40
6	SMA-B07	9/24/2007	22,925	3.20
7	SMA-B03	9/24/2007	22,410	1.50
8	RFA-B23	9/25/2007	19,674	3.60
9	NEA-R04	9/24/2007	17,356	2.30
10	SMA-B11	9/24/2007	17,346	2.30
11	NEA-R05	9/24/2007	17,269	2.80
12	SMA-B21	9/24/2007	16,712	1.40
13	RFA-B21A	9/26/2007	16,641	5.30
14	NEA-R03	9/24/2007	16,393	2.20
15	RFA-B17A	9/26/2007	16,283	2.00
16	SMA-B23	9/24/2007	16,233	2.70
17	MPA-R02	9/24/2007	16,059	2.60
18	SMA-B04	9/24/2007	15,263	1.00
19	RFA-B28	9/25/2007	15,246	2.40
20	RFA-B10	9/25/2007	14,825	1.80
21	SMA-B14	9/24/2007	14,483	1.40
22	RFA-B29	9/25/2007	14,345	1.70
24	RFA-B12	9/25/2007	14,253	1.80
23	RFA-B03	9/25/2007	14,253	1.50
25	MPA-B02	9/25/2007	14,176	1.10
26	RFA-B22	9/25/2007	14,087	1.50
27	RFA-B13A	9/26/2007	13,987	1.60
28	RFA-B04	9/25/2007	13,963	1.10
29	RFA-B14	9/25/2007	13,872	1.70
30	RFA-B18	9/25/2007	13,835	1.70
31	MPA-B01	9/25/2007	13,824	1.40
32	RFA-B06	9/25/2007	13,819	1.70
33	RFA-B27	9/25/2007	13,794	1.50
34	MPA-R01	9/24/2007	13,749	1.40
35	RFA-B19	9/25/2007	13,689	1.20
36	RFA-B16	9/25/2007	13,675	0.90

Table 1. Summary of One-Minute Gamma Measurements and Radium-226 Soil Sampling Data Ordered from Highest to Lowest Gamma Measurement (Cont'd)

Obs. No.	Surface Soil Sample ID	Date	One-Minute Gamma Measurement (cpm)	Radium-226 (pCi/g)
37	RFA-B15A	9/26/2007	13,535	1.40
38	RFA-B09	9/25/2007	13,528	1.00
39	RFA-B08	9/25/2007	13,433	1.10
40	RFA-B34	9/25/2007	13,408	1.00
41	RFA-B11	9/25/2007	13,366	1.00
42	RFA-B02A	9/26/2007	13,360	1.10
43	RFA-B43	9/25/2007	13,264	1.70
44	SMA-B13	9/25/2007	13,252	1.70
45	RFA-B33	9/25/2007	13,221	0.90
46	SMA-B10	9/25/2007	13,184	1.40
47	NEA-R02	9/24/2007	13,176	1.30
48	RFA-B01A	9/26/2007	13,115	1.20
49	RFA-B20	9/25/2007	13,113	1.30
50	MPA-B03	9/25/2007	13,006	1.30
51	SMA-B09	9/24/2007	12,879	1.20
52	RFA-B24	9/25/2007	12,766	1.30
53	RFA-B07	9/25/2007	12,700	0.90
54	SMA-B24	9/24/2007	12,662	1.30
55	RFA-B40	9/25/2007	12,629	1.10
56	RFA-B36A	9/25/2007	12,465	1.00
57	RFA-B30A	9/26/2007	12,461	1.80
58	NEA-R01	9/24/2007	12,302	1.10
59	RFA-B35	9/25/2007	12,290	1.20
60	RFA-B45	9/25/2007	12,242	1.60
61	RFA-B31	9/25/2007	12,221	1.30
62	RFA-B38	9/25/2007	11,852	1.00
63	MPA-R05	9/24/2007	11,850	1.20
64	RFA-B41	9/25/2007	11,806	1.20
65	RFA-B26	9/25/2007	11,791	1.10
66	RFA-B39	9/25/2007	11,478	1.10
67	RFA-B44	9/25/2007	11,436	1.40
68	RFA-B37A	9/26/2007	11,170	0.90
69	SMA-B20	9/27/2007	10,897	0.90
70	MPA-R04	9/24/2007	10,810	0.90
71	MPA-R03	9/24/2007	10,796	1.10

Table 1. Summary of One-Minute Gamma Measurements and Radium-226 Soil Sampling Data Ordered from Highest to Lowest Gamma Measurement (Cont'd)

Obs. No.	Surface Soil Sample ID	Date	One-Minute Gamma Measurement (cpm)	Radium-226 (pCi/g)
72	SMA-B22	9/24/2007	10,618	0.80
73	SMA-B01	9/24/2007	10,459	0.90
74	RFA-B25	9/25/2007	10,300	1.20
75	SMA-B16	9/24/2007	10,235	0.90
76	SMA-B17	9/24/2007	10,139	1.00
77	SMA-B19	9/24/2007	10,074	1.20
78	SMA-B25	9/24/2007	9,991	1.00
79	SMA-B18	9/25/2007	8,511	0.50
80	SMA-B15	9/24/2007	8,474	0.80

cpm – counts per minute
pCi/g – picocuries per gram

The project team then applied statistical analysis, judgment based on site knowledge, box plot review, and the methodology described in ASTM E178-08 to exclude five high outliers. The following linear regression equation with an R^2 of 0.43 resulted:

y = 0.000187x – 1.04 (Equation 2) (Powertech, 2009)

where: y = predicted radium-226 concentration in pCi/g
x = gamma measurement in cpm

The current analysis reevaluates gamma measurements and radium-226 soil sampling data to satisfy draft LC 12.11. To begin, outliers are identified using ProUCL 4.1.00, a statistical analysis tool developed by the U.S. Environmental Protection Agency for evaluating environmental data. After reviewing outliers and excluding erroneous values, a revised statistical relationship is presented as Equation 3. Lastly, results of the statistical analysis are compared to correlation studies prepared by Whicker et al. (2008) and Johnson et al. (2006). These studies are provided in Appendices B and C, respectively.

4.0 Outlier Analysis and Development of Statistical Relationships

High outliers are identified and treated using the following five steps, which are recommended in the Draft Technical Guide for ProUCL 4.1.00 (EPA, 2010):

1. Identify extreme high values as potential outliers.
2. Perform a statistical test and supplement with graphical displays.
3. Review statistical outliers and decide proper disposition.
4. Conduct data analyses with and without statistical outliers.
5. Document the entire process.

Gamma measurements are reviewed for high outliers in Section 4.1, radium-226 soil sampling data are evaluated for high outliers in Section 4.2, and correlated data are reviewed for high outliers in Section 4.3.

Since sufficient goodness of fit is achieved in the current analysis without excluding low outliers, evaluation of low outliers is not performed. Evaluation of low outliers is complicated by the presence of detections below, at and near lower limits of detection, which are subject to fluctuation based on laboratory error and method precision.

Section 4.4 discusses results in light of information provided for two similar studies, one by Whicker et al. (2008) and the other by Johnson et al. (2006).

4.1 Evaluation of Gamma Measurements for High Outliers

<u>Step 1 - Identify Extreme High Values as Potential Outliers</u>

The ProUCL 4.1.00 Draft Technical Guide recommends construction of a Q-Q plot to identify high values. Review of the Q-Q plot in Figure 1 indicates the presence of five high values and three somewhat high values. These are labeled on the figure.

Before proceeding to Step 2, it is noted that outlier tests in ProUCL 4.1.00 assume that data are normally distributed. As shown in Figure 1, and as previously described in the TR and TR RAI responses (Powertech, 2009 and 2011), gamma measurements are not normally distributed. Departure of data from the straight line in the Q-Q plot and a correlation coefficient, R, of less than 0.95 confirm this. Accordingly, additional care is utilized when evaluating and treating outliers in Step 3.

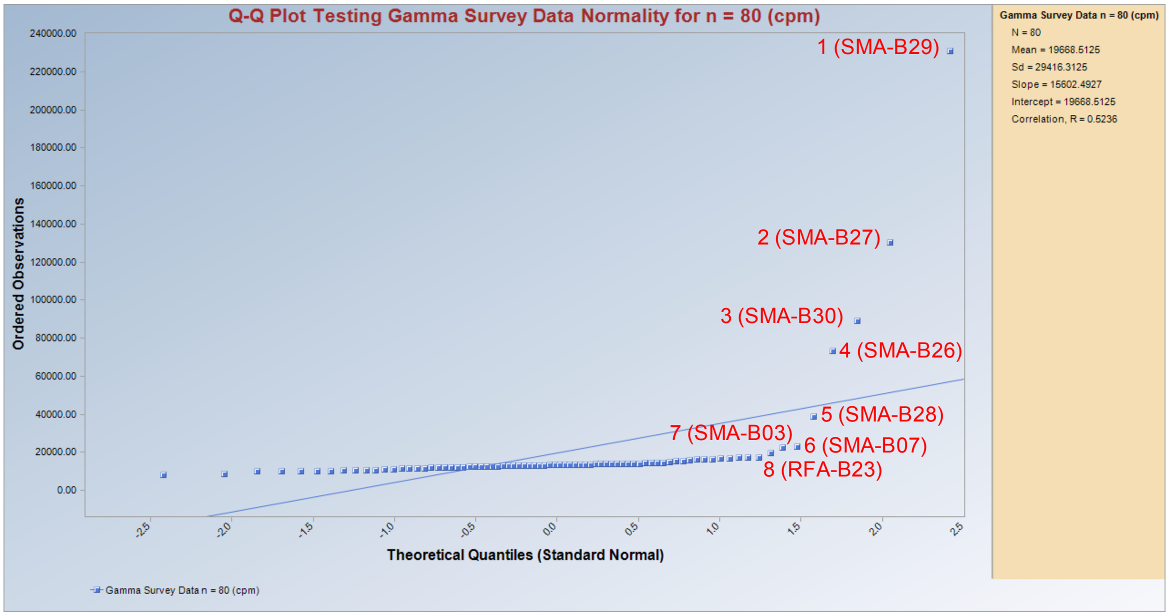


Figure 1. Q-Q Plot for One-Minute Gamma Measurements (n = 80)

<u>Step 2 – Perform Statistical Test and Supplement with Graphical Displays</u>

ProUCL 4.1.00 contains two simple and commonly used classical outlier tests, the Dixon test and the Rosner test. The Dixon test is used for data sets with 25 or fewer samples, while the Rosner test is appropriate for data sets with more than 25 samples. The Rosner test was selected for use in the current analysis since the number of samples is greater than 25 (n =80).

After importing gamma measurements into ProUCL 4.1.00, the Rosner test was selected under Outlier Test and the number of estimated outliers from the Q-Q plot in Figure 1, eight, was entered into the dialogue box. Choosing “OK” generated Table 2.

Results of the Rosner test indicate that for a 5% significance level, the seven highest gamma measurements are potential outliers. The eighth highest measurement was not indicated as an outlier. The box plot in Figure 2 agrees with the Rosner output by displaying seven potential high outliers.

<u>Step 3 - Review Statistical Outliers and Decide Proper Disposition</u>

Field notes and calibration records were reviewed for each of the seven potential high outliers identified in Step 2. No apparent sample collection errors, data transcription errors or field equipment malfunctions were identified.

Table 2. Rosner Test Output for One-Minute Gamma Measurements

				Outlier Tests for Selected Variables			
User Selected Options							
From File				Gamma.wst			
Full Precision				OFF			
Test for Suspected Outliers with Dixon test				1			
Test for Suspected Outliers with Rosner test				8			
Rosner's Outlier Test for One-Minute Gamma Measurements (cpm)							
Mean			**19,669**				
Standard Deviation			**29,416**				
Number of data			**80**				
Number of suspected outliers			**8**				
#	Mean	sd	Potential outlier	Obs. number	Test value	Critical value (5%)	Critical value (1%)
1	19,669	29,232	231,041	1	7.231	3.31	3.67
2	16,993	17,215	130,293	2	6.581	3.3	3.67
3	15,540	11,461	89,139	3	6.421	3.3	3.66
4	14,585	7,803	73,243	4	7.517	3.29	3.66
5	13,813	3,902	39,061	5	6.471	3.29	3.65
6	13,476	2,588	22,925	6	3.651	3.284	3.646
7	13,348	2,356	22,410	7	3.846	3.278	3.642
8	13,224	2,115	19,674	8	3.05	3.272	3.638
For 5% significance level, there are 7 Potential Outliers. Therefore, Potential Statistical Outliers are 231,041, 130,293, 89,139, 73,243, 39,061, 22,925, and 22,410.							
For 1% Significance Level, there are 7 Potential Outliers. Therefore, Potential Statistical Outliers are 231,041, 130,293, 89,139, 73,243, 39,061, 22,925, and 22,410.							

As described in the TR and TR RAI responses (Powertech, 2009 and 2011) and reiterated in the ProUCL 4.1.00 Draft Technical Guide (EPA, 2010), exclusion of extremely high outliers is often justified when calculating summary statistics (mean, minimum, maximum, etc.) since extremely high outliers distort summary statistics computations. For purposes of developing a statistical model relationship, however, extremely high values do not cause distortion of the model equation. Instead, high values can benefit an equation by increasing the upper limit of the equation.

In the present case, all seven gamma measurements identified as potential high outliers were taken in areas of historical surface mining (locations with SMA in the sample number), where higher gamma counts were expected (Powertech, 2009 and 2011).

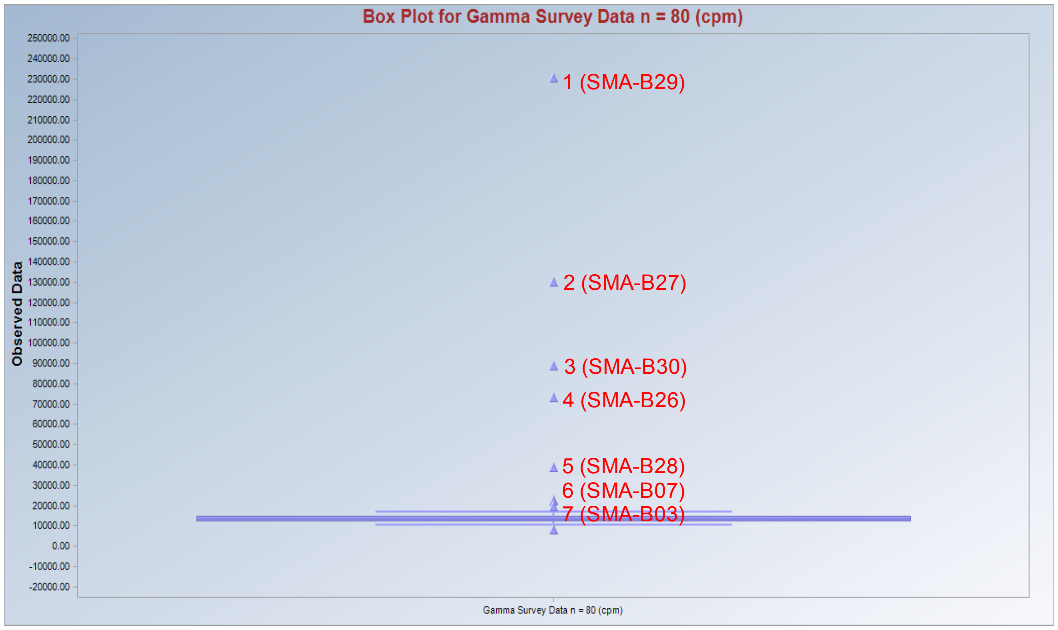


Figure 2. Box Plot Displaying One-Minute Gamma Measurements (n = 80)

The seven measurements are therefore considered valid and are tentatively retained for purposes of statistical relationship development. Final disposition of the seven outliers, however, is dependent upon review of the correlated data in Section 4.3.

Step 4 – Conduct Data Analysis with and without Statistical Outliers

Statistical analysis incorporating all data is shown in Figure 3. The linear regression equation varies somewhat from the one presented in the TR and TR RAI responses (Powertech, 2009 and 2011) due to minor data entry corrections made to the input table.

Since exclusion of the seven highest gamma measurements is not proposed, statistical analysis without outliers is not performed.

Step 5 – Document the Entire Process

The entire process for evaluating gamma measurements for outliers is documented in the TR and TR RAI responses (Powertech, 2009 and 2011) and in Steps 1 through 4 above.

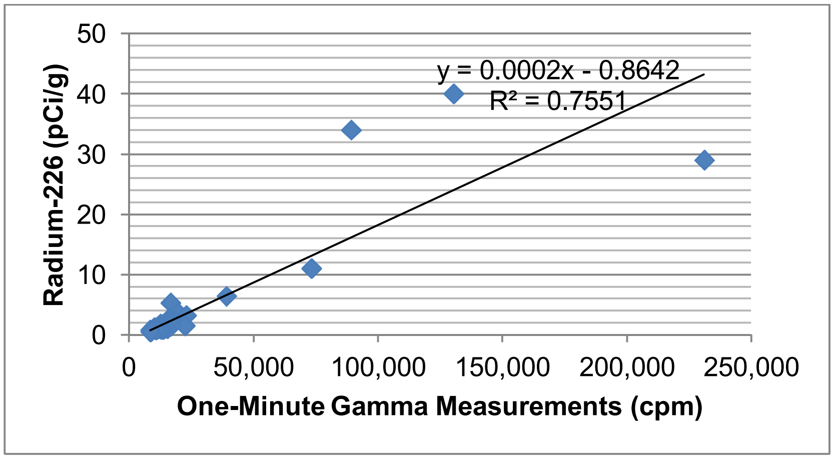


Figure 3. Statistical Modeling with All Data Included (n = 80)

4.2 Evaluation of Radium-226 Soil Sampling Data for High Outliers

<u>Step 1 - Identify Extreme High Values as Potential Outliers</u>

A Q-Q plot showing radium-226 soil sampling data is presented in Figure 4. As shown, six values are higher than the majority of data and two values are somewhat higher than the majority of data. All eight samples are labeled on the Q-Q plot below.

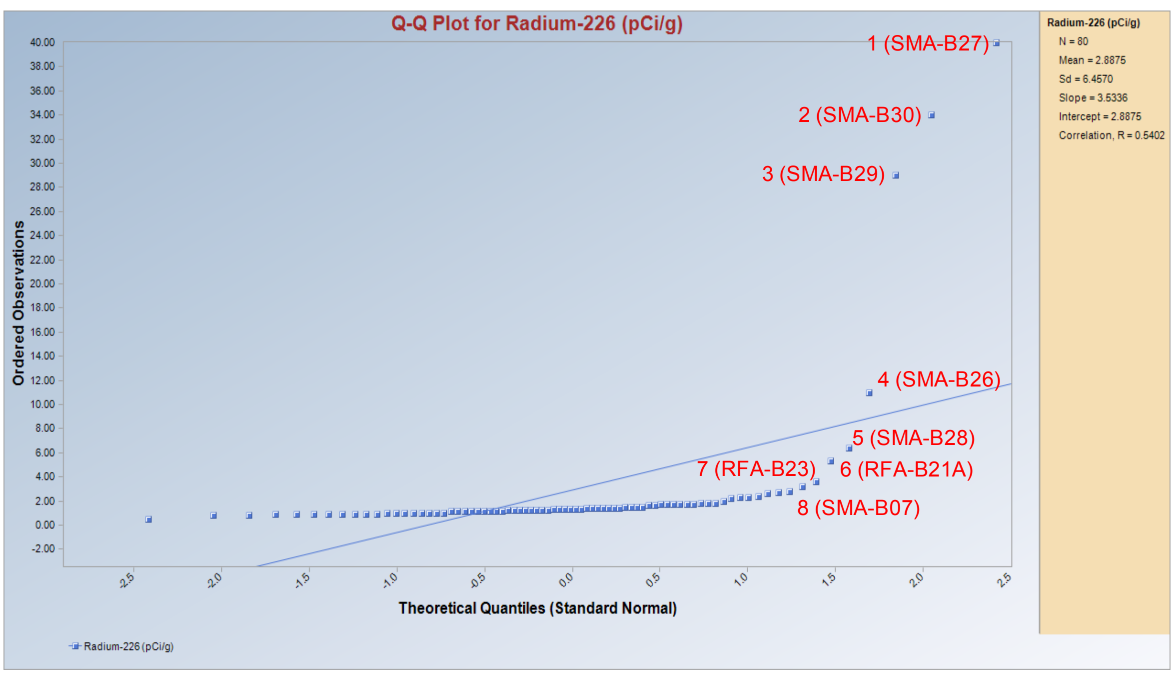


Figure 4. Q-Q Plot for Radium-226 Soil Sampling Data (n = 80)

As discussed in the TR and TR RAI responses (Powertech, 2009 and 2011), radium-226 soil sampling data are not normally distributed. Departure of data from the straight line in the Q-Q plot and a correlation coefficient, R, of less than 0.95 confirm this. Accordingly, additional care is used to evaluate and treat outliers in Step 3.

Step 2 – Perform Statistical Test and Supplement with Graphical Displays

The Rosner outlier test was selected in ProUCL 4.1.00. Eight outliers were estimated first, based on the number of high outliers identified on the Q-Q plot. The Rosner test confirmed all eight values were high outliers. A second Rosner test was performed using an estimated number of outliers of nine. The test confirmed eight potential outliers. Results are presented in Table 3.

For a 5% significance level, the eight highest radium-226 results are potential outliers. The box plot presented on Figure 5 agrees with the Rosner output by displaying eight potential high outliers.

Step 3 - Review Statistical Outliers and Decide Proper Disposition

Field notes and calibration records were reviewed for each of the eight potential high outliers identified in Step 2. No apparent sample collection errors, data transcription errors or laboratory equipment malfunctions were identified.

Six of the eight potential high outliers were collected from historical surface mining areas (samples with SMA in the sample number), where radium-226 concentrations were expected to be higher (Powertech, 2009 and 2011). These six values are therefore considered valid and are tentatively retained for purposes of statistical relationship development. Final disposition of the six outliers, however, is dependent on review of the correlated data in Section 4.3.

Results for RFA-B21A and RFA-B23 also appear to be valid since no sample collection errors, data transcription errors or laboratory equipment malfunctions were identified. Accordingly, results for RFA-B21A and RFA-B23 are tentatively retained for purposes of statistical relationship development. Final disposition of the two outliers, however, depends upon review of the correlated data in Section 4.3.

Step 4 – Conduct Data Analysis with and without Statistical Outliers

Statistical modeling incorporating all data is presented in Figure 3. Since exclusion of the eight highest radium-226 results is not proposed, data analysis without outliers is not performed.

Table 3. Rosner Test Output for Radium-226 Soil Sampling Data

				Outlier Tests for Selected Variables			
User Selected Options							
From File				Radium.wst			
Full Precision				OFF			
Test for Suspected Outliers with Dixon test				1			
Test for Suspected Outliers with Rosner test				9			
Rosner's Outlier Test for Radium-226 Soil Sampling Data (pCi/g)							
Mean			**2.888**				
Standard Deviation			**6.457**				
Number of data			**80**				
Number of suspected outliers			**9**				
#	Mean	sd	Potential outlier	Obs. number	Test value	Critical value (5%)	Critical value (1%)
1	2.888	6.417	40	2	5.784	3.31	3.67
2	2.418	4.934	34	3	6.401	3.3	3.67
3	2.013	3.397	29	1	7.943	3.3	3.66
4	1.662	1.41	11	4	6.625	3.29	3.66
5	1.539	0.914	6.4	5	5.318	3.29	3.65
6	1.475	0.723	5.3	13	5.288	3.284	3.646
7	1.423	0.572	3.6	8	3.805	3.278	3.642
8	1.393	0.515	3.2	6	3.509	3.272	3.638
9	1.368	0.471	2.8	11	3.038	3.266	3.634
For 5% significance level, there are 8 Potential Outliers. Therefore, Potential Statistical Outliers are 40, 34, 29, 11, 6.4, 5.3, 3.6, and 3.2.							
For 1% Significance Level, there are 7 Potential Outliers. Therefore, Potential Statistical Outliers are 40, 34, 29, 11, 6.4, 5.3, and 3.6.							

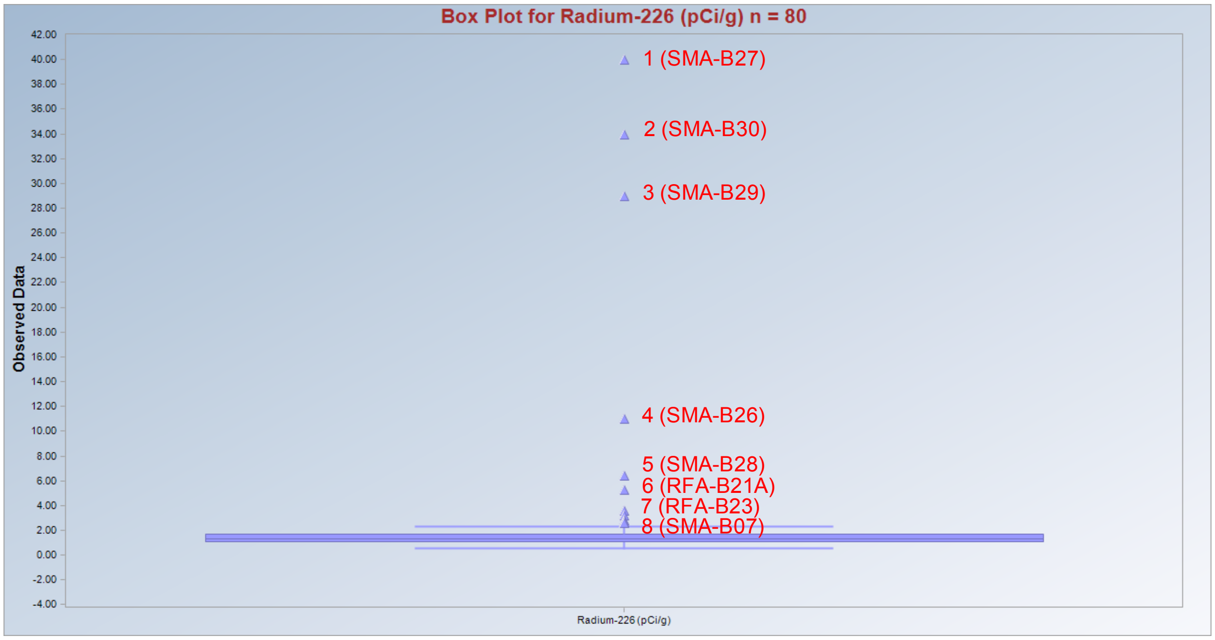


Figure 5. Box Plot Displaying Radium-226 Soil Sampling Data (n = 80)

<u>Step 5 – Document the Entire Process</u>

The entire process for evaluating radium-226 soil sampling data for outliers is documented in the TR and TR RAI responses (Powertech, 2009 and 2011) and in Steps 1 through 4 above.

4.3 Evaluation of Correlated Data for Outliers

<u>Step 1 - Identify Extreme High Values as Potential Outliers</u>

Figure 6 presents gamma measurements and radium-226 data in order of lowest gamma measurement to highest. The five highest values identified in Sections 4.1 and 4.2 are readily visible on the figure. Closer review indicates the *three* highest results do not correspond with each other in order, prompting additional evaluation in Step 3. In addition, the result for RFA-B21A, circled in Figure 6, stands out as a possible outlier.

<u>Step 2 – Perform Statistical Test and Supplement with Graphical Displays</u>

The Rosner test in ProUCL 4.1.00 applies to single variable tests. Accordingly, a formal outlier test was not applied to the correlated data set.

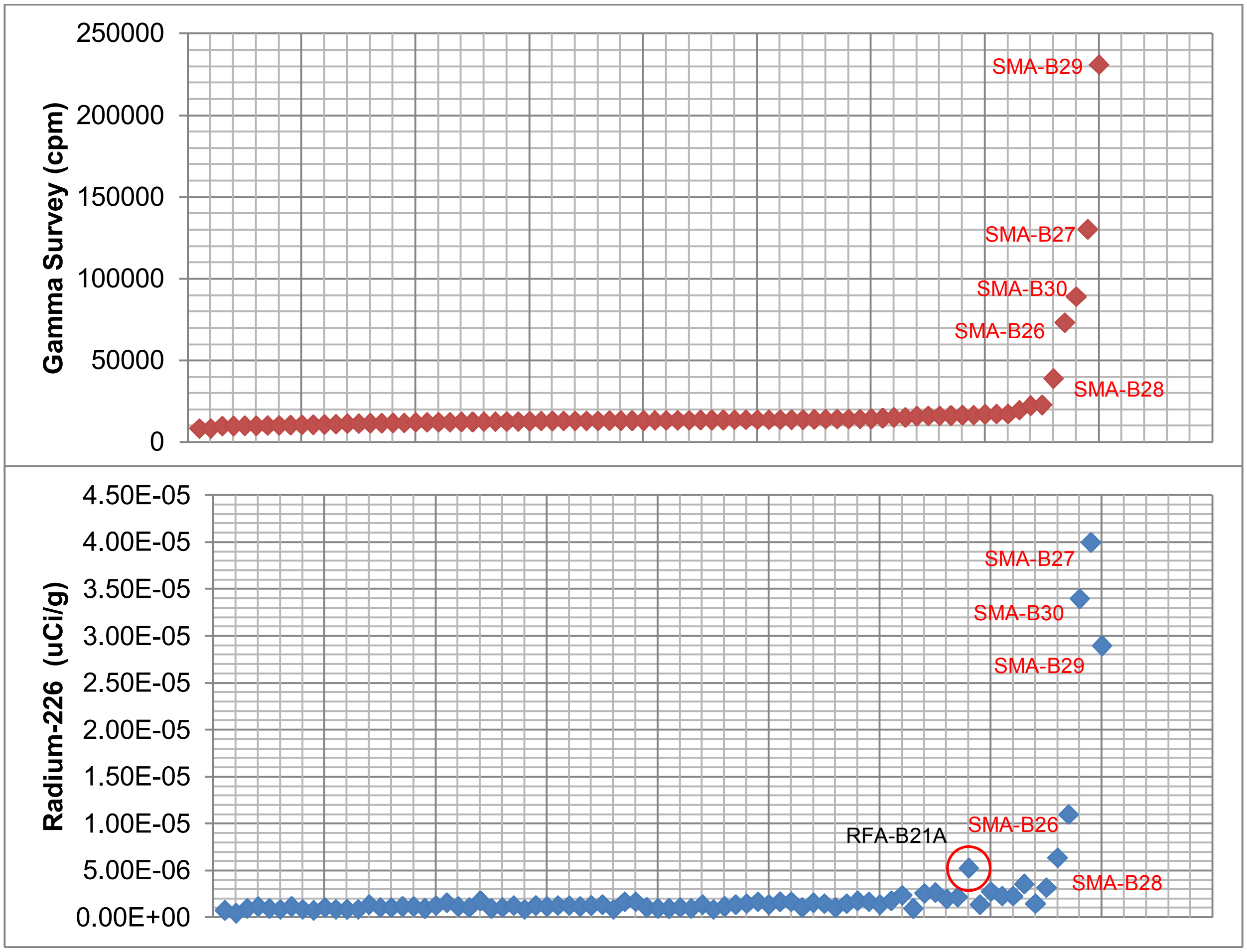


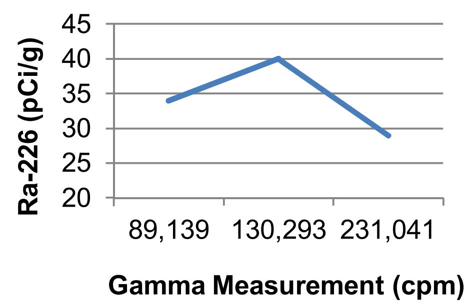
Figure 6. Comparison of Gamma Measurements and Radium-226 Soil Sampling Data Ordered from Lowest to Highest Gamma Measurement

Step 3 - Review Statistical Outliers and Decide Proper Disposition

Qualitative review of the three highest gamma measurements and radium-226 values shows a discrepancy in the order of the data. As shown in Table 4, which is adapted from Table 1, the three highest gamma measurements correspond with the three highest radium-226 surface soil results, as one would expect. However, the values do not correspond with each other in order. The lowest gamma measurement corresponds with the middle radium-266 result, the middle gamma measurement corresponds with the highest radium-226 result, and the highest gamma measurement corresponds with the lowest radium-226 result.

Table 4. Summary of Three Highest Gamma Measurements and Radium-226 Soil Sampling Data

Sample ID	Sample Collection Date	Gamma Measurement (cpm)	Radium-226 (pCi/g)
SMA-B30	9/28/2007	89,139	34
SMA-B27	9/28/2007	130,293	40
SMA-B29	9/28/2007	231,041	29



It is noted that the higher radium-226 concentrations are found in soils associated with the historic surface mining areas (SMA in the sample number), and that the soils have been randomly mixed and are no longer as homogeneous as they were prior to mining activities.

Some overlap in data is reasonably expected at lower concentrations where differences in laboratory uncertainty can cause this to occur. However, results above uncertainty variations, as in the case here, should not be noticeably affected. Laboratory uncertainties range from +/- 0.1 to +/- 1.1 pCi/g for the three highest radium-226 soil samples, well below the range detected of 29 to 40 pCi/g.

One possible explanation for data occurring out of order is that the upper calibration ranges of field equipment, laboratory instruments or both were exceeded in gamma measurements or radium-226 concentrations. Laboratory reports and field notes, however, do not mention such occurrences.

Another possible explanation is that samples collected on a slope received gamma input from more than one plane (gamma shine), raising the gamma count in that particular location but not the radium-226 concentration.

Alternatively, samples or sample numbers may have been switched, either in the field or at the laboratory, causing data to appear out of order.

Regardless of the cause, because the three highest observations occur out of order, the project team has agreed proper disposition of the values is to exclude them from the statistical modeling data set. Although the values appear valid on their own, as described in Sections 4.2 and 4.3, a discrepancy is apparent when correlated.

Excluding the values for SMA-B30, SMA-B27 and SMA-B29 decreases the upper range of the statistical model for radium-226 from 40 pCi/g to 11 pCi/g and for gamma from approximately 231,000 cpm to approximately 73,000 cpm.

Additional evaluation was performed to determine whether exclusion of the highest value (SMA-B29) or exclusion of the second and third highest values (SMA-B30 and SMA-B27) was warranted. Although R^2 values in both cases were higher, the average difference between observed and predicted concentrations increased. Appendix D provides the additional evaluation.

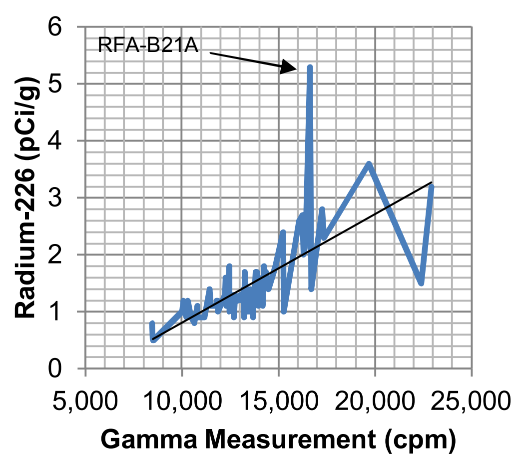
With regard to the result for RFA-B21A, Table 5, which is adapted from Table 1, shows the detection is more than 2 pCi/g higher than results on either side of it. The result for RFA-B21A is 5.30 pCi/g while values on either side of it are 1.40 and 2.20 pCi/g.

Laboratory uncertainty was checked to see if uncertainty was causing a higher value for RFA-21A, but at +/- 0.4 pCi/g, it is evident that it is not. Possible explanations for the discrepancy include laboratory and/or gamma reporting errors.

Regardless of the cause, because the radium-226 concentration for RFA-B21A falls outside the expected range for the gamma measurement recorded, the project team has concluded that proper disposition of the value is to exclude it from the statistical modeling data set.

Table 5. Comparison of RFA-B21A Result with Surrounding Values

Surface Soil Sample ID	Sample Collection Date	Gamma Measurement (cpm)	Radium-226 (pCi/g)
RFA-B17A	9/26/2007	16,283	2.00
NEA-R03	9/24/2007	16,393	2.20
RFA-B21A	9/26/2007	16,641	5.30
SMA-B21	9/24/2007	16,712	1.40
NEA-R05	9/24/2007	17,269	2.80



Step 4 – Conduct Data Analysis with and without Statistical Outliers

The resulting linear regression model with the three highest values excluded is shown in Figure 7.

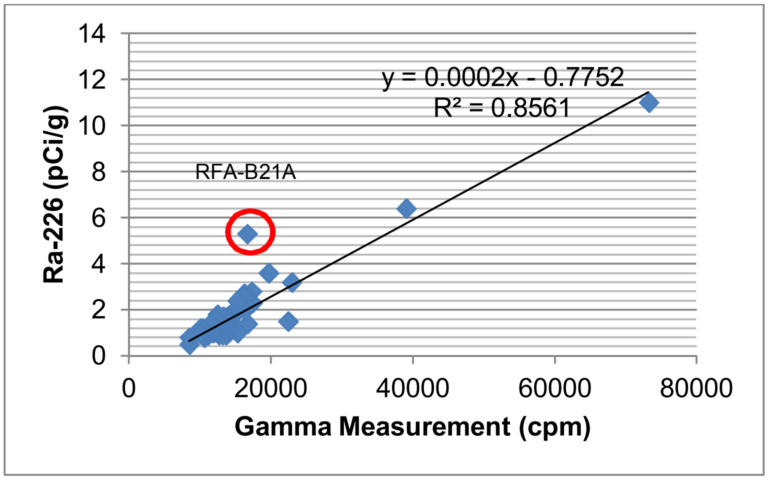


Figure 7. Statistical Model with Three Highest Values Excluded (n = 77)

The resulting linear regression model with the three highest values and RFA-B21A excluded is shown in Figure 8.

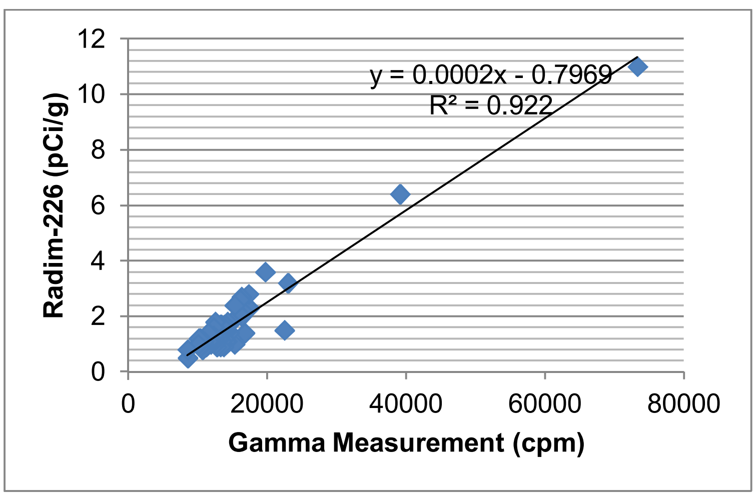


Figure 8. Statistical Model with Three Highest Values and RFA-B21A Excluded (n = 76)

As shown in Figure 8, the coefficient of determination, R^2, is 0.922 and the statistical model equation, which replaces Equations 1 and 2, is:

y = 0.0002x – 0.7969 (Equation 3)

where: y = predicted radium-226 concentration in pCi/g
x = gamma measurement in cpm

It is noted here that since Equation 3 replaces Equation 2, median and quartile values for Equation 2 are no longer applicable to the statistical model relationship. Explanation of the basis for median and quartile values for Equation 2 requested in draft LC 12.11 is, therefore, not provided.

Step 5 – Document the Entire Process

The entire process for evaluating correlated gamma measurements and radium-226 soil sampling data for high outliers is documented in the TR and TR RAI responses (Powertech, 2009 and 2011) and in Steps 1 through 4 above.

4.4 Comparison of Correlated Data with Similar Studies

Two examples of similar correlation studies are reviewed.

In the first, “Radiological Site Characterizations: Gamma Surveys, Gamma/^{226}Ra Correlations, and Related Spatial Analysis Techniques” (Whicker et al., 2008), sampling from approximately 17 - 10 x 10-meter (m) plots was conducted with 10 surface soil samples composited from each plot at a proposed in situ uranium recovery site. Each 10 x 10-m plot was subsequently surveyed using an off-highway vehicle and portable gamma field detector. The average gamma reading over each plot was paired with corresponding laboratory radium-226 soil sample results for regression analysis. The range of radium-226 concentrations detected was approximately 1 to 17 pCi/g with all but 5 detections being less than approximately 4 pCi/g. The R^2 values for linear and nonlinear regression models were 0.84 and 0.94, respectively. The importance of minimizing gamma shine impacts by choosing plot locations without nearby regions of significantly higher readings was noted in the study. A copy of the paper prepared by Whicker et al. (2008) is provided in Appendix B.

Radium-226 concentrations detected in soil samples collected at the Dewey-Burdock Project were similar to those detected in the Whicker et al. study. Concentrations at the Dewey-Burdock Project range from 0.5 to 40 pCi/g, with all but six detections being less than 4 pCi/g. With high outliers excluded, the range of detections is 0.5 to 11 pCi/g, which is closer to the range presented in Whicker et al., and the number of detections greater than 4 pCi/g is two. The R^2 of 0.922 for the Dewey-Burdock Project is also similar to the Whicker et al. study. Although field methods and the number of samples collected differed, similar data sets and statistical relationships for the Dewey-Burdock Project and the Whicker et al. study resulted. At both sites, gamma shine is identified as having the potential to increase gamma measurements in areas of higher gamma readings.

In the second example, “Characterization of Surface Soils at a Former Uranium Mill” (Johnson et al., 2006), composite soil sampling from approximately 50 - 10 x 10-m plots was conducted with 10 surface soil samples collected from each plot. Each 10 x 10-m plot was surveyed using an ATV- and backpack-mounted gamma detector system. The average gamma reading over each plot was paired with corresponding soil radium-226 concentrations for statistical regression analysis. Radium-226 concentrations ranged between approximately 0.7 and 8.6 pCi/g, with all but 12 detections occurring below 4 pCi/g. It is noted in the paper that the study intentionally targeted this range to bracket a 5 pCi/g cleanup standard. The R^2 for the linear regression model was 0.8084. A copy of the paper is provided in Appendix C.

Although field methods and the number of samples collected differed, a similar range of detections and statistical model relationships resulted for the Dewey-Burdock Project and the Johnson et al. study.

Comparison of Dewey-Burdock Project field procedures, data ranges and coefficients of determination with those presented in Whicker et al. (2008) and Johnson et al. (2006) indicates that although different field methods and different numbers of samples were collected, similar data sets and fits of statistical models to site conditions were achieved. Table 6 summarizes data collection procedures and results for the Dewey-Burdock Project and studies performed by Whicker et al. (2008) and Johnson et al. (2006).

Table 6. Comparison of Dewey-Burdock Correlation Results with Other Studies

Study	n	Radium-226 (pCi/g)	Number of Radium-226 Results > 4 pCi/g	R^2	Field Procedure
Dewey-Burdock (fieldwork 2007)	76	0.5 – 11	2	0.922	One-minute gamma measurement at each soil sampling location
Whicker et al. (fieldwork 2006 and 2007)	17	1 - 17	5	0.84 to 0.94	Survey and composite sampling across grid
Johnson et al. (fieldwork 2004)	50	0.7 – 8.6	12	0.8084	Survey and composite sampling across grid

5.0 Conclusions

Analysis of gamma measurements and radium-226 results identified four values that were excluded from the statistical modeling data set. These were the three highest gamma/radium-226 values in samples SMA-B29, SMA-B30, and SMA-B27 and the result for RFA-B21A.

The three highest gamma/radium-226 values were excluded because data do not correspond in order. Removing the values decreased the upper range of the statistical model equation from 40 to 11 pCi/g radium-226, or from approximately 231,000 to 73,000 cpm gamma.

The result for RFA-B21A was excluded as an erroneous result, possibly stemming from a field or laboratory reporting error. Excluding the value does not affect the range of the model equation.

The final number of samples used in the regression analysis, with outliers removed, then is n = 76. The resulting linear equation is $y = 0.0002x – 0.7969$ (Equation 3). The resulting model range is approximately 0.5 to 11 pCi/g or approximately 8,500 to 73,000 cpm. The model coefficient of determination, R^2, is 0.922.

6.0 References

EPA, 2010. ProUCL Version 4.1.00 Technical Guide, Draft, Statistical Software for Environmental Applications for Data Sets with and without Nondetect Observations, EPA/600/R-07/041, May 2010.

Johnson, J.A., H.R. Meyer, and M. Vidyasagar, 2006. Characterization of Surface Soils at a Former Uranium Mill, Operational Topic, Radiation Safety Journal, Vol. 90, Suppl. 1, Health Physics Society, February 2006.

NRC, 2013. Safety Evaluation Report for the Dewey-Burdock Project, Fall River and Custer Counties, South Dakota, Materials License No. SUA-1600, Docket No. 40-9075, Powertech (USA) Inc., Office of Federal and State Materials and Environmental Management Programs, March 2013.

Powertech, 2009. Dewey-Burdock Project Application for NRC Uranium Recovery License, Fall River and Custer Counties, South Dakota, Technical Report for the U.S. Nuclear Regulatory Commission, Appendix 2.9-A Baseline Radiological Report, February 2009.

Powertech, 2011. Dewey-Burdock Project Application for NRC Uranium Recovery License, Fall River and Custer Counties, South Dakota, Technical Report RAI Responses for the U.S. Nuclear Regulatory Commission, TR RAIs 2.9-30, 31, 35, 38, and 39, June 2011.

Whicker, Randy, Paul Cartier, Jim Cain, Ken Milmine, and Michael Griffin, 2008. Radiological Site Characterizations: Gamma Surveys, Gamma/^{226}Ra Correlations, and Related Spatial Analysis Techniques, Operational Topic, Radiation Safety Journal, Vol. 95, Suppl. 5, Health Physics Society, November 2008.

Appendix A

Field Notes

9/25/07

7:15 am: Started planning out today's soil samples.

7:50 am: Function checked NaI's.

8:15 am: Left barn.

9:10 am: Began collecting soil samples, 0-15cm, with a small spade shovel + taking 1 minute measurements w/ NaI detector A (at same location).

9:10 am: 1-min count @ site RFA-B29: 14345
Collected sample RFA-B29 at a flat grass land.

9:20 am: 1-min count @ MPA-B02: 14176
Collected sample MPA-B02 at a flat grass land.

9:40 am: 1-min count @ RFA-B34: 13408
Collected sample ~~MPA~~ RFA-B34 at a flat field, next to a barbed wire fence.

10:00 am: 1-min count @ RFA-B16: 13675
Collected sample RFA-B16 on an edge of a wooded area.

10:15 am: 1-min count @ RFA-B24: 12766
Collected sample RFA-B24 on a flat grassland, next to a wooded area

10:30 am: 1-min count @ ~~RFA-B31~~: 12221
Collected sample RFA-B31 on a ~~ft~~ flat grassland.

10:40 am: 1-min count @ MPA-B01: 13824
Collected sample MPA-B01 on a flat grassland.

10:55 am: 1-min count @ RFA-B40: 12629
Collected sample ~~M~~ DRF 9/25/07 RFA-B40 on a flat grassland, next to a wooded area.

11:15 am: 1-min count @ RFA-B04: 13963
Collected sample R~~B~~ DRF 9/25/07 FA-B04 on a flat area next to a wooded area

"Rite in the Rain"

11:30 am: 1-min count @ RFA-B19: 13689
Collected sample RFA-B19 at a flat grassland.

11:45 am: 1-min count @ RFA-B27: 13794
Collected sample RFA-B27 at a flat area near a small storage area.

12:05 pm: 1-min count @ RFA-B07: 12700
Collected sample RFA-B07 at a flat area near a road.

12:15 pm: 1-min count @ RFA-B38: 11852
Collected sample RFA-B38 at a flat grassland.

12:30 pm: 1-min count @ RFA-B33: 13221
Collected sample RFA-B33 at a flat grassland.

12:50 pm: 1-min count @ RFA-B08: 13433
Collected sample RFA-B08 + RFA-B08 duplicate at a slightly hilly grassland.

"Rite in the Rain"

1:10pm: 1-min count @ RFA-B26: 11791
Collected sample RFA-B26 at a slightly hilly grassland, next to a barbed wire fence.

1:30pm: 1-min count @ RFA-B39: 11478
Collected sample RFA-B39 at a rolling grassland, next to a road.

1:45pm: 1-min count @ RFA-B11: 13366
Collected sample RFA-B11 at a slightly hilly area.

2:00pm: 1-min count @ RFA-B22: 14087
Collected sample RFA-B22 at a flat area.

2:25pm: 1-min count @ RFA-B44: 11436
Collected sample RFA-B44 at a flat area between a barbed wire fence + a vehicle path.

3:00pm: 1-min count @ RFA-B12: 14253
Collected sample RFA-B12 in a wooded area.

"Rite in the Rain"

3:10pm: 1-min Count @ RFA-B09: 13528
Collected sample RFA-B09 at an area near a wooded area.

3:20pm: 1-min count @ RFA-B20: 13113
Collected sample RFA-B20 at a flat area.

Finished collecting soil samples for today. Need to survey areas that I sampled yesterday.

Sample Area	Time of Survey	1-minute count
MPA-R01	4:15pm	13749
NEA-R02	4:30pm	13176
NEA-R03	4:35pm	16393
NEA-R04	4:50pm	17356
NEA-R05	5:00pm	17269

5:15pm: Left for barn.

5:45pm: Arrived at barn, function checked.

6:00pm: Done for the day.

David R. [illegible] 9/25/07

Rite in the Rain

9-25-07

Hike to SMA B-13

0916

1 min NaI ; Detection System B

13252 cpm

collect sample. low-mod. density juniper, ponderosa pine ; dense rocks red + tan sandstone.

0945 1 min NaI @ SMA B-08 = 12,653

rocky drainage, dense juniper, ponderosa

sample is gravely sand silt clay light brown

1006 1 min NaI @ SMA B-10 = 13184

rocky, steep slope, dense ponderosa, juniper

hit rock @ ~ 2-in bgs. topsoil is dark brown silty clay

1025 1 min NaI @ SMA B-18 = 8511 cpm

low slope rocky area, mod density juniper.

v. dry light brown silty clay

1135 1-min NaI @ RFA B43 = 13264

low-flat area in drainage 6-in - 12-in sparse grass, moist dk brown silty clay

9-25-07 (cont'd)

1146 1 min NaI @ RFA-18 = 13935

Flat area, no trees, no rocks, light-dk brown silty clay

1156 1 min. NaI @ RFA B15 = 14825

Flat area, no trees, some rocks in area but not @ sample location. lt-dk brown silty clay.

1224 1 min NaI @ RFA B23 = 19674

barrow area, sparse vegetation, none at sample location, soils in area are very dark brown, heavily drained, sparse rocks that are dark reddish brown

1235 1 min NaI @ RFA B14 = 13872

flat, bare area light brown silty clay

1248 1 min NaI @ RFA B28 = 15246

flat, bare area, light brown silty clay

1258 1 min NaI @ RFA B06 = 13819

flat area, sparsely vegetation. sample location is bare, light brown silty clay, some small rocks

Rite in the Rain

9-25-07 (cont'd)

1310 1 min NaI @ RFA B03 = 14253
flat, sparsely vegetated area, some small rocks
light brown silty clay

1325 1 min NaI @ RFA B25 = 12800
Flat area descending into flat. within prairie dog colony. only vegetation is a well-grazed grass.
dry, light brown silty clay

1339 1 min NaI @ RFA B41 = 11806 cpm
gently sloping area w/ sparse vegetation; grazed grass + prickly pear no rocks. light brown silty clay

1353 1 min NaI @ RFA B45 = 12242
flat area, sparsely vegetated w/ grass + sagebrush
sparse small rocks. light brown silty clay, dry
move to South to find David Farrar.

1457 1 min NaI @ RFA B35 = 12290
sparsely vegetated w/ well-grazed grass
gently rolling hills. light brown silty clay

1506 1 min NaI @ MPA-B03 = 13006
flat - sparsely vegetated sparse rocks
lt brown silty clay

9-25-07 (cont'd)

1541 1 min NaI reading @ RFA-B12 = 13135
mod. density ponderosa pine, no junipers, gently rolling, no rocks.
light brown silty clay

1 min counts on David's southern five from yesterday.

MPA-R01
found hole
× 13,302

black exposed rock
16,059 : no hole observed

MPA-R02 ×

× found 2 holes
/10,810 cpm
MPA-R04

MPA-R05
× 1 min: 11,850 cpm
found no hole

MPA-R03
× @ yesterday's hole
1 min = 10,796 cpm

1705 mob. back to lodge.
1735 arrive @ lodge
1930 Mad Mountain arrives to inspect ATVs.
All ok.

[signature]
9-25-07

"Rite in the Rain"

9-26-07

Plan: 9 hand auger samples (9×3 = 27 plus one dup. in south one in north = 33 samples)

0825 Set up @ RFA B21A
1-min NaI w/ Detector System A = 16641 cpm
- Collect A, B, C (3 bags)
- 0851 Deploy ERG # 91 Flux canister

0904 Set up @ RFA - B37A
1-min NaI = 11170 cpm
0925 Deploy ERG # 72 flux canister @ this location

0933 Set up @ RFA - B02A
1-min. NaI = 13360 cpm
0948 Setup ERG # 73 flux canister

1000 Set up @ RFA - B15A Collect 1a of soil samples using hand
1-min NaI = 13535 cpm
Deploy ERG # 23 @ 1015

9-26-07 (Cont'd)

1105 Set up on RFA - B36A
1 min NaI: 12465 cpm
collect 0-15 cm, 15-30 cm, 30-100 cm sample
1118 deploy ERG Flux Canister #55

1204 Set up on RFA - B17 - in drainage
1 min NaI = 16283
Collect 0-15, 15-30, 30-100 cm Samples Rock Refusal @ 85 cm
Deploy ERG Flux Canister # 63 @ 1212

1229 Set up on RFA - B13A
1 min NaI = 13987 cpm
flat area, sparse vegetation
sample location is bare
Deploy ERG Flux Canister # 105 @ 1240

1251 Set up @ RFA-B30A
1 min. NaI = 12461 cpm
Deploy ERG Flux canister # 102 @ 1304

1317 Set up @ RFA - B01 - Collect Dup
1-min. NaI = 13115 cpm
Deploy ERG Flux canister nos. 45 ~~# 48~~ New STET @ 1350

Rite in the Rain

9-27-07 (cont'd)

Time	Loc	1-min count	Found hole	
1441	SMA B25	9991		
1451	SMA B15	8474		
1457	SMA B17	10139	✓	
1508	SMA B03	22410		Drainage
1518	SMA B23	16233	✓	
1524	SMA B22	10618	NW ✓	
1535	SMA B20	~~10855~~ 10897	NA	
1548	SMA B01	10459	✓	
1559	SMA B24	12662	✓	
1608	SMA B12	14097	✓	
1613	SMA B14	14483	✓	
1623	SMA B19	10074	✓	
1629	SMA B05	9999	✓	
1637	SMA B16	10235	✓	
1648	SMA B11	17346	✓	
1657	SMA B04	15263	✓	
1708	SMA B21	16712	✓	
1715	SMA B06	12449	✓	
1720	SMA B09	12879	✓	
1726	SMA B02	13408	✓	
1732	SMA B07	22925	✓	

1535 SMA B-20 gently rolling, well-grazed grass, lt. br. dry silty clay

1813 back @ lodge

9/28-07

0700 DRF, NW start [illegible]

Pull samples

SMA B02

SMA B03

SMA B05

SMA B06

SMA B12

2821 Plant St.

Deadwood [North to 90]
left @ Prairie Ways Communication = Plant
takes a sharp right ;

Be there @ 0800

0859 SMA-B26 Record in R092808DRFO1
1 min NaI @ 18-in. = 73,243, using Detection
System B. Collect sample using shovel.

0906 SMA-B27
1-min. NaI = 130,293 cpm.

9-28-07 (cont'd)

0915 SMA B28 at radio-track etc.
detector at triangle mine.
1 min. NaI = 39061 cpm
Collect sample.

0930 SMA B29, grey sand
1 min NaI = 231,041 cpm
observed > 999,999 cpm in this area.

0956 SMA B30, yellow and grey waste rock in
1 min. NaI = 89139 lg. mine area
Collect soil sample.

~1 hour lunch ~

1 Daniels
2 Spencer
3 Beaver Creek Ranch
4 Dewey
5 Everett Englebert
6 School
7 Heck Ranch
BHG

1730 Complete packing boxes, coolers.
1600-1800 work on COCs

[illegible] 9-28-07

"Rite in the Rain"

Appendix B

Whicker et al. Study (2008)

Advances in radiological survey capabilities for large sites are discussed.

Radiological Site Characterizations: Gamma Surveys, Gamma/^{226}Ra Correlations, and Related Spatial Analysis Techniques

Randy Whicker, Paul Cartier,† Jim Cain,‡ Ken Milmine,§ and Michael Griffin§*

Abstract: *Radiological surveys of a uranium mill site in Colorado and several proposed uranium recovery sites in Wyoming were conducted in 2006 and 2007. Advancements in Global Positioning System (GPS)-based gamma scanning systems combined with gamma/^{226}Ra correlations and Geographic Information Systems (GIS)-based spatial analysis techniques produced comprehensive and detailed characterizations of the spatial distributions of gamma exposure rates and ^{226}Ra concentrations in surface soils across extensive study areas. Aside from limitations on gamma-based estimates of soil ^{226}Ra related to soil heterogeneity or gamma shine effects, soil sampling results to date show good general agreement between estimated and measured values. Spatial characterization aspects of the survey approach are clearly more effective than conventional grid sampling methods, particularly for such large sites. Example project applications, data collection and analysis methods, challenges encountered, and resulting mapped estimates of various aspects of these radiological parameters are presented. Health Phys. 95(Supplement 5): S180–S189; 2008*

Key words: *operational topics; surveys; ^{226}Ra; soil*

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INTRODUCTION

Remediation of uranium mining/milling sites or other sites where naturally occurring radioactive materials are present usually requires characterizations of gamma exposure rates and ^{226}Ra concentrations in soil. Establishing pre-operational (background) and post-operational conditions for these radiological parameters is important for assessment of areas requiring remediation. Past approaches include taking discrete gamma measurements and soil samples across a systematic grid pattern. A grid sampling approach is indicated by the U.S. Nuclear Regulatory Commission (U.S. NRC) in Regulatory Guide 4.14 for uranium mills (U.S. NRC 1980), with 40 soil samples collected along a radial grid and 80 individual discrete gamma measurements collected along a similar pattern.

More recent radiological survey guidelines found in MARSSIM, the Multi-Agency Radiation Survey and Site Investigation Manual (U.S. NRC 2000), also indicate grid-based designs for soil sampling and direct measurement of radionuclides in soil, but the number of soil samples needed varies according to statistical requirements and continuous gamma scanning (rather than discrete gamma measurements) is used to augment the soil sampling.

At some sites, natural background soil ^{226}Ra concentrations are quite variable and may exceed levels commonly used as cleanup criteria. If such areas are not identified prior to site operations, they can be misidentified during decommissioning as contaminated areas in need of remediation. Improvement in radiological characterization methods for background and potentially impacted areas can help improve assessment of areas in need of remediation and verification of the effectiveness of that remediation.

Since the above mentioned agency guidance documents were published, advanced Global Positioning System (GPS)-based gamma scanning systems with automated electronic data collection have been developed and used in the field (Meyer et al. 2005a and b; Johnson et al. 2006). These systems can record up to 3,600 individual gamma readings and corresponding GPS measurements per hour, providing

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a detailed record of gamma exposure rate conditions across scanned areas. Multiple scanning systems mounted on vehicles can quickly survey large areas and provide a high spatial density of measurements. This gamma survey technology represents a substantial increase in the amount of radiological information that can be efficiently collected relative to technology available when earlier agency guidance documents were published.

Gamma surveys of a uranium mill site in Colorado and several proposed in-situ recovery (ISR) uranium project areas in Wyoming were conducted in 2006 and 2007 using multiple GPS-based gamma scanning systems mounted on off highway vehicles (OHVs). In conjunction with these surveys, correlations between gamma readings and ^{226}Ra concentrations in surface soils (0–15 cm) were established. These correlations enabled spatial and statistical information about soil ^{226}Ra concentrations to be extracted from the gamma survey data to help meet various project characterization objectives. Geographical Information Systems (GIS) software was used for statistical conversion of large survey data sets, interpolation with kriging methods, field sampling support, special investigation/analysis needs, and for data presentation purposes.

The objectives of surveys at the uranium mill site were to develop various probability-based estimates of the areal extent of surface soils having ^{226}Ra concentrations in excess of pre-specified cleanup criteria. At the proposed ISR uranium project areas, the objective was to establish pre-operational baseline gamma exposure rates and soil ^{226}Ra concentrations for licensing/permitting applications. These project objectives each have implications with respect to eventual site decommissioning and termination of radioactive source materials licenses. Continued improvement in methods to characterize gamma exposure rates and soil ^{226}Ra concentrations at such sites can benefit all stakeholders.

MATERIALS AND METHODS

Gamma surveys

Various automated, GPS-based scanning system configurations have been developed for different site conditions. For projects discussed in this paper, two Yamaha Rhino (Yamaha Motor Corp., 6555 Katella Avenue, Cypress, CA 90630) OHV-mounted systems were used (Fig. 1). Given the large size of these sites, along with occasional rugged terrain, tall vegetation and other obstacles, Rhino OHVs were well suited for these projects. Backpack scanning systems were also used in a few small areas inaccessible to OHVs.

These OHVs are equipped with adjustable outriggers designed to mount three 5 × 5 cm sodium iodide (NaI) scintillation gamma detectors (Ludlum Model 44-10; Ludlum Measurements, Inc., 501 Oak Street, Sweetwater, TX 79556) and paired GPS receivers. The gamma detectors are coupled to Ludlum Model 2350 rate meters housed in a container in the cargo bed. Simultaneous GPS and gamma exposure rate data are recorded every 1–2 s using an onboard PC with special data acquisition software (comReader; Tetra Tech, 3801 Automation Way, Fort Collins, CO 80525).

System configuration involves about 2.5 m spacing between detectors (measured perpendicular to direction of travel), with each detector positioned at either 1 or 1.4 m above the ground surface. For many of these projects a detector height of 1.4 m was the lowest practical height for the system under site conditions given the need for adequate clearance of frequently encountered obstacles such as tall vegetation, ravine crossings, and other features. As discussed later in this paper, experimental measurements were performed as needed to model approximate equivalent readings as measured by a high-pressure ionization chamber (HPIC) at 1 m above the ground surface (Fig. 1).

Based on qualitative field observations of detector response under similar measurement geometries, the scanning track width representing each vehicle's lateral range of general scanning sensitivity to elevated planar (non-point) source areas is estimated to be about 8 m across, perpendicular to the direction of travel. Vehicle scanning speeds range between 3 and 16 km h^{-1} depending on the roughness of the terrain, with a typical average speed of 6–10 km h^{-1}.

Data are downloaded daily into a project database and results are viewed each night with special field mapping software (Gamma Data Map Viewer; Tetra Tech, 3801 Automation Way, Fort Collins, CO

Figure 1. Three-detector OHV-mounted scanning systems (left) and static HPIC cross-calibration measurements (right).

80525). This allows scan coverage assessment and planning on a daily basis and helps to identify any problems with systems performance.

For routine scanning across large areas, a target distance of 100 m between vehicles is estimated to achieve about 14% ground scanning coverage. For areas of particular interest, higher-density target coverages can range from 25–100% but typically involve a vehicle spacing of 20–30 m (35–45% coverage). Practical considerations such as safety, terrain, and natural obstructions often dictate actual distances maintained between survey vehicles.

HPIC/NaI cross-calibration

Gamma exposure rates measured by NaI detectors are only relative measurements as response characteristics of NaI detectors are energy dependent. True gamma exposure rates are best measured with a less energy dependent system such as the HPIC. Depending on the radiological characteristics of a given site, NaI detectors can have measurement values significantly different from corresponding HPIC measurement values. NaI detectors are typically calibrated against a ^{137}Cs source. At photon emission energies near that of ^{137}Cs (662 keV), relative detector response is close to 100% (Ludlum 2006). Under field scanning conditions at uranium recovery sites, a preponderance of lower photon energies can be present due to primary and secondary scattered photons from naturally occurring terrestrial radionuclides. At these lower photon energies, response of NaI detectors relative to ^{137}Cs is significantly greater than 100% and NaI detectors will overestimate true exposure rates. In some locations, terrestrial concentrations of gamma emitting radionuclides can be very low and higher-energy cosmic sources can dominate detector response resulting in underestimates of true exposure rates.

NaI systems are useful because they can quickly and effectively demonstrate relative differences between pre- and post-remediation gamma exposure rate conditions. Unless the same equipment and scanning geometry are used for both surveys, however, it is necessary to normalize the data to a common basis of comparison. This is the purpose of performing HPIC/NaI cross-calibration measurements. Cross-calibration ensures that the results of future gamma scans, which may use different detectors, detector types, or measurement geometries, can be meaningfully compared against the results of pre-operational gamma surveys. HPIC/NaI cross-calibrations are also necessary in cases where external dose assessments are part of survey objectives.

To perform HPIC/NaI cross-calibrations, static measurements are taken at various discrete locations covering a range of exposure rates representative of the site. At each measurement location, 10–20 individual readings from the HPIC and each OHV-mounted NaI detector are separately collected and averaged. A picture of this process is shown in Fig. 1 (right). The resulting paired HPIC/NaI data are analyzed by linear regression to enable conversion of NaI-based gamma survey data to approximate 1 m HPIC equivalents.

Gamma/^{226}Ra correlations

Depending on the nature and strength of the relationship between gamma exposure rates and soil ^{226}Ra concentrations at a given site, statistical correlations can be used to estimate approximate soil ^{226}Ra concentrations across the entire site based on gamma survey results.

Following methods described in Johnson et al. (2006), correlation soil sampling is conducted as composite sampling over 10 × 10 m plots. Correlation plot locations are selected to be representative of the range of exposure rates found at the site, with additional efforts made to select plots having relatively homogeneous gamma readings in the general area. Gamma survey maps are used to help determine appropriate locations. Within each plot, 10 soil sub-samples are collected to a depth of 15 cm then composited into a single sample to give an average ^{226}Ra concentration over each 100 m^2 plot. Samples are sent to a qualified laboratory for ^{226}Ra analysis.

Each 100 m^2 soil sampling plot is also scanned using the same OHV-mounted systems and detector configuration used to scan the entire study area. The average NaI gamma reading over each plot is paired with the corresponding average ^{226}Ra concentration for statistical regression analysis.

RESULTS AND DISCUSSION

General observations

Radiological survey study areas at individual sites ranged from 75–4,358 hectares (185–10,770 acres). Scanning rates ranged from about 12 to 135 acres h^{-1} depending on terrain and ground scanning coverage attained. In general, instrument quality control (QC) charts and field QC charts for scan systems demonstrated acceptable performance. In cases of unacceptable system performance, affected data were eliminated from the project database and the system was not used again until the issue was resolved.

Although some cases of unexpected and problematic results were observed during the course of these projects, supplementary field investigations and/or additional data analyses revealed possible explanations and provided a basis for appropriate ways to address related issues. Final ^{226}Ra estimates based on gamma survey data have thus far generally agreed well with confirmatory soil sampling results.

Uranium mill site surveys

Survey activities at the uranium mill site included two separate projects. The first involved a 75-hectare portion of the site scheduled for remedial action. The survey objective was to estimate the extent of areas with greater than 80% statistical probability of having surface soil ^{226}Ra concentrations in excess of the respective cleanup criterion of 6 pCi g^{-1} (222 Bq kg^{-1}). Gamma scan results are shown in Fig. 2 (top).

A GIS-based spatial analysis program was used to krig the gamma survey data in order to provide continuous estimates of gamma exposure rate readings across the study area and better illustrate spatial distributions (Fig. 2, bottom). Kriging is a geostatistical interpolation procedure commonly used in various earth sciences.

Correlation plot measurements across the study area initially demonstrated a statistically weak linear relationship between gamma reading and ^{226}Ra soil concentration. Horizontal and vertical heterogeneity in soil ^{226}Ra concentrations and/or scattered photons reaching the gamma detectors from underlying subsurface sources or areas adjacent to the correlation plots (i.e., gamma "shine") may have been contributing factors to this result as the outliers all had unusually low concentration results relative to gamma readings.

To investigate potential reasons for weak initial correlation results, correlation plots were rescanned using a shielded (collimated) gamma detector. Shielded measurements improved the correlation and revealed evidence that 4 of the 14 correlation plots may have been significantly affected by gamma shine from adjacent areas and/or subsurface sources. When data from these potentially "shine impacted" plots were removed, the statistical strength of the unshielded correlation improved (Fig. 3) with an R-squared value nearly as high as the corresponding shielded correlation.

One-tailed upper and lower 80% prediction limits for the correlation were separately calculated and plotted along with the regression line (Fig. 3). Gamma values corresponding to the cleanup criterion for soil ^{226}Ra concentration (6 pCi g^{-1}) at these prediction limits were used to create a soil ^{226}Ra probability map as shown in Fig. 4. This spatial information is being used to help with remedial action planning. The small circular omitted portion of the study area represents a lined pond that could not be surveyed.

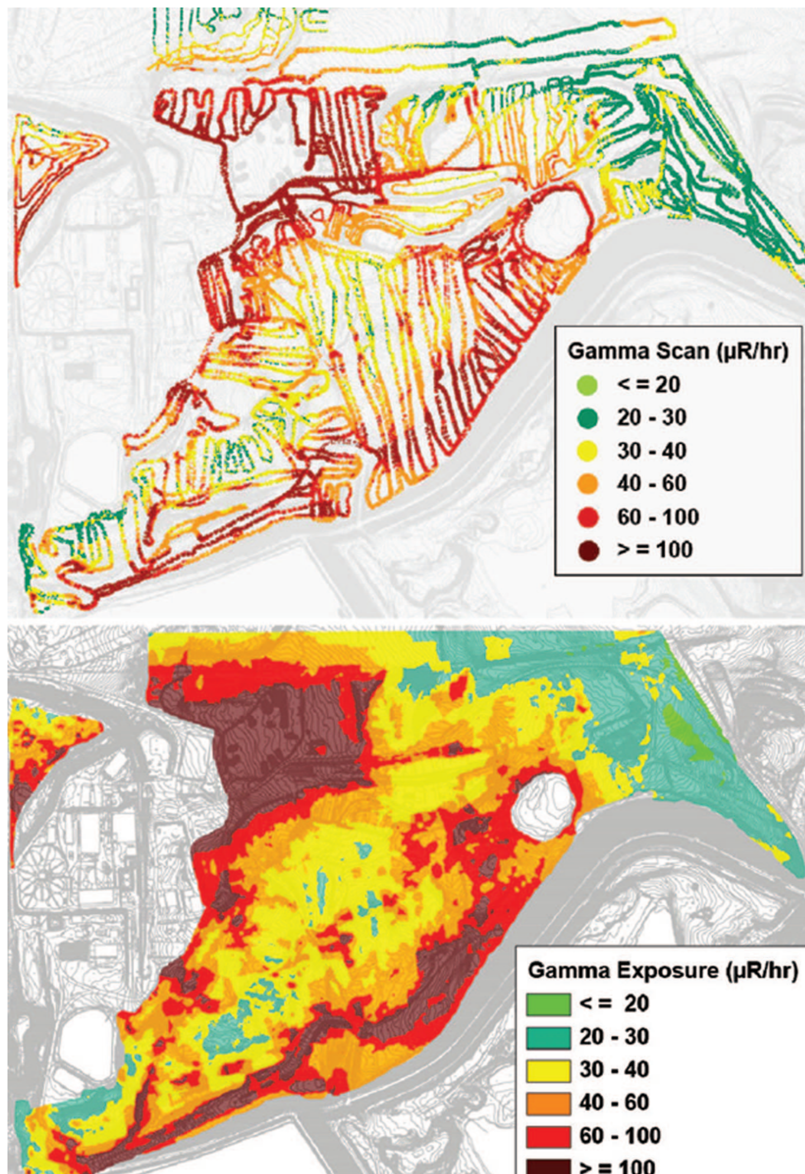

Figure 2. Gamma scan (top) and kriged mapping results (bottom) for the remedial action study area at the uranium mill site.

The second project at the uranium mill site involved a much larger portion of the site beyond the smaller remedial action study area. The objective for this project was also to estimate the areal extent of soil ^{226}Ra concentrations exceeding the 6 pCi g^{-1} cleanup criterion, but in this case the information was used to determine a conservative estimate of the volume of surface soils that could potentially require remediation upon site decommissioning. This volume estimate will be used to update remedial surety bonding and thus a more conservative 95% statistical probability for the estimate was needed.

As with the remedial action survey project, initial results of the gamma/^{226}Ra correlation developed for the volume study area were relatively weak. Again, however, comparisons between shielded and unshielded gamma data for correlation plots revealed a few locations where gamma shine may have contributed to this result. When those data were omitted from the analysis the statistical strength of the regression improved (Fig. 5).

The UPL line in Fig. 5 indicates that for this study area a gamma reading of about 23 μR h^{-1} has a 95% statistical probability of compliance with the 6 pCi g^{-1} criterion for soil ^{226}Ra. An approximate boundary corresponding to 23 μR h^{-1} was drawn on the kriged gamma survey map and confirmatory soil samples were collected just outside this line to verify the reliability of the estimate. Kriged survey results with overlays of the 95% UPL line and confirmatory sampling results are shown in Fig. 6. Areas outside the 95% UPL line above 23 μR h^{-1} were not included in the volume estimate because they are included in remediation plans. Note that the actual regression line in Fig. 5 (rather than the UPL line) predicts that on average, areas with gamma readings of 23 μR h^{-1} will have corresponding ^{226}Ra soil concentrations of about 3.2 pCi g^{-1}. This prediction agrees well with the confirmatory sampling results (Fig. 6).

Limitations on spatial and probabilistic estimates regarding soil ^{226}Ra concentrations for the uranium mill site study areas include uncertainty due to a limited number of correlation plots, analytical uncertainty in the measured correlation plot data, and significant potential for estimation error in areas where considerable gamma shine effects or soil ^{226}Ra heterogeneity exist. For areas significantly influenced by these latter conditions, characterization using conventional grid soil sampling approaches would likely prove more effective provided sufficient sampling density were used. The data suggest, however, that such areas represent a small fraction of overall study areas and that the correlation method was an effective overall approach.

An important lesson learned from all project examples presented in this paper is that correlation plot selection criteria are very important. Careful evaluation and planning must be exercised when selecting correlation plot locations to ensure that the data are representative of the range of gamma values found at the site, and that gamma readings in the general vicinity of each plot are as homogeneous as possible. This can be difficult to achieve for locations selected to represent higher readings as these areas tend to be small with a higher degree of small scale spatial variability. It is also desirable to try and avoid choosing locations with nearby regions of significantly higher readings to help avoid shine issues. A related problem that is more difficult to address is that it is seldom possible to predict areas that may be affected by shine from shallowly buried subsurface materials.

Proposed ISR uranium project area surveys

Because survey objectives at the various proposed ISR uranium project areas in Wyoming were focused on pre-operational baseline characterizations, NaI-based scan data were normalized to 1 m HPIC readings to approximate true gamma exposure rates

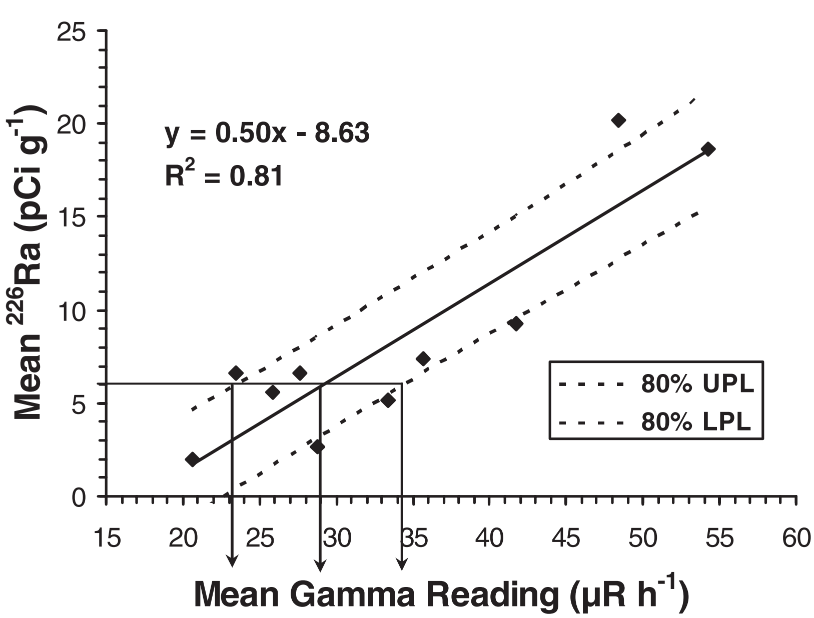

Figure 3. Correlation results for the remedial action study area at the uranium mill site.

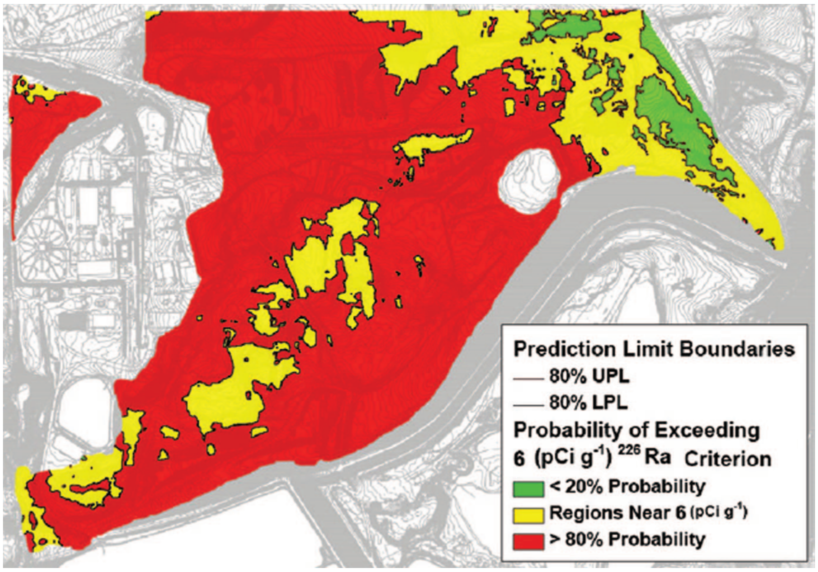

Figure 4. Soil ^{226}Ra probability map for the remedial action study area at the uranium mill site.

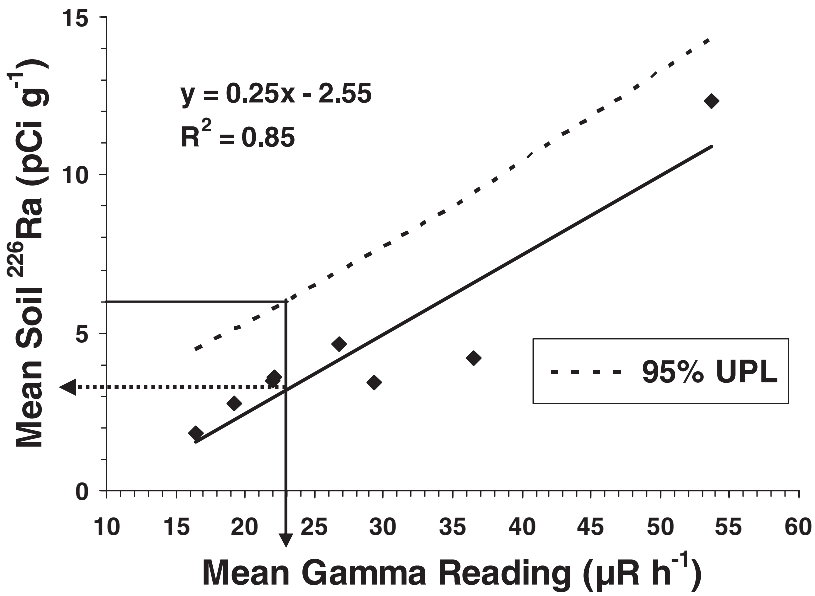

Figure 5. Gamma/^{226}Ra correlation results for the volume study area.

and provide a common basis of comparison for post-operational surveys. Typically, HPIC/NaI cross-calibration curves demonstrated highly significant linear relationships (Fig. 7, left). As illustrated at right in Fig. 7, the numerical difference between NaI readings and HPIC readings was proportional to the magnitude of exposure rate being measured (HPIC readings were modeled based on the regression equation shown at left in Fig. 7, and using a range of hypothetical NaI readings as the independent variable).

An example map of kriged HPIC equivalent gamma exposure rate survey data for a proposed ISR site in Wyoming is shown in Fig. 8. The use of kriged survey data overlays on aerial photos can be an effective way of illustrating distributional patterns of gamma exposure rates or soil ^{226}Ra concentrations in relation to certain geomorphic features. Note that the lowest gamma exposure rates at the site shown in Fig. 8 tend to coincide with drainage channel basins. Areas of higher gamma readings tend to coincide with areas of higher topographical relief such as ridges or hill tops.

For these proposed ISR sites, cases of apparent spatial relationships between geomorphic features and baseline gamma exposure rates are likely related to erosional and depositional processes that may expose elevated deposits of terrestrial radionuclide concentrations at the surface, bury such deposits, or gradually transport elevated materials off site. Sometimes, transitions between areas of consistently higher and lower gamma exposure rates are relatively abrupt. Such transitions can occasionally be associated with visible features like changes in slope, rock type, and soil color or texture (Fig. 9). In other cases, there are no obvious features associated with areas of higher or lower readings or with transition zones.

With respect to gamma-based estimates of baseline ^{226}Ra concentrations in surface soils at proposed ISR sites, conservative estimation using statistical prediction limits on correlations was not relevant. Instead, actual regression equations from correlation plot data were used to provide the average or "best" statistical estimates of soil ^{226}Ra concentrations based on the gamma survey data.

Relative to the Colorado mill site surveys, correlation plot measurements for proposed ISR sites in Wyoming tended to demonstrate stronger statistical relationships between gamma readings and soil ^{226}Ra soil concentrations. In general, fewer cases of unusually low ^{226}Ra concentrations in areas of high gamma readings were observed.

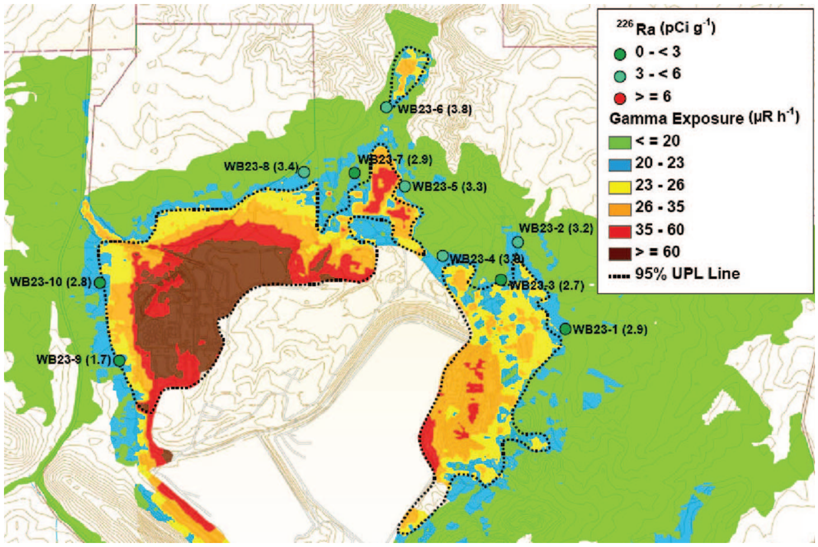

Figure 6. Gamma survey results for the volume study area showing approximate regions with gamma readings above and below 23 μR h^{-1}, the gamma value with a 95% statistical probability of compliance with the ^{226}Ra cleanup criterion. Confirmatory soil sampling locations and annotated ^{226}Ra results (pCi g^{-1}, in parentheses) are also shown.

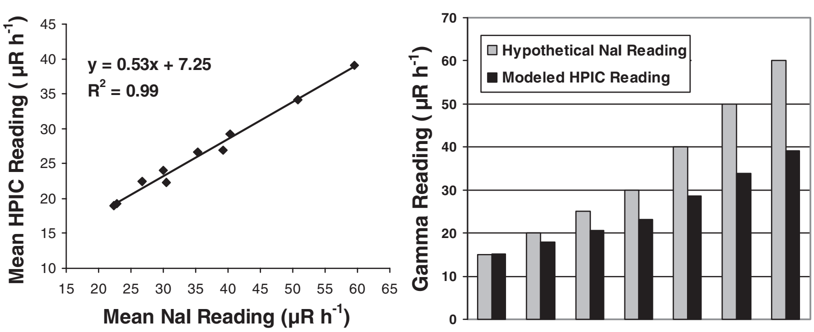

Figure 7. Example HPIC/NaI cross-calibration curve (left) and corresponding modeled differences between NaI and HPIC readings (right) for a proposed ISR uranium site in Wyoming.

Again, such cases are likely related to gamma shine from adjacent areas and/or subsurface sources and those data were not used for the correlations.

Another notable feature of correlation results for the Wyoming ISR sites was that the data sometimes demonstrated nonlinear characteristics (Fig. 10). This raised the possibility that use of nonlinear "best fit" models in such cases could reduce potential prediction error for soil ^{226}Ra estimates based on gamma survey data.

Reasons for apparent nonlinearity observed in correlation data from some sites appear to be related to a kind of threshold effect in the relationship between detector response and the ratio of terrestrial to cosmic sources of gamma radiation. Cosmic sources can dominate detector response until terrestrial sources become concentrated enough to have significant correlative impact on readings. This idea is consistent with a comparison of observed correlation data between various sites.

Sites with higher minimum measured soil ^{226}Ra concentrations (e.g., 4–5 pCi g^{-1}) tended to exhibit linear correlation characteristics. Sites with lower minimum measured soil ^{226}Ra concentrations (e.g., 1 pCi g^{-1}) tended to exhibit nonlinear correlation characteristics, with relatively little change in ^{226}Ra concentration over the lower range of measured gamma values until a kind of threshold is reached and ^{226}Ra begins to increase with increasing gamma readings.

Reasons for this threshold effect are likely partially related to those mentioned in the earlier discussion of differences between NaI detector and HPIC readings. At a given site, cosmic sources are relatively constant and variations in NaI readings are due to variations in terrestrial radionuclide concentrations. When terrestrial ^{226}Ra sources begin to exceed about 1 pCi g^{-1} at these sites, a greater percentage of lower energy photons interact with the NaI detectors and relative response appears to cross a threshold between underprediction and overprediction of true exposure rates. As gamma readings increase above this threshold, a more linear correlative relationship between ^{226}Ra and gamma readings becomes apparent.

Despite the potential explanations above for an apparent threshold effect, both linear and nonlinear models were used to convert gamma survey data to estimates of ^{226}Ra concentrations in surface soils. Both data sets were kriged and mapped to help assess which model at each site is best supported by subsequent radial grid soil sampling results (U.S. NRC Regulatory Guide 4.14 soil sampling protocols are also being implemented as part of baseline studies at these sites). This type of confirmation sampling can also help to assess the representativeness of correlation plot sampling locations.

Spatial differences in the distributions of estimated soil ^{226}Ra concentrations based on linear and nonlinear models for a proposed ISR site are shown in Fig. 11. In terms of remedial issues, the

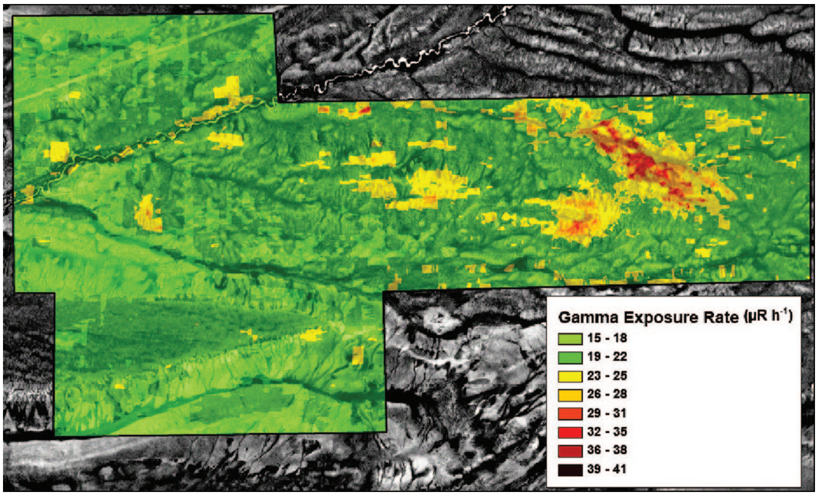

Figure 8. Kriged 1 m HPIC equivalent gamma survey map of a proposed 1,618 hectare (4,000 acre) ISR uranium project area in Wyoming.

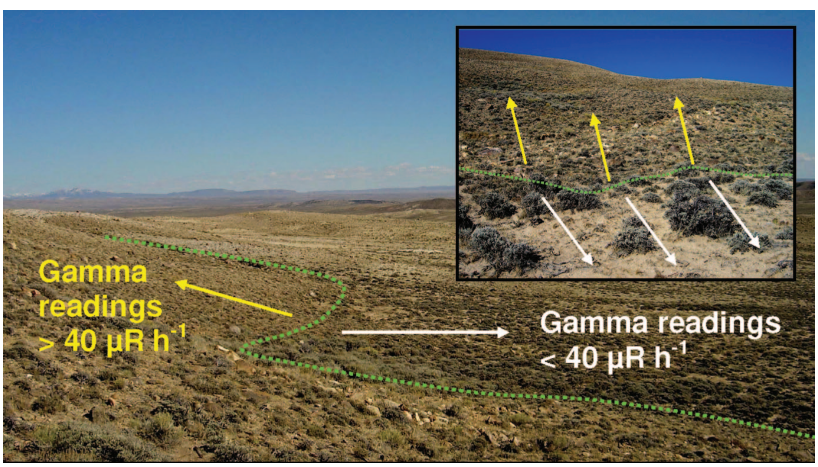

Figure 9. Visible, geomorphic boundary delineating abrupt transition in gamma exposure rates.

implications of which predictive model is used are quite apparent at this particular site. Regardless of what model is ultimately used, it is unlikely that areas with elevated radiological baseline conditions would be adequately characterized based solely on grid sampling as indicated by currently applicable regulatory guidelines. These elevated areas are generally downwind of the proposed plant location and often fall just outside of respective radial grid sampling locations as indicated in Regulatory Guide 4.14. This observation highlights a key advantage of using GPS-based, high-density gamma scanning and correlation techniques to characterize entire sites.

Available data to date have enabled one proposed ISR site to be evaluated with respect to which type of predictive model is most strongly supported by confirmatory soil sampling results. Overall, a nonlinear model predicted soil ^{226}Ra concentrations at this site more accurately than a linear model. Nonlinear modeling estimates and actual soil sampling results are shown in Fig. 12. Optimal spatial detail at individual sampling locations is not resolved in this figure but locally enlarged views of the data indicate that

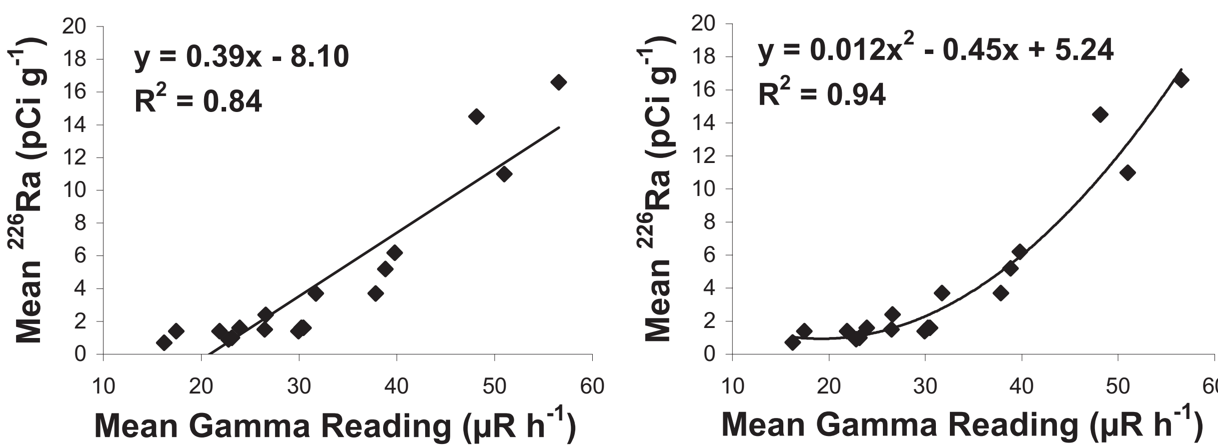

Figure 10. Comparison of linear (left) and nonlinear (right) models fitted to combined gamma/^{226}Ra correlation plot data from two nearby ISR sites in Wyoming.

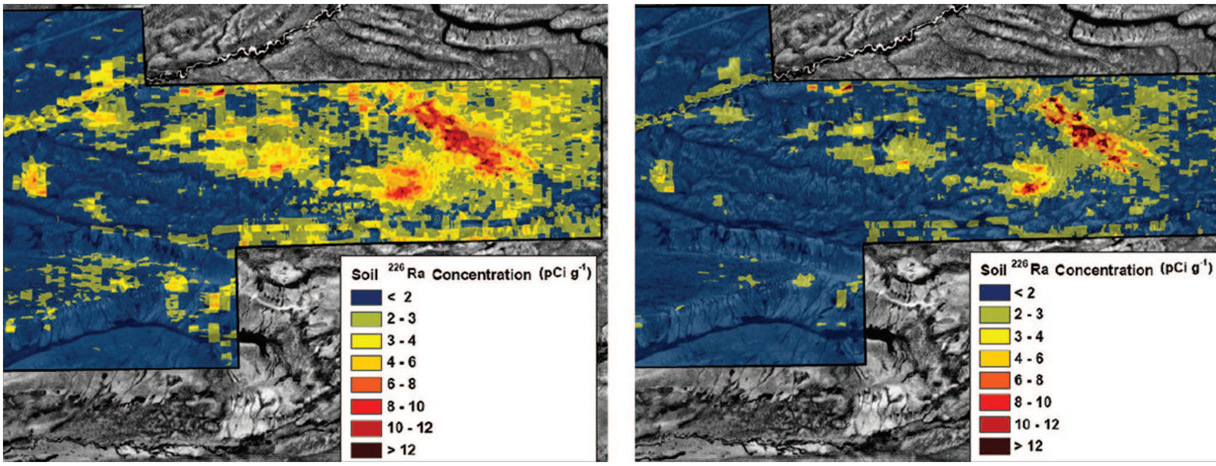

Figure 11. Comparison of continuously estimated soil ^{226}Ra concentrations based on linear (left) and nonlinear (right) models fitted to gamma/^{226}Ra correlation plot data for a proposed ISR site in Wyoming.

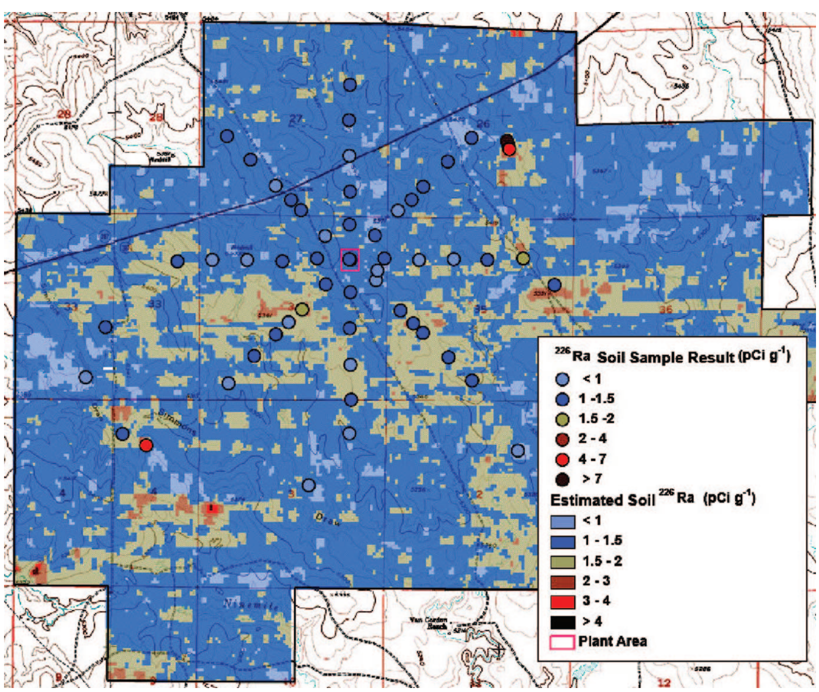

Figure 12. Comparison of continuous estimates of soil ^{226}Ra concentrations predicted with a nonlinear model vs. actual soil sampling results at a proposed ISR site in Wyoming.

differences between modeled and measured values are generally less than ± 1 pCi g^{-1}, not greatly different from analytical uncertainties reported by the laboratory (which ranged up to ± 0.6 pCi g^{-1}). As mentioned, however, not all sites demonstrate nonlinear correlation characteristics and correlation data need to be adequately representative to have the best chance of choosing the appropriate model.

Finally, caution must be exercised with respect to extrapolating predictive models beyond the range of measured correlation data. In these studies, prediction data outside this range were sometimes artificially truncated to avoid such extrapolation, depending on the nature of the correlation and respective potential to significantly impact kriging results. In all cases, the validity of gamma-based estimates of ^{226}Ra are limited to the range of measured correlation data and beyond that range only general qualitative statements such as "less than" or "greater than" are justified. Furthermore, limitations mentioned earlier for uranium mill site estimates also apply to estimates developed for the proposed ISR uranium project area studies.

CONCLUSION

Although gamma/^{226}Ra correlation techniques are not new, the GPS-based scanning systems used for these projects involve more recent technology that can quickly and efficiently collect large amounts of information about the spatial distribution of terrestrial sources of gamma radiation across extensive areas. Mapped data presentations and confirmatory soil sampling results suggest that high-density gamma scanning combined with correlation techniques was an effective overall survey approach for these projects and represents general improvement in characterization capabilities for large sites.

Limitations on correlation-based ^{226}Ra estimates include potential prediction error in areas with significant heterogeneity in soil ^{226}Ra concentrations, gamma shine effects, or areas beyond the range of measured correlation data. Poor correlation results can result from insufficient sample size, inadequate representativeness of correlation plot locations, soil ^{226}Ra heterogeneity, or gamma shine. Nonlinearity in correlation characteristics can result at sites where pervasively low ^{226}Ra concentrations are reflected in the measured correlation data, possibly due to a threshold effect between detector response and the ratio of terrestrial to cosmic gamma sources.

Integrating a full range of GIS spatial analysis capabilities into this radiological survey approach allows various and sometimes subtle types of information contained in the survey data to be successfully identified, interpreted, and assessed with respect to project objectives. Kriging results displayed on topographical contour maps or aerial photos can provide detailed and highly informative characterizations of various radiological parameters across entire sites. This information can have important implications with respect to site decommissioning and license termination.

REFERENCES

Johnson JA, Meyer HR, Vidyasagar M. Characterization of surface soils at a former uranium mill. Health Phys 90(Suppl 1):S29–S32; 2006.

Ludlum Measurements, Inc. Energy response curve for Ludlum Model 44-10 NaI detector [online]. 2006. Available at: http://www.ludlums.com/RespCurvHtm/RC_M44-10.htm. Accessed 30 August 2008.

Meyer R, Shields M, Green S. A GPS-based system for preliminary or remedial action gamma scanning. In: Proceedings of the American Nuclear Society Topical Meeting on Decommissioning, Decontamination, & Reutilization, Denver, Colorado, 7–11 August 2005. La Grange Park, IL; ANS; 2005a: 131–134.

Meyer R, Shields M, Green S, Johnson J. A GPS-based system for radium/uranium contamination gamma scanning. In: Broder J, Merkel AH, eds. Uranium mining and hydrogeology IV. Uranium in the Environment, conference proceedings, 11–16 September 2005. Freiberg, Germany: Technische Universitat Bergakademie Freiberg (TU BAF); 2005b: 751–756.

U.S. Nuclear Regulatory Commission. Radiological effluent and environmental monitoring at uranium mills, Revision 1. Washington, DC: Nuclear Regulatory Commission Office of Standards Development; Regulatory Guide 4.14; 1980.

U.S. Nuclear Regulatory Commission. Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), Revision 1. Washington, DC: U.S. NRC; NUREG 1575; 2000.

Appendix C

Johnson et al. Study (2006)

Experiences are presented for characterization of soils at a former uranium mill.

Characterization of Surface Soils at a Former Uranium Mill

*J. A. Johnson, H. R. Meyer, and M. Vidyasagar**

Abstract: *Dawn Mining Company operated a uranium mill in Stevens County, Washington, from 1957 to 1982, to process ore from the Midnite Mine, and from 1992 through 2000, to extract uranium from mine water treatment sludge. The mill was permanently shut down in 2001 when the Dawn Mining Company radioactive materials license was amended to allow direct disposal of water treatment sludge to a tailings disposal area at the mill. The mill building was demolished in 2003. Site soil characterization took place in 2004. Soil cleanup is ongoing. Contaminated soils on the site were characterized using a GPS-based gamma scanning system. A correlation between shielded gamma exposure rate and concentration of* ^{226}*Ra in surface soils was developed. Subsurface soils were sampled using backhoe trenches. This system proved efficient and accurate in guiding development of the remedial action planning for the site and subsequent soil cleanup. Health Phys. 90(Supplement 1):S29–S32; 2006*

Key words: *operational topics; tailings, uranium; sampling; gamma radiation*

INTRODUCTION

Dawn Mining Company (DMC) operated a uranium mill in Stevens County, Washington, from 1957 to 1982 to process ore from the Midnite Mine. The mine ceased operating in 1982. The DMC mill processed water treatment sludge from the mine to recover uranium from 1992 to 2001. The mill was permanently shut down in 2001 when the DMC radioactive materials license was amended to allow direct disposal of sludge to a tailings disposal area at the mill. The mill building was demolished in 2003. Site soil characterization took place in 2004. Cleanup of contaminated soils based on the characterization data is ongoing. Direct disposal of water treatment plant sludge from the Midnite Mine will continue to the former impoundment for several more years. Final site cleanup, closure of the impoundments, license termination, and transfer to the Department of Energy for long-term surveillance will take place after DMC ceases sludge disposal.

With the deployment of the U.S. Global Positioning System (GPS) satellite constellation, a number of new approaches to surveying large sites became possible. Development of small, inexpensive, handheld GPS receivers has since made such approaches more feasible, user friendly, and cost-efficient. Gamma detection units may be linked with GPS and computer systems to allow the development of very high density mapped shielded gamma exposure rate data sets. These data are useful to identify areas of soil contamination at sites including uranium mills and mines, other mine facilities (copper, vanadium, and rare earth) with elevated naturally-occurring radionuclide concentrations, and facilities with other contamination signatures, including those resulting from accidental releases. The GPS-based detection systems may also be used to direct remedial action at such sites and may become especially valuable when providing a record of the final radiological status of a remediated site.

We used a GPS-based gamma scanning technique during preoperational site surveys at a large in-situ leach uranium mine being developed in Central Asia. Since that time, the system has been enhanced and used at a variety of radium/uranium-contaminated sites in the western U.S. Under optimum conditions, data acquisition occurs at a rate of seven acres h^{-1}. Such high-speed input allows 100% coverage in a short time period, providing color-coded output defining shielded gamma exposure rates for the entire site. The system is described in detail in Meyer et al. (2005). The system currently in use also allows for immediate download-

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ing of the data and color-coded display on a site base map.

ELEMENTS OF THE SOIL CHARACTERIZATION PLAN

The potentially contaminated portion of the DMC mill site was completely scanned for gamma exposure using a shielded NaI detector. The data were entered into a GIS database. Color-coded maps of the initial results were printed out and examined to allow for selection of soil sample locations to be used for correlating shielded gamma exposure with ^{226}Ra concentration in soil. Soil sampling grid locations (correlation grids), nominally 10 × 10 m areas, were identified such that the range of shielded gamma exposure rates would be likely to bracket the clean-up criteria. It is important to note that clean-up criteria are based on average soil concentrations within the correlation grid without regard to small areas of elevated concentration. That is, this is not a Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) site cleanup. Two background or reference locations were selected prior to the characterization survey based on site history and results of previous scoping surveys. Based on visual observation, the two reference areas consisted of different soil types. Subsurface samples were collected in approximately 25 areas on the site using backhoe trenches. Surface soils were sampled in the correlation grids and reference areas as described below. ^{226}Ra concentrations in soil were determined by a commercial laboratory. The measured ^{226}Ra concentrations in surface soils were correlated with the average shielded gamma exposure rates for the grids to create a data pair. A correlation equation to relate ^{226}Ra concentration in surface soil and shielded gamma exposure rate was developed. The upper 90% prediction interval at the surface soil cleanup criterion (5 pCi g^{-1} ^{226}Ra above background) was calculated. Color-coded maps were prepared showing areas where the shielded gamma exposure rate indicated that the ^{226}Ra concentration in surface soil could exceed the cleanup criterion. These data were used in conjunction with the subsurface sample concentration data to plan remedial action.

The GPS-based scanning system

The GPS-based gamma scanning equipment is described in detail elsewhere (Meyer et al. 2005). The current system, using a data storage device, either a handheld Personal Digital Assistant (PDA)/GPS unit from Garmin (Garmin International Inc., 1200 East 151st Street, Olathe, KS 66062-3426) or a pen-top computer with a separate Garmin GPS unit, coupled to a Ludlum (Ludlum Measurements, Inc., P.O. Box 810, Sweetwater, TX 79556) 2-inch sodium iodide detector/data logger unit, is easily hand-carried, or multiple systems may be run simultaneously from a four-wheel-drive platform [all-terrain vehicle (ATV) or truck]. Data units, each consisting of latitude, longitude, elevation, date, time, and shielded gamma exposure rate, are recorded at 1-s intervals with a transit speed of approximately 1 m s^{-1}. System resolution is thus 1 m. System surface location accuracy is limited by acquisition conditions, but is typically 3–5 m in the U.S. using Wide Area Augmentation System (WAAS)-enabled GPS units. Precision, defined here as the ability to relocate a specific point onsite, is typically 1–2 m, which is adequate for remedial activities involving heavy equipment to remove contaminated soil.

All gamma measurements using this system are taken using vendor-calibrated scintillator systems with digital outputs linked to the GPS/PDA or pen-top computer data collection device. A key aspect of system enhancement has been the linking of GPS, PDA, or pen-top computer with gamma detector units via proprietary software. Because the system is simple to set up and operate, it was employed to characterize the DMC site. It will also be used to perform follow-up scans when specific areas are subjected to earth removal.

The system used at DMC consisted of two ATV-mounted shielded NaI detectors and a single backpack-mounted system. Most of the site was surveyed using the ATV; however, where site conditions precluded safe operation of the ATV, the backpack mounted system was used. The ATV or truck with multiple systems, spaced approximately 2 m apart, allows for more rapid coverage of a site even though the rate of travel is the same for the backpack-mounted system and the ATV- or truck-mounted systems. The truck-mounted system has been used at a site in Texas.

Correlation grids

Developing a correlation between actual soil radionuclide concentrations and measured shielded gamma exposure rates requires careful attention to the location selection and sample collection procedure. In particular, relatively uniform exposure rate areas (typically 10 × 10 m) must be identified prior to soil sampling. Between 10 and 20 aliquots of soil, typically taken to a 15 cm depth, are composited from each such correlation grid and sent to a qualified laboratory for ^{226}Ra concentration analysis. Ten samples per grid were deemed adequate for the DMC site correlation grids. The DMC samples were dried and homogenized prior to analysis. The correlation grid is carefully scanned using either a backpack or vehicle-mounted GPS/gamma scan setup. Alternatively, the average shielded gamma exposure rate for the correlation grid can be determined from scan data obtained previously. For the DMC site characterization, candidate areas for correlation grids were selected from scan maps. The suitability of the correlation location was verified on the ground by the sampling technician prior to final grid definition.

Approximately fifty 10 × 10 m areas were delineated as correlation grids at the DMC site based on initial shielded gamma exposure rate measurements. The correlation grid locations were identified by latitude and longitude at the center point using the GPS location. The intent of selecting a variety of correlation grids was to cover the range of expected ^{226}Ra concentrations with emphasis on concentrations in the range of the surface soil cleanup criterion, i.e., below 0.3 Bq g^{-1} (10 pCi g^{-1}). Composite surface soil samples, consisting of 10 randomly selected sub-samples, were taken from each grid. Energy Laboratories, Inc., analyzed the samples for ^{226}Ra by gamma spectroscopy after full ingrowth of ^{222}Rn and its short-lived decay products.

Background (reference) areas

Two reference areas were selected at DMC based on prior scoping surveys and site history. The reference areas were approved by the Washington Department of Health (WDOH) prior to final selection. Each reference area was scanned using the ATV-mounted scanning system. Average shielded exposure rates and soil concentrations for the reference areas are shown in Table 1.

Table 1. Reference area shielded gamma exposure rates and ^{226}Ra concentrations in surface soil.

Reference area	Mean shielded gamma exposure (μR h^{-1})	Mean ^{226}Ra concentration in soil (Bq g^{-1})
1 (NW)	5.28	3.5×10^{-2}
2 (SE)	7.56	5.1×10^{-2}

RESULTS

Gamma scanning

Using the GPS-based gamma scanning system, complete scanning of the mill site resulted in collection of approximately 600,000 individual data units, with each data unit consisting of latitude, longitude, elevation, date, time of day, and shielded gamma exposure rate. The shielded gamma exposure rates were mapped and color-coded depending on the magnitude of the reading. Each dot on the map indicated the coverage for the individual measurement (assumed to be a circle with a 1-m radius). A gray-scale representation of scanning results from the mill site itself is shown in Fig. 1. Darker colors represent higher exposure rates.

In order to ensure that the gamma scan results were reproducible, three quality control measurements were performed on each instrument or system each day scanning was performed. The reproducibility of gamma detector measurements was evaluated each day using a check source. Background measurements were also taken in the same location with each detector each day of use. A 100-m^2 control grid was established to evaluate reproducibility of the systems. The control grid was scanned using the ATV- and backpack-mounted systems at least once a day during use. Control charts were maintained for each instrument and each type of measurement. No significant problems were identified.

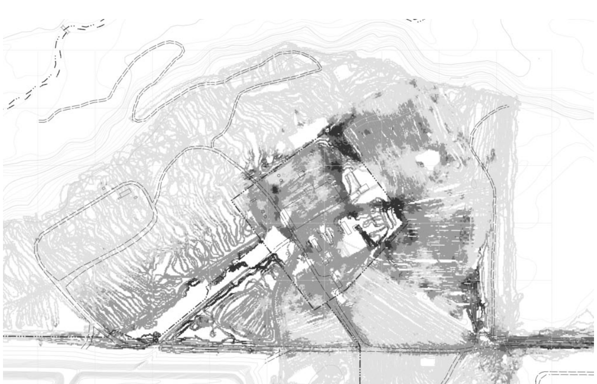


Figure 1. Gray-scale gamma scanning results for the Dawn Mining Company uranium millsite. In field use, the map is color-coded according to gamma exposure rate.

Correlation results

Concentration of ^{226}Ra in surface soil was well correlated with gamma exposure rate as measured with a shielded crystal as shown in Fig. 2. The correlation coefficient of 0.81, derived for and applicable to the population of observations with ^{226}Ra concentrations less than 0.37 Bq g^{-1}, was highly significant ($p < 0.05$). The 90% prediction interval on the 5 pCi g^{-1} ^{226}Ra concentration release limit corresponds to a shielded gamma exposure rate of 12.5 μR h^{-1} and was calculated using the following equation (Kleinbaum and Kupper 1979):

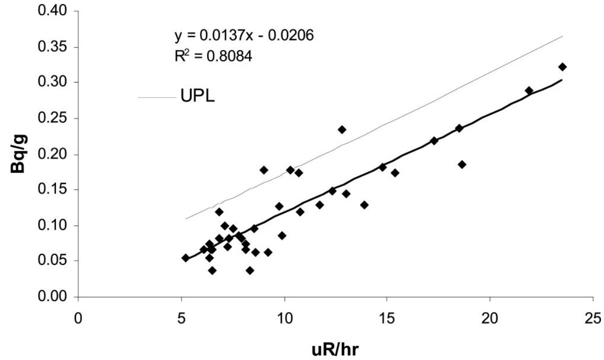


Figure 2. Regression and upper prediction limit for ^{226}Ra concentration in soil as a function of gamma exposure with shielded detector mounted on an ATV.

$$Y_{up190} = \bar{Y} + \hat{\beta}_o(x_o - \bar{x}) + (t_{n-2,1-\alpha/2})S_{y|x}\sqrt{1 + \frac{1}{n} + \frac{(x_o - \bar{x})^2}{(n-1)S_x^{\ 2}}}\ , \qquad (1)$$

where:

Y_{up90} = 90% upper prediction interval for ^{226}Ra concentration at a shielded gamma exposure rate of 12.5 μR h^{-1};

$\bar{Y}$ = average ^{226}Ra concentration;

$\hat{\beta}_o$ = estimated slope of the regression line;

x_o = 12.5 μR h^{-1};

$\bar{x}$ = average shielded exposure rate;

$t_{n-2,1-\alpha/2}$ = t statistic for $n - 2$ observations;

= 1.69 for 39 observations;

$S_{y|x}$ = population variance for Y dependent on X;

$S_x^{\ 2}$ = variance of the exposure rates;

n = number of data points;

$S^2_{y|x}$ = $\frac{n-1}{n-2}(Sy^2 - \hat{B}^2 S_x^{\ 2})$; and

Y_{up190} = 0.21.

Based on the correlation and the 90% upper prediction limit, a cut-off shielded exposure rate of 12.5 μR h^{-1} was established for both the ATV- and backpack-mounted systems. This provided for an error rate of less than 5%. That is, at the upper 90% prediction limit, the probability would be less than 5% that the soil ^{226}Ra concentration in any area with a shielded exposure rate less than 12.5 μR h^{-1} would exceed the cleanup criterion. Subsequent, more rigorous statistical analysis by the WDOH confirmed the cut-off exposure rate.

The average ^{226}Ra concentrations in the two reference areas with two different soil types were 5.0 $\times$ 10^{-2} Bq g^{-1} (1.35 pC g^{-1}) and 3.5 $\times$ 10^{-2} Bq g^{-1} (0.95 pCi g^{-1}). In practical terms, the use of 12.5 μR h^{-1} as a cut-off ensures that soil with a ^{226}Ra concentration in excess of 0.21 Bq g^{-1} (5.66 pCi g^{-1}), including background, would be removed during remedial action. For the average background at the site of 4.3 $\times$ 10^{-2} Bq g^{-1} (1.16 pCi g^{-1}), this means that there is only a 5% chance that any soils in excess of 1.7 $\times$ 10^{-1} Bq g^{-1} (4.50 pCi g^{-1}) above background would be left behind following remedial action if the site is cleaned up to meet the 12.5 μR h^{-1} shielded gamma exposure rate cut-off level.

SUMMARY AND CONCLUSION

Use of the GPS-linked gamma scanning system provides an efficient method of characterizing a site that is slated for remedial action. The visual display is well suited to decision-making and selection of sample locations. If scanning of removal areas is conducted following remedial action, the visual display gives a clear picture that the site has been well characterized and cleaned up.

The correlation grids provided a defensible basis for characterizing surface soils based on shielded gamma measurements. Use of the upper prediction limit on the correlation ensured that the probability of mischaracterizing an area as meeting the cleanup criterion (0.185 Bq g^{-1} or 5 pCi g^{-1} above background) when it did not was less than 5%.

REFERENCES

Kleinbaum DG, Kupper LL. Applied regression analysis and other multivariable methods. Boston: PWS Publishers; 1978.

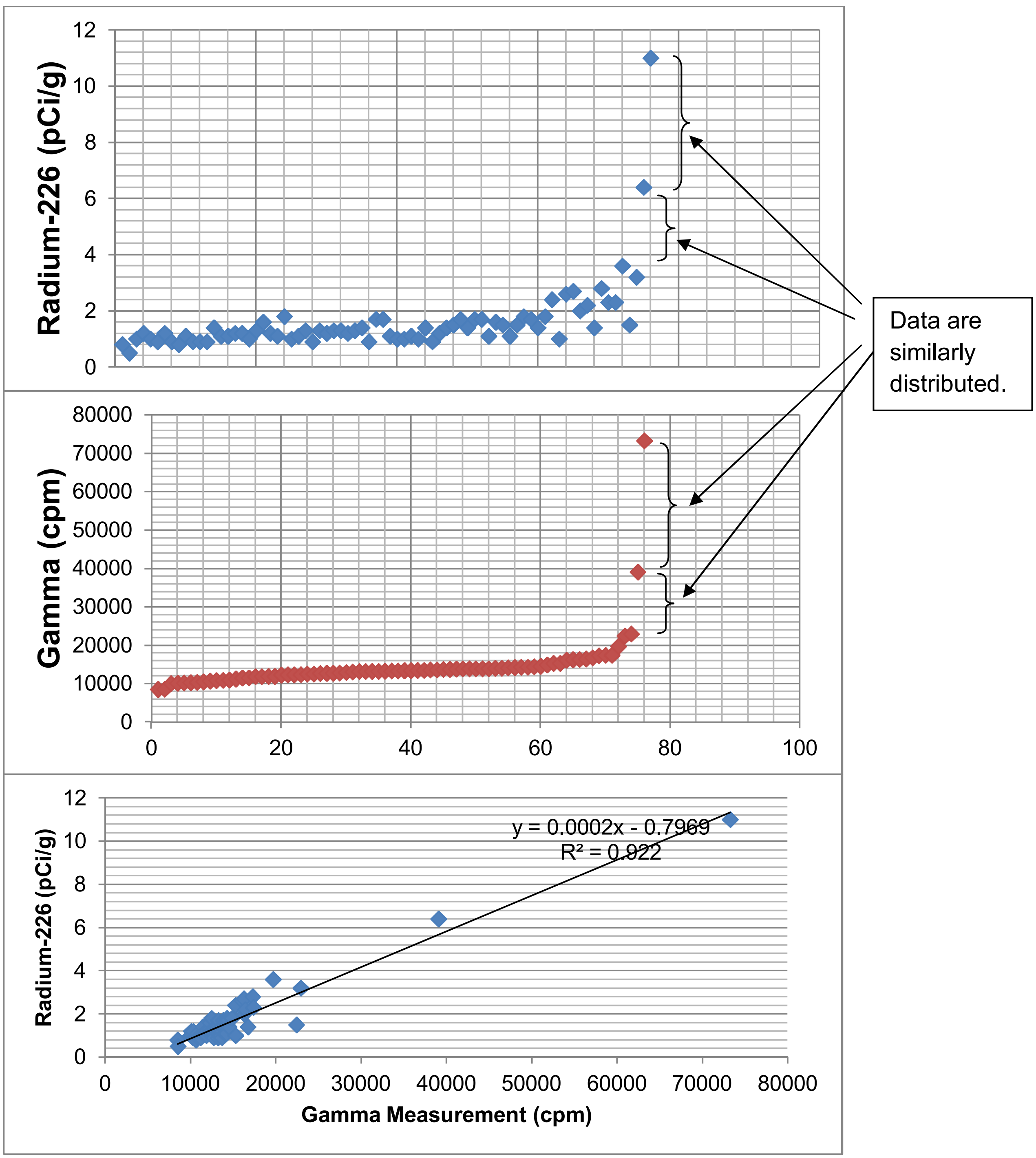
Meyer HR, Shields M, Green S. A GPS-based system for radium contamination gamma scanning. In: Proceedings of ANS Topical Meeting on Decommissioning, Decontamination, and Reutilization, Denver, Colorado, August 7–11, 2005. La Grange Park, IL: American Nuclear Society; 2005.

Appendix D

Additional Evaluation of SMA-B29, SMA-B27 and SMA-B30

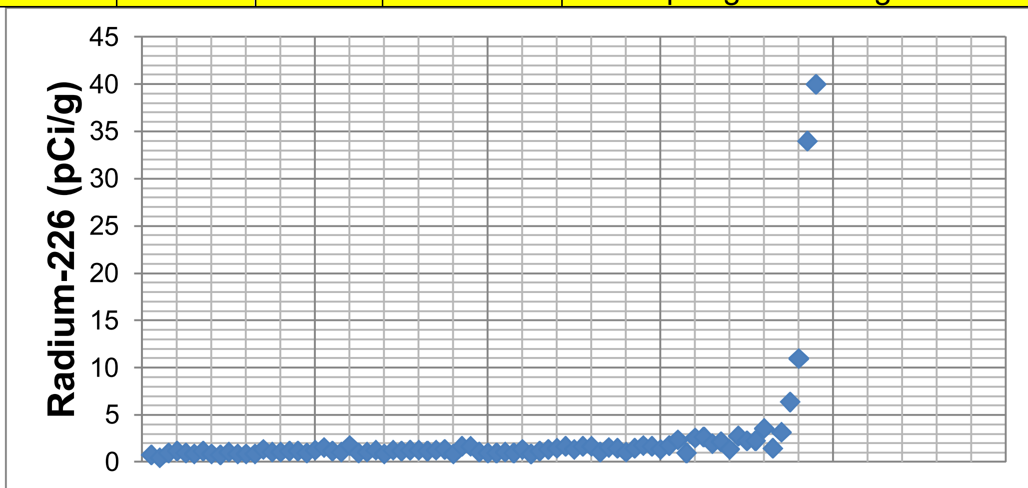
<u>Option 1: Without SMA-B29, SMA-B27, SMA-B30, and RFA-B21A</u>

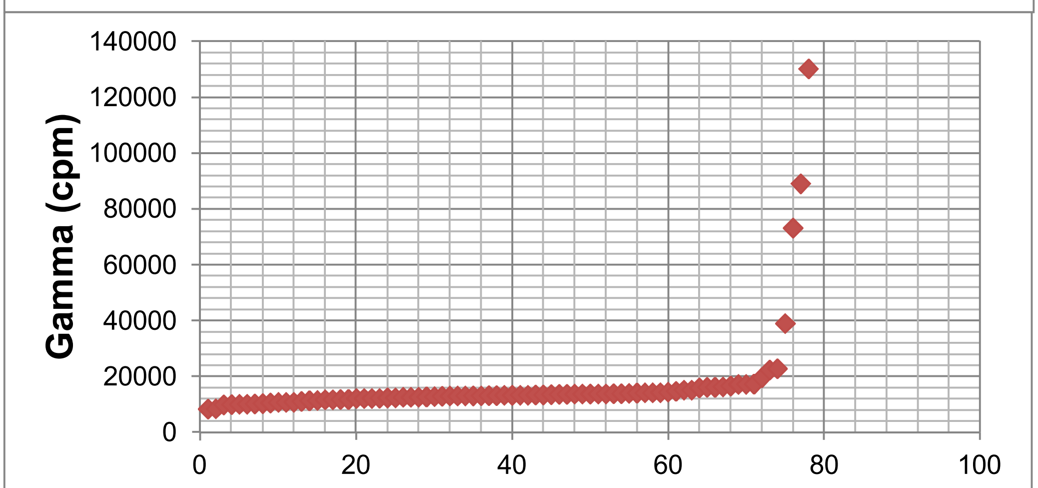
R	m	b	R^2	Mean *e*	Notes
0.96	0.0002	-0.7969	0.9220	-0.508	Similar spread of gamma and radium-226 data. Over-predicts by 0.508 pCi/g on average. Good R^2.

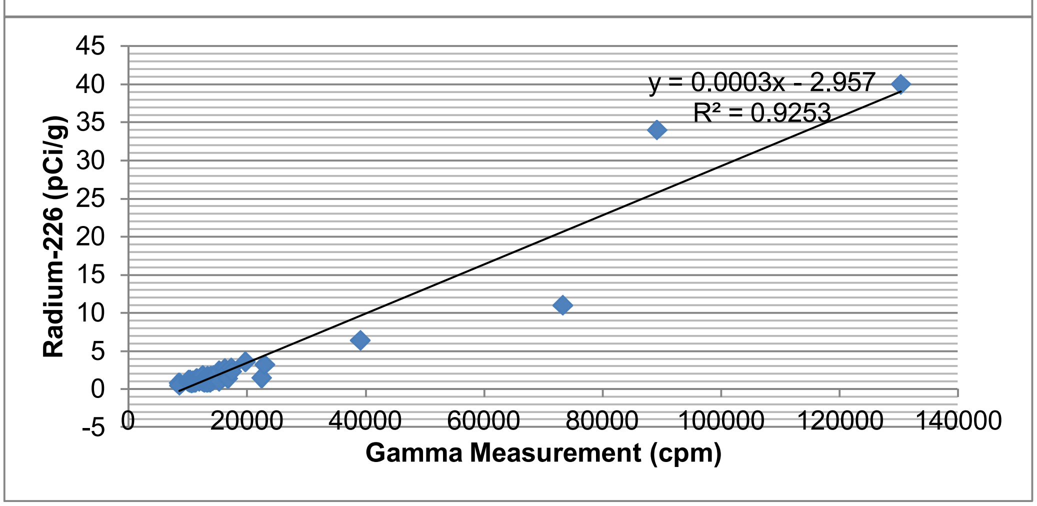


Option 2: Without SMA-B29 and RFA-B21A

R	m	b	R^2	Mean *e*	Notes
0.96	0.0003	-2.957	0.9253	0.381	Uneven spread. Under-predicts by 0.381 pCi/g on average. Good R^2.

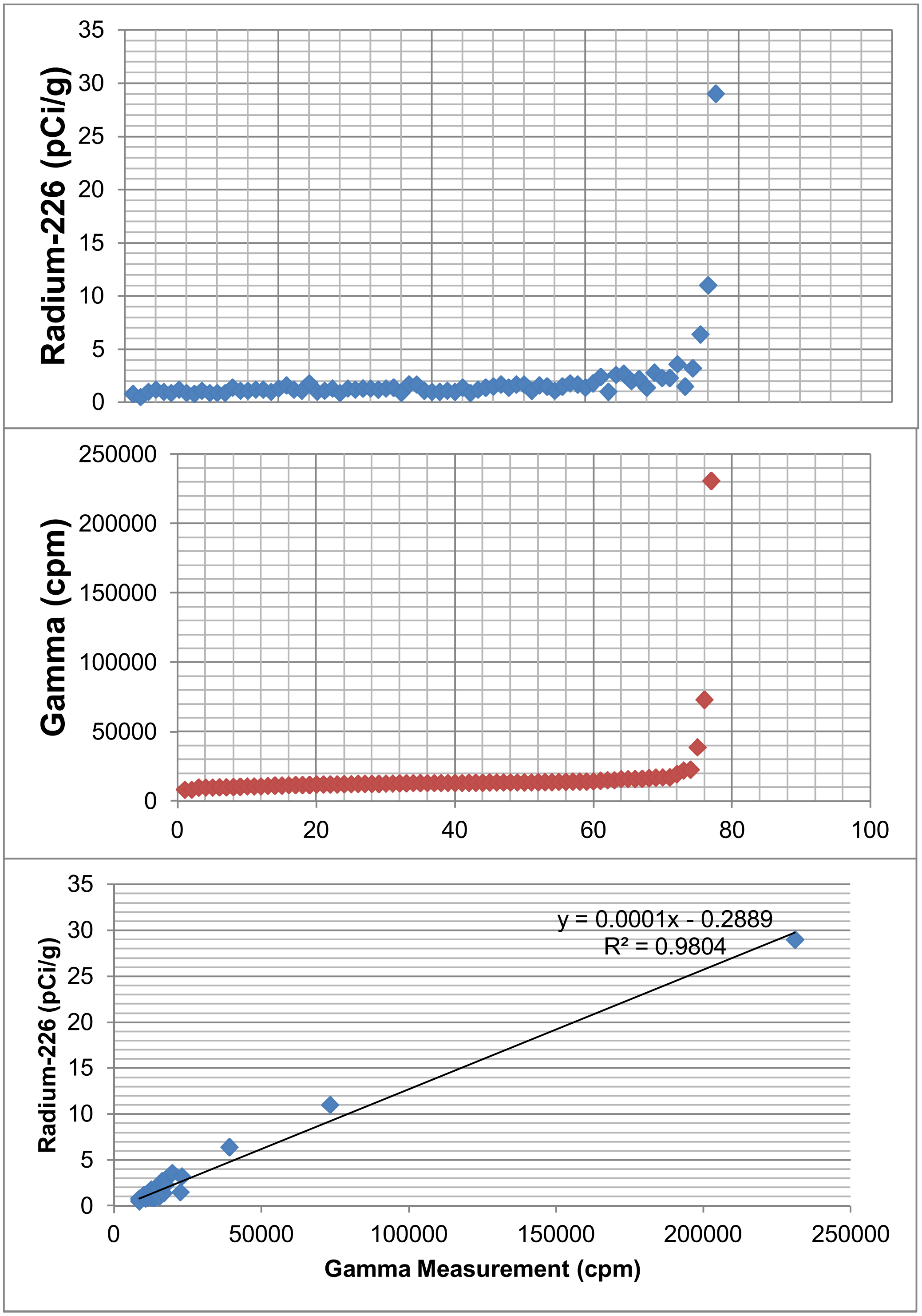






Option 3: Without SMA-27, SMA-B30 and RFA-B21A

R	m	b	R^2	Mean *e*	Notes
0.99	0.0001	-0.2889	0.9804	0.526	Even spread. Under-predicts by 0.526 pCi/g on average. Good R^2.



The residual, *e*, is defined as the difference between the observed value of the dependent variable (*y*) and the predicted value ($\hat{y}$). The equation is $e = y - \hat{y}$. Each data point has one residual. Radium-226 residuals for Options 1, 2 and 3 are plotted in Figure D-1 below.

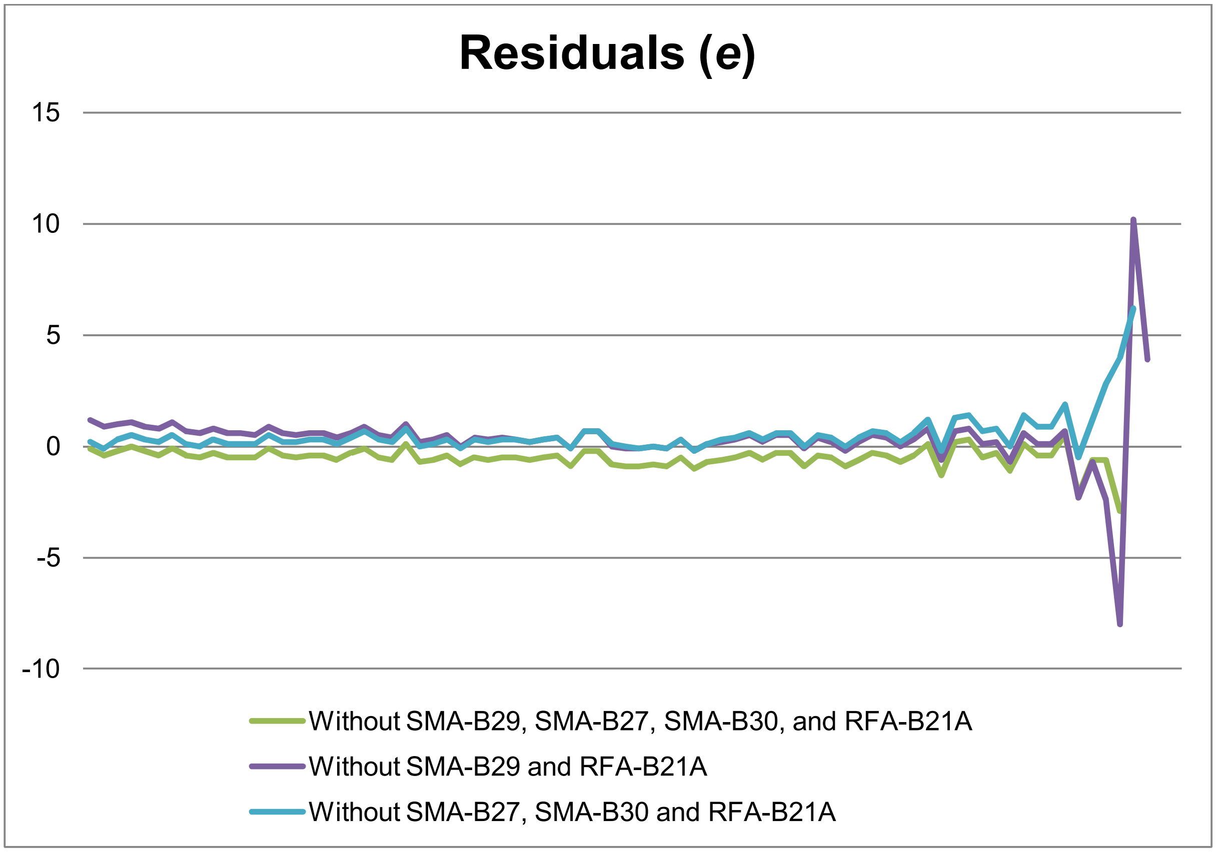


Figure D-1. Radium-226 Residuals for Options 1, 2 and 3

Option 1: Without SMA-B29, SMA-B27, SMA-B30, and RFA-B21A, the model equation from 3.2 to 11 pCi/g over-predicts radium-226 an average of 1.4 pCi/g.

y	$\hat{y}$	*e*
3.2	3.8	-0.6
6.4	7.0	-0.6
11	13.9	-2.9
Mean		-1.4

Option 2: Without SMA-B29 and RFA-B21A, the model equation from 3.2 to 11 pCi/g over-predicts radium-226 an average of 3.7 pCi/g.

y	$\hat{y}$	e
3.2	3.9	-0.7
6.4	8.8	-2.4
11	19.0	-8.0
Mean		-3.7

Option 3: Without SMA-B27, SMA-B30 and RFA-B21A, the model equation from 3.2 to 11 pCi/g under-predicts radium-226 an average of 2.7 pCi/g.

y	$\hat{y}$	e
3.2	2.0	1.2
6.4	3.6	2.8
11	7.0	4.0
Mean		2.7

The first option (without SMA-B29, SMA-B27, SMA-B30, and RFA-B21A) was selected over the second option (without SMA-B29 and RFA-B21A) because the second option increases the residual, *e*, particularly in the higher range. In addition, data are distributed similarly for the first option, but not for the second option.

The first option was selected over the third option because the first option over-predicts radium-226 concentrations by a smaller amount than the third equation under-predicts radium-226 concentrations particularly at lower concentrations. The third option is strong otherwise. Data are distributed similarly and the R^2 is high.