

DRAFT
Applicability of X-Ray Fluorescence
(XRF)
For Rattlesnake Creek

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1 INTRODUCTION

A final status survey plan was developed for the Rattlesnake Creek portion of the Ashland sites and will be used to determine whether residual radionuclide concentrations comply with cleanup criteria as defined in *Record of Decision for the Ashland 1 (including Seaway Area D) and Ashland 2 Sites, Tonawanda, New York* (ROD) (U.S. Army Corps of Engineers [USACE] 1998) and associated *Explanation of Significant Differences for the Rattlesnake Creek Portion of the Ashland Sites, Tonawanda, New York* (ESD) (USACE 2004a). The *Rattlesnake Creek Final Status Survey Plan, Tonawanda, New York* (USACE 2004b) was prepared consistent with the guidance found in the *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)* (U.S. Environmental Protection Agency [EPA] 2000). MARSSIM uses two activity concentration cleanup requirements known as derived concentration guideline levels (DCGLs). They are derived from dose or risk goals. The first, the DCGL_w, refers to a wide area average that must be met over areas the size of a survey unit. The second, the DCGL_{emc}, refers to an elevated measurement comparison that addresses more localized elevated areas that may significantly exceed the DCGL_w at specific locations but not when averaged over a survey unit. DCGLs are developed so that post-remediation residual activity concentrations are consistent with the dose or risk goals set for the site. DCGLs for Rattlesnake Creek were developed for the following three principal radionuclides of concern, radium-226, thorium-230, and uranium-238 (USACE 2004b). Because there are multiple contaminants of concern in Rattlesnake Creek soils, cleanup requirements are implemented through the use of a sum of ratios (SOR) calculation.

An analysis of the historical data from the Rattlesnake Creek area indicates that thorium-230 is the primary contaminant of concern from the SOR and final status survey or closure perspective (USACE 2000b). There is no evidence that uranium-238 exceeds the DCGLs defined for the site, and only very limited evidence that radium-226 exceeds the DCGLs in a few isolated locations. The primary remediation driver for Rattlesnake Creek and contributor to elevated SOR values is thorium-230. The primary requirement of concern, based on a review of historical data, is the 100-square meters (m²) DCGL_{emc} criterion of 14 picocuries/gram (pCi/g) for thorium-230. This requirement applies to each 15-centimeter (cm) (six-inch [in.]) core interval of soil/sediment extending down to a depth of at least 1 m (3 feet [ft]). On the basis of results from field survey activities, the vertical study boundary may be adjusted to a depth greater than 1 m (3 ft). At Rattlesnake Creek, it is not possible to directly detect and quantify thorium-230 with in-field instrumentation at the DCGL levels. At the Ashland 1 and 2 sites, sufficient radium-226 was commingled with thorium-230 to use radium-226 as a surrogate for thorium-230 and to allow detection with gross gamma sensors. For Ashland 1 and Ashland 2, gamma walkover surveys proved extremely effective in demonstrating DCGL compliance during the final status survey process, and in providing information during the pre-design and remediation efforts that could be used to delineate excavation footprints.

Although the contamination found in the Rattlesnake Creek soils/sediments originated from contaminated residuals disposed of on the Ashland 1 and 2 properties, there are two key differences that complicate the characterization and closure process for

Rattlesnake Creek. The first is that a significant portion of the contamination is buried beneath more recent, clean sediments, making gamma walkover surveys ineffective. The second is that the radium-226 activity concentrations are also much lower, making the use of radium-226 as a reliable surrogate for the presence of thorium-230 problematic.

Thorium-230 is also commingled with uranium, presenting the possibility of using above background concentrations of uranium as an indicator of thorium-230 DCGL concerns. While the levels of uranium are not sufficiently high to be quickly and reliably detectable by in-field gamma sensing techniques, they are at levels that can be detected and quantified by x-ray fluorescence (XRF). Consequently, both the final status survey process and the pre-design data collection strategies propose to use XRF as a means for quickly and cost-effectively screening for thorium-230 DCGL concerns at Rattlesnake Creek. The purpose of this document is to provide a technical justification for the selection of XRF for implementation at Rattlesnake Creek. This technical justification is based on past experience where XRF has been used to detect heavy metals (in general) and uranium (in particular), and results from a recent site test of XRF capabilities on Rattlesnake Creek archived soil samples.

2 BACKGROUND AND PRECEDENT

XRF makes use of x-ray sources to irradiate sample material. When a sample is irradiated, source x-rays may be absorbed by sample atoms, producing what is known as the photoelectric effect. The process of absorption results in the emission of fluorescent x-rays whose energies are characteristic of specific elements. XRF instruments excite samples and then use the resulting fluorescent emissions to identify the elements present and estimate their concentrations. In general, XRF can be used for metals with an atomic number 16 or greater. Detection limits for any individual element depend on a variety of factors including count times, excitation source and strength, sample preparation, matrix effects, and inter-element spectral interferences.

XRF systems can be deployed in a laboratory setting or as field portable instruments. Measurements can be made on prepared samples, or *in situ*; in both cases the detector window is pressed against a sample's (or sub-sample's) surface. An XRF instrument typically measures concentrations in a very small sub-sample of an original sample; proper sample homogenization is critical to ensuring replicability and adequate precision in measurements. Measurement times typically range from 60 to 600 seconds. Although the XRF instrument is not measuring radioactivity of material, the measurement analysis involves the same type of spectroscopy as radionuclide measurements (e.g., gamma and alpha spectroscopy); hence, the same principals of counting errors and counting statistics as a function of count times apply.

XRF has made steady gains in regulatory acceptance for heavy metal characterization, including its inclusion in EPA SW-846 as Method 6200 (EPA 1998). EPA's Method 6200 reports excellent method performance for some metals (e.g., arsenic, copper, lead, and zinc) as compared to confirmatory laboratory analyses. XRF is

currently used widely to characterize heavy metals (particularly lead) in environmental media.

Method 6200 lists 26 analytes that it identifies as amenable to analysis by XRF. Although uranium is not among these, XRF has been used with success at the Department of Energy (DOE) Ashtabula site both as a laboratory-based and field-deployed system to estimate total uranium concentrations in soils. When controlling for sample homogenization affects, the Ashtabula site reported a correlation coefficient of 0.96 (1.0 being perfect) for XRF results as compared to gamma spectroscopy. Detection limits were estimated to be in the range of 10 to 40 parts per million (ppm) total uranium.

When comparing total uranium results from XRF measurements to those obtained using gamma or alpha spectroscopy, several points must be kept in mind. First, XRF measures total uranium but provides no information on the isotopic composition of uranium present. In contrast, gamma spectroscopy typically quantifies only uranium-238 and possibly uranium-235, but does not quantify total uranium mass concentrations directly. Comparing XRF results to gamma spectroscopy results requires making assumptions about the relative ratios of uranium isotopes present. Secondly, uranium mass concentrations are measured directly by XRF. In contrast, alpha spectroscopy measures the uranium concentration that has been extracted from samples through a digestion process. If the extraction process is incomplete, alpha spectroscopy may underestimate the mass concentration present as compared to that measured by XRF.

Method 6200 identifies several generic sources of error for field-based XRF measurements. These include physical matrix effects resulting from x-ray attenuation and samples that are not homogenous, excessive soil moisture content (identified as greater than 20%), inconsistent presentation of samples to the detector, chemical matrix effects resulting from inter-element interferences, and spectral effects resulting from inter-element interferences. Homogenization, soil moisture, and sample presentation issues are addressed through proper sample handling, preparation, and measurement procedures and are discussed in Appendix D of the *Field Sampling Plan for the Ashland-Rattlesnake Creek Site, Tonawanda, New York* (Cabrera Services, Inc. 2004).

3 SITE-SPECIFIC XRF METHOD EVALUATION

To address potential site-specific issues, an on-site evaluation of a portable XRF unit was completed on December 11, 2003. XRF measurements were conducted on 20 archived Rattlesnake Creek soil/sediment samples collected during previous investigation work (Table 1). These twenty samples were selected because they contained uranium concentrations in the range of interest, with total uranium mass concentrations ranging from approximately 30 to 240 ppm (10 to 80 pCi/g uranium-238). The lower value, 30 ppm (10 pCi/g uranium-238), was the expected detection limit of the XRF system. The higher value, 240 ppm (80 pCi/g uranium-238), represented uranium values that are expected to be consistently associated with SOR values exceeding one. All samples had previously been prepared, sub-sampled, and analyzed using alpha spectroscopy. Some of

the samples had also had been analyzed using gamma spectroscopy. A factor of three was used to convert reported uranium-238 activity concentrations as reported by alpha and gamma spectroscopy to total uranium mass concentrations. This factor is consistent with the assumption that uranium at the site exists at natural isotopic ratios.

The XRF system employed was an INNOV-X System, Inc. tube-based XRF spectrometer. Samples were removed from their archived containers to labeled zipper bags. Sample measurements were conducted in two different ways, by sub-sampling historical samples using single open-ended XRF sample measurement cups supplied with the system and by directly measuring soils through the zippered plastic bags. These data were used to compare XRF-measured uranium concentrations with those previously reported using alpha and gamma spectroscopy.

In addition to measuring total uranium concentrations using these two methods for all twenty samples, a sample was selected for repeated measurements. This sample was measured consecutively ten times. These data were used to evaluate method precision, detection limits, and quantitation limits for the instrument. Two other samples were selected to evaluate the effects of measurement time on analytical quality.

Table 1 presents the original alpha and gamma spectroscopy results for the twenty samples, along with the corresponding XRF data and calculations of relative percent differences (RPD) and absolute relative percent differences (ARPD). RPD and ARPD were calculated for gamma spectroscopy, XRF cup measurements, and XRF bag measurements assuming alpha spectroscopy results as the point of comparison. The average RPD for gamma spectroscopy, XRF cup, and XRF bag results was -3%, 27%, and 20%, respectively. Average RPD measures systematic bias present in the data. The average ARPD for gamma spectroscopy, XRF cup, and XRF bag results was 27%, 29%, and 27%, respectively. Average absolute RPD measures the average level of agreement between the various alternative analysis methods and alpha spectroscopy for total uranium. These data suggest that the XRF, on average, systematically overestimated the amount of uranium present, but that the level of discrepancy between individual XRF and alpha spectroscopy results was approximately the same as that between gamma spectroscopy and alpha spectroscopy. Both alpha and gamma spectroscopy are established, accepted methods for determining uranium-238 activity concentrations.

Figure 1 presents the XRF and alpha spectroscopy total uranium results contained in Table 1 as a scatter plot for those data points where the XRF reported uranium values are above detection levels. If XRF cup and alpha spectroscopy total uranium results were in perfect agreement, all of those paired samples would plot on the diagonal line. The same is true for the XRF bag and alpha spectroscopy total uranium results. For these archived samples, the XRF tended to overestimate total uranium concentrations (as evidenced by the fact that most points fell below the diagonal), but there was a strong correlation between XRF results and alpha spectroscopy results. The Pearson correlation coefficient measures the linear relationship among the split sample results (a perfect correlation is 1.0, no correlation is 0). EPA's Method 6200 identifies correlation coefficients that are 0.9 or greater as representing data that are potentially definitive. The

Pearson correlation coefficient relating XRF cup analysis results with alpha spectroscopy results for those samples that yielded detectable total uranium concentrations was 0.92. If a regression is done (with intercept zero) that predicts alpha spectroscopy results based on the XRF cup results, the slope of the regression line is 0.81. This again indicates a relative systematic bias (i.e., alpha spectroscopy results are 81% of XRF cup results, on average). The Pearson correlation coefficient relating XRF bag analysis results with alpha spectroscopy results for those samples that yielded detectable total uranium concentrations was 0.90. A regression provides a slope of 0.83, indicating, on average, alpha spectroscopy results are 83% of XRF bag results. The XRF bag regression provided slightly lower adjusted r-square values than the XRF cup regression, indicating slightly more scatter or variability in the data for the XRF bag results, which is to be expected since the geometry of the sample and its presentation to the detector is not as controlled as via the sample cup.

Sample RC27-SB2-2 was measured ten consecutive times. The XRF measurements ranged from 79 to 124 ppm with an average value of 97 ppm and a standard deviation of 13 ppm. The relative standard deviation (RSD) was 13%. SW-846 Method 6200 describes an acceptable RSD as one less than 20%. Assuming that samples are well homogenized, the standard deviation calculated also provides insights into practical detection and quantitation limits. These limits can be calculated in a variety of ways. One method, as proposed by Method 6200, is to use 3 times the standard deviation as the detection limit and 10 times the standard deviation as the quantitation limit.

Another way is to develop a statistically-based estimate of detection and quantitation limits. The detection limit can be defined as the observed concentration that would unlikely be associated with no uranium present. This would be represented by measurement values that fall in the upper tail of the distribution of measurement values when actual uranium concentrations are near zero (i.e., a measurement result that is a certain number of standard deviations above zero). The quantitation limit can be defined as the true concentration that can be reliably identified as being above detection limits (i.e., a true value that is a certain number of standard deviations above the detection limit). Using these definitions, assuming the 13 ppm standard deviation observed in the repeat measurements of RC27-SB2-2 is representative of analytical error, and assuming that analytical error is normally distributed, then a 95% detection limit would be 21 ppm and an associated quantitation limit would be 43 ppm.

The XRF tested in the field has an internal algorithm for calculating detection limits. On the basis of the non-detects reported, the average detection limit as calculated by the instrument for XRF cup analyses was 57 ppm. Whatever methodology is used to calculate detection limits for the instrument, the detection limit for the XRF appears to be well below the 90 ppm investigation level currently proposed for use at Rattlesnake Creek as a means for screening soils that might pose DCGL concerns.

A further review of variability in results was conducted to determine the relative contributions of measurement error and heterogeneity within samples to the differences observed between XRF and alpha spectroscopy results. The replicate measurements of

one sample by XRF suggested a standard error of 13 ppm for repeated measurements. The standard errors associated with the regression of XRF results and alpha spectroscopy indicated an error of around 22 ppm. Assuming that alpha spectroscopy results would have the same standard error as XRF for repeat measurements and that the alpha spectroscopy laboratory thoroughly ground and homogenized its samples prior to analysis, then the contribution of heterogeneity in the sample to overall error would be approximately 14 ppm. Measurement error can be reduced for the XRF by increasing count times. The contribution of heterogeneity in the samples themselves can be reduced either by more thoroughly homogenizing the sample prior to analysis by the XRF, or by performing multiple measurements of the same sample (e.g., once on one side of a sample bag, followed by once on the other side). Four one minute measurements of a bagged sample, for example, would reduce errors associated with heterogeneity by a factor of two and provide the same measurement error as one four minute measurement.

Sample RC27-SB3-1 was analyzed twice, once for 120 seconds and the second time for 300 seconds. The results as reported by the XRF were 304 +/- 21 ppm and 305 +/- 13 ppm, respectively. This reduction in reported analytical error is consistent with expectations for increased measurement acquisition time. A NIST 2710 sample (with a non-certified value of 25 mg/kg for uranium) was evaluated using the cup analysis for 120 and 300 seconds. The reported results were < 60 ppm and < 41 ppm, respectively. Again, the reductions in detection limits were consistent with expectations for increased measurement acquisition times.

4 RELATIONSHIP OF RATTLESNAKE CREEK TOTAL URANIUM CONCENTRATIONS TO THORIUM-230

The proposed use of the XRF system is to screen for SOR DCGL exceedances (which are primarily driven by the presence of elevated thorium-230) using total uranium as a surrogate. XRF performance in this regard depends on a usable relationship between total uranium concentrations and the presence/absence of SOR values greater than one. XRF performance is best assessed by reviewing its usability for decision-making purposes. The decisions that need to be made for Rattlesnake Creek require differentiating between soils with SOR values greater than one, versus those with SOR values less than one. One measure of usability is the likelihood that incorrect decisions would result from the use of total uranium results (i.e., identifying locations with SOR values greater than one when the SOR values are actually less than one [false positive], or alternatively identifying locations with SOR values less than one when the SOR values actually exceed one [false negative]). The lower the false positive/false negative rates, the more utility XRF data potentially has.

Historical subsurface soil samples from Rattlesnake Creek were reviewed that had both thorium-230 and uranium-238 results via alpha spectroscopy. There were 196 subsurface samples with alpha spectroscopy results for both radionuclides. Table 2 contains the results for these 196 samples. Of these, twelve had SOR values greater than one. Of these twelve, ten had uranium-238 greater than 30 pCi/g. This would suggest a false negative error rate of approximately 17% if 30 pCi/g uranium-238 (90 ppm total

uranium) is used as the lower investigation level for XRF screening. Of the 196 subsurface samples, 34 had uranium-238 results greater than 30 pCi/g. Of the 196 subsurface soil samples, five had uranium-238 results greater than 100 pCi/g. Of these five, four had SOR scores greater than one. This would suggest a false positive error rate of approximately 20% if 100 pCi/g uranium-238 (300 ppm total uranium) is used as the upper investigation level. Uranium-238 results between 90 and 300 ppm (29 samples in all) were found to be inconclusive regarding the presence/absence of thorium-230 above DCGL requirements.

A similar, although more limited, analysis can be done with the 20 samples measured using XRF. Of these 20 archived samples, five had SOR values of one or greater. Of these, four had XRF results via cup analyses greater than 110 ppm (equivalent to an alpha spectroscopy result of 90 ppm after accounting for the apparent XRF bias), representing a false negative error rate of 20%. Of the 20 archived samples, nine had XRF readings greater than 110 ppm but less than 380 ppm (equivalent to an alpha spectroscopy result of 300 ppm total uranium). Of these nine, four had SOR scores greater than one, indicating a false positive rate of around 56% for this data set. This was also consistent with the historical data review findings, indicating that the XRF information is not conclusive in this range regarding the presence or absence of thorium-230 above DCGL requirements. There were no samples among the 20 analyzed by XRF that had total uranium XRF results above 300 ppm, so false positive rates in this range of total uranium concentrations could not be evaluated.

5 CONCLUSIONS

Several conclusions can be drawn from a review of XRF-pertinent work at other sites, and the site-specific testing of the XRF on Rattlesnake Creek archived soil samples conducted in December, 2003. They are as follows:

- The XRF displayed excellent correlation with alpha spectroscopy results for the archived samples, although a marked relative systematic bias was observed. The Pearson correlation coefficient (a measure of a linear relationship) for the XRF compared to alpha spectroscopy was greater than 0.9.
- The ARPD observed in the paired XRF/alpha spectroscopy data sets was approximately the same as that observed in the paired gamma spectroscopy/alpha spectroscopy data sets. The conclusion is that the XRF displayed the same inter-method performance relative to alpha spectroscopy as did gamma spectroscopy.
- The XRF produced acceptable precision for replicate measurements, with a coefficient of variation less than 0.2 for 120 second readings.
- The observed detection limits for the XRF as applied to these historical samples (as well as the self-calculated detection limits reported by the instrument) were well below the proposed 90 ppm investigation level for total uranium.

- Increasing XRF measurement time did improve system precision and decrease detection limits.
- Agreement with alpha spectroscopy results can be improved by multiple measurements of the same sample. For example, increasing the number of measurements to four while decreasing the measurement times for each measurement by a factor of two can be expected to improve the agreement between alpha spectroscopy and XRF results by approximately 25%.
- The XRF data did exhibit a systematic relative bias. Based on a regression analysis of the XRF cup data, on average alpha spectroscopy results were 81% of XRF cup readings for total uranium.
- Based on published information, soil sample moisture content below 20% is not expected to have a significant impact on the quality of XRF results.
- Based on an analysis of historical data results, uranium does appear to be a relatively reliable surrogate for the presence/absence of thorium-230 above DCGL requirements. In particular, alpha spectroscopy total uranium results less than 90 ppm were associated with SOR values less than one. Conversely, total uranium results greater than 300 ppm were associated with SOR values greater than one.
- The XRF total uranium results for the twenty samples analyzed displayed the same relationship with SOR scores as did the historical alpha spectroscopy total uranium results.
- The overall conclusion is that the XRF can accurately quantify total uranium concentrations with 120 second measurement times, and that these data will provide valuable information pertinent to the presence of thorium-230 above DCGL levels as measured by alpha spectroscopy and SOR values.

Based on the results of XRF-related literature reviews, the site test deployment, and the conclusions drawn from both, the following action items will be carried into the proposed pre-design field work and later FSS data collection:

- XRF samples will be handled in such a fashion that moisture content is kept below 20% before XRF measurements are made.
- An appropriate correction factor will be developed and/or site-specific recalibration conducted to eliminate the total uranium concentration bias observed in the analyses of archived samples.
- The relationship between SOR values and XRF total uranium results will be monitored during the course of field work using the alpha spectroscopy results generated for individual samples. Investigation levels for the XRF derived from

historical analysis (i.e., the 90 ppm and 300 ppm investigation levels) will be modified as needed based on alpha spectroscopy results.

- To further establish the correlation of the XRF results to alpha spectroscopy total uranium and thorium-230 results, 5% of samples yielding an XRF value greater than 300 ppm and less than 90 ppm will be sent for alpha spectroscopy analysis until the data can better establish the relationship between XRF total uranium values and SOR exceedances.

6 REFERENCES

Cabrera Services, Inc. 2004, *Draft III Field Sampling Plan for the Ashland-Rattlesnake Creek Site, Tonawanda, New York*, January.

EPA 1998, *Method 6200, Field Portable X-Ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment Revision 0*, January.

EPA 2000, *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)*, EPA 402-R-97-016, Rev. 1, August.

USACE, 1998, *Record of Decision for the Ashland 1 (including Seaway Area D) and Ashland 2 Sites, Tonawanda, New York*, Final, April.

USACE 2004a, *Explanation of Significant Differences for the Rattlesnake Creek Portion of the Ashland sites, Tonawanda, New York*, February.

USACE 2004b, *Rattlesnake Creek Final Status Survey Plan, Tonawanda, New York*, February.

FIGURE 1 Scatter Plot of XRF versus Alpha Spectroscopy Results (ppm)

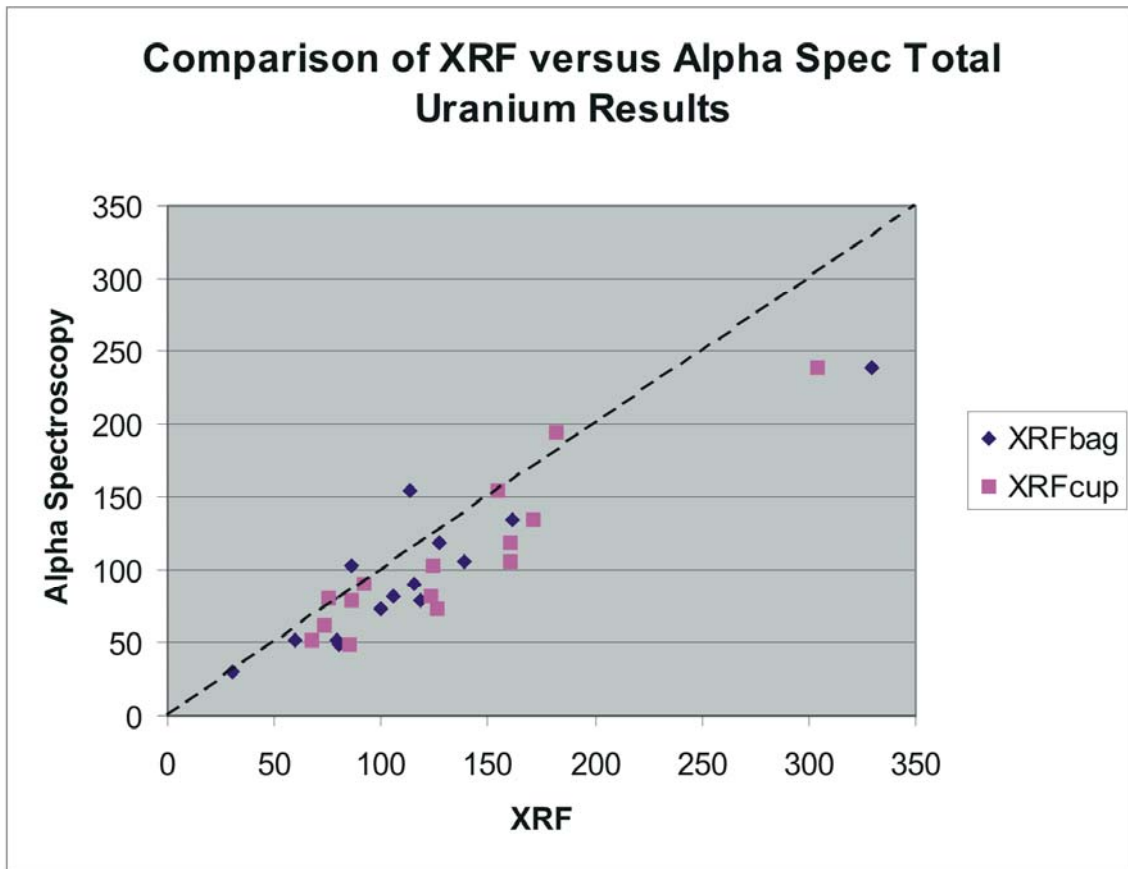


TABLE 1 Total Uranium (ppm) XRF, Alpha Spectroscopy, and Gamma Spectroscopy Results

Sample ID	Collected	Interval (ft)	Alpha Spec. ppm ¹	Gamma Spectroscopy			XRF (cup)			XRF (bag)		
				ppm ¹	%RPD ²	Absolute %RPD ²	XRF ppm	%RPD ²	Absolute %RPD ²	XRF ppm	%RPD ²	Absolute %RPD ²
RC11-SS001	07/31/00	0.0-0.5	30	25	-17	17	<57	NA ⁴	NA	30	0	0
RC11-SS021	08/01/00	0.0-0.5	90	82	-9	9	92	2	2	115	28	28
RC12-SS002	08/02/00	0.0-0.5	154	94	-39	39	154	0	0	113	-27	27
RC12-SS003	08/02/00	0.0-0.5	62	50	-19	19	73	18	18	<59	NA	NA
RC12-SS005	08/02/00	0.0-0.5	40	43	8	8	<61	NA	NA	<59	NA	NA
RC12-SS014	08/03/00	0.0-0.5	103	84	-18	18	124	20	20	86	-17	17
RC12-SS015	08/03/00	0.0-0.5	51	42	-18	18	67	31	31	60	18	18
RC12-SS017	08/03/00	0.0-0.5	194	140	-28	28	182	-6	6	182	-6	6
RC12-SS021	08/03/00	0.0-0.5	80	79	-1	1	75	-6	6	76	-5	5
RC27-SB1-1	09/04/01	0.5-1.0	106	NP ³	NP	NP	160	51	51	139	31	31
RC27-SB1-2	09/04/01	1.0-1.5	49	NP	NP	NP	85	73	73	80	63	63
RC27-SB1-3	09/04/01	1.5-2.0	33	NP	NP	NP	<55	NA	NA	<53	NA	NA
RC27-SB2-1	09/04/01	0.5-1.0	118	NP	NP	NP	160	36	36	127	8	8
RC27-SB2-2	09/04/01	1.0-1.5	78	NP	NP	NP	86	10	10	118	51	51
RC27-SB2-3	09/04/01	1.5-2.0	73	NP	NP	NP	126	73	73	100	37	37
RC27-SB2-4	09/04/01	2.0-2.5	81	NP	NP	NP	123	52	52	106	31	31
RC27-SB2-5	09/04/01	2.5-3.0	52	NP	NP	NP	<56	NA	NA	79	52	52
RC27-SB3-1	09/04/01	0.5-1.0	238	NP	NP	NP	304	28	28	329	38	38
RC27-SB3-2	09/04/01	1.0-1.5	134	NP	NP	NP	171	28	28	161	20	20
RC27-SS001	08/10/00	0.0-0.5	74	160	116	116	<55	NA	NA	<53	NA	NA

- a. Alpha and gamma spectroscopy report uranium-238 values measured as pCi/g. These were converted to total uranium ppm using a conversion factor of 3.
- b. RPD is defined as relative percent difference, e.g. (XRF - alpha spec)/alpha spec * 100.
- c. NP means the analysis was not performed.
- d. NA means the calculation of an RPD was not possible.

TABLE 2 Historical Subsurface Results

Sample	Date Sampled	Depth from (in)	Depth to (in)	Ra226 (pCi/g)	U238 (pCi/g)	Th230 (pCi/g)	SOR
RC27-SB1-1	09/04/01	6	12	1.97	35.2	26.39	2.03
ASH2-SL-0705	12/16/98	18	18	1.47	152.6	20.91	1.80
RC26-SB007	08/18/00	0	36	1.61	52.7	22.67	1.73
ASH2-SL-0731	12/17/98	18	18	1.70	88.0	20.40	1.67
RC11-SB016	08/02/00	0	36	1.64	32.0	21.65	1.62
RC25-SB021	08/16/00	0	36	1.79	17.7	20.95	1.57
RC27-SB3-1	09/04/01	6	12	1.86	79.2	16.52	1.40
ASH2-SL-0726	12/17/98	18	18	1.82	75.9	16.60	1.39
ASH2-SL-0729	12/17/98	18	18	1.85	109.1	15.20	1.37
ASH2-SL-0704	12/16/98	18	18	1.68	148.1	14.00	1.34
ASH2-SL-0732	12/17/98	12	12	1.46	133.9	11.80	1.11
RC25-SB2-5	09/04/01	30	36	1.03	1.2	15.63	1.00
RC27-SB2-1	09/04/01	6	12	1.56	39.4	12.91	0.99
RC12-SB011	08/03/00	0	36	0.85	64.1	13.44	0.95
RC12-SB001	08/02/00	0	36	0.96	18.3	13.64	0.88
RC13-SB003	08/04/00	0	36	1.06	25.4	11.85	0.79
RC11-SB005	08/01/00	0	36	1.01	41.5	11.45	0.79
RC11-SB018	08/02/00	0	36	0.98	14.3	12.34	0.78
RC12-SB020	08/03/00	0	36	1.21	56.8	10.24	0.77
RC12-SB019	08/03/00	0	36	1.13	64.9	10.06	0.76
RC24-SB015	08/15/00	0	36	1.14	25.3	10.60	0.71
RC27-SB3-2	09/04/01	12	18	1.17	44.8	9.75	0.70
RC11-SB019	08/02/00	0	36	1.11	24.8	10.32	0.69
RC12-SB006	08/02/00	0	36	1.04	30.5	10.27	0.68
RC12-SB004	08/02/00	0	36	0.66	31.4	11.16	0.67
RC11-SB001	07/31/00	0	36	1.09	5.0	10.15	0.63
RC26-SB011	08/17/00	0	36	0.92	47.5	9.17	0.62
RC24-SB013	08/15/00	0	36	1.37	15.3	8.80	0.61
RC11-SB008	08/01/00	0	36	1.18	60.3	7.51	0.58
RC28-SB005	08/11/00	0	12	0.86	16.1	9.65	0.57
RC27-SB001	08/10/00	0	36	1.30	16.0	8.36	0.57
RC11-SB004 DUP	08/01/00	0	36	1.05	53.5	7.72	0.55
RC12-SB017	08/03/00	0	36	0.90	79.2	7.27	0.55
RC24-SB005	08/14/00	0	36	0.97	11.1	9.06	0.54
RC13-SB002	08/04/00	0	36	1.03	18.9	8.28	0.51
RC12-SB013	08/03/00	0	36	0.63	19.9	9.10	0.49
ASH2-SL-689	12/05/98	10	13	1.06	40.3	7.16	0.49
RC11-SB004	08/01/00	0	36	0.92	38.6	7.65	0.49
RC24-SB012	08/15/00	0	36	1.17	13.5	7.56	0.48
ASH2-SL-0733	12/17/98	12	12	1.45	165.3	1.99	0.47
RC11-SB015	08/02/00	0	36	1.13	37.8	6.73	0.46
RC12-SB002	08/02/00	0	36	0.79	22.6	7.91	0.45
RC11-SB006	08/01/00	0	36	0.67	16.0	8.23	0.43
RC13-SB004	08/04/00	0	36	0.87	5.5	7.94	0.43
RC11-SB021	08/01/00	0	36	1.03	41.6	6.19	0.41
RC27-SB005	08/10/00	0	36	1.04	19.8	6.21	0.37
RC24-SB021	08/14/00	0	36	0.83	12.2	6.95	0.36
RC12-SB009	08/03/00	0	36	0.84	35.7	6.15	0.36
RC11-SB014	08/02/00	0	36	1.18	14.9	5.72	0.35
RC12-SB009 DUP	08/03/00	0	36	0.71	33.6	6.43	0.35
RC24-SB002	08/14/00	0	36	1.02	8.1	6.20	0.34
RC25-SB2-1	09/04/01	6	12	0.63	1.7	7.43	0.33
RC26-SB008	08/18/00	0	36	0.59	29.4	6.35	0.31
RC11-SB017	08/02/00	0	36	0.67	35.3	5.91	0.31

Sample	Date Sampled	Depth from (in)	Depth to (in)	Ra226 (pCi/g)	U238 (pCi/g)	Th230 (pCi/g)	SOR
RC12-SB005	08/02/00	0	36	0.80	17.0	6.12	0.31
RC24-SB007	08/14/00	0	36	0.91	13.3	5.82	0.30
RC11-SB017 DUP	08/02/00	0	36	0.82	29.4	5.31	0.28
RC24-SB001	08/14/00	0	36	1.11	3.8	5.21	0.28
RC26-SB009	08/17/00	0	36	0.59	26.0	5.94	0.27
RC12-SB014	08/03/00	0	36	0.66	18.7	5.95	0.27
RC26-SB003	08/18/00	0	36	0.71	27.0	5.53	0.27
RC24-SB011 DUP	08/15/00	0	36	0.77	7.9	5.68	0.25
RC13-SB011	08/04/00	0	36	1.05	3.4	4.99	0.25
RC12-SB003	08/02/00	0	36	1.04	18.6	4.52	0.25
RC26-SB010	08/17/00	0	36	0.91	14.4	4.83	0.23
RC24-SB011	08/15/00	0	36	0.82	5.1	5.23	0.22
RC24-SB020	08/14/00	0	36	0.69	6.8	5.47	0.22
RC13-SB009	08/04/00	0	30	0.78	3.5	4.92	0.19
RC12-SB021	08/03/00	0	36	0.55	88.9	2.83	0.18
RC25-SB020	08/16/00	0	36	1.00	2.4	4.17	0.18
RC25-SB009	08/15/00	0	36	0.67	1.4	5.10	0.17
RC27-SB009	08/10/00	0	36	0.92	6.2	4.18	0.17
RC12-SB008	08/03/00	0	36	0.81	21.7	3.72	0.15
RC13-SB007	08/04/00	0	36	0.71	1.8	4.56	0.15
RC11-SB009	08/01/00	0	36	0.65	13.5	4.34	0.14
RC26-SB020	08/17/00	0	36	1.00	9.9	3.46	0.14
RC12-SB007	08/03/00	0	36	0.79	45.9	2.85	0.14
RC27-SB016	08/09/00	0	36	1.09	20.5	2.47	0.11
RC11-SB002	07/31/00	0	36	0.71	9.6	3.83	0.11
RC26-SB021	08/18/00	0	36	0.76	19.4	3.36	0.11
RC12-SB010	08/03/00	0	36	0.73	31.3	3.06	0.11
RC24-SB004	08/14/00	0	36	0.98	6.8	3.08	0.10
RC12-SB012	08/03/00	0	36	0.68	16.4	3.53	0.10
RC11-SB010	08/01/00	0	36	0.62	12.1	3.77	0.09
RC26-SB019	08/17/00	0	36	0.76	7.5	3.35	0.08
RC26-SB013	08/17/00	0	36	0.76	14.3	3.11	0.08
RC13-SB010	08/04/00	0	36	0.86	2.8	3.09	0.07
RC28-SB008	08/11/00	0	36	0.75	36.1	2.34	0.07
RC11-SB007	08/01/00	0	36	0.92	7.4	2.61	0.06
RC24-SB019	08/14/00	0	36	0.68	9.4	3.13	0.06
RC11-SB011	08/01/00	0	36	0.94	6.8	2.49	0.05
RC26-SB017	08/17/00	0	36	0.71	8.5	2.95	0.05
RC27-SB2-2	09/04/01	12	18	0.75	26.0	2.17	0.04
RC27-SB012	08/10/00	0	36	0.81	17.9	2.27	0.04
RC28-SB014	08/11/00	0	24	1.00	8.2	2.01	0.03
RC25-SB002	08/16/00	0	12	0.89	2.0	2.48	0.03
RC13-SB015	08/07/00	0	36	0.55	1.7	3.42	0.03
RC12-SB016	08/03/00	0	36	0.67	4.9	2.97	0.03
RC26-SB016	08/17/00	0	36	0.62	4.8	3.11	0.03
RC11-SB020	07/31/00	0	36	0.74	7.5	2.66	0.03
RC26-SB018	08/17/00	0	36	0.74	3.5	2.79	0.03
RC24-SB016	08/14/00	0	36	0.51	2.3	3.44	0.03
RC27-SB002	08/10/00	0	36	0.68	9.1	2.76	0.03
RC27-SB013	08/10/00	0	36	0.57	21.9	2.67	0.03
RC26-SB005	08/18/00	0	36	0.71	9.4	2.61	0.02
RC24-SB006	08/14/00	0	36	0.76	4.9	2.59	0.02
RC28-SB007	08/11/00	0	36	0.90	12.0	1.95	0.02
RC12-SB018	08/03/00	0	36	0.56	15.9	2.73	0.02
RC27-SB004	08/10/00	0	36	0.59	5.0	2.98	0.02
RC24-SB018	08/14/00	0	36	0.73	4.4	2.57	0.01

Sample	Date Sampled	Depth from (in)	Depth to (in)	Ra226 (pCi/g)	U238 (pCi/g)	Th230 (pCi/g)	SOR
RC13-SB006	08/04/00	0	36	0.58	1.9	2.99	0.01
RC27-SB018	08/10/00	0	36	0.91	8.8	1.85	0.01
RC25-SB008	08/16/00	0	24	0.91	2.7	2.00	0.00
RC13-SB014	08/04/00	0	30	0.73	2.6	2.48	0.00
RC13-SB021	08/07/00	0	36	0.86	2.3	2.10	0.00
RC11-SB012	08/01/00	0	36	0.65	7.1	2.52	0.00
RC24-SB008	08/14/00	0	36	0.79	5.7	2.10	-0.01
RC27-SB008	08/10/00	0	36	0.75	3.5	2.27	-0.01
RC27-SB006	08/10/00	0	36	0.60	4.4	2.63	-0.01
RC27-SB2-3	09/04/01	18	24	0.56	24.3	2.08	-0.01
RC24-SB003	08/14/00	0	36	0.76	2.4	2.17	-0.01
RC13-SB016	08/07/00	0	30	0.57	2.4	2.69	-0.02
RC11-SB003	07/31/00	0	36	0.72	5.3	2.17	-0.02
RC13-SB013	08/04/00	0	24	1.00	1.4	1.50	-0.02
RC13-SB016 DUP	08/07/00	0	36	0.69	2.6	2.32	-0.02
RC26-SB004	08/18/00	0	36	0.94	2.9	1.62	-0.02
RC26-SB006	08/18/00	0	36	0.84	5.8	1.80	-0.02
RC26-SB012 DUP	08/17/00	0	36	0.91	2.3	1.64	-0.02
RC26-SB002	08/18/00	0	36	0.62	3.1	2.40	-0.03
RC26-SB012	08/17/00	0	36	0.92	2.9	1.55	-0.03
RC28-SB009 DUP	08/11/00	0	36	0.86	5.9	1.63	-0.03
RC25-SB2-3	09/04/01	18	24	0.48	1.5	2.82	-0.03
RC25-SB007	08/15/00	0	36	0.58	1.7	2.43	-0.03
RC13-SB018	08/07/00	0	36	0.61	1.8	2.30	-0.04
RC28-SB001	08/11/00	0	36	0.69	5.8	1.94	-0.04
RC27-SB2-4	09/04/01	24	30	0.67	27.0	1.30	-0.04
RC27-SB003	08/10/00	0	36	0.88	1.4	1.51	-0.04
RC24-SB014	08/15/00	0	36	0.78	2.2	1.74	-0.04
RC25-SB014	08/16/00	0	36	0.88	2.0	1.39	-0.05
RC26-SB014	08/17/00	0	36	0.66	2.8	1.97	-0.05
RC27-SB2-5	09/04/01	30	36	0.69	17.2	1.47	-0.05
RC27-SB3-4	09/04/01	24	30	0.56	2.1	2.24	-0.05
RC25-SB019	08/16/00	0	36	0.72	4.2	1.68	-0.05
RC24-SB010	08/15/00	0	36	0.76	2.7	1.58	-0.06
RC28-SB004	08/11/00	0	24	0.81	1.0	1.47	-0.06
RC25-SB2-2	09/04/01	12	18	0.54	1.7	2.24	-0.06
RC13-SB012	08/04/00	0	24	0.79	2.3	1.44	-0.06
RC25-SB003	08/15/00	0	36	0.79	1.5	1.47	-0.06
RC26-SB015	08/17/00	0	36	0.73	3.0	1.55	-0.06
RC28-SB009	08/11/00	0	30	0.82	5.5	1.20	-0.07
RC13-SB019	08/07/00	0	36	0.54	3.3	2.01	-0.07
RC25-SB013	08/16/00	0	36	0.81	5.3	1.18	-0.07
RC27-SB015	08/09/00	0	36	0.59	6.5	1.72	-0.07
RC28-SB003	08/11/00	0	18	0.81	0.8	1.27	-0.07
RC13-SB008	08/04/00	0	36	0.64	2.5	1.69	-0.07
RC25-SB012	08/16/00	0	36	0.62	4.3	1.69	-0.07
RC13-SB001 DUP	08/03/00	0	36	0.60	4.3	1.72	-0.08
RC11-SB013	08/01/00	0	36	0.73	2.7	1.38	-0.08
RC25-SB010	08/16/00	0	36	0.56	1.7	1.89	-0.08
RC13-SB005	08/04/00	0	36	0.53	2.3	1.91	-0.08
RC28-SB012	08/11/00	0	36	0.60	1.8	1.65	-0.09
RC27-SB007	08/10/00	0	36	0.49	7.0	1.77	-0.09
RC12-SB015	08/03/00	0	36	0.60	7.5	1.43	-0.09
RC26-SB001	08/18/00	0	36	0.54	3.1	1.72	-0.09
RC27-SB1-2	09/04/01	12	18	0.57	16.5	1.23	-0.09
RC27-SB1-3	09/04/01	18	24	0.56	10.9	1.36	-0.09

Sample	Date Sampled	Depth from (in)	Depth to (in)	Ra226 (pCi/g)	U238 (pCi/g)	Th230 (pCi/g)	SOR
RC25-SB016	08/16/00	0	36	0.69	1.6	1.34	-0.09
RC28-SB002	08/11/00	0	36	0.47	2.9	1.90	-0.09
RC13-SB017	08/07/00	0	36	0.51	2.4	1.77	-0.09
RC27-SB010	08/10/00	0	36	0.70	1.6	1.26	-0.09
RC13-SB001	08/03/00	0	36	0.59	4.7	1.40	-0.10
RC25-SB1-4	09/04/01	24	30	0.65	1.3	1.37	-0.10
RC27-SB3-3	09/04/01	18	24	0.65	2.7	1.32	-0.10
RC25-SB015	08/16/00	0	36	0.63	1.6	1.32	-0.10
RC25-SB017	08/16/00	0	36	0.59	1.5	1.37	-0.11
RC13-SB020	08/07/00	0	36	0.58	2.3	1.37	-0.11
RC27-SB1-5	09/04/01	30	36	0.53	2.6	1.46	-0.11
RC25-SB018	08/16/00	0	36	0.69	2.1	1.03	-0.11
RC25-SB011	08/16/00	0	36	0.56	1.8	1.39	-0.11
RC28-SB015	08/11/00	0	24	0.56	2.0	1.35	-0.11
RC25-SB005	08/16/00	0	36	0.68	1.3	1.01	-0.12
RC28-SB013	08/11/00	0	24	0.64	1.6	1.08	-0.12
RC25-SB1-2	09/04/01	12	18	0.63	1.5	1.14	-0.12
RC27-SB1-4	09/04/01	24	30	0.48	3.6	1.49	-0.12
RC25-SB1-3	09/04/01	18	24	0.60	1.4	1.02	-0.13
RC25-SB1-5	09/04/01	30	36	0.49	1.0	1.30	-0.13
RC25-SB3-2	09/04/01	12	18	0.48	0.9	1.36	-0.13
RC28-SB006	08/11/00	0	18	0.43	1.6	1.46	-0.13
RC25-SB1-1	09/04/01	6	12	0.66	0.9	0.69	-0.14
RC25-SB3-1	09/04/01	6	12	0.59	0.9	0.91	-0.14
RC25-SB2-4	09/04/01	24	30	0.44	1.0	1.26	-0.15
RC27-SB017	08/10/00	0	36	0.57	1.1	0.82	-0.15
RC27-SB014	08/09/00	0	36	0.39	3.4	1.22	-0.15
RC25-SB3-3	09/04/01	18	24	0.41	1.0	1.19	-0.16
RC25-SB3-4	09/04/01	24	30	0.46	1.4	0.92	-0.17
RC27-SB3-5	09/04/01	30	36	0.31	1.4	0.79	-0.21