Attachment 2.9-5 Additional Information - Background Gamma Radiation Survey and Soils Sampling

Attachment 2.9-5

The following is the LCI ISR, LLC's January 16, 2009 response to NRC's November 2008 Request for Additional Information 2.9 #7. A footer has been added to indicate the attachment number to the Technical Report and page number in that attachment. The article referenced in Subsection 7.j of the response is included after the response.

2.9 Background Radiological Characteristics

7. Background gamma radiation survey and soils sampling:

a. Considering that LCI has stated "There is an unexpected degree of variability in gamma exposure rates in the Permit Area" and that increased exposure rates were detected over ore bodies and at Permit Area boundaries, it is not clear why only ten correlation grids were chosen and how these ten correlation grids accurately represent the Permit Area as a whole. Demonstrate and provide justification that the ten correlation grid samples are representative of the Permit Area as a whole.

An intensive gamma survey with hundreds of thousands of individual measurements across the entire site was conducted prior to selecting correlation plot locations and performing related measurements and soil sampling. The gamma survey data provided a highly detailed and comprehensive basis for selecting correlation plot locations that are clearly representative of the site as a whole with respect to the intent of the correlation and its connection to the gamma survey data. In this context, "representativeness" rests on several facts:

1) The elevation across the site is relatively constant and the gamma survey was essentially completed within a few weeks. Cosmic sources of gamma radiation are likely to have been fairly constant across the site during the survey, and diurnal fluctuations in ambient radon and associated progeny in air usually produce only minor variations in gamma exposure rates (NRC, 1994). Thus, significant variations in gamma readings across the site are expected to be largely due to variations in terrestrial sources of gamma radiation residing in surface soils.

2) Radium-226 (Ra-226) levels in surface soils are known to influence gamma survey readings, primarily due to photon emissions from lead (Pb-214) and bismuth (Bi-214) (both of which are short-lived decay products of radon-222 (Rn-222)). Because Ra-226 and its decay products normally exist in approximate secular equilibrium in soil, soil Ra-226

concentrations and ambient gamma exposure rates above the soil surface can often be well correlated, particularly under baseline conditions at undisturbed sites. This was true at the Lost Creek site.

3) Based on maps of the gamma survey data, correlation plot locations were selected to span the range of gamma readings observed across the entire site, with a reasonably even distribution of intermediate gamma levels represented. Furthermore, the spatial distribution of correlation plot locations across the site was also taken into account (locations were spread out across various areas of the site, rather than clustered in a small area). This latter consideration should help to account for potential variability in soil properties that might influence the correlation such as potential variability in the concentrations of other gamma-emitting radionuclides like potassium-40 (K-40).

The approach used to characterize gamma exposure rates and Ra-226 concentrations in surface soils at Lost Creek has advantages in terms of representativeness because the gamma survey component of the methodology captures spatially extensive portions of the entire population of possible values (well distributed across the entire site). These results, in turn, can be used to select correlation locations that are representative of the range of gamma exposure rates (and likely soil Ra-226 concentrations as well) found at the site.

Assuming other location selection criteria are also adequately addressed (e.g. gamma shine issues are avoided, plots have uniform gamma readings, etc), as few as five or six carefully-selected plots can result in a regression model that provides reasonably reliable estimates of soil Ra-226 concentration based on gamma survey data. Although five or six grids is a minimum number, ten plots is usually a minimum goal as this provides a more robust statistical analysis.

Based on the Lost Creek gamma survey data, the correlation results, and considerable experience with successful application of this technique at many other sites (e.g. Whicker et al., 2008, Johnson et al., 2006), the number of correlation plots and their locations are considered adequately representative of the entire site with respect to converting gamma survey data into estimates of approximate soil Ra-226 concentrations in surface soils.

The gamma survey and correlation methodology used at Lost Creek is not intended to replace the soil sampling recommendations provided in NRC Regulatory Guide 4.14. This methodology has been developed to help address spatial limitations of grid-based sampling approaches such as the one described in Regulatory Guide 4.14. It also helps to address other, more recent and ISR-specific guidance such as

NUREG-1569 (NRC, 2003) which indicates that 15-centimeter soil depths should also be characterized for consistency with decommissioning protocols and methods as outlined in the Multi-Agency Radiation Surveys and Site Investigation Manual (MARSSIM) (NRC, 2000). The overall approach used at Lost Creek draws on a combination of relevant regulatory guidance, state-of-the-art scanning technologies, and basic correlation techniques that have been used and accepted for decades. The goal was to produce the most detailed and comprehensive baseline characterization possible with respect to the spatial distribution of gamma exposure rates and Ra-226 concentrations in surface soils.

LC ISR, LLC acknowledges that baseline radiological data for surface soils at Lost Creek deviate from Regulatory Guide 4.14 recommendations in that 10 rather than 40 surface soil samples were collected and analyzed for Ra-226. However, the intensive gamma survey in conjunction with the correlation results and related sampling/analyses of surface soils as provided in the application should be sufficient to meet the basic intent and technical basis of relevant regulatory guidance with respect to surface soils at the site.

LC ISR, LLC also acknowledges that the lack of subsurface soil samples deviates from Regulatory Guide 4.14 guidance. LC ISR, LLC has collected baseline subsurface soil sampling consistent with Regulatory Guide 4.14 recommendations and will submit results to the NRC as an addendum to the Technical Report as soon as results are available.

References:

Johnson, J.A. Meyer, H.R., and Vidyasagar, M. 2006. *Characterization of Surface Soils at a Former Uranium Mill*. Operational Radiation Safety. Supplement to Health Physics, Vol. 90, February, 2006.

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

U.S. Nuclear Regulatory Commission (NRC). 1994. *NUREG-1501, Background as a Residual Radioactivity Criterion for Decommissioning.* Division of Regulatory Applications, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC). 2003. *NUREG-1569, Standard Review Plan for In Situ Leach Uranium Extraction License Applications.* Final Report. U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. Washington, D.C.

Whicker, R.; Cartier, P.; Cain, J.; Milmine, K.; Griffin, M. 2008. *Radiological Site Characterizations: Gamma Surveys, Gamma/Ra-226 Correlations and Related Spatial Analysis Techniques*. Operational Radiation Safety, Health Physics, Vol. 95 (Supplement 5): S180-S189; November, 2008.

b. Estimates in the literature (e.g., Faw and Shultis, 1993) indicate that the average concentration of K-40 in soils is 12 pCi/g. Considering that the method proposed to characterize Lost Creek depends on exposure rate correlated to radium concentrations, how is the presence and variation of K-40 and other naturally occurring radionuclides taken into consideration in the proposed methodology?

The correlation is site-specific. Because correlation plot measurements and sampling was conducted in a consistent manner at various representative onsite locations, correlation results include a representative measure of all sources of variability that might influence the correlation. This includes variability associated with K-40 and other naturally occurring radionuclides. A site-specific regression provides a statistical tool for estimating soil Ra-226 concentrations that takes into account site-specific and method-specific sources of variability in paired gamma/Ra-226 data including:

- Heterogeneity in soil Ra-226 concentrations and all other terrestrial sources of ambient gamma radiation, including K-40 and other gamma-emitting radionuclides.

- Scattered radiation reaching the detectors from adjacent areas or subsurface soils (i.e. “gamma shine”). Mild gamma shine effects are believed to introduce small amounts of variability into most correlation data sets as horizontal and vertical distributions of soil radionuclide concentrations are seldom perfectly uniform. Associated variability will be reflected in data collected from representative correlation plot locations and will thus be accounted for in the regression statistics. Strong gamma shine affects, however, can produce strong outliers that badly affect the predictive reliability of the regression. Any location with an abrupt, dramatic transition between low and high soil radionuclide levels has the potential for such effects. Fortunately, areas with strong gamma shine are normally limited to very small portions of any given site and are thus not representative of the site as a whole. Such areas are avoided when selecting correlation plot locations. There was no evidence of strong gamma shine effects at the correlation plots used for Lost Creek.

- Uncertainty in field measurements due to variability in instrument response characteristics. In addition to inherent variability in the precision or reproducibility of readings within or between specific instruments, this factor includes potential differences in counting efficiencies for photons of different energies (e.g. counting efficiency for primary K-40 photons may be less than that attained for lower-energy primary photons from Ra-226 and its decay products, or from secondary scattered radiation).

- Uncertainty in laboratory results due to counting error and all other potential sources of total propagated analytical uncertainty (e.g. incomplete homogenization of composite samples, slight errors in sample weights, etc.)

- Uncertainty in results due to sampling error (e.g. slight inconsistencies in sampling depths, slight differences in volumes of each sub-sample that make up the composite sample, tendency to sample between vegetation rather than near root systems, tendency to avoid collecting larger rocks, etc.).

There are likely other sources of variability as well. Using site-specific data and a consistent methodology helps to account for various sources of sampling and measurement variability in the predictive model. There is considerable evidence to support this view. At a number of other uranium recovery sites, separate soil sampling has been conducted and direct laboratory analysis results for these samples have been compared to corresponding gamma-based estimates of Ra-226 concentrations (Whicker et al., 2008). To date, such "verification" sampling efforts have demonstrated that the scanning/correlation methodology is generally effective and reliable. This does not mean that gamma-based estimates of soil Ra-226 will agree perfectly with direct soil sampling results, but in most cases differences observed by Tetra Tech have been relatively small (e.g. within ± 1-2 pCi/g). In general, this level of agreement does not greatly exceed typical uncertainties reported by analytical laboratories for direct measurement of Ra-226 in baseline soil samples.

The coefficient of determination (R-squared) of the linear relationship between mean Ra-226 and Gamma reading at the Lost Creek site was 0.88. Therefore, the mean Sodium Iodide (NaI) gamma reading was able to explain 88% of the observed variability in mean Ra-226 concentration, despite many additional sources of potential variability and uncertainty as described above. The specific influence of variability from naturally occurring radionuclides other than Ra-226 and its decay products (such as K-40) is believed to be comparatively small.

Reference:
Whicker, R.; Cartier, P.; Cain, J.; Milmine, K.; Griffin, M. 2008. *Radiological Site Characterizations: Gamma Surveys, Gamma/Ra-226 Correlations and Related Spatial Analysis Techniques*. Operational Radiation Safety, Health Physics, Vol. 95 (Supplement 5): S180-S189; November, 2008.

c. Considering that the main product from Lost Creek is uranium in slurry form, and that uranium is not well correlated to radium on the Lost Creek site, demonstrate that the proposed preoperational soil sampling methodology is sufficient to allow LCI to clean up land as a result of spills and accidents, including on proposed transport routes, and meet the requirements of 10 CFR 40, Appendix A, Criterion 6(6), for decommissioning for radionuclides other than radium.

NRC Regulatory Guide 4.14 recommends that 40 surface soil samples be collected in a radial grid surrounding the mill, and 10% (four) of these samples be analyzed for uranium (NRC, 1980). In addition, it recommends that soil samples collected at the five air particulate monitoring stations be analyzed for uranium. Therefore Regulatory Guide 4.14 recommends that fewer than ten surface soil samples be analyzed for uranium.

At the Lost Creek site, ten surface soil samples were collected in a roughly radial pattern relative to the center of the site. These samples were analyzed for Ra-226, U-nat, Th-230, and Pb-210. For characterizing baseline uranium in surface soils, this sampling design is reasonably consistent with the Regulatory Guide 4.14 recommendations, and should satisfy the basic intent and technical basis of the regulatory guidance. Furthermore, the gamma survey goes far beyond Regulatory Guide 4.14 recommendations and this information can be used to indirectly estimate approximate baseline concentrations of both Ra-226 and uranium in surface soils anywhere on the site.

The statement that uranium is not well correlated with radium at the Lost Creek site is inconsistent with the statistical analysis provided in the application. Although the data suggest that uranium and radium in surface soils at the site may commonly be in moderate disequilibrium, the R-squared value on the statistical regression between the two parameters was 0.73 and the p-value (0.001502) indicates that the correlation is statistically significant at a confidence level greater than 99.8%. This suggests that approximate baseline uranium concentrations could be estimated reasonably well anywhere on the site based on the Ra-226/U-nat regression equation, and using the kriged contour map of estimated soil Ra-226 values across the site (both of which are provided in Section 2.9 of the Technical Report).

The baseline sampling design for radionuclides in surface soils in Regulatory Guide 4.14 calls for discrete grab samples spaced 300 meters apart. Plant decommissioning standards and assessment criteria described in MARSSIM call for more detailed measurements. Radiological survey results from Lost Creek and other proposed ISR sites in Wyoming have demonstrated that baseline soil radionuclide concentrations can occasionally vary by an order of magnitude across areas significantly smaller than this amount of grid spacing. The survey described by Regulatory Guide 4.14 may not include measurements in areas where spills or accidents are most likely, and also has the potential to mischaracterize areas between designated grid sampling points. The increased density of measurements and improved spatial detail provided offers a distinct advantage over the sampling design recommended in Regulatory Guide 4.14.

The intensive gamma survey performed across the entire site helps to overcome limitations of a Regulatory Guide 4.14 design for characterizing spatial variability in baseline concentrations of Ra-226 in surface soils. The statistical correlation between Ra-226 and uranium suggests that survey data can also be used to indirectly infer approximate uranium concentrations. Had the baseline soil sampling and gamma survey designs for this site strictly adhered to Regulatory Guide 4.14, far less spatial information relevant to the question of assessing potential uranium contamination due to spills and accidents would be available.

Reference:

U.S. Nuclear Regulatory Commission (NRC). 1980. *Regulatory Guide 4.14. Radiological Effluent and Environmental Monitoring at Uranium Mills. Revision 1.* Nuclear Regulatory Commission Office of Standards Development. Washington, D.C.

d. LCI states: "Within each grid, ten soil sub-samples were collected to a depth of six inches (15 centimeters) then composited into a single sample." Demonstrate that the subsurface (greater than 15 cm below the surface) is properly characterized so as to be able to comply with 10 CFR 40 Appendix A, Criteria 6 (6).

The gamma survey and correlation methodology was not intended to characterize radiological conditions in subsurface soils. LC ISR, LLC will perform baseline subsurface soil sampling consistent with Regulatory Guide 4.14 recommendations and will submit results to the NRC as an addendum to the Technical Report as soon as results are available.

e. In discussing the cross-calibration of the sodium iodide (NaI) detector with a High-Pressure Ionization Chamber (HPIC), LCI states: "NaI detectors were crosscalibrated in the field at each site against an HPIC. Results were consistent with cross-calibrations at other uranium sites as well as with the literature in terms of the energy dependence of NaI detectors (Ludlum, 2006; Schiager, 1972)." Regarding the Schiager reference, please address the following: The Schiager paper describes a process where the NaI detector was calibrated with a radium point source which was then used to measure exposure from radium. The NaI detectors used in the Lost Creek evaluation were calibrated with cesium-137 (Cs-137) then used to measure exposure from radium. Explain why Cs-137 was chosen as the calibration source and the relevance of the Schiager paper to the Lost Creek survey cross-calibration.

Cesium-137 (Cs-137) is the normal source routinely used by Ludlum for calibration of their Ludlum Model 44-10 NaI detectors. The Schiager paper provides a graph of cross-calibration measurement results showing relative response characteristics of a NaI detector versus a high-pressure ionization chamber, with two of the locations measured directly above a tailings pile (see Figure 3 in the Schiager paper).

The corresponding equation from Schiager's cross-calibration was:

Equation (a)
HPIC reading (microRem/hour, μR/hr) = 0.46 × (NaI reading in μR/hr) + 7.9

The two cross-calibration equations measured at Lost Creek (for the two different NaI detector heights) were:

Equation (b)
HPIC reading (μR/hr) = 0.57 × (3-ft NaI reading in μR/hr) + 6.97

Equation (c)
HPIC reading (μR/hr) = 0.69 × (4.5-ft NaI reading in μR/hr) + 3.99

In the Schiager paper, radium was the point source used for calibration of the NaI instrument. The photon energies from Ra-226 and its decay products (namely Pb-214 and Bi-214) are lower, and the mix of energies more complex, than that for Cs-137. We are not suggesting that there are no differences in energy response characteristics between our instruments and the instrument used by Schiager.

The intent of the reference is to demonstrate that the regression coefficients shown in Figure 3 of the Schiager paper are reasonably consistent with those observed for

the cross-calibration from Lost Creek, particularly considering the fact that Schiager took two measurements directly above a tailings pile and performed a number of measurements at other locations with gamma readings well in excess of those found anywhere at Lost Creek. Presumably, Schiager positioned the NaI detector at the same height as the HPIC, so Equation (b), above, would be the most applicable to compare with Schiager's regression, Equation (a).

As ambient gamma exposure rates increase, the difference between NaI and HPIC readings becomes more pronounced and the slope of any corresponding regression should theoretically decrease. Although differences in calibration sources between instruments probably contribute to the observed differences in regression coefficients, the mix of terrestrial sources present at each site and differences in ambient gamma exposure rates could easily be responsible for most of the difference between these regressions. Again, the point is that the differences are not large.

Schiager points out that each cross-calibration is unique to the NaI instrument; each cross-calibration is also site- and geometry specific. Further discussion of the nature of differences between NaI and HPIC readings at various sites and factors that can affect such cross-calibrations (as well as gamma/Ra-226 correlations) can be found in Whicker et al. (2008).

Finally, the correct reference for the Schiager paper is:

Schiager, K. J. 1974. *Analysis of Radiation Exposures on or Near Uranium Mill Tailings Piles*. Radiation Data and Reports, Vol. 15, No. 7. Office of Radiation Programs. US EPA. July 1974.

The correct publication date is 1974, not 1972.

References:

Schiager, K. J. 1974. *Analysis of Radiation Exposures on or Near Uranium Mill Tailings Piles*. Radiation Data and Reports, Vol. 15, No. 7. Office of Radiation Programs. US EPA. July 1974.

Whicker, R.; Cartier, P.; Cain, J.; Milmine, K.; Griffin, M. 2008. *Radiological Site Characterizations: Gamma Surveys, Gamma/Ra-226 Correlations and Related Spatial Analysis Techniques*. Operational Radiation Safety, Health Physics, Vol. 95 (Supplement 5): S180-S189; November, 2008.

f. The intent of the Schiager paper is to demonstrate that the exposure rate over a uranium mill tailings pile can be estimated if there is a known uniform concentration of radium in the tailings. The technique proposed in the Lost Creek analysis attempts to correlate known exposure rates with unknown radium concentrations that may or may not be uniform outside of the correlation grids. Aside from the references noted, are there other outside references that establish this type of relationship?

The 100 m^2 correlation plot technique has been proven effective at statistically determining a valid average relationship between mean gamma readings and mean soil Ra-226 concentrations (Whicker et al. 2008, Johnson et al., 2006). Elements of the technique designed to address issues of variability include: 1) use a correlation plot large enough to significantly reduce measurement error associated with small-scale spatial variability; 2) select plots that have generally uniform gamma readings; and 3) collect a sufficient number of soil sub-samples to provide a good representation of the true mean concentration.

Relating point measurement gamma readings to Ra-226 concentrations in discrete soil samples can yield unreliable results. Data variability is much higher with unshielded (non-collimated) detectors because the gamma detector senses photons that originate across a significantly wider area. An individual soil sample is less likely to accurately represent the true mean Ra-226 concentration across the field of view of the gamma detector versus a composite soil sample.

We acknowledge that results from a 100 m^2 correlation plot model are applied to point data across the site (and areas outside of correlation plots may not be uniform). Furthermore, the converted point data are subsequently kriged in GIS to provide continuous estimates across the site. Kriging has advantages and disadvantages with respect to spatial accuracy. It tends to reduce small-scale spatial detail associated with individual point data and interpolates between vehicle scan tracks where no data exist. It can also, however, help to improve overall survey reproducibility along the scan tracks themselves as it tends to average out variability in point data associated with sources of measurement and estimation error (e.g. small inaccuracies in GPS readings, random variability in gamma count data, application of a 100 m2 correlation plot model to point data, etc.).

Aside from advantages and limitations of the overall method, larger scale distributional characteristics are most relevant to baseline characterizations at such large sites and the method appears to be reasonably reliable in this regard. On a number of occasions, we have evaluated locations corresponding to given contour lines in kriged gamma exposure rate maps and verified good agreement between

measured and predicted values (e.g. within ± 2 µR/hr from one another). In addition, soil Ra-226 sampling results to date have generally agreed well with the values predicted based on the gamma survey data, the correlation, and the kriging technique. The data indicate that the overall methodology is generally reliable.

We are aware of the limitations of the technique, but believe that these limitations relative to those of traditional grid-based sampling or measurement approaches are fewer and less problematic. The sheer volume of information on terrestrial radiation that can now be efficiently collected overcomes many of the spatial limitations of earlier techniques. Short of collecting thousands of soil samples along a high-density grid across the entire site, we are not aware of a viable approach that is as effective or reliable as the method selected. The most pertinent and current reference for this issue is Whicker et al. (2008).

References:

Johnson, J.A. Meyer, H.R., and Vidyasagar, M. 2006. *Characterization of Surface Soils at a Former Uranium Mill*. Operational Radiation Safety. Supplement to Health Physics, Vol. 90, February, 2006.

Whicker, R.; Cartier, P.; Cain, J.; Milmine, K.; Griffin, M. 2008. *Radiological Site Characterizations: Gamma Surveys, Gamma/Ra-226 Correlations and Related Spatial Analysis Techniques*. Operational Radiation Safety, Health Physics, Vol. 95 (Supplement 5): S180-S189; November, 2008.

g. LCI states: "Each 1,076-square-foot (100m2) soil sampling grid was also, scanned to determine the average gamma exposure rate over the same area, following methods described in Johnson et al. (2006)." The Johnson reference indicates that the site was scanned with a "shielded sodium iodide detector." Verify if a shielded sodium iodide detector was used to survey Lost Creek and if so provide details on the shielding, including its purpose and how it alters the unshielded energy response.

The NaI detectors used for the gamma survey or for cross-calibration and correlation measurements were not shielded.

h. For all linear regression analyses presented (Figures 2.9-7 – 2.9-9, 2.9-11 and 2.9-14), provide calculations and results of testing the null hypothesis (i.e., that no correlation exists).

The p-value for the correlation in shown Figure 2.9-7 is 0.000054:

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      StatMost for Windows        Friday, November 21, 2008     5:15:36 AM
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                    Pearson Correlation Analysis Results
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Ra-226 vs. NaI_Gamma:

      Column Name    Ra-226       NaI_Gamma
      Sample Size          10          10
            Minimum Sample Size = 10
                    Correlation = 0.939677
                     Fisher's z = 1.735278
                    Probability = 0.000054


************************************* The End ******************************
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The p-value for the correlation in shown Figure 2.9-8 is 0.001502:

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      StatMost for Windows        Friday, November 21, 2008     5:12:05 AM
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                    Pearson Correlation Analysis Results
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Ra-226 vs. U-nat:

      Column Name    Ra-226       U-nat
      Sample Size          10          10
            Minimum Sample Size = 10
                    Correlation = 0.857795
                     Fisher's z = 1.284938
                    Probability = 0.001502


************************************* The End ******************************
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The p-values for the correlations in shown Figure 2.9-9 are 0.000275 (3-foot NaI vs HPIC) and 0.000579 (4.5-foot NaI vs HPIC).

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      StatMost for Windows        Friday, November 21, 2008     5:03:09 AM
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                     Pearson Correlation Analysis Results
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NaI_(3-ft) vs. HPIC:

       Column Name    NaI_(3-ft)        HPIC
       Sample Size           6           6
             Minimum Sample Size = 6
                     Correlation = 0.986434
                      Fisher's z = 2.493252
                     Probability = 0.000275


************************************* The End ******************************
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      StatMost for Windows        Friday, November 21, 2008     5:04:27 AM
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                     Pearson Correlation Analysis Results
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NaI_(4.5-ft) vs. HPIC:

       Column Name    NaI_(4.5-ft)        HPIC
       Sample Size           6           6
             Minimum Sample Size = 6
                     Correlation = 0.980291
                      Fisher's z = 2.304961
                     Probability = 0.000579


************************************* The End ******************************
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The p-value for the correlation in shown Figure 2.9-11 is 0.000012:

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      StatMost for Windows        Friday, November 21, 2008     4:57:59 AM
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                     Pearson Correlation Analysis Results
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NaI_(3-ft) vs. NaI_(4.5-ft):

       Column Name    NaI_(3-ft)        NaI_(4.5-ft)
       Sample Size           6           6
             Minimum Sample Size = 6
                     Correlation = 0.997198
                      Fisher's z = 3.284658
                     Probability = 0.000012


************************************* The End ******************************
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The p-values for the correlations in shown Figure 2.9-14 are 0.000055 (LC) and 0.000002 (LS):

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      StatMost for Windows        Friday, November 21, 2008     5:29:36 AM
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                     Pearson Correlation Analysis Results
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3-ft_HPIC_Eq_(LC) vs. Ra-226_(LC):

      Column Name    3-ft_HPIC_Eq_(LC)       Ra-226_(LC)
      Sample Size          10           10
            Minimum Sample Size = 10
                    Correlation = 0.939430
                     Fisher's z = 1.733173
                    Probability = 0.000055


************************************** The End ******************************
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      StatMost for Windows        Friday, November 21, 2008     5:31:10 AM
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                     Pearson Correlation Analysis Results
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3-ft_HPIC_Eq._(LS) vs. Ra-226_(LS):

      Column Name    3-ft_HPIC_Eq._(LS)       Ra-226_(LS)
      Sample Size          10           10
            Minimum Sample Size = 10
                    Correlation = 0.974875
                     Fisher's z = 2.182200
                    Probability = 0.000002


************************************** The End ******************************
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The calculated p-values above indicate that all of these correlations are significant at a confidence level of at least 99.8%. In each case there is less than a 0.2% probability that the correlation has resulted from random chance, or that rejecting the null hypothesis would be an incorrect conclusion.

i. For Figures 2.9-7 – 2.9-9, 2.9-11 and 2.9-14, provide the paired X and Y coordinate data points and where these are located in the application.

The locations of NaI/HPIC cross-calibration measurements and gamma/Ra-226 correlation plots are shown in Figure 2.9-4, with correlation plot locations shown again in Figure 2.9-6. Some of the analytical values used for the correlations provided in the cited figures are shown in Table 2.9-1 of the application. For

completeness and ease of reference, all sampling/measurement location coordinates and respective analytical data used for the correlations in the cited figures are presented in the table below.

Sampling Location ID	Latitude (DD North)	Longitude (DD West)	Mean Ra-226 (pCi/g)	Mean U-nat (pCi/g)	Mean HPIC Reading (uR/hr)	3-foot HPIC Equivalent (uR/hr)	Mean 4.5-foot NaI Reading (µR/hr)	Mean 3-foot NaI Reading (µR/hr)
LC-1	42.14155	107.88055	8.8	8.7		25.8	31.6	
LC-2	42.11874	107.88639	4.1	2.0		20.1	23.4	
LC-3	42.10628	107.87012	6.7	2.6		24.3	29.4	
LC-4	42.11892	107.86263	5.9	3.0		23.7	28.6	
LC-5	42.13146	107.87123	4.2	1.1		20.0	23.2	
LC-6	42.14215	107.85717	7.7	3.4		27.9	34.6	
LC-7	42.13118	107.85932	7.8	4.4		27.1	33.4	
LC-8	42.13024	107.85688	5.7	1.9		22.6	26.9	
LC-9	42.13038	107.84396	4.6	1.1		20.8	24.4	
LC-10	42.13951	107.82803	4.7	1.1		20.8	24.4	
PIC-LC-1	42.11733	107.86353			23.6		30.2	31.4
PIC-LC-2	42.10687	107.87045			33.0		41.4	44.0
PIC-LC-3	42.12827	107.87157			20.7		22.2	22.1
PIC-LC-4	42.13095	107.85934			25.7		34.3	35.5
PIC-LC-5	42.13122	107.85960			37.7		47.2	53.4
PIC-LC-6	42.13195	107.84903			21.7		24.9	25.3
LS-1	42.25496	107.62914	4.0			18.0		
LS-2	42.24552	107.63335	7.0			26.7		
LS-3	42.24333	107.62289	7.6			27.8		
LS-4	42.23494	107.61988	11.9			35.9		
LS-5	42.23527	107.62859	6.9			28.3		
LS-6	42.23888	107.62864	5.1			23.0		
LS-7	42.23656	107.63339	7.5			26.8		
LS-8	42.23776	107.63977	8.8			31.8		
LS-9	42.23095	107.65234	5.5			22.3		
LS-10	42.22769	107.63492	3.9			19.7		

j. For the relevant dates that data was used for correlation, provide the quality control charts titled "Lost Creek: Check Source QC chart for ATV Instruments" or indicate where these can be found in the application.

After a careful review of all relevant information and data, instrument control charts have been revised to include all QC data collected during the survey. Explanations and discussion are provided in this response, along with supporting data and analyses to provide the most complete assessment possible concerning instrument performance and data uncertainty.

QA/QC Program Overview

The purpose of the QA/QC program for this project was to ensure and demonstrate that the data and information generated would be of sufficient quality to meet the project objectives. The project objectives were to provide reliable (reproducible)

characterizations of the spatial distributions of gamma exposure rates and gamma-based estimates of Ra-226 concentrations in surface soils (0-15 cm) across a large site (about 4,400 acres). A recent peer-reviewed paper discussing the same survey methodology used for this project has been published in the journal Health Physics (Whicker et al., 2008). That paper is included as an attachment to this response because it contains information pertinent to the reliability of this survey approach.

Overall components of the applied QA/QC program for the baseline gamma survey at Lost Creek are summarized in Section 2.9.1.2 of the application. Specific elements of the program that are most relevant to this discussion are as follows:

1. All gamma detectors used during the survey were calibrated by the manufacturer within one year prior to use on this project.

   Purpose: Maintain detector accuracy relative to known gamma exposure rates from a Cs-137 calibration source under controlled measurement conditions at the manufacturer's laboratory

2. Daily QC measurements during the project included static readings of ambient background gamma exposure rates as well as readings from a Cs-137 check source.

   Purpose: Establish the degree of measurement agreement (precision) within and between detectors on each individual day of survey activities, both at low gamma field intensities (background readings) and at high gamma field intensities (check source readings). These measurements are used to evaluate each instrument against performance acceptance criteria (quality control limits), and to provide a daily indication of data uncertainty due to normal instrument variability at different gamma field intensities. Another purpose is to provide an indication of the degree of data uncertainty associated with natural temporal variability in background gamma exposure rates.

3. Scan results for each vehicle are reviewed daily for consistency along scan track paths for all onboard detectors.

   Purpose: Assess the degree of spatial agreement between onboard detectors along each vehicle's scan tracks and evaluate detector/system performance under actual scanning conditions. Obvious inconsistencies result in elimination of the questionable data from the project database and replacement of the subject detector with a factory-calibrated spare detector. Spare detectors immediately become subject to standard QC

assessment protocols to verify consistency with all other properly functioning scan detectors/systems.

Bullet number 2 above warrants additional discussion as it references "quality control limits" for evaluating instrument performance. Radioactive decay is a random process that follows a binomial probability distribution. Detector readings will thus naturally vary from one counting interval to the next. If the total number of measured counts exceeds about 20, both Poisson and normal distributions can be used to accurately describe radiation measurements (Martin & Lee, 2003). Both of these distributional approximations are valid for measurements of ambient gamma radiation with NaI scintillation detectors.

A Chi-Square dispersion test can be used to assess the performance of individual radiation measurement instruments against the Poisson distribution (Martin & Lee, 2003). This test is broadly applicable to many different types of instruments because in certain applications, the number of counts measured is less than 20 and only the Poisson distribution applies. For environmental gamma surveys using NaI detectors, properties of the normal distribution can be used as simple, effective way to assess individual detector performance.

With a correctly functioning NaI detector, a series of successive readings in a fixed location and measurement geometry should approximate a normal distribution, meaning that over 99% of the data should fall within ± 3 standard deviations from the mean of all measurements. Whether taking a single measurement, or the mean of several measurements, the normal distributional characteristics of the underlying count data are preserved (Martin & Lee, 2003). Taking the mean of several measurements, however, provides a better estimate of a true average count rate. The standard procedure for daily QC measurements from each NaI detector is to record the mean of 10-20 successive readings for assessment of instrument performance.

For this gamma survey application, we are equally concerned with the relative performance between instruments as multiple detectors are used. Even properly calibrated detectors will have slight differences in response characteristics between different instruments and this will add additional variability to survey data in the form of small relative biases between various detectors. Variability within and between detectors is additive. Analyses of various QC data sets, collected indoors under fixed counting geometries for different gamma survey projects, each indicate that combined variability from both sources will still approximate a normal distribution (Figure A). Properties of the normal distribution can thus be used to evaluate the performance of each detector relative to the total degree of measurement precision attained by the entire set of detectors used for the survey.

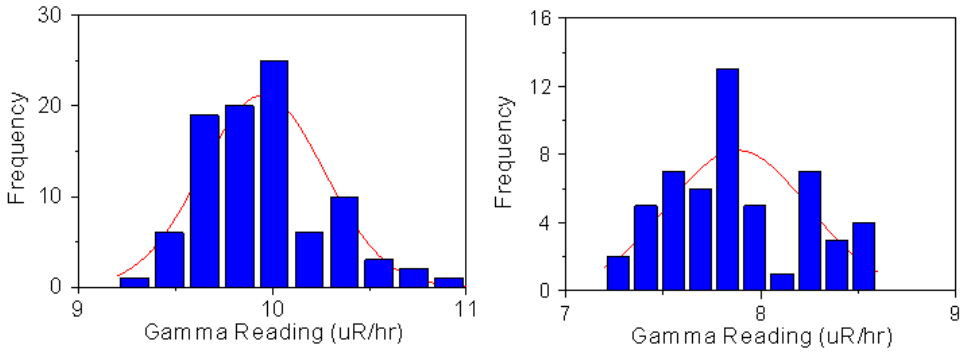

Figure A: Example frequency histograms for two series of QC measurements from different NaI detector sets used for two separate gamma survey projects. Each series was taken indoors under controlled measurement geometries. The red lines represent theoretical normal distributions.

Quality control data for each detector are plotted on QC charts that include control limit lines calculated for the particular set of detectors used on a given survey project. Field background and check source QC charts also show other lines that are useful for QC assessment, including the mean, as well as ± 1, 2, and 3 standard deviations from the mean, as separately calculated from their respective QC data sets. This enables a quick visual assessment of individual QC data relative to the overall degree of measurement precision attained by the entire set of detectors used for the survey. For each individual detector, daily QC measurements plotted on QC charts should fall within ± 3 standard deviations from the mean of all QC measurements. If QC readings are outside of these control limits, further investigation is warranted. This is true for both background readings as well as check source readings.

Background QC readings can occasionally fall outside of respective control limits due to natural temporal variations in ambient gamma exposure rates. Temporal variability can result from changes in natural shielding factors for terrestrial or cosmic sources such as changes in soil moisture or barometric pressure, and from fluctuations in radon decay product concentrations in air. To help account for temporal sources of variability not related to actual detector performance, control limits are calculated on a moving average basis. In addition, when a control limit is exceeded, data from the affected detector are not automatically excluded from the survey data set unless control limits were exceeded on both background and check source QC charts. In cases where only one control limit is exceeded, the corresponding scan track data are carefully reviewed for spatial/quantitative consistency with tracks for other on-board detectors to make a final determination regarding data validity.

Field Background QC Assessment for Lost Creek

An updated QC chart containing all field background QC data collected during the project is shown in Figure B. The indicated control limits (± 3 standard deviations) are based only on data collected from 9/6/06 through 9/11/06 because scan system staging locations and related QC protocols were consistent during these dates. These control limits are conservative with respect to QC data collected outside of this period because the consistency of location helps limit data variability to that associated with the detectors themselves, effectively minimizing control limit width relative to the mean.

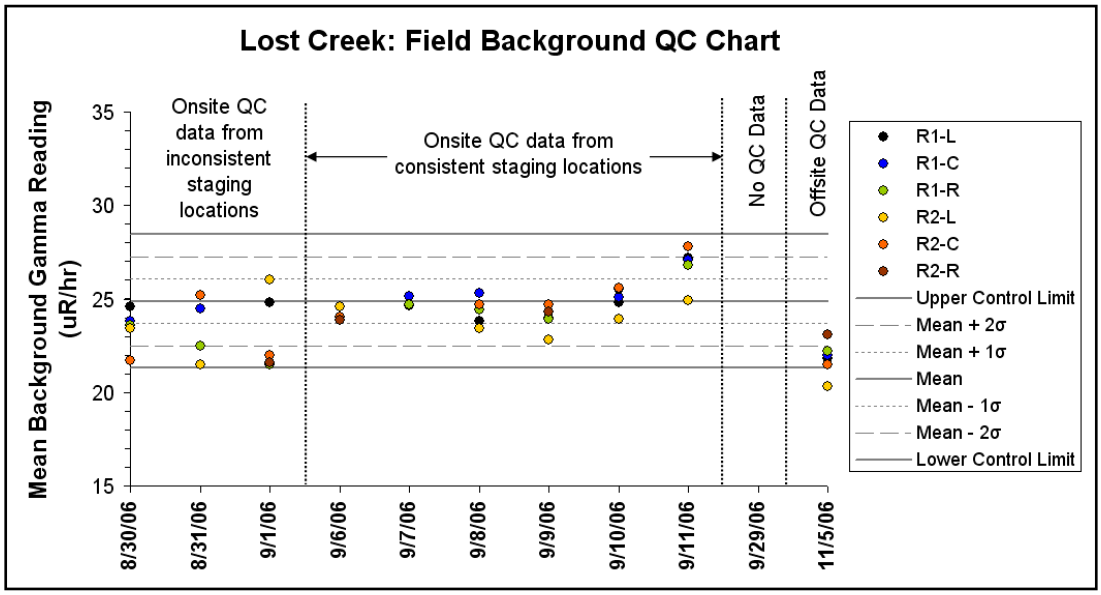

Figure B: Field background QC measurements for the dates of all activities related to the gamma survey at Lost Creek.

Although QC readings for the first three days of the survey are within conservatively calculated quality control limits, the variability of these data was higher because staging locations and related QC protocols were inconsistent during this initial period. These initial inconsistencies were related to: 1) a need to adapt the Rhino ATV systems' mounting infrastructure and suspension systems to handle unexpectedly rough micro-topography from soil mounds associated with the dense sagebrush vegetation; and 2) a determination that a 3-foot detector height was not practical for this type of survey given the frequency of deep ravine crossings, tall vegetation, and fence gate crossings.

These circumstances contributed to initial difficulties in determining a practical, consistent, and effective protocol for static QC measurements. As a result, background QC data through 9/1/06 are questionable and were not considered useful for assessment of data uncertainty, nor a valid reflection of actual instrument performance during this period, and were thus not included in the license application. We now recognize that a discussion explaining the excluded data could have facilitated complete review, had it been included in the original license application.

Background QC data from 9/6/06 through the final day of general site scanning on 9/11/06 were collected at a consistent staging location and are well within acceptable control limits. However, on 9/6/06 and 9/7/06, QC data were only collected for one of the two sets of Rhino ATV detectors. Rhino-1 measurements were missing on 9/6/06, and Rhino-2 measurements were missing on 9/7/06. It is believed that incomplete QC measurements on these two days were related to circumstances surrounding continued modifications or repairs to detector mounting systems. Background QC data from the period 9/8/06 through 9/11/06 were included in the application because these data provide a reliable measure of data uncertainty and instrument performance, and all six onboard detectors used for site scanning on these days were evaluated.

On 9/29/06, the day that gamma/soil Ra-226 correlation plot scanning and sampling was conducted, no static QC measurements were performed. These measurements were planned for the end of the day but insufficient time remained after performing all scheduled correlation activities. However, quantitative evidence of measurement precision within and between the detectors used on this date is inherent in the nature of the data collected. Mean scan data for each of the three individual detectors used at each correlation plot (Figure C) demonstrate excellent consistency of readings between detectors, at locations representing the most pertinent range of ambient gamma exposure rates with respect to the ultimate use of the data collected.

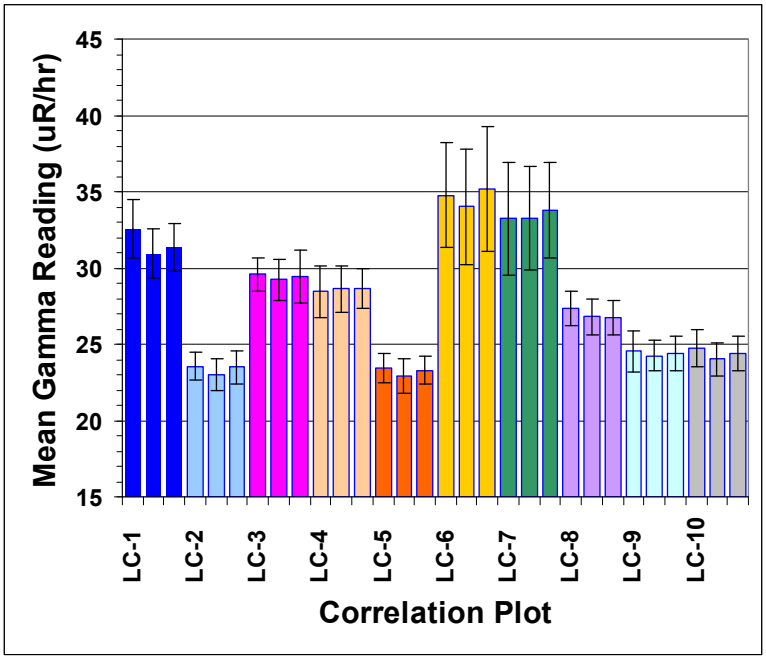

Figure C: Mean readings at each correlation plot location for each of the three individual detectors used for plot scanning. Error bars represent ± 1 standard deviation from the mean of approximately 45-50 readings for each detector across each plot.

The scale of the Y-axis shown in Figure C corresponds to the general range of virtually all gamma measurements at the Lost Creek site. As is readily apparent in Figure 2.9-3 of the license application, the vast majority of survey readings were between 20-35 µR/hr. Because this latter range of survey readings is most representative of the entire site, it demonstrates the relevance of the range of the data shown in Figure C with respect to data QC issues. This is important to note because correlation data were used to convert gamma survey data into estimates of soil Ra-226 concentrations across the site. Error bars on mean readings from each detector (± 1 standard deviation) suggest that on the day correlation measurements were performed, the detectors would have easily satisfied analogous control limit criteria across this range of values.

In addition to the above assessment of the data shown in Figure C, the coefficient of variation (CV) was calculated from the standard deviation of the three mean gamma scan results among the three detectors, divided by the average of the three

mean scan results, at each correlation plot (Table A). The average CV for all plots was 0.012, which demonstrates low variability between detectors, and a high degree of precision, across this key range of gamma levels.

Table A: Mean, standard deviation, and coefficient of variation for mean scan results among the 3 detectors at each correlation plot location.

Correlation Plot	Average of the 3 mean scan results	Standard deviation of the 3 mean scan results	CV for mean scan results among the 3 Detectors
LC-1	31.6	0.86	0.027
LC-2	23.4	0.30	0.013
LC-3	29.4	0.18	0.006
LC-4	28.6	0.10	0.004
LC-5	23.2	0.27	0.012
LC-6	34.7	0.60	0.017
LC-7	33.4	0.30	0.009
LC-8	27.0	0.33	0.012
LC-9	24.4	0.14	0.006
LC-10	24.4	0.35	0.014
		Average CV =	0.012

Finally, background QC data for 9/11/06 and 11/5/06 also demonstrate consistency between detectors on dates that bracket 9/26/06 (see Figure B). QC measurements performed on 11/5/06 in association with high pressure ionization chamber (HPIC)/NaI cross-calibration activities were conducted in an offsite location, several miles from the original staging area. Although these data are not truly applicable to the control limits shown in Figure B, consistency of readings between detectors on this day is clear and there is no reason to suspect the validity of instrument performance during the cross-calibration measurements.

Based on the above follow up assessments of all available information relevant to field background QC data for this project, the evidence demonstrates that the detectors were performing within acceptable limits throughout the survey. The original estimates of data uncertainty as provided in the license application have not changed. Although there were several cases in which detectors exhibited suspect performance or actual malfunctions during the day's scanning (i.e. following morning QC measurements), associated scan track data were clearly identified as being spatially inconsistent with readings from other on-board detectors and the affected data files were eliminated from the project database.

Check Source QC Assessment for Lost Creek

Regarding the collection of QC measurements using a Cs-137 check source (Figure D), additional discussion is required. On 9/9/06 it was discovered that small inconsistencies in the dimensions of protective foam padding placed around the detectors while mounted on the Rhino ATV support systems (intended to reduce vibration and potential impact damage to the detectors) may have introduced error into previous QC measurements [periods (1) and (2) as shown in Figure D] due to slight variations in distance between the check source and the detectors. As a result, none of the check source QC data collected prior to the removal of the foam padding from all detectors (on 9/9/06) were included in the license application. Other QC protocols, including documented calibration status of all instruments, background QC measurements, and daily review of the consistency of scan track data plotted with field mapping software, remained in effect during this period.

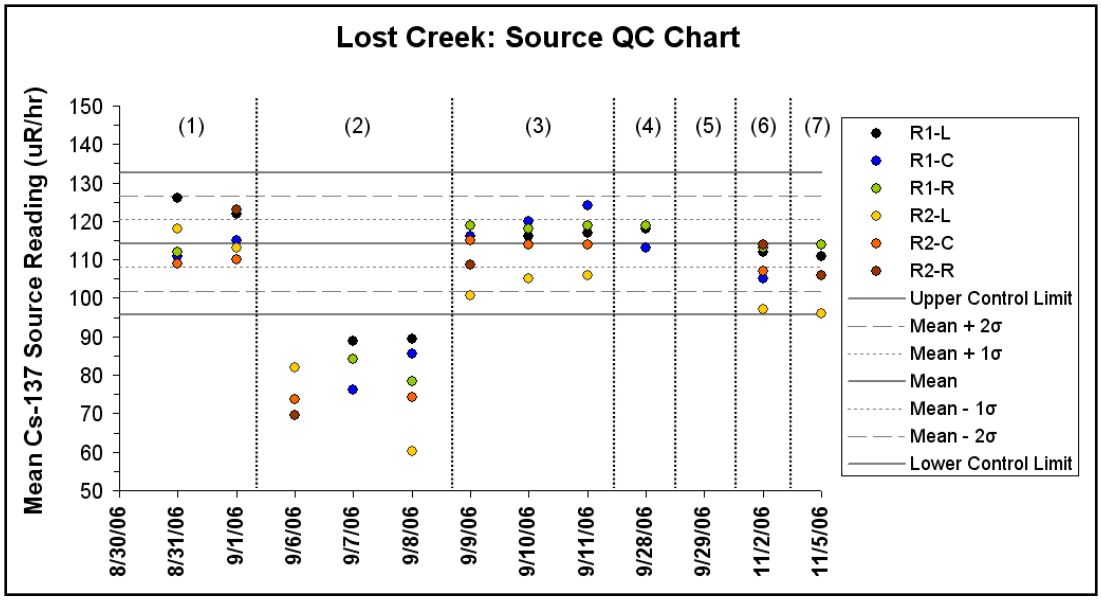

Figure D: Cesium-137 check source QC data for the dates of all activities related to the gamma survey at Lost Creek. Periods or dates of interest are numbered for ease of reference.

After the discovery of geometry problems associated with the protective foam padding, the padding was removed in favor of resilient nylon boom supports and the daily check source measurements became consistent. The control limits shown in Figure D are based only on data collected during period (3) and are thus the same as those provided in the application. Data review indicates that the reason for

the inconsistency in check source readings during time period (2) is related to the foam padding rather than to the detectors themselves. The other QC data and data reviews for this period confirm this conclusion.

After time period (1), the Rhinos were taken back to Fort Collins, CO and the detector mounting systems were modified or re-designed to better handle the rugged site conditions. However, the protective foam padding remained in place during time period (2). When the padding was removed on 9/9/06, the readings return to the normal range of check source QC values and remained this way throughout time period (3). It is likely that during mounting system redesign in Fort Collins, the foam pads were inadvertently shifted downwards, leaving more excess material extending below the detector than before. This could explain the reduction in count data as the distance from the source to the detector would have increased. When measuring a Cs-137 point source, small differences in counting geometry can make a large difference in readings and this element is critical to the applicability of such data.

The anomalous results shown for period (2) do not mean the detectors were functioning improperly during those particular days of scanning activities. The field background data for the same dates are very consistent and clearly indicate proper instrument function. More importantly, review of the scan track data for these dates showed spatial/quantitative consistency between onboard detectors, as well as consistency with other scan tracks along portions of site access roads that were repeatedly scanned throughout the survey. As described in the license application, re-scanning and daily review of consistency between on-board detectors are key components of an overall data QC program for this survey methodology. Such measures are more effective than static QC measurements in terms of evaluating instrument performance under actual scanning conditions. Static QC measurements are only part of an overall QC program to help quantify data uncertainty and assess instrument performance.

With respect to the lack of check source QC data on the date of gamma/Ra-226 correlation measurements [9/29/06, period (5) in Figure D], the correlation plot measurement data shown in Figure C clearly demonstrate the consistency of readings among detectors used on this date, across the pertinent range of gamma exposure rate values with respect to the correlation. Furthermore, check source data collected the previous day [9/28/06, period (4)] from a nearby proposed ISR site (the Lost Soldier project area) are also included in Figure D, along with check source data collected later at the Lost Soldier location [11/2/06, period (6)]. Although the Lost Soldier measurement locations were different from the staging location at Lost Creek, these data bracket the date of the missing check source QC

data for period (5) and indicate consistency in check source measurements between the detectors.

Finally, the day that HPIC/NaI cross-calibrations were performed [11/5/06, period (7) in Figure D], there had been a modification to the Rhino ATV mounting systems that allowed detectors to be easily removed from the vehicles and for QC measurements to be performed in a more controlled indoor environment at a hotel room in Rawlins, WY. Check source QC readings on this day were performed in the hotel room. Although this measurement location was different from the original survey staging area at Lost Creek, these results show consistency in check source measurements between the various detectors used on this day.

Based on the above follow up assessment of all available information relevant to check source QC data for this project, the evidence supports the conclusion that the detectors were performing properly throughout the survey, even at higher gamma radiation levels such as those found in several small areas at the site. It also reinforces the conclusion that the original estimates of data uncertainty provided in the application are based on reliable data.

Summary

The above follow up assessments of data QC for this project demonstrate that throughout this survey, the detectors in use were performing properly and within acceptable limits at both lower (background) and higher (check source) levels of incident gamma radiation. Although there were several instances of missing or inconsistent QC data during the project, numerous other QA/QC measures and protocols were in place at all times, providing both quantitative evidence and qualitative assurance of continuous data reliability with respect to the results and analyses provided in the license application.

The estimates of data uncertainty provided in the license application were based on all available reliable data from field background and check source QC measurements. No changes to those estimates are warranted based on this follow up evaluation. Assessment of both data uncertainty and instrument performance is further strengthened by the data shown in Figure C and the accompanying analyses provided in this response.

Throughout this project, terrain, plant height and other environmental conditions required that constant attention be paid by the system operators to the operational status of each gamma detector instrument system. Only factory-calibrated detector systems were utilized during the work, and a combination of formal QA/QC procedures, combined with extensive operator experience in the application of a

variety of field quality control practices, has resulted in a data set that is of sufficient quality to meet the objectives established for the project.

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Whicker, R.; Cartier, P.; Cain, J.; Milmine, K.; Griffin, M. 2008. Radiological Site Characterizations: Gamma Surveys, Gamma/Ra-226 Correlations and Related Spatial Analysis Techniques. Operational Radiation Safety, Health Physics, Vol. 95 (Supplement 5): S180-S189; November, 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).

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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 high-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

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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.

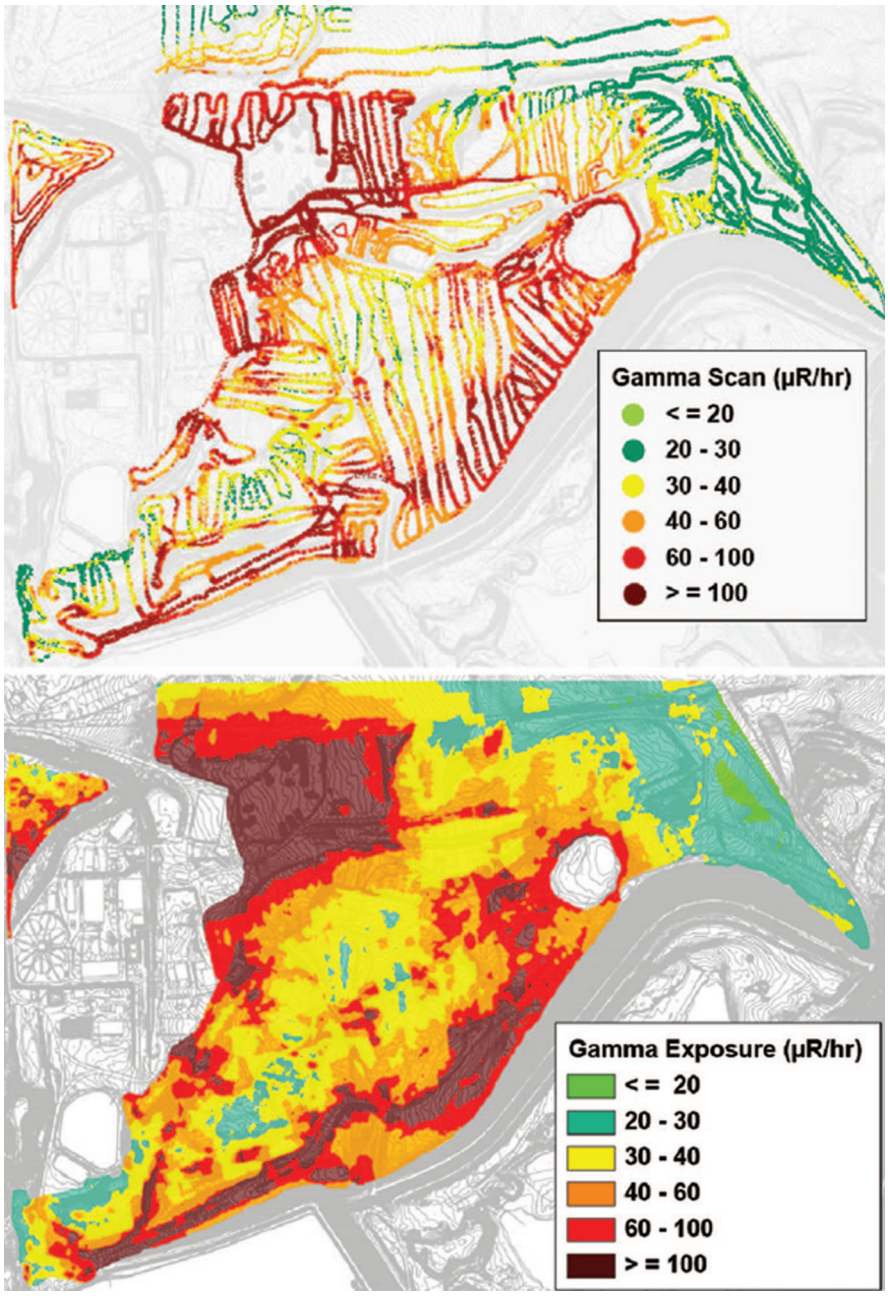

Figure 2. Gamma scan (top) and kriged mapping results (bottom) for the remedial action study area at the uranium mill site.

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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

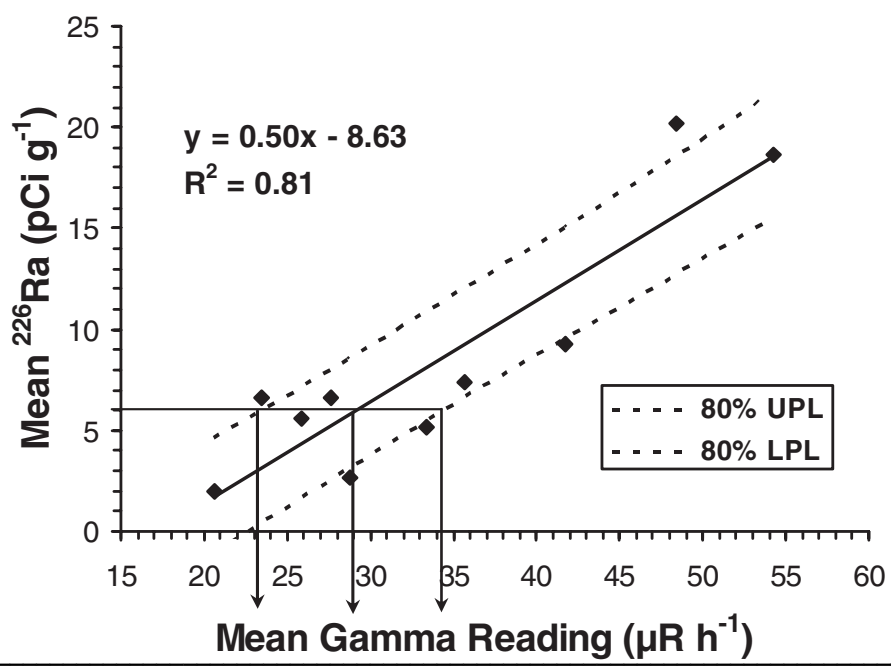

Figure 3. Correlation results for the remedial action study area at the uranium mill site.

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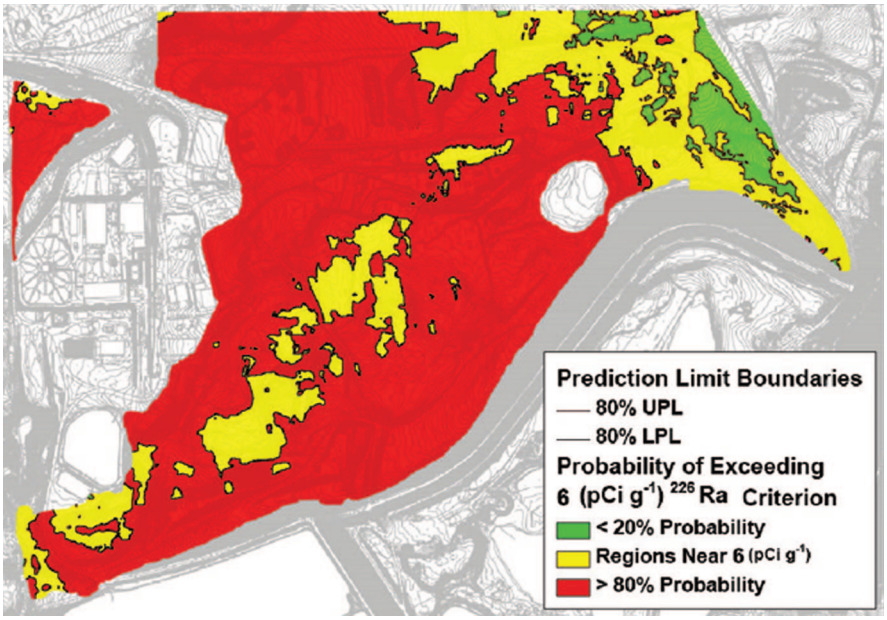

Figure 4. Soil ^{226}Ra probability map for the remedial action study area at the uranium mill site.

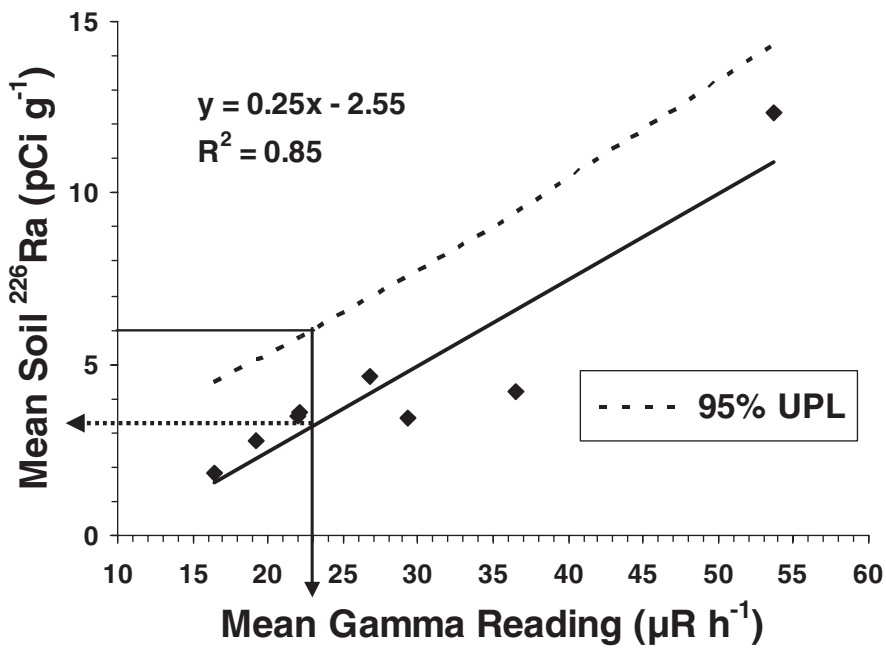

Figure 5. Gamma/^{226}Ra correlation results for the volume study area.

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 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.

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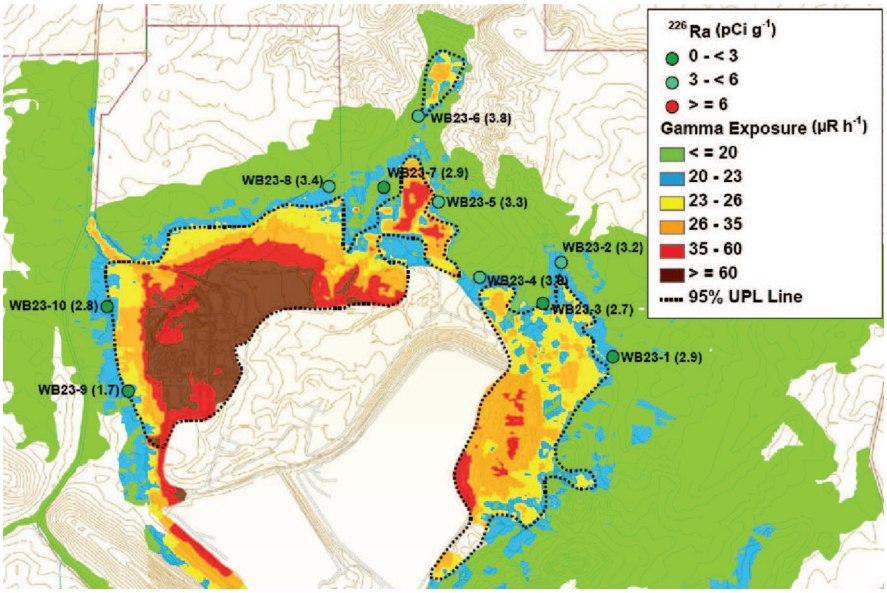

Figure 6. Gamma survey results for the volume study area showing approximate regions with gamma readings above and below 23 μR h^{-1}, the gamma value with a 95% statistical probability of compliance with the ^{226}Ra cleanup criterion. Confirmatory soil sampling locations and annotated ^{226}Ra results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

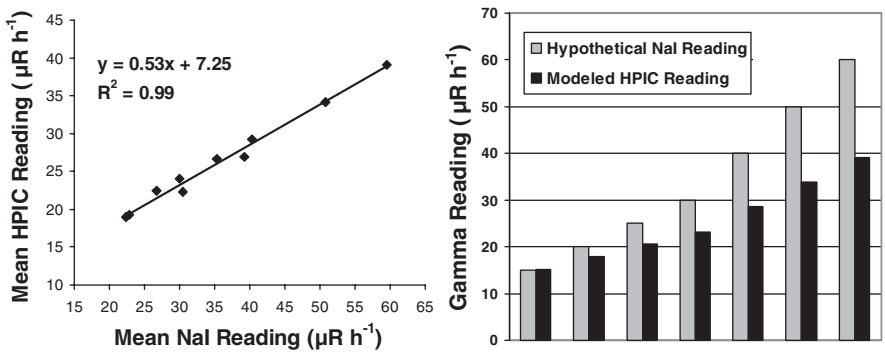

Figure 7. Example HPIC/NaI cross-calibration curve (left) and corresponding modeled differences between NaI and HPIC readings (right) for a proposed ISR uranium site in Wyoming.

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 appeared 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

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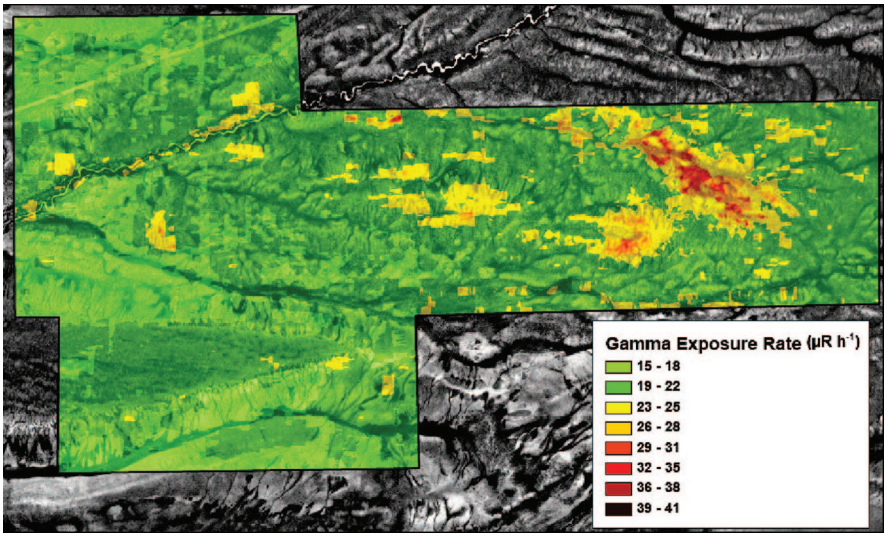

Figure 8. Kriged 1 m HPIC equivalent gamma survey map of a proposed 1,618 hectare (4,000 acre) ISR uranium project area in Wyoming.

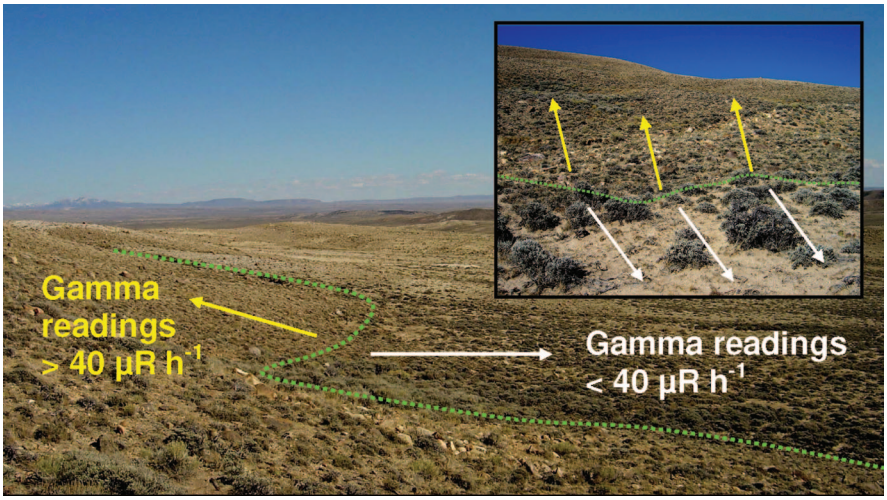

Figure 9. Visible, geomorphic boundary delineating abrupt transition in gamma exposure rates.

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

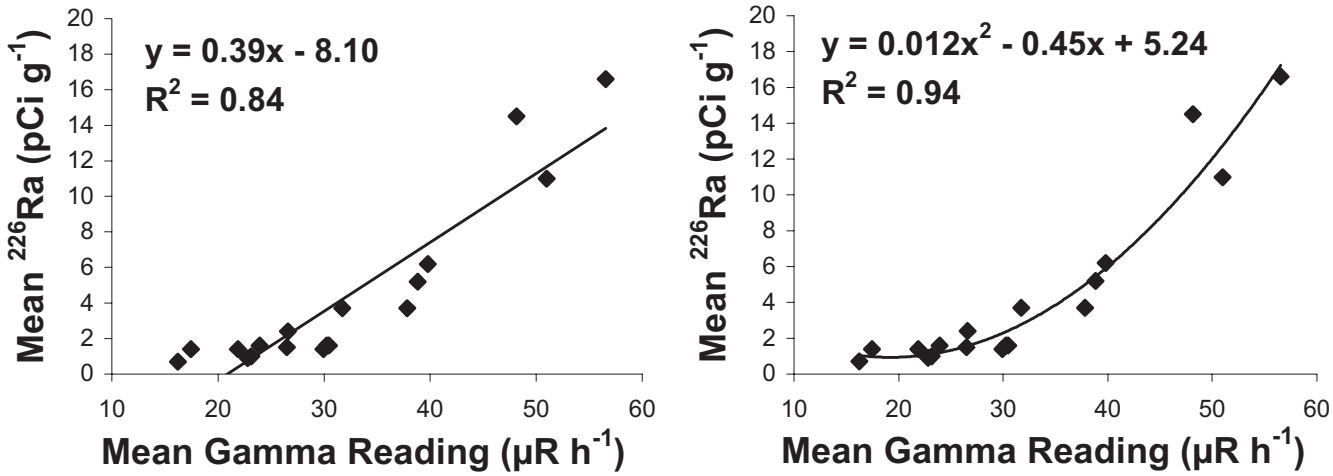

Figure 10. Comparison of linear (left) and nonlinear (right) models fitted to combined gamma/^{226}Ra correlation plot data from two nearby ISR sites in Wyoming.

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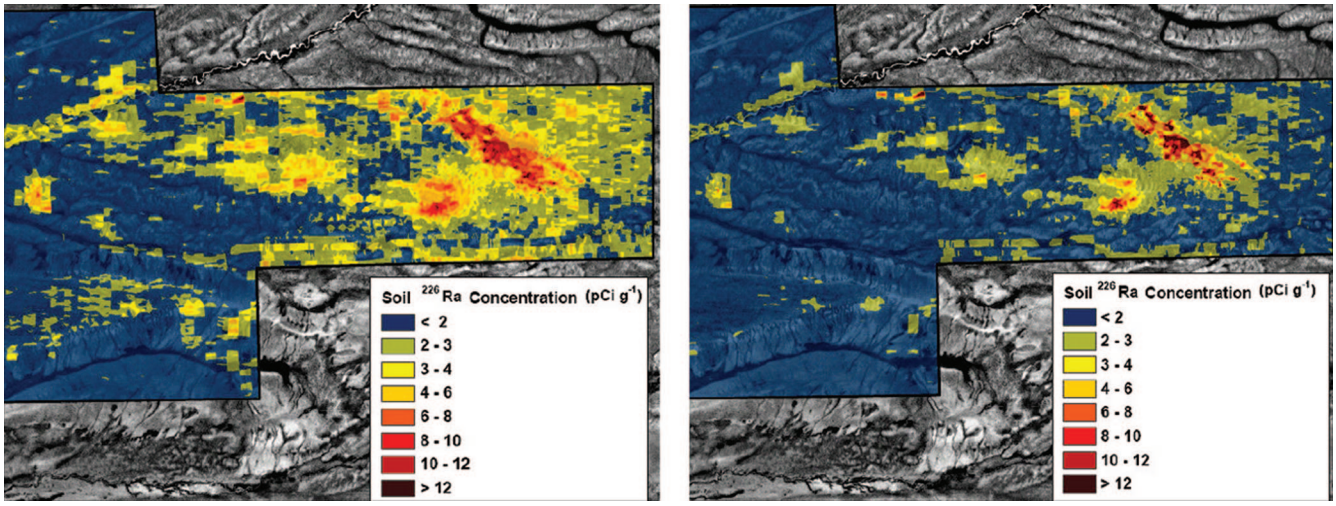

Figure 11. Comparison of continuously estimated soil ^{226}Ra concentrations based on linear (left) and nonlinear (right) models fitted to gamma/^{226}Ra correlation plot data for a proposed ISR site in Wyoming.

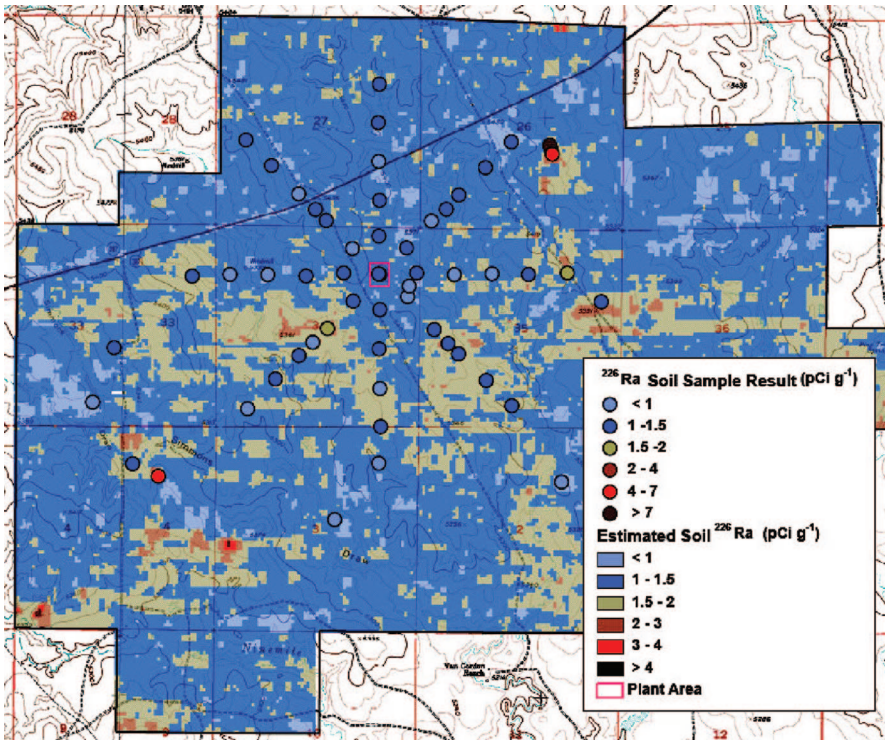

Figure 12. Comparison of continuous estimates of soil ^{226}Ra concentrations predicted with a nonlinear model vs. actual soil sampling results at a proposed ISR site in Wyoming.

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 represented 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.

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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.

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