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Advances in radiological survey capabilities for large sites are discussed.

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

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

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

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INTRODUCTION

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

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

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

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

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

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

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

MATERIALS AND METHODS

Gamma surveys

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

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

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

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

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

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

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

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

HPIC/NaI cross-calibration

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

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

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

Gamma/^{226}Ra correlations

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

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

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

RESULTS AND DISCUSSION

General observations

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

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

Uranium mill site surveys

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

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

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

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

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

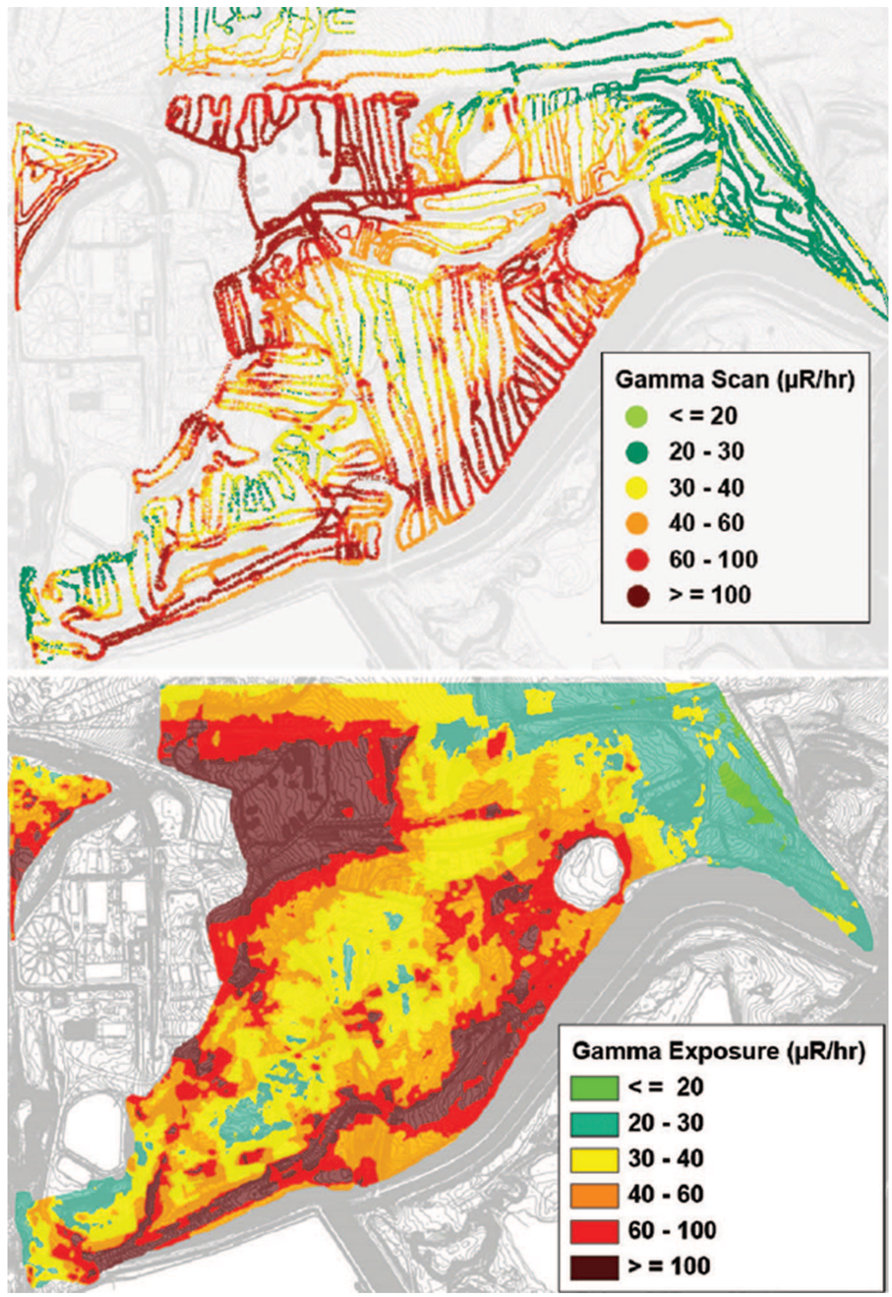

Figure 2. Gamma scan (top) and kriged mapping results (bottom) for the remedial action study area at the uranium mill site.

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

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

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

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

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

Proposed ISR uranium project area surveys

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

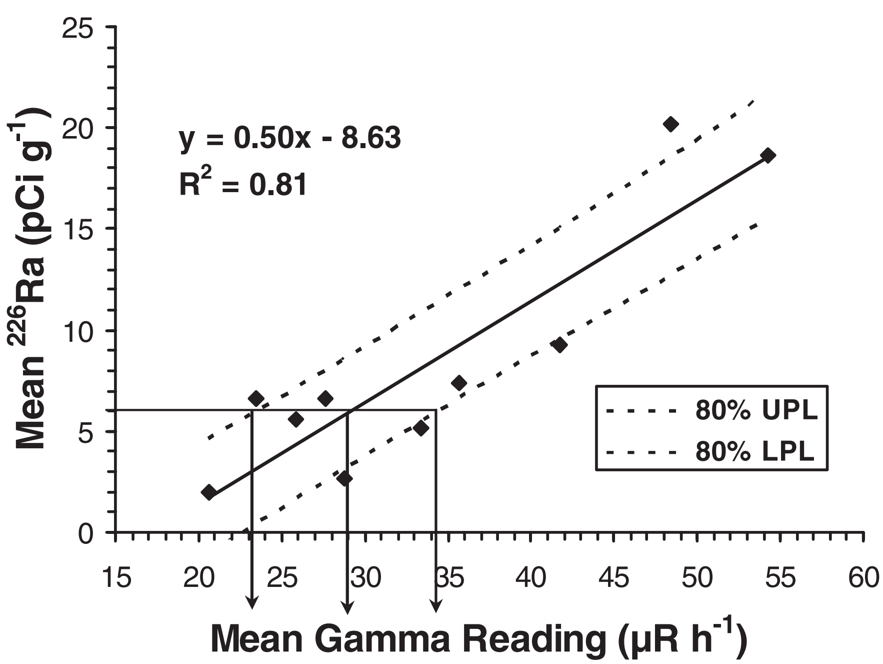

Figure 3. Correlation results for the remedial action study area at the uranium mill site.

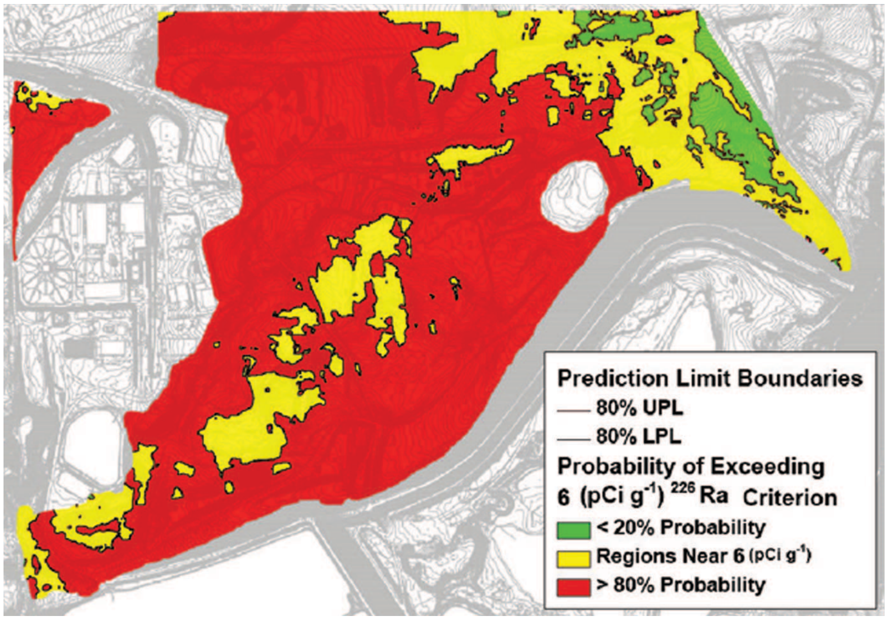

Figure 4. Soil ^{226}Ra probability map for the remedial action study area at the uranium mill site.

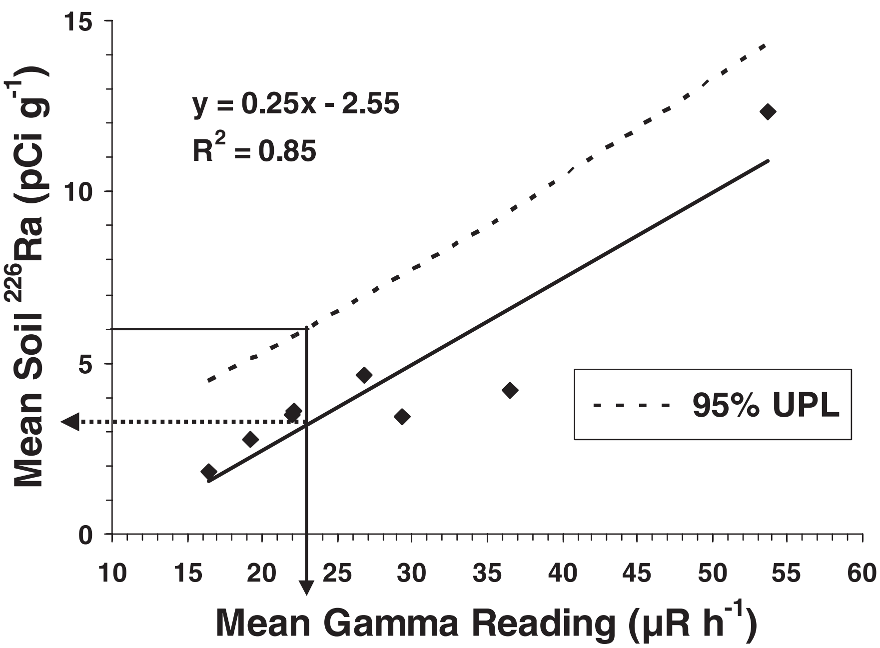

Figure 5. Gamma/^{226}Ra correlation results for the volume study area.

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

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

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

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

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

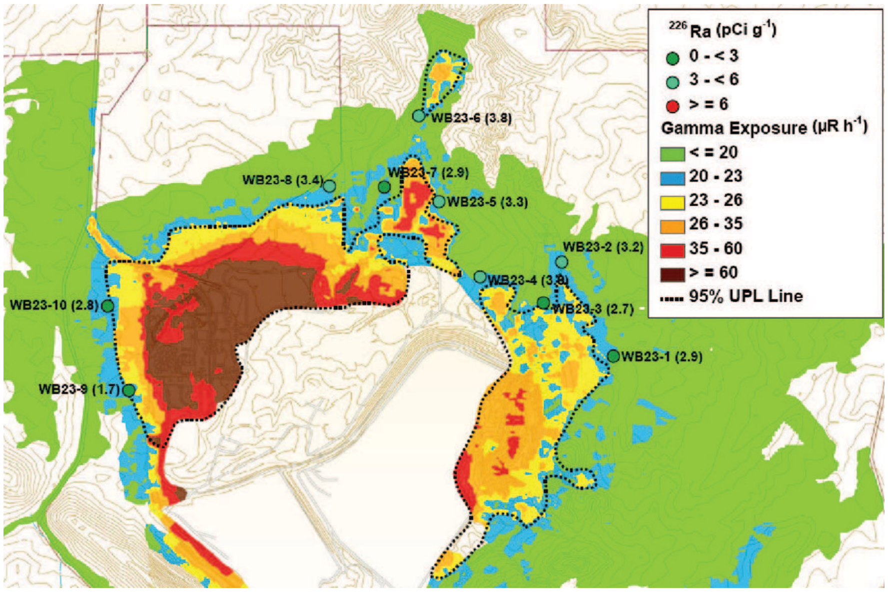

Figure 6. Gamma survey results for the volume study area showing approximate regions with gamma readings above and below 23 μR h^{-1}, the gamma value with a 95% statistical probability of compliance with the ^{226}Ra cleanup criterion. Confirmatory soil sampling locations and annotated ^{226}Ra results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

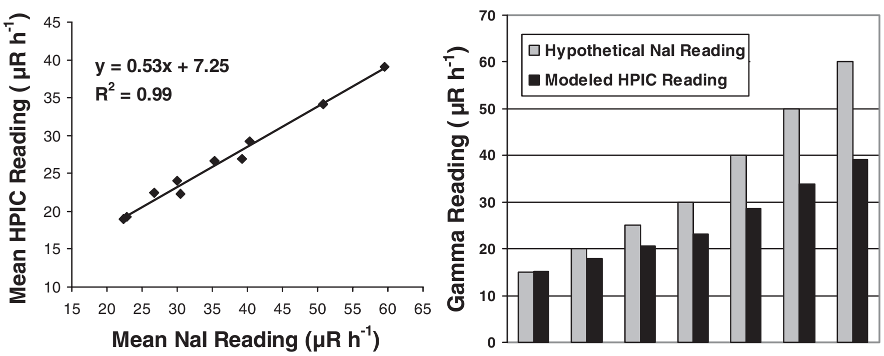

Figure 7. Example HPIC/NaI cross-calibration curve (left) and corresponding modeled differences between NaI and HPIC readings (right) for a proposed ISR uranium site in Wyoming.

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

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

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

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

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

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

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

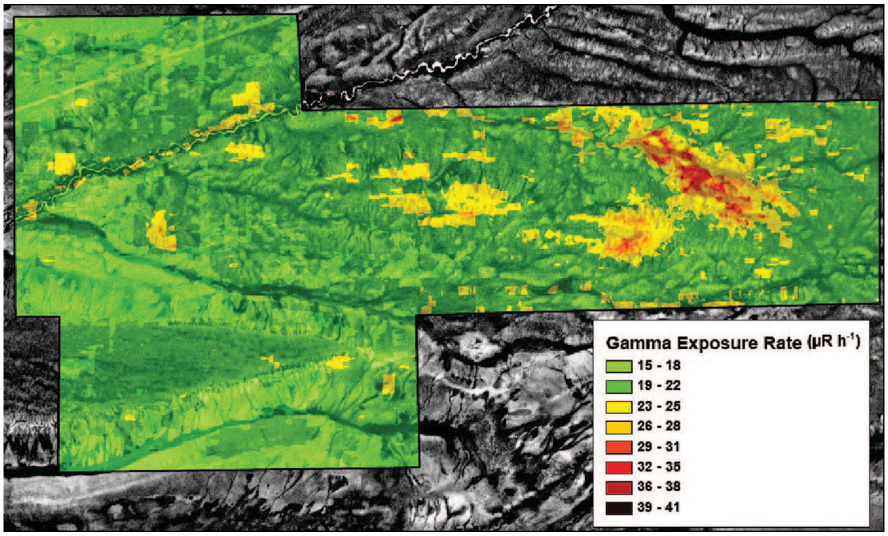

Figure 8. Kriged 1 m HPIC equivalent gamma survey map of a proposed 1,618 hectare (4,000 acre) ISR uranium project area in Wyoming.

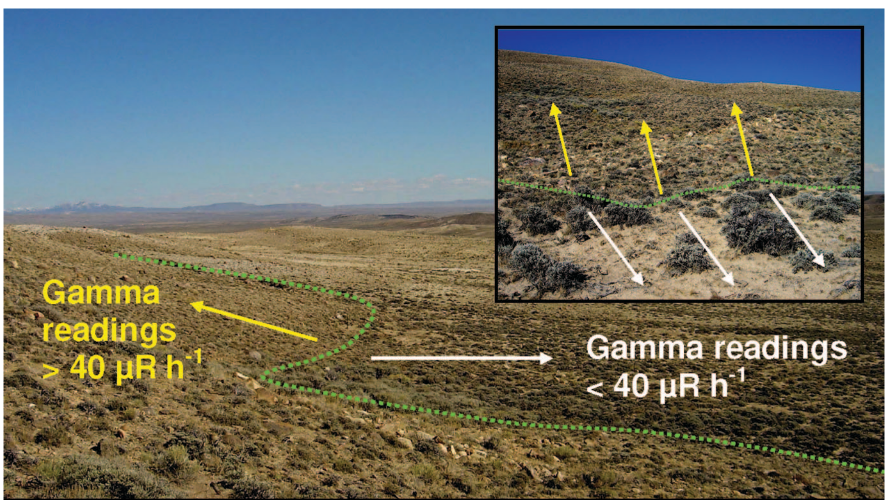

Figure 9. Visible, geomorphic boundary delineating abrupt transition in gamma exposure rates.

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

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

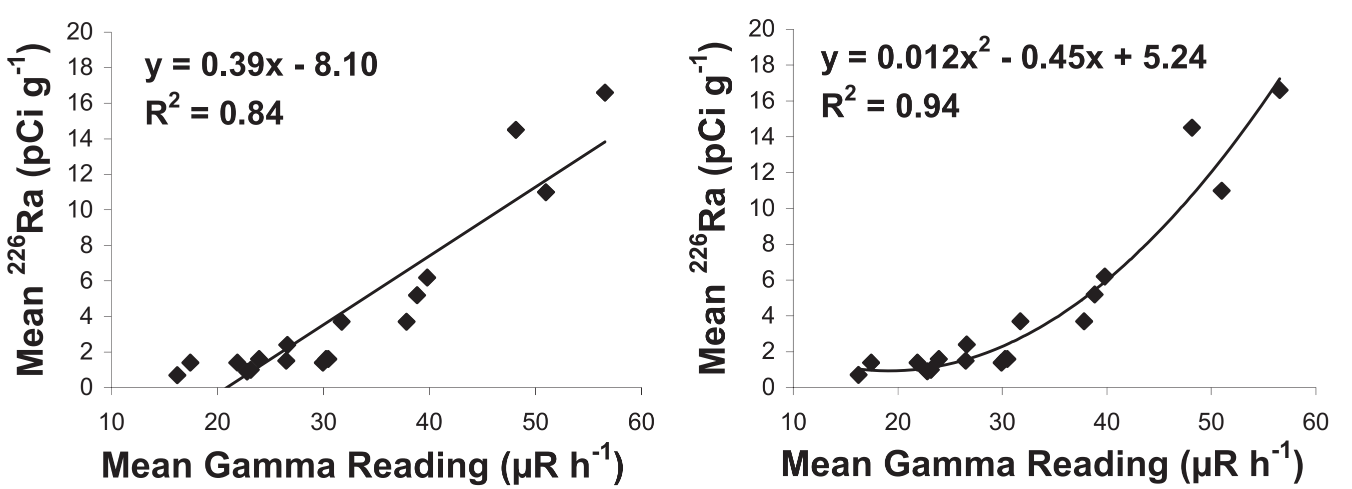

Figure 10. Comparison of linear (left) and nonlinear (right) models fitted to combined gamma/^{226}Ra correlation plot data from two nearby ISR sites in Wyoming.

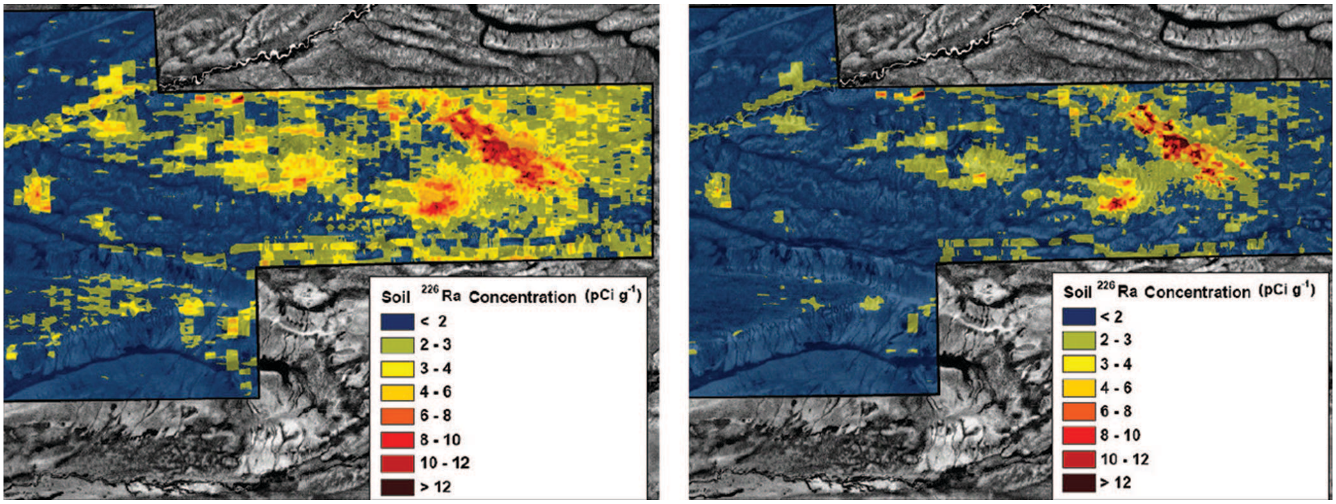

Figure 11. Comparison of continuously estimated soil ^{226}Ra concentrations based on linear (left) and nonlinear (right) models fitted to gamma/^{226}Ra correlation plot data for a proposed ISR site in Wyoming.

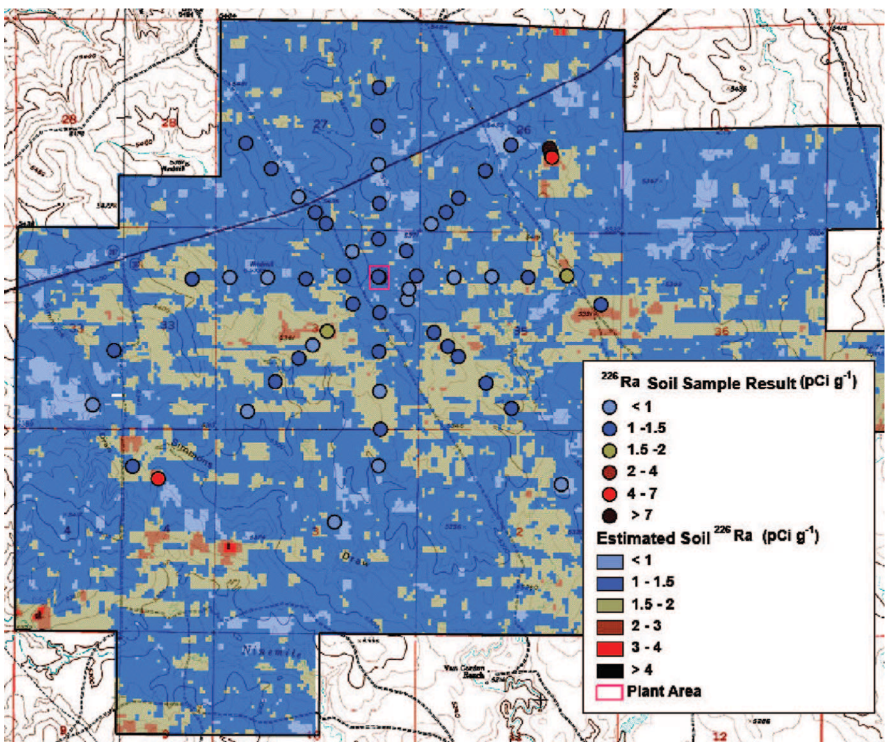

Figure 12. Comparison of continuous estimates of soil ^{226}Ra concentrations predicted with a nonlinear model vs. actual soil sampling results at a proposed ISR site in Wyoming.

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

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

CONCLUSION

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

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

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

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