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PROBABILISTIC COMPARISON OF ALTERNATIVE CHARACTERIZATION TECHNOLOGIES AT THE FERNALD URANIUM-IN-SOILS INTEGRATED DEMONSTRATION PROJECT

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ABSTRACT

The performance of four alternative characterization technologies proposed for use in characterization of surficial uranium contamination in soil at the Incinerator and Drum Baling Areas at the Fernald Environmental Management Project in southwestern Ohio has been evaluated using a probabilistic, risk-based decision-analysis methodology. The basis of comparison is to minimize a computed total cost for environmental cleanup:

$$\text{Total Cost} = \text{Cleanup Cost} + \text{Risk} \quad .$$

This total-cost-based approach provides a framework for evaluating the trade-offs among remedial investigation, the remedial design, and the risk of regulatory penalties. The approach explicitly recognizes the value of information provided by remedial investigation; additional measurements are only valuable to the extent that the information they provide reduces total cost.

Because cost data associated with various aspects of the environmental restoration program at Fernald are rudimentary and incomplete, a simplified objective function for the comparison was developed that focused on minimizing the number of regulatory failures of the alternative characterization technologies to identify parcels indicated as contaminated by standard soil-geochemical analyses, after accounting for geologic uncertainty in site characterization. Uranium concentrations were estimated for an array of 3-m-square grid panels at the Fernald Incinerator and Drum Baling Areas using the data from each of the four alternative characterization technologies (long-range alpha detection, LRAD; wide-area beta-scintillation counting, Beta; high-resolution gamma spectroscopy, Gamma; and, laser ablation-inductively coupled plasma-atomic emission spectrometry, ICP-AES). An unbiased, minimum-variance interpolation technique (kriging) was used to create comprehensive estimated models of the distribution of uranium contamination in space, as characterized by each alternative technology. To provide a basis for comparison and to address uncertainty, 100 stochastic simulations of uranium contamination were generated for the same 3-m panels using geostatistical simulation and conditioned to the soil geochemistry data. Each realization represents a plausible map of uranium concentration that is consistent with the measured data, the histogram, and variogram displayed by the actual soil geochemistry samples. A false negative misclassification error, or regulatory failure, occurs when the alternative characterization technology failed to identify a parcel indicated by the soil-geochemistry measurements as likely to be contaminated.

The comparison indicates that the LRAD detector produced the smallest number of regulatory failures at low remediation thresholds, which probably approximate as-yet undetermined regulatory cleanup criteria. The LRAD device achieves this performance at the expense of producing a large number of false positive determinations. Whether this conservatism reduces *total* cost requires additional cost data not yet available. At higher contaminant thresholds, the several alternative technologies appear to produce roughly comparable results, generally resulting in many fewer regulatory failures.

INTRODUCTION

A large number of sites at U.S. Department of Energy (DOE) facilities are currently contaminated with mixtures of radioactive, inorganic, and organic waste. The combined costs of remedial investigations and remediation activities at these facilities is expected to cost hundreds of millions of dollars with existing environmental technology (1). The objectives of the Uranium-in-Soils Integrated Demonstration (ID) Program in the DOE Office of Technology Development are to develop and evaluate alternative technologies that have the potential for reducing these costs. This report presents the preliminary results of a case study designed to evaluate the utility of risk-based decision analysis to problems of uranium contamination of surface soils at the Fernald Environmental Management Project (FEMP) (2, 3).

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Background

The remediation of a contaminated site has traditionally been performed in a series of sequential steps that are typically classified as remedial investigation, feasibility study, remedial design, construction/operation, and performance monitoring. During remedial investigation, information is collected on the nature, extent, and severity of contamination. This information is then used to evaluate the applicability of alternative remedial strategies (feasibility study). Information provided by remedial investigation is often incomplete. Incomplete information translates into uncertainty in the boundaries between contaminated and uncontaminated zones, and increases the risk that the remedial design may fail to meet regulatory requirements.

To reduce uncertainty in the estimated distribution of contaminants, additional samples can be collected and analyzed; as the number of measurements increases, uncertainty decreases. Increasing the number of measurements increases the cost of remedial investigation; however, the increase in investigation costs may be offset by decreased treatment costs. This reduction results from more precise definition of contaminated soil zones and by a decrease in the risk of failing to identify contaminated zones at the site.

Decision-Analysis Approach

The decision-analysis process utilizes an approach wherein decisions are evaluated by computing the effect that decisions have on a computed total value (4):

Value = Benefit - Cost - Risk . (Eq. 1)

In the case of contaminant remediation, there is usually no "benefit" in the sense of income to the client; all benefits are accrued through a reduction in costs and risk. Costs can be represented as the sum of the cost of remedial investigation and the cost of site remediation. The risk term is the expected cost of failure, that is, the costs that are accrued if site remediation does not meet regulatory requirements.

Eq. 1 provides an objective framework for quantifying the interrelationships and trade-offs among remedial investigation and design activities. Perhaps the most important feature of this approach is that it explicitly recognizes the value of information obtained during remedial investigation; *measurements are valuable only to the extent that the information they provide reduces total cost.* Thus, the approach provides a rational procedure for evaluating the quantity of actual information provided by the alternative technologies being developed in the ID Program.

METHODS

Site Description

The Fernald site is located near the town of Fernald, Ohio, approximately 100 miles northwest of Cincinnati (Fig. 1). Soils at the site have been contaminated with particulate uranium metal and other compounds by operation of the DOE Feed Materials Production Center over a period of approximately 40 years between 1950 and 1990. Portions of the site are also known to be contaminated by heavy metals and organic solvents (2, 3).

Two study areas at the Fernald Site, the Incinerator Area and the Drum Baling Area, were selected for the ID Program (Fig. 2). The Drum Baling Area was selected to represent portions of the site with highly localized regions of contaminated soils and high uranium concentrations. Contamination at the Drum Baling Area is attributed to spills of uranium-bearing powders and to waste waters from cleaning of uranium-contaminated shipping drums. The Incinerator Area was selected to represent portions of the site with extensive areas of contaminated soils, but much lower uranium concentrations. Contamination at the Incinerator Area is attributed to aerial deposition of uranium particulates produced by incineration of uranium-contaminated waste (e.g., lab coats, gloves).

Data Collection

Remedial investigations at Fernald collected measurements of uranium concentration obtained in the laboratory by conventional analysis of soil samples (soil geochemistry) and in the field using four alternative characterization technologies. The sampling plan was designed to obtain measurements of uranium concentration at identical locations on regular sampling grids. However, for various logistical and historical reasons, soil geochemistry measurements were made on a different sampling grid than the one used for the four screening technologies. Other problems resulted in

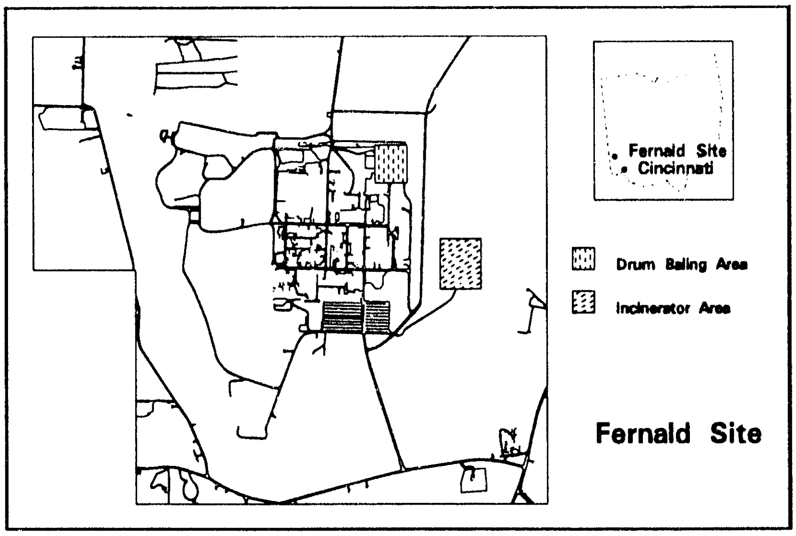

Fig. 1. Location map of the Fernald site in southwestern Ohio and showing the location of the study areas for the Uranium-in-Soils Integrated Demonstration Project within the Feed Materials Processing Center complex.

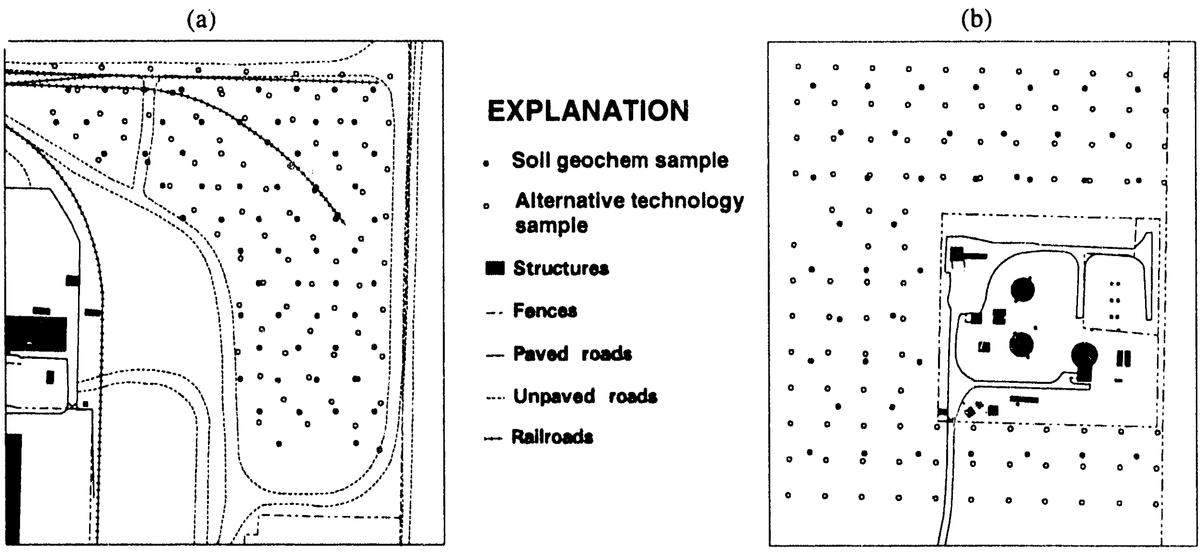

Fig. 2. (a) Sample grid locations and relevant features of the Drum Baling Area. (b) Sample grid locations and relevant features of the Incinerator Site.

incomplete sampling by some technologies; not all technologies were demonstrated in both locations. The final sample locations for the Drum Baling and Incinerator Areas are shown in Fig. 2.

Alternative Characterization Technologies

The LRAD, Beta, and Gamma technologies are radiometric methods that measure emission of various types of radiation associated with uranium and uranium daughter-product decay. The ICP-AES method is a novel field implementation of standard atomic-emission spectroscopy.

The LRAD system, developed at Los Alamos National Laboratory (5), detects the emission of alpha particles (and other ionizing radiation) by collecting and measuring ions produced when alpha particles are stopped in air. Because ambient air forms the detecting medium, the field LRAD system is configured to be placed directly upon the ground and detects uranium in the surface soil. The LRAD system tested at Fernald was designed to monitor contamination over an approximately 1-m^2 surface area.

The Beta detection system, developed at Pacific Northwest Laboratories (PNL) (6), consists of multiple layers of plastic scintillating material designed to measure the emission of beta particles from the upper approximately 1-cm of soil. The device detects the 2.29-MeV beta particles from ^{234}protactinium, a daughter product of ^{238}U decay. The system attempts to discriminate between high-energy beta particles and interfering background radiation by using coincidence-counting techniques, which identify the target high-energy beta particles by the depth to which they penetrate into the plastic layers. The device used in the field tests was designed to monitor a surface area of approximate 0.1 to 0.2 m^2.

The Gamma system, also developed by PNL (6), is an adaptation of standard gamma-ray spectrometry techniques. Gamma radiation incident on the detector is converted to electrical pulses with magnitudes that are directly proportional to the energies of gamma rays from specific radionuclides. A germanium diode is suspended 1 m above the ground from a tripod and is collimated by specially shaped heavy metal shields to collect data from an area of approximately 100 m^2. Because of the penetrating nature of gamma rays, the spectrometer detects uranium from both exposed and subsurface soils to a maximum depth of 40 to 50 cm, with sensitivity decreasing both with depth and outward from the center point of the measurement.

The ICP-AES system is a standard laboratory analytical method that was adapted for field applications by Ames Laboratory (7). A neodymium-yttrium-iron-garnet laser is used to ablate a small quantity (10-20 mg) of *in-situ* soil while an argon gas stream entrains the sample particles and transports them directly into an inductively-coupled plasma (ICP) burner located in a field trailer. The atomic emission spectrum from the ICP is transferred by fiber optics to a spectrometer for quantitative analysis of total uranium. During the course of an individual measurement, the ablating laser beam is incrementally scanned over a sampling area of about 6.5 cm^2.

EVALUATION APPROACH

Decision Model

The evaluation process (4) consists of first identifying a set of *i* alternative actions, here, the use of one of four alternative measurement technologies, and then selecting from among those alternatives the one that results in the maximum value of an objective function, Φ:

Maximize: $$\Phi_i = Benefits - Costs - Risks \quad \text{(Eq. 2)}$$

In the case of uranium contamination at Fernald, the benefits are negligible and the objective is to *minimize* the sum of the cost and risk terms, resulting in selection of the lowest cost alternative. The costs consist of the sum of remedial investigation and remediation, and risk is the expected cost of failure. The objective function can be written:

Minimize: $$\Phi_i = C_{total} = C_{char} + C_{treat} + C_{fail} \cdot P_{fail} \quad , \quad \text{(Eq. 3)}$$

where C_{total} is total cost required to remediate the site associated with alternative *i*, C_{char} is the remedial investigation cost, C_{treat} is the treatment cost, C_{fail} is the cost of failure, and P_{fail} is the probability that failure occurs and C_{fail} is incurred. It is important to note that P_{fail} is a non-zero quantity. If there is no tolerance of risk, there is only one alternative: the entire site for which the site operator is responsible must be treated. It is only through accepting a finite probability of failure that the site operator is able to invest in remedial investigation in hope of reducing the region that must be treated to less than the entire area of responsibility.

Definition of Failure

In any environmental restoration effort, regions will be classified as "contaminated" or "uncontaminated" with respect to some criterion, presumably specified by or negotiated with a regulatory agency. This classification forms the basis for remedial action. Inevitably, the classification is made by estimating (modeling) the complete spatial distribution of the contaminant based upon scattered measurements. The estimated concentration for each parcel of minimum-treatable size is compared to the regulatory threshold. If the estimate is above the threshold, the parcel will be treated. Otherwise, the parcel will be left undisturbed. In this context, "failure" may be thought of as a classification error with respect to the true, *but generally unknowable* level of contamination that is an inherent property of a particular parcel.

In an ideal world, estimated concentrations would correspond exactly with the true concentrations (the 1:1 line in Fig. 3). In actuality, however, all estimates contain error. Now consider the effect of estimation errors with respect to a

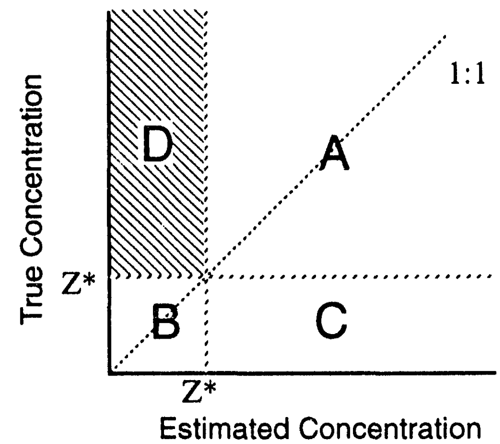

Fig. 3. Conceptual cross plot of potential classifications of true contaminant concentrations for a given parcel based upon some type of estimator derived from measurements with respect to a regulatory criterion for remediation (Z*). Shaded region "D" is defined as regulatory failure in this evaluation.

regulatory criterion, Z* (Fig. 3). If the estimated and true concentrations both exceed the regulatory criterion for a specific location that parcel of soil will be correctly classified as "contaminated." In the region labeled "A" in Fig. 3, both the estimated and true concentrations are above Z*. Similarly, if both the estimated and true concentrations are below the regulatory criterion, the parcel will be correctly classified as "uncontaminated" (region "B" in Fig. 3). By contrast, if the estimated concentration is above the regulatory criterion when, in fact, the true concentration is below the regulatory criterion, the soil parcel is classified as "contaminated" and marked for cleanup even though the area is not contaminated (region "C"), a false positive. Note, however, that a regulatory body probably is not particularly concerned with this type of error. In the final analysis, the concentration of the contaminant within the parcel is below the regulatory threshold. Although the site operator has expended some funds on cleanup unnecessarily, the site remediation effort is successful.

The most important category of estimation error for decision making occur when the estimated concentration is below the regulatory criterion, when in fact, the true concentration exceeds that criterion. Parcels plotting in region "D" in Fig. 3 will be marked as "uncontaminated" and not treated, whereas in fact, the contaminant concentration is above the regulatory threshold. These are false negatives and they represent regulatory failures. This type of misclassification may subject the site operator to fines, penalties, loss of credibility, and requirements to redo various portions of the remedial investigation or remediation. The probability of failure is related principally to any tendency of the selected alternative technology to produce false negative estimates, and it can be quantified through the results of geostatistical simulation (8).

Cost Terms

The cost terms in Eq. 3 are relatively complex functions of a number of different, discrete costs that must be estimated in some manner. Although the information currently available is insufficient to develop a full formulation of the cost equation for each of the alternative technologies, some principal driving factors in each cost term may be identified. Support for estimating characterization and treatment costs is provided by Oak Ridge National Laboratory (9).

The cost of remedial investigation, C_{char}, using a particular technology is affected principally by the number of samples taken and the operating cost per sample. The cost of mobilizing and demobilizing the equipment associated with the technology is also a factor. Other costs that may, at some level, be factored into a per-sample cost, but which may change if the number of samples involved changes markedly, are the cost of analyzing and evaluating the data and the cost of dealing with any secondary waste streams generated by the sampling and measurement process.

The cost of treatment, C_{treat}, at any contaminated site is determined primarily by the volume of contaminated material. If the assumption of surficial contamination of soil at Fernald is valid, this cost is then proportional to the area of contamination multiplied by the unit cost to treat and remove that contamination. Area may be determined directly from maps showing the extent of contamination (8). Also included in the cost of treatment is the capital cost associated with construction of the treatment facility. It is important to note that operational decisions of treat vs. leave as-is are to be made on the basis of some form of estimate; the site operator will pay to treat all regions indicated as exceeding the regulatory threshold by the selected characterization and modeling method.

The cost of failure, C_{fail}, is taken to comprise the various consequences of regulatory failure to identify and remediate contaminated soils. These include (a) fines and penalties imposed by the responsible regulatory agency, (b) litigation expenses, (c) costs to identify and remediate contaminated areas that were missed during the initial investigation, and (d) costs to perform secondary investigations of other untreated or treated areas to convince the regulatory body that there are no other failures. Identification of an expected cost of failure through engineering estimates is extremely difficult. However, experience indicates that litigation invariably is expensive, if from no other standpoint than that significant time periods are involved. Simply assuming that, in the event of a regulatory failure, the time on-site would be extended for an additional one to two years, an estimate of the cost of failure is $375 million at FEMP. In any event, the cost is expected to be large and to be essentially independent of the characterization technology.

Objective Function for Technology Assessment

The complete decision model applicable to this evaluation of the alternative characterization technologies is that given in Eq. 3. However, it is not possible to implement that model at this time, because the required cost information is not available. Furthermore, the initial round of technology demonstrations at the Fernald site did not proceed as originally planned. Uranium concentrations were not measured by all technologies at all locations at the two study areas. Thus, some type of alternative decision model and objective function is required.

We have chosen to focus initial evaluation on the risk term in the complete decision model for several reasons. First, the cost of failure, C_{fail} is believed to be a very large value, potentially dwarfing the cost of any remedial investigation effort, C_{char}. Second, if the technologies under consideration are reasonable alternatives, the areal extent of contaminated soil identified for remediation by each technology should be comparable within an order of magnitude. Thus, *a priori*, there are reasons to believe that C_{treat} for each technology would be approximately equal, leaving the risk term as the determining factor in the objective function, Φ.

If the actual cost of failure, C_{fail} is large and does not depend upon the characterization alternative considered, then the objective function of Eq. 3 reduces to:

Minimize: $$\Phi_i = P_{fail} \quad \text{(Eq. 4)}$$

The definition of failure implies that there is some standard against which the various alternative technologies may be judged. A exact point-by-point comparison of standard soil-geochemistry values with the alternative technology measurements is not possible. This is because the locations of these soil geochemistry samples do not correspond to the locations of the measurements taken by the alternative technologies, even though the absolute number and spacing of measurements are comparable. Thus, the cross-plot of Fig. 3 cannot be constructed. Therefore, we decided that the objective function should be evaluated based on a comparison of exhaustive models of contamination, one for each available type of measurement. The minimum treatable size parcel was arbitrarily assumed to be approximately 3 m x 3 m (the approximate width of a bulldozer blade), and the probability of failure, P_{fail}, was evaluated simply by counting the number of false negatives (regulatory failures) for each alternative technique compared with the soil-geochemistry-based reality. This version of the objective function may be stated as:

Minimize: $$\Phi_i = \frac{\sum \text{False Negatives}}{\text{No. Compared Nodes}}, \quad \text{(Eq. 5)}$$

where the summation is over all parcels available for comparison in the study area.

Computation of the Objective Function

A well-known and widely used interpolation technique that incorporates observed spatial correlation patterns was adopted to estimate the unknown contaminant concentrations at the unsampled parcel locations based on the alternative technology measurements. Kriging is recognized as an unbiased, minimum-estimation-variance form of linear regression. The choice is arbitrary. We could have easily selected some other inverse-distance weighting scheme for interpolation or assumed that the nearest-neighboring measurement was the most appropriate estimate of the unknown concentration. However, the kriged estimate essentially represents the local, conditional expectation of the probability-density function at each location. Also, the theory and limitations of kriging as a modeling technique are relatively well understood (10, 11, 12). An additional pragmatic factor is that for relatively well-sampled sites, such as at Fernald, it is likely a regulatory agency could be convinced that the modeled distributions of contamination produced by kriging are reasonable models of the real world. Accordingly kriged maps of uranium contamination at the Incinerator Area and Drum Baling Area were produced through standard geostatistical techniques using the appropriate measured data.

We also recognize that modeling the spatial distribution of both true and estimated concentrations in the absence of a direct point-for-point comparison adds an increment of uncertainty to the evaluation. There is no assurance that a kriged model of the soil geochemistry values represents, in fact, the actual contaminant levels prevailing at the unsampled locations. Therefore, to address uncertainty in the model of the "true" contaminant distribution, one hundred (100) simulations of uranium contamination were generated conditioned to the actual soil-geochemistry values in each area (8). According to simulation theory (13, 14), any one of those 100 realizations could reasonably represent the actual contamination distribution. Each realization is statistically indistinguishable from the others and from reality. Each realization reproduces the measured data at sampled locations, possesses virtually the same univariate distribution of values (histogram), and the simulated values exhibit the same type of spatial continuity pattern (variogram). The variability among a suite of simulations is therefore an explicit representation of the uncertainty that results from non-exhaustive site knowledge (8).

The 100 simulations of soil-geochemistry uranium contamination were then compared on a parcel-by-parcel basis with the unbiased, least-square expectation produced by kriging. The comparison focused on the decision confronted by the site manager: *given a cleanup threshold, would the alternative technology indicate the same remediate vs. leave-in-place determination as the soil-geochemistry model?* The comparison was cast in the framework from Fig. 3. The number of incorrect decisions (areas indicated as false negatives) were thus tabulated for each technology in each geographic area. These data provided the information necessary for evaluation of the objective function (Eq. 5). Information regarding the number of parcels mapped as in agreement and as false positives was also tabulated for further analysis.

The choice of comparing 100 soil-geochemistry simulations as a surrogate for the actual, but unknown, uranium contamination level with a single, deterministic estimate of the contaminant as measured by the alternative technologies is arbitrary. We could equally well have created 100 simulations for each alternative measurement technology and selected the 90 percent probability outline for exceeding a particular threshold and compared that region with the 90 percent probability outline for the soil geochemistry data. However, the specified approach was adopted to avoid compounding uncertainty upon uncertainty, given the limitations of the available data. In any event, the methodology is applied uniformly across the various characterization alternatives.

RESULTS

The results of computing the objective function defined in Eq. 5 for the various alternative technologies are shown in Table I. The evaluation is less than clean-cut because not all of the technologies were demonstrated at any single site. However, it is apparent from the pattern of the table that the LRAD device performed better overall, particularly at lower average levels of contamination, as exemplified by the results for the 35-pCi/g threshold. At higher thresholds, such as the 100-pCi/g level in Table 1, the differences among the demonstrated technologies are less pronounced and the advantage of the LRAD device is less apparent.

These results are presented in another format in Fig. 4, which goes beyond the simple value of the objective function to include information regarding false-positive estimates. From this information, it is clear that the LRAD detector achieves its superior performance in avoiding false negatives by greater conservatism, which results in classifying a number of uncontaminated parcels as contaminated (i.e., in generating a moderately large number of false positive

Table I

Values of the objective function, Φ, defined in Eq. 5 as P_{fail}, for the alternative characterization technologies, computed across the 100 simulated "realities." Decision model is to minimize Φ.

Location	Incinerator	Drum Baling Area	
Threshold	35 pCi/g	35 pCi/g	100 pCi/g
LRAD	0.08	0.014	0.03
Beta	0.59	0.004	0.03
Gamma	n/a[a]	0.10	0.17
ICP-AES	0.33	n/a	n/a

[a] n/a - This technology not demonstrated at this location.

values). Although the objective function was specifically chosen to focus on regulatory failures, it is clear that minimizing the risk term in Eq. 3 for this analysis (through a low value for P_{fail}) is at the expense of increasing the cost of treatment (C_{treat}). Whether this trade-off is a good value in terms of minimizing *total* cost depends upon the relative costs that enter into the characterization and treatment terms. This cost information is not yet sufficiently well defined to provide a final answer in this regard.

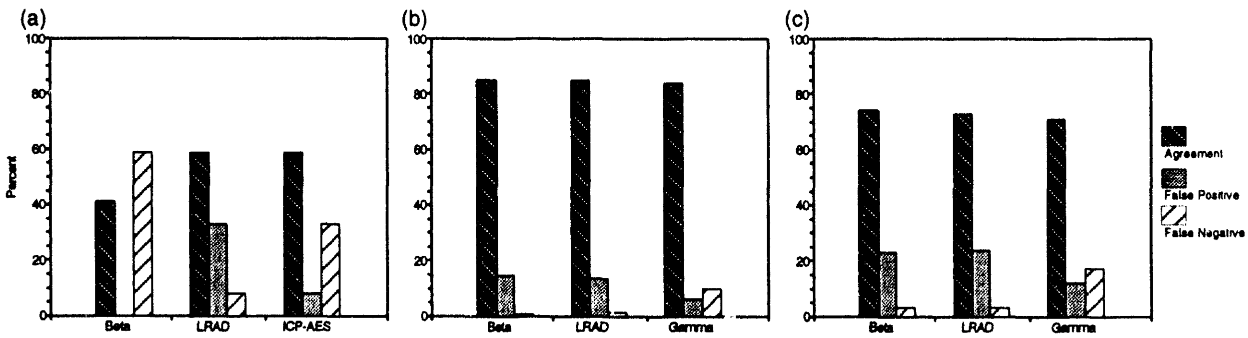

Fig. 4. Comparison of performance of the alternative characterization technologies in terms of false negatives, false positives, and correct classifications of contaminated parcels. (a) Incinerator Area at 35 pCi/g; (b) Drum Baling Area at 35 pCi/g; (c) Drum Baling Area at 100 pCi/g.

It is important to understand the causes of potential regulatory failures attributable to the various alternative technologies. If the failures are general in nature, there may be a general problem with the technique itself, whereas if the failures are localized in some manner, a specific environmental factor may be influencing the measurements. Fig. 5 presents the areal distribution of false-negative estimates for the three alternative technologies demonstrated at the low-contamination Incinerator Area. The widespread errors indicated for the Beta detector and the ICP-AES device suggests some fundamental difficulty is affecting these technologies. In contrast, the areal pattern of failures for the LRAD detector is quite restricted. Comparison of this areally restricted pattern of failures with the original map of the Incinerator Area (Fig. 2a) indicates that the LRAD technique performed worst in the vicinity of the topographic depression related to a small drainage swale located on the western margin of the demonstration area. This interpretation is confirmed by investigation of sampling records which indicated that the ground in this region was relatively moist during field operations. Excess moisture in this region may reduce the ability of the LRAD device to detect low-energy alpha particles emitted by uranium decay.

Fig. 6 is an equivalent comparison of the location of false negatives produced by the alternative technologies at the higher-concentration Drum Baling Area. It appears that all three technologies demonstrated, which in this case are all radiometric methods, fail in the northern portion of the area, a region of lower-than-typical contamination. The additional region of failure for the Gamma detector is also located in an area of generally lower concentrations. These

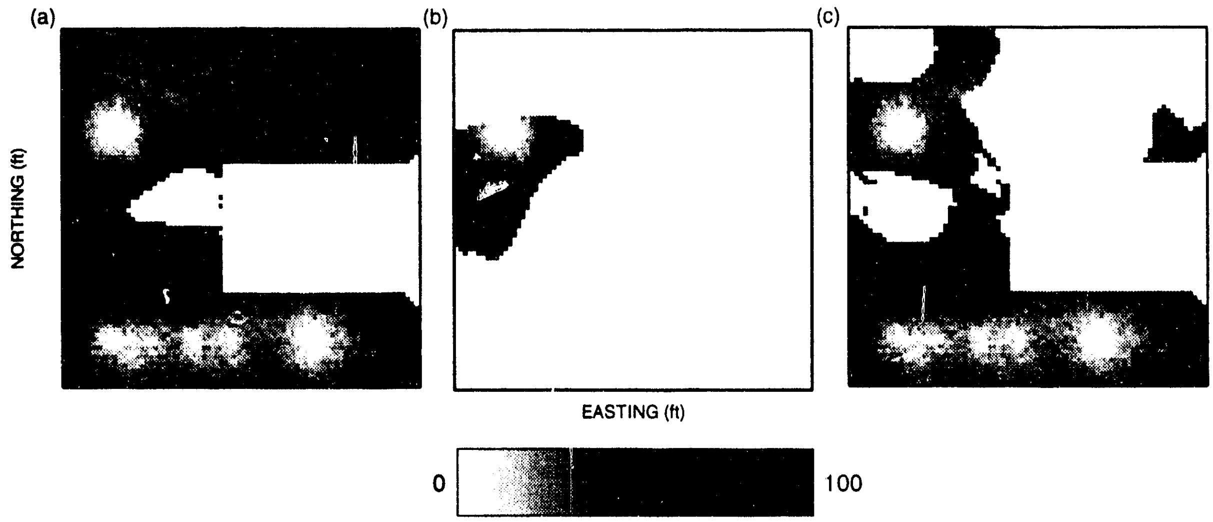

Fig. 5. Maps showing locations of false negatives indicated by the alternative characterization technologies compared with the soil geochemistry data at the Incinerator Area (35 pCi/g threshold). (a) Beta detector; (b) LRAD detector; (c) ICP-AES. Grey-scale coded values indicate percent false negatives in 100 simulations.

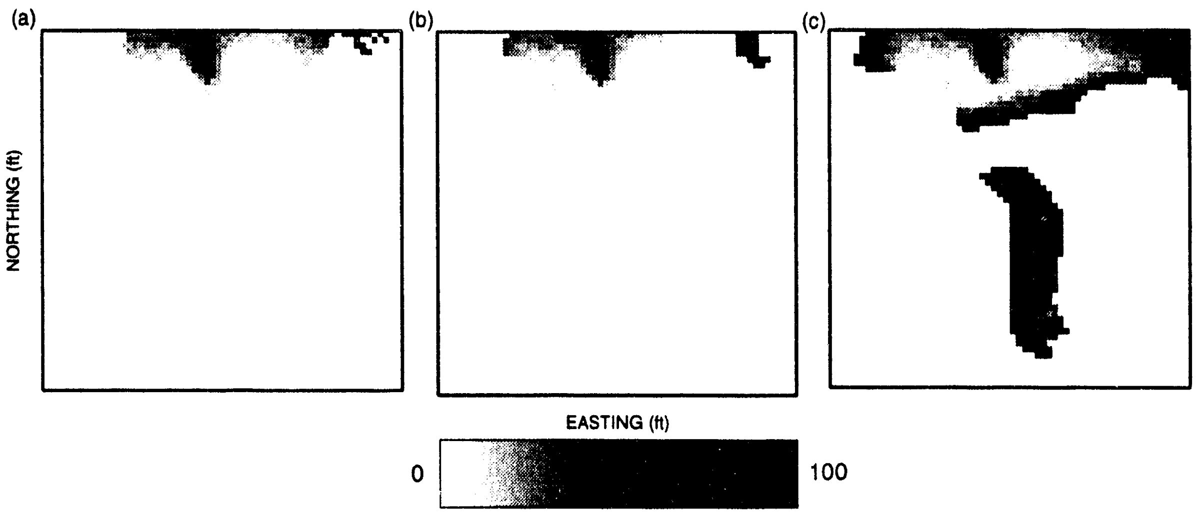

Fig. 6. Maps showing locations of false negatives indicated by the alternative characterization technologies compared with the soil geochemistry data at the Drum Baling Area (100 pCi/g threshold). (a) Beta detector; (b) LRAD detector; (c) Gamma detector. Grey-scale coded values indicate percent false negatives in 100 simulations.

types of failures, related to the magnitude of contamination, suggests that radiometric methods are poorly suited to detecting lower levels of uranium in soil; this is not particularly surprising, given the physics of radiometric methods. That the Gamma detector fails in this respect to a greater extent than the other two technologies is almost assuredly related to the scale of the measurement compared to the scale of the contamination. The area investigated by the Gamma detector in the current demonstration is several orders of magnitude larger than that investigated by either the LRAD or Beta detector. This suggests that the Gamma detector, as currently configured, is ill-suited to its task, and is averaging smaller areas of contaminated ground together with uncontaminated regions and reporting an absence of material above threshold. The implication is that the scale of the measurement needs to be more closely aligned with the scale of the smallest practical remediation unit.

Need for Regulatory Interaction

At the Fernald site, a regulatory limit for the allowable amount of uranium in the soil has not been negotiated. Based on available information and current, preliminary practice at Fernald, alternative limits of 35 and 100 pCi/g were assumed for this study. No information is currently available on the scale over which this criteria would apply. These determinations become critical in areas such as the Incinerator Area, where the concentrations are at or near the potential regulatory limit. Clearly the choice of a characterization technology, particularly a proposed alternative to accepted standard practice, must be thoroughly evaluated in light of the specific method agreed upon with the regulator for evaluating final compliance with applicable regulations.

CONCLUSION

Evaluation of four alternative characterization technologies at the Fernald site using a risk-based decision-analysis process indicates that the evaluation paradigm offers significant insight into both the performance of the alternative technologies and the environmental restoration decision process. The decision-analytic framework employed casts the decision in an economic framework and provides a quantitative means of addressing the economic risk posed by characterization uncertainty.

The four alternative characterization technologies were compared against a ground-truth standard based upon conventional soil geochemical analyses. Because the soil geochemistry data were not collected at the same locations as the alternative technology measurements, the evaluation focused comparing comprehensive models of uranium contamination at the site constructed using geostatistical methods and accounting for characterization uncertainty. The metric for comparison was whether the remediation decisions on a parcel-by-parcel basis indicated by a particular alternative technology, based upon assumed cleanup-threshold levels, were the same as that indicated by the soil geochemistry data. Because of the large-magnitude economic consequences of failing to identify (and presumably to remediate) actually contaminated parcels, the alternative characterization technologies were ranked according to the number of false negative determinations.

The performance of the alternative technologies appears strongly sensitive to the absolute magnitude of the uranium contamination prevailing at a test location. At high average concentrations, all tested technologies appear to perform at approximately equal levels of accuracy, although the Gamma detector system produced more regulatory failures than the LRAD and Beta devices. At lower contaminant levels, however, the LRAD system was by far the better performer compared with the Beta detector and the field ICP-AES system. It is clear that the LRAD detection system achieves this performance level, with respect to minimizing regulatory failures, by greater conservatism and the indicated remediation of a moderate number of uncontaminated parcels. Whether or not this is a good economic trade-off depends upon the actual costs of failure and of characterization (and remedial treatment) using that technique. Environmental factors, such as soil moisture, may have diminished the ability of the LRAD detector locally to identify low concentrations of uranium contamination.

It is also clear that the scale of measurement, which varied markedly among the various alternative characterization technologies, cannot be divorced from the regulatory criterion for remediation. A method that averages a large amount of uncontaminated material with a small hot spot of contamination probably will not report a reading above threshold. If the scale of measurement does not mesh with the scale on which compliance will be evaluated, significant regulatory failures, and their economic consequences, are virtually inevitable.

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