

**GEOSTATISTICS AND COST-EFFECTIVE ENVIRONMENTAL
REMEDiation**

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Christopher A. Rautman
Sandia National Laboratories
P. O. Box 5800; MS-1324
Albuquerque, New Mexico 87185
USA

1. Introduction

Numerous sites within the U.S. Department of Energy (DOE) complex have been contaminated with various radioactive and hazardous materials by defense-related activities during the post-World War II era. The perception is that characterization and remediation of these contaminated sites will be too costly using currently available technology. Consequently, the DOE Office of Technology Development has funded development of a number of alternative processes for characterizing and remediating these sites. The former Feed-Materials Processing Center near Fernald, Ohio (USA), was selected for demonstrating several innovative technologies. Contamination at the Fernald site consists principally of particulate uranium and derivative compounds in surficial soil.

A field-characterization demonstration program was conducted during the summer of 1994 specifically to demonstrate the relative economic performance of seven proposed advanced-characterization tools for measuring uranium activity of in-situ soils. These innovative measurement technologies are principally radiation detectors of varied designs (table 1). Four industry-standard measurement technologies, including conventional, regulatory-agency-accepted soil sampling followed by laboratory geochemical analysis, were also demonstrated during the program for comparative purposes.

A risk-based economic-decision model has been used to evaluate the performance of these alternative characterization tools. The decision model computes the dollar value of an objective function for each of the different characterization approaches. The objective function is defined as the total cost to remediate the demonstration site, including the cost of characterization, the cost of treatment, and the expected cost of failure to clean the entire site to regulatory standards. The preferred characterization method is that which minimizes the value of the objective function.

Although this application of the methodology at the Fernald site involves a number of site- and situation-specific considerations, the cost-risk-benefit decision framework is completely general. The methodology not only can assist site operators to choose among engineering alternatives for site characterization and/or remediation, but also can provide an objective and quantitative basis for decisions with respect to the completeness of site characterization. The quantitative framework may also serve as a basis for more productive and focused discussions with regulatory agencies and other stakeholders in the environmental remediation arena.

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2. Economic Cost-Risk-Benefit Decision Framework

The decision model employed at the Fernald field-demonstration program builds upon a comprehensive logical framework for economic-decision analysis that was outlined by Freeze and others (1990). The framework attempts to quantify the various costs, risks, and benefits associated with the design and implementation of a given engineering decision. What distinguishes the approach of Freeze and others from many other cost-benefit decision frameworks is the quantitative emphasis placed on *economic risk*: the likely costs that result from uncertainty regarding the ultimate performance of the system being evaluated. The entire analysis is denominated in currency units (dollars or otherwise), thus reducing all components of the analysis to a common reference familiar to business decision-makers. The goal of the economic-decision analysis is to maximize an objective function (Φ_i) that represents the overall monetary return associated with a given project. The objective function is computed as the net present value of all revenues or benefits resulting from the project, less all relevant expenses or costs including the expected cost of uncertain performance, for a reasonable number of engineering alternatives.

TABLE 1: Classification, brief description, and sampling costs of alternative characterization technologies demonstrated at the Fernald site. [All costs in U.S. dollars]

ID	Technology Description	Detection Principle		Total Cost	Sample Cost
Advanced Field-Measurement Technologies					
ATD	Alpha-track detector	passive	alpha particles	10,131	87
Beta	Beta scintillometer	passive	beta particles	15,391	167
EIC	Electret ionization chamber	passive	alpha particles	9,337	92
GMH	High-mount gamma spectrometry	passive	gamma rays	13,183	155
GML	Low-mount gamma spectrometry	passive	gamma rays	13,669	155
ICP	Laser-ablation inductively coupled plasma atomic emission spectrometry	active	visible and ultraviolet light	22,540	272
LRAD	Long-range alpha detector	passive	alpha particles	15,336	162
Industry-Standard Field-Screening Techniques					
FID	FIDLER scintillometer	passive	gamma rays	4,771	50
Lab	Mass spectroscopy	active	ionized elements	35,055	340
NAD	NaI scintillometer	passive	gamma rays	3,709	42
XRF	X-ray fluorescence	active	photons	9,588	99

In the case of environmental remediation activities, there generally are no particular economic benefits to the site operator in the sense originally implied by Freeze and others. For example, there are no dollar inflows to the DOE that result directly from cleaning up the Fernald site. This functionally transforms the profit-maximization framework into a total-cost minimization exercise, which can be stated mathematically as follows:

$$\text{Minimize: } \Phi_i = C_{total_i} = C_{char_i} + C_{treat_i} + E\{C_{fail_i}\} \quad (1)$$

across the suite of i different alternative characterization technologies. In equation (1),

C_{total_i} is the total cost associated with characterizing and remediating the site using characterization technology i . This cost is comprised of the cost of characterization (C_{char_i}), the cost of treatment (C_{treat_i}), and the expected cost of failure ($E\{C_{fail_i}\}$). The expected cost of failure is defined as:

$$E\{C_{fail_i}\} = P_{fail_i} \cdot C_{fail_i} \quad (2)$$

where P_{fail_i} is the probability of failure and C_{fail_i} is the cost incurred if that failure actually takes place. Uncertainty and economic risk enter the decision model through this probability of failure term. One minimizes the economic cost of a project by trading-off these different cost components against one another, and potentially, by trading costs (including risk costs) against variable benefits.

3. Application to the Fernald 1994 Field Characterization Demonstration Program

The 1994 Fernald field characterization demonstration program provides a near-ideal application of this form of economic-decision analysis. The problem is to choose a measurement technique for characterizing uranium contamination in soil from among a number of alternative characterization technologies. Some measurement technologies may be relatively inexpensive to operate, but the readings may be less accurate than the readings produced by a more expensive technology. Some technologies may be roughly comparable in costs, but may produce differing predictions of the contaminated region. A more conservative measurement technique, one which indicates more contamination than is actually present, may reduce the likelihood that the remediated site will fail to meet regulatory inspections, but at the increased cost of removing and treating soil that might have been left in place. Conversely, a less conservative measurement technique may suggest a lower initial remediation cost, but leave the operator exposed to a large potential liability if residual contamination is detected later. Additionally, because of the technology-development nature of the demonstration program, measurements of uranium contamination were also obtained using laboratory analytical methods currently accepted by the cognizant regulatory agencies. Thus, under the presumption that it is the regulator's perception of what is and what is not contaminated that is a prime determinant of environmental remediation success or failure, a reasonable model of ground truth is available as a benchmark against which to compare the other technologies that have been proposed as *alternatives* to current practices.

3.1 SITE DESCRIPTION AND FIELD CHARACTERIZATION PROGRAM

The 1994 Fernald field characterization demonstration program was conducted at a location known as the incinerator area. A simple combustion unit operated at this site from 1954 until 1979, and this incinerator burned combustible wastes generated from both plant administrative and process areas. Some of the process wastes contained low levels of radioactive materials, principally uranium, and particulate uranium was dispersed across nearby areas as an aerosol plume. Activities representing a mixture of both natural and depleted uranium vary from background of 5–10 picocuries per gram (pCi/g) to more than several thousand pCi/g (DOE, 1992). Other site characterization activities at

the Fernald site have indicated that the bulk of the uranium above likely, but not yet final, action levels is present in the top 2 inches or so of the soil (Schilk and others, 1993; Rautman and others, 1995).

The 1994 demonstration program focused on a 2.9-acre portion of the incinerator area. A generally regular grid consisting of a total of 85 sample locations on nested 60-, 30-, and 5-ft spacings was defined and marked in the field. All alternative technologies recorded measurements at these marked locations. Each technology was calibrated to a common set of native Fernald soils spiked with known levels of uranium; calibration beds were sampled and analyzed by laboratory mass spectroscopy techniques.

3.2 IDENTIFICATION OF "CONTAMINATED" REGIONS

We have assumed that excavation of contaminated soil at the Fernald site will take place using mechanical equipment, thus limiting somewhat the selectivity of excavation units. For purposes of this comparison, a selective remediation unit is presumed to consist of a square panel 10-ft by 10-ft in size (approximately the width of a bulldozer blade) and 4 inches deep. This convention is consistent with previous geostatistical modeling of uranium contamination at Fernald (Rautman and others, 1994).

Because the uranium activity of each potential remediation unit, or parcel, has not been measured directly, it is necessary to compare both sampled and unsampled locations. We have used conventional variography and sequential gaussian simulation conditioned on the relevant characterization data (Deutsch and Journel, 1992) to model the exhaustive spatial distribution of uranium. The simulation methodology results in a suite of equally likely maps of contaminant distribution, all of which reflect the measured values at their spatial locations and all of which exhibit essentially the same statistical and spatial character as the data. This stochastic approach explicitly acknowledges that the models of contaminant distribution derived from the alternative characterization technologies and the model of true contamination derived from soil geochemistry are uncertain. With no *a priori* means of determining which of the many possible simulated models is the actual "true" map of uranium contamination, we "decide" to clean up all parcels that have an empirically determined (through post-processing the suite of simulations) probability of exceeding a specified action threshold greater than some probability level, p .

3.3 ECONOMIC COSTS

3.3.1 Characterization Costs

Actual costs for the characterization portion of the 1994 Fernald field demonstration program have been tabulated by Douthat and others (1995). These cost data are summarized in table 1. There is an order-of-magnitude variation in cost among the several technologies examined. The industry-standard field screening methods generally were significantly less expensive than the proposed alternative characterization technologies. Cost of completing the field survey using the newer, alternative-characterization technologies ranged from US\$9,300 to more than \$22,500. The currently accepted characterization method for regulatory purposes, consisting of soil sampling followed by conventional laboratory geochemical analysis was, in fact, the most expensive characterization

method. The cost of completing the field survey and associated supporting measurements using soil sampling exceeded \$35,000.

3.3.2 Treatment Costs

Costs to treat Fernald soils selected for remediation via the various characterization techniques are somewhat more uncertain because a remediation technology has not yet been selected for the Fernald site. However, there are several treatment methods that involve roughly comparable costs of approximately \$200 per ton of soil processed. Adjusting this cost per ton for the volume and bulk density of a selective remediation unit results in a dollar cost of \$437 per contaminated panel.

3.3.3 Failure Costs

In the case of environmental remediation, “failure” essentially results from a misclassification error in predicting actual contaminant levels from some type of site characterization activity. Figure 1 illustrates this classification problem. The true contaminant concentration of any given parcel of land is assumed to be unknown. The site operator conducts site characterization and predicts that contamination level for all unsampled locations. Depending upon whether the predicted concentration, Z , is above or below a regulatory threshold or action level, Z^* , the operator will decide whether to remediate that parcel. Note that absolute accuracy of the prediction does not particularly matter. The remediation decision is based solely upon whether the prediction is that the parcel is above (contaminated) or below (not contaminated) the regulatory action level. It is the correctness of the remediation *decision* that matters, not the accuracy of the prediction itself.

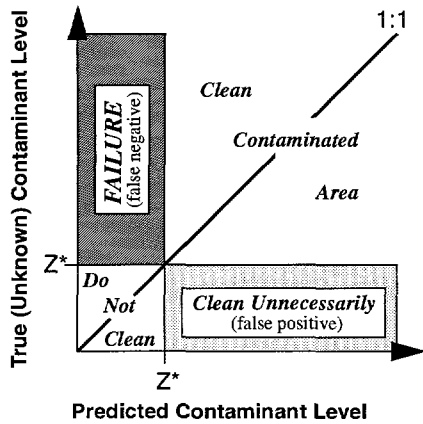


Figure 1. Classification problem for a contaminated site. Decision to remediate or leave as-is will be based upon a predicted contaminant level.

TABLE 2: Contingency table showing alternative costs of failure. [All values in US dollars]

	Small-Value [†] Failure	Large-Value Failure
Small No. [‡] of Failures	\$a=437/parcel	\$b=2,000/ parcel
Large No. of Failures	\$c=35,000	\$d=500,000

[†] distinction set at twice the standard deviation of the soil geochemistry/lab analyses

[‡] distinction set at 30 percent of the 2016 parcels covering the demonstration site

After the site operator determines that the site has been cleaned-up to regulatory standards, we assume that the regulatory agency examines some or all of the site area and makes its own determination of whether or not the various remaining parcels are below

the regulatory threshold. Although the in-fact “true” concentration for a given panel may still be unknown (even unknowable) to the regulatory agency, we assume that the agency’s determination is what matters in determining success or failure. If the regulatory agency’s determination is that the parcel is still above threshold—that the parcel has been misclassified (a false negative figure 1)—we count the site characterization-remediation effort a failure.

Note that not all misclassification errors count as failures under this scenario. If the site operator conducts remediation activities, when in fact a parcel is not above threshold, there has been a misclassification error. However, this false positive (figure 1) does not constitute *regulatory* failure, because the parcel is presumed clean following treatment. There are economic costs to this second type of misclassification error; however, the cost of failure is not one of them.

Actual costs of failure for the Fernald site are more problematical than the costs involved in either site characterization or remediation. We have defined a cost of failure, C_{fail} , that varies according to the degree of that failure according to the contingency table given as table 2. A “small-value” failure is defined as one in which the contaminant concentration of a given “uncontaminated” parcel actually exceeds the regulatory threshold by only a small value. Conversely, a “large-value” failure would be defined as one in which the prediction from site characterization was below threshold when, in fact, the actual contamination level exceeded the regulatory threshold by a large amount.

The values of $\$a$, $\$b$, $\$c$ and $\$d$ are arbitrary, but they follow the logic of a small penalty ($\$a$) for small errors, and a large penalty ($\$b$) for large errors that could be construed as “flagrant.” This approach is consistent with the power-curve concept related to the data-quality-objective process published by the U.S. Environmental Protection Agency (EPA, 1993). If the small errors are so abundant as to constitute “negligence,” an additional one-time cost of failure ($\$c$) is assessed as a penalty. A complete breakdown of an alternative characterization program resulting in an unacceptably large number of large-value failures is penalized by a very large cost of failure ($\$d$).

We have elected to set $\$a = C_{treat}$, in keeping with a philosophy that a few small errors do not constitute systematic failure of the characterization effort. Because failure cost $\$a$ is intended merely to include the cost of after-the-fact treatment, it is necessary to accrue this cost for every parcel that fails. Similar logic applies to failure cost $\$b$, only in this case the cost is higher to cover expenses associated with additional sampling and paperwork intended to assure the regulatory body that such large-value errors are relatively isolated occurrences. Failure costs $\$c$ or $\$d$ are assumed to be incurred only once.

3.4 STOCHASTIC EVALUATION OF THE OBJECTIVE FUNCTION

The objective function for the decision model (equation 1) was evaluated using the logic presented in figure 2. There are several important features about this formulation of the stochastic approach that follow from stochastic simulation of the ground-truth model. (1) The loop structure focuses on the uncertainty and the expected cost associated with each remediation panel, \mathbf{x} . Thus, although the comparison of Φ_i is technology by technology, preservation and appropriate presentation of the intermediate, \mathbf{x} -subscripted results allows direct spatial mapping of *dollars* for any technology, i . This illustrative

technique may be very effective for communicating comparisons, particularly to lay audiences. (2) It is possible to iterate over several probability levels and to plot $E\{C_{total_i}\}$ as a function of p to identify any prominent break in slope (change in behavior). (3) It is also possible to iterate over several remediation threshold values, Z^* , to demonstrate changes in $E\{C_{total_i}\}$ or differences in technology ranking as a function of clean-up threshold.

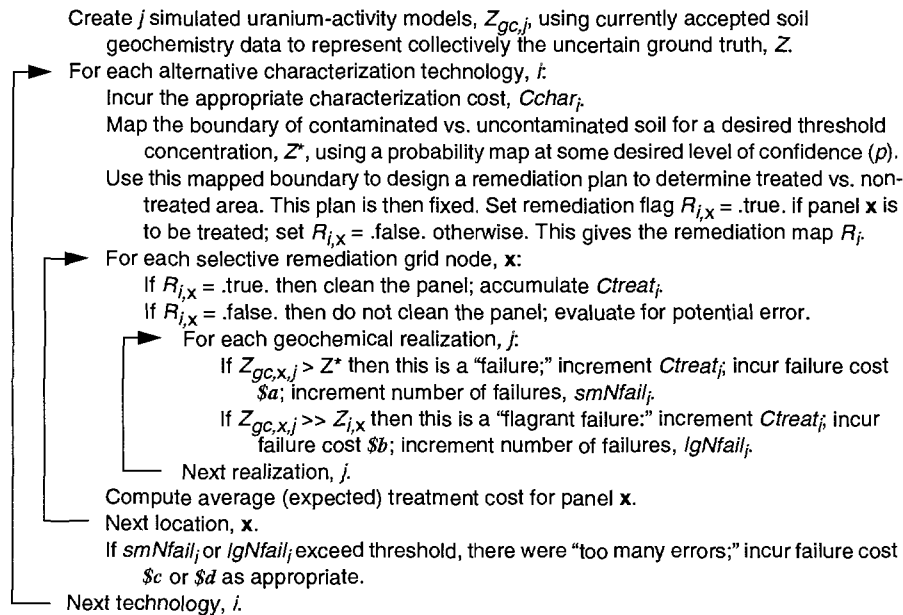


Figure 2. Pseudo-computer-code algorithm for stochastic evaluation of the objective function in the economic decision model using geostatistical simulation to capture uncertainty in the actual level of uranium

4. Results

The values of the objective function, Φ_i , that result from the stochastic comparison of the alternative characterization methods at three different action levels and one specific probability level are presented in figure 3; the different components of the objective function are indicated. Note that the value of the objective function, and the ranking of the technologies, varies depending upon the question being asked (the specified action level). The total expected costs to remediate the site for an action level of 60 pCi/g, including the likely cost of regulatory failure, vary by a factor of 2 from \$554,000 (Beta) to more than \$1.24 million (ATD and EIC). The cost of treatment alone varies from a low of \$57,000 to the *a priori* full-site treatment cost of \$880,992 (2016 panels@\$437). The lowest-treatment-cost option resulted from use of the EIC characterization methodology, which was one of the relatively low cost innovative demonstration techniques. However, despite the low characterization and indicated treatment costs, this method is actually the

overall most expensive alternative because of the high probability of failure. Note that four characterization technologies (FID, LRAD, NAD, XRF) are associated with a zero expected cost of failure. Each of these methods indicated that the entire site is contaminated. Conversely, the ATD technology indicated virtually no contamination and thus its costs are overwhelmingly related to regulatory failure.

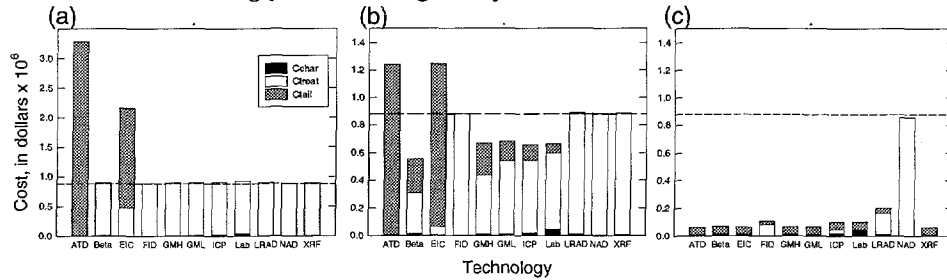


Figure 3. Components of the objective function value (Φ_i) for the 11 different characterization technologies at a probability level of 0.30 and a uranium action threshold of (a) 35 pCi/g, (b) 60 pCi/g, and (c) 100 pCi/g. Horizontal line is the *a priori* cost to treat the entire site. Note expanded cost scale in (a).

Comparison of the different characterization techniques is expanded in figure 4, in which the value of Φ_i is shown as a function of the probability level (p) used to define the remediation plan. If the site operator is unwilling to accept any risk of an incorrect remediation decision, p is equal to zero and there is no alternative to treating the entire site area. Characterization in this case is worthless, and the cost of conducting characterization activities is in addition to the zero-risk cost of treatment. As the probability level acceptable to the site operator increases (the operator becomes less risk-averse), figure 4 indicates that $\Phi = C_{total}$ typically decreases. There are two characterization technologies for which this reduction in the value of the objective function does not occur: the ATD and EIC methodologies. These two alternative technologies are adaptations of indoor radon-monitoring devices, and their performance has been documented as notably inaccurate and sensitive to changes in environmental conditions in the field (Rautman, 1996).

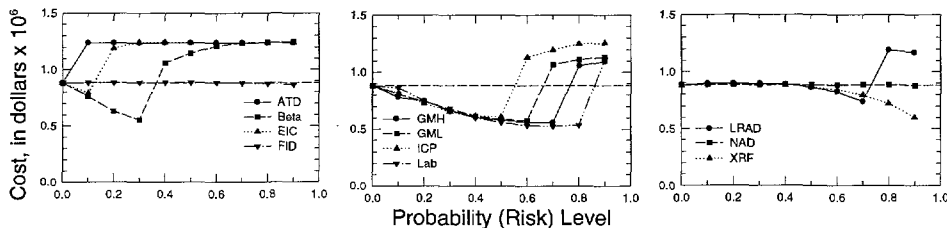


Figure 4. Objective function values (Φ_i) for the different field-characterization technologies as a function of probability level for a uranium action threshold of 60 pCi/g. Horizontal line is *a priori* cost to treat entire site.

Figure 4 also indicates that at some increased probability level, C_{total} begins to increase abruptly. This increase reflects the changing interplay of the likely costs of treatment and failure with changes in probability level that determine the initial remediation plan. The individual cost components that result from this trade-off between C_{treat}

and $E\{C_{fail}\}$ are shown in figure 5 for three of the characterization technologies. These graphs emphasize that one can only achieve a net reduction in total remediation cost by trading part of the cost of treatment for a finite probability of failure corresponding to a non-zero $E\{C_{fail}\}$. At some probability level, the likelihood of failure simply becomes too great, and it is cheaper simply to clean up the parcel and be done with it. Note however, that very low probability levels, perhaps corresponding to the “95-percent confidence level” of classical statistics, may not be the most cost-effective level of site characterization and remediation.

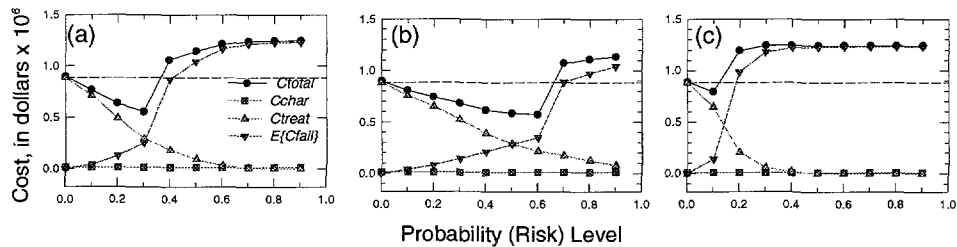


Figure 5. Individual cost curves for three technologies: (a) beta scintillometer, (b) low-mount gamma-ray spectrometer, and (c) electret-ionization chambers. Horizontal line is *a priori* cost to treat entire site.

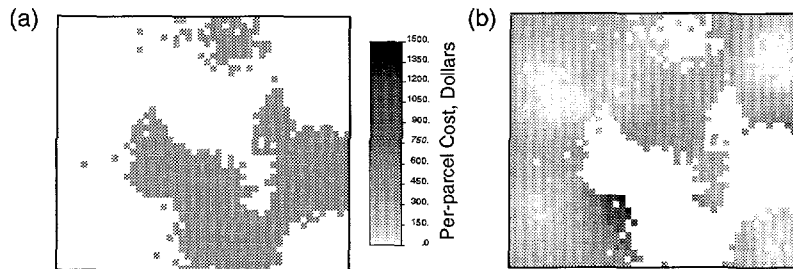


Figure 6. Maps showing the spatial distribution of (a) C_{creat} and (b) $E\{C_{fail}\}$ for the beta scintillometer characterization technique at a probability level of 0.30; action level 60 pCi/g.

Maps of the per-parcel expected costs are shown in figure 6 for the lowest-cost characterization alternative (Beta). Figure 6(a) simply indicates the initial remediation plan developed using probability mapping of the Beta scintillometer data at the minimum-cost probability level of 0.30. The cost of treatment is presumed constant at \$437 per parcel. Figure 6(b) presents the spatially variable per-parcel expected cost of failure. The white areas correspond exactly to the grey parcels in figure 6(a). This map of figure 6(b) clearly contains information relevant to continued site characterization at this site. The darker parcels are those associated with the highest expected cost of failure, up to nearly \$1,500 per parcel. Because the combined cost of taking an additional sample and cleaning up that parcel is only $\$167 + \$437 = \$604$, one should be able to reduce the total expected cost through additional sampling in regions where the $E\{C_{fail}\}$ exceeds this amount. Note that because of spatial correlation, a single additional sample probably will provide information about more than one remediation unit.

5. Conclusions

A quantitative cost-risk decision framework using geostatistical simulation to quantify uncertainty related to less-than-exhaustive site characterization can be used to identify cost-effective plans for environmental remediation. This framework has been demonstrated for the problem of selecting among alternative technologies for measuring the uranium activity of in-situ soils adjacent to an aerosol contamination source at the U.S. Department of Energy Fernald (Ohio USA) site. The decision framework involves minimizing the total expected cost of site characterization, site treatment, and potential regulatory failure to clean the site to established standards across a reasonable number of engineering alternatives. The preferred alternative technology has been shown to be a function of the regulatory action level and the degree of risk-aversion of the decision maker. The lowest total-cost alternative may not be associated with the lowest probability of making incorrect treat vs. leave-in-place decisions for individual remediation units. Characterization, treatment, and potential failure costs vary spatially, and maps of these likely costs can provide useful information with respect to staged sampling efforts and stopping criteria for site characterization work.

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