# EVALUATION OF SOIL CHARACTERIZATION TECHNOLOGIES USING A STOCHASTIC, VALUE-OF-INFORMATION APPROACH

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## INTRODUCTION

The U.S. Department of Energy has initiated an integrated demonstration program to develop and compare new technologies for the characterization of uranium-contaminated soils. As part of this effort, a performance-assessment task was funded in February, 1993 to evaluate the field tested technologies. Performance assessment can be defined as the analysis that evaluates a system's, or technology's, ability to meet the criteria specified for performance. Four new technologies were field tested at the Fernald Environmental Management Restoration Co. in Ohio. In the next section, the goals of this performance assessment task are discussed. The following section discusses issues that must be resolved if our goals are to be successfully met. I conclude with a discussion of the potential benefits to performance assessment of the approach taken.

This paper is intended to be the first of a series of documentation that describes the work. Also in this proceedings is a paper on the field demonstration at the Fernald site and a description of the technologies (Tidwell et al, 1993) and a paper on the application of advanced geostatistical techniques (Rautman, 1993). The overall approach is to simply demonstrate the applicability of concepts that are well described in the literature but are not routinely applied to problems in environmental remediation, restoration, and waste management. The basic geostatistical concepts are documented in Clark (1979) and in Issaks and Srivastava (1989). Advanced concepts and applications, along with software, are discussed in Deutsch and Journel (1992). Integration of geostatistical modeling with a decision-analytic framework is discussed in Freeze et al (1992). Information-theoretic and probabilistic concepts are borrowed from the work of Shannon (1948), Jaynes (1957), and Harr (1987). I see the task as one of introducing and applying robust methodologies with demonstrated applicability in other fields to the problem at hand.

## GOALS

The Department of Energy has sponsored the development of 4 new technologies for characterizing uranium contamination in surficial soils in the hope that at least one of the technologies will be "faster, better, safer, cheaper" than the current practice of obtaining a soil sample and analysis of the sample. This task has been asked to evaluate the technologies with respect to "faster, better, cheaper". The Department of Energy will be satisfied if the evaluation can articulate the advantages of each of the new technologies with respect to the soil samples and with respect to each other.

In addition, I hope to demonstrate the utility and viability of an economic, value-of-information approach (Freeze et al, 1992). Within this framework I ask the question "which of the 4 technologies is worth the most?" To make the evaluation meaningful, worth is defined as the net present value of the technology's ability to minimize the cost of the environmental restoration. For example, the Department of Energy indicated an early desire to evaluate the technologies on the basis of "faster and cheaper" and was willing to assume that these two criteria were proof of "better". The argument is that, given the purpose of the measurement - to determine whether contamination at a particular point on the surface was greater or less than a criterion specified by a regulatory agency - the evaluation had to consider the degree to which the measurement provided information relevant to the regulatory criterion. In other words, faster and cheaper are not sufficient conditions that, if met, make a technology better.

The real issue was identified as economic advantage. The technology that provides the greatest opportunity for reducing overall remediation costs is, from the program's point of view, the best technology in terms of economic advantage.

The purpose of a measurement, irrespective of the technology, is to obtain information that will be used to make a decision. The information, in the context of the Fernald demonstration, is at what locations and to what degree contamination exists on the surface. The degree is specified by a regulatory criterion. If the amount of uranium in the soil is in excess of the specified criterion, the soil is contaminated. If the amount of uranium in soil is less than the specified criterion, the soil is not contaminated. Therefore, at least one essential criterion the technologies must meet is the ability to distinguish between contaminated and uncontaminated soil at the level specified by the regulatory criterion at an appropriate level of confidence.

Confidence, within the framework I am working, has a specific meaning and relates to the following two questions: at the location of the samples, what is the likelihood of exceeding the regulatory criterion given the measurements? and, at the locations not sampled, what is the likelihood of exceeding the regulatory criterion given the measurements? There are two important issues that are implicit in the way I have just defined confidence that must be addressed explicitly in the technology evaluation. The first is the issue raised by the use of the word likelihood. By the use of the word "likelihood" I have defined a probabilistic problem and I wish to answer, in quantitative terms now, the following question: at any point on the site what is the probability I am in excess of the regulatory criterion? This is the question upon which remedial decisions will be based and this is the question the technologies must answer. The degree to which the technologies answer this question is an important factor in determining their worth. The second issue is raised by the fact that I asked two questions. The first question dealt with confidence in a measurement at the location in space where the measurement was taken. The second question dealt with confidence at a location in space where no measurement was obtained. This is a classic problem in estimating values of interest in a geologic domain. One of the substantial areas of work in the evaluation of the technologies is the application of advanced techniques for geostatistical simulation (Rautman, 1993).

What have we established so far in this discussion? We have determined that the purpose of a technology and the measurement it takes is to assess whether or not contamination, as defined by the regulator, exists and that the uncertainties associated with that measurement must become part of the evaluation. This information is contained in the probability maps described in Rautman, 1993. The next step in the evaluation of the worth of the technologies is to relate this information to the economic objectives of the remediation. I assume that the overall economic objective is to adopt a strategy that minimizes the cost of the environmental restoration and meets the regulatory criteria for compliance. For the purpose of the technology evaluation, a simple objective function can be used to summarize the total cost of the remediation and its relationship to the site characterization data obtained by sampling. The function is given as:

***Total Cost = Cost of Characterization + Cost of Treatment + (P[failure])(Cost of Failure)***

Note that the equation is written entirely in units of dollars. There are 3 important concepts here that merit further discussion. The first is the concept of economic risk as defined by the last term in the equation. The last term is expressed as the product of the probability of failure and the cost of failure. The probability of failure, for any location at the site, is described graphically and quantitatively by the probability map. The probability of failure is a quantitative answer to the following question: if I choose not to remediate the soil at this particular location, what is the likelihood that the contamination level at this location is in excess of the regulatory criterion given the information currently available to me from the site characterization? The cost of failure is the future costs, in today's dollars, of penalties, fines, and other costs that may be incurred if you do not meet the regulatory compliance criteria due to a classification error. The function explicitly states that the worth of a measurement, and therefore the measurement technology, is related to the measurement's ability to provide information that minimizes the risk of failure at sometime in the future. The second concept is a simple extension of the probability concepts already introduced. The total cost can be expressed entirely as a function of random variables and expressed either as an expected value or as a probability function. What do I mean by a function of random variables? If we inspect each of the terms in the equation, it is obvious that there are uncertainties associated with the cost of characterization, the cost of treatment, and great uncertainty associated with the cost of failure. The third concept is that of technology worth which directly relates to the problem of how best to compare and evaluate new technologies with respect to each other and with respect to an acceptable current standard. For example, I can define the value or worth of a new technology as:

***Total Cost Old Technology - Total Cost New Technology = Worth Of New Technology***

which instantly illustrates the fact that a new technology can have a negative worth. There are no prior assumptions that a new technology is more valuable just by virtue of the fact that it is new.

In summary, I can articulate four broad and specific goals - (1) evaluate the worth of the technologies for characterizing uranium contamination that were demonstrated at the Fernald site, (2) demonstrate the broad utility and applicability of working within an economic, value of information framework, (3) demonstrate the compelling logic of working within a probabilistic framework, and (4) demonstrate the feasibility and application of advanced geostatistical modeling techniques. I believe that the last three goals are essential elements in successfully meeting the first goal. In addition, I have identified a number of goals that are driven by technology transfer and economic criteria.

The first of these additional goals is the reduction of time it takes to complete an analysis. However, with added emphasis on software engineering, information management and visualization, and training I believe that real-time analysis in the field is attainable. There are compelling economic incentives behind this goal. Obviously, time is money, but another motivating factor is the ability of advanced geostatistical techniques to optimize field sampling strategies and the potential for the overall framework to determine stopping points for data collection. The second additional goal is to demonstrate the feasibility of PC-based technology applications. This goal is dictated by the desire to see these ideas broadly accepted and applied to wide variety of environmental and geotechnical problems. A third additional goal is to define the relationship between national laboratory, university, private industry, regulator, public, and Department of Energy. This project now has strong ties to all but the public. The current absence of a key stakeholder in an environmental application is, at this point, not for lack of trying but for lack of mechanism and time.

## CONCERNS

There are three elements of this approach that are not in common use by the legal, industrial, and regulatory communities. Therefore, these elements may not be readily acceptable. The first is the explicitly probabilistic approach. The second is the application of geostatistical techniques as opposed to statistical techniques to describe the sampled data. The third is the application of decision-analytic techniques.

There are at least three issues associated with probabilistic assessments and modeling. The first is that probabilistic modeling admits explicitly to uncertainty in an outcome. That uncertainty often results in a quantifiable, irreducible, probability of failing to meet objectives. For a program that has invested time and money in an effort to guarantee satisfactory results, this lingering probability of failure can be unnerving. The second is the centuries old debate over the meaning of a probability assignment. There are three common ways of defining a probability assignment. I can define a probability as a frequency, a degree of belief, or a state of knowledge. Except for frequency assignments, there is no universally agreed on method for assigning a probability to a degree of belief or a state of knowledge. The third is lack of experience in environmental applications of probabilistic modeling. To many, the techniques are new and challenging.

I believe that the eventual adoption of probabilistic approaches is inevitable. There are some straightforward arguments for this belief. As economic risk becomes a common factor in environmental assessments, the problem will look more familiar. Economic risk and the consequences are factors that we all cope with individually. We are all insured to different degrees. We are all familiar with the concept of investment strategy. In other words, we are all accustomed to probability and uncertainty in our own future. Whether we explicitly calculate the probabilities of the outcome we desire or rely strictly on intuition is irrelevant. Perhaps the most important factor that will lead to the routine adoption of probabilistic models is the tremendous advances in computing power over the past decade in conjunction with the advances in user friendly software. The ability to do probabilistic modeling is no longer the exclusive domain of Ph.D. scientists supported by super computers.

The second concern is the application of geostatistical techniques to data interpretation, as opposed to classical statistical approaches. Geostatistics evolved as a discipline in support of the mining industry. In geostatistical applications, spatial relationships in the sampled values are important in both the description of the sampled data and the estimates of parameters at unsampled locations. The fundamental, underlying concept, that properties in a geologic domain bear some resemblance to the same properties nearby and that resemblance decreases with increasing distance, is intuitively comfortable to any analyst with an earth-science background. To many, without that background, the approach seems alien. Like probability methods, geostatistical techniques are not routinely applied in environmental restoration. It is this lack of routine that accounts for most of the resistance. Like probability methods, the advances in computing hardware, software, and theory development will facilitate the application of these tools.

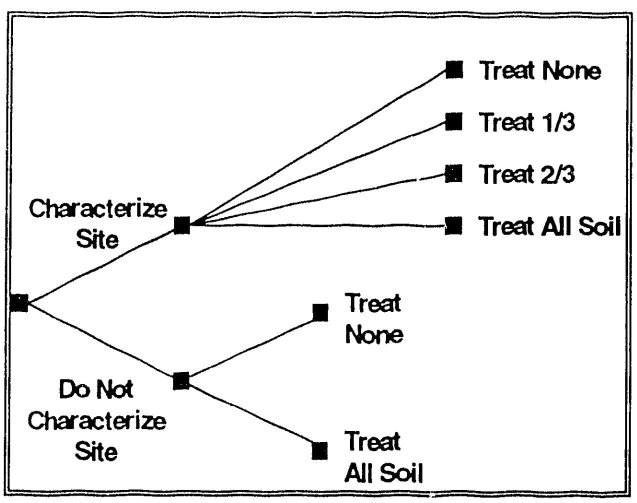


**Figure 1. Fernald Decision Model**

The third concern is decision analysis. It is a relatively new and highly controversial discipline. There are cognitive and mathematical schools of decision analysis. There is also concern that decision analysis usurps the authority of the decision maker. I can address all these concerns if I adopt the simple view that the purpose of decision analysis is to relate the data to the decision. Data collection in support of environmental restoration or technology evaluation is not an arbitrary exercise. Figure 1 is a decision model. Having decided to characterize the site, the decision model illustrates four possible outcomes. One outcome is to treat none of the soils assuming that no contamination is found. Another outcome is to treat all of the soils assuming that all the soils are found to be contaminated. Other outcomes are associated with varying amounts of contaminated soil. The purpose of data collection is to choose between alternatives and provide increased confidence in that choice. The alternatives, within the context of the Fernald technology evaluation, are the soil at a particular location on the surface is contaminated and it will be removed for treatment or the soil at that same location is not contaminated and no further action will be taken.

The discussion so far has focused on issues of concern. Issues that, if not resolved, could have a major impact on the acceptability of the approach. These issues also define the rather unique role assumed by the national laboratory and university community in support of environmental restoration - the ability and charter to introduce new concepts and technologies to the marketplace. New concepts and technologies are not recommended because they are new, but because of the need to reduce the economic costs of environmental remediation, restoration, and waste management

There is a second class of concerns that are defined by the nature of the work and the goals I have set. These concerns do not distinguish this project from any other but, if left unresolved, impair the chances of success. These are also concerns that, in many cases, could have tremendous economic benefit within the framework of environmental restoration.

One of the concerns is the suitability of the PC environment. The PC world has clear economic advantage both in terms of hardware and software. There is also a "friendly factor" associated with use of PCs. This suggests that applications developed for the PC are more likely to be used than workstation, mini, mainframe, or super computer applications. With this project's emphasis on probabilistic simulation and visualization tools, a high-power workstation is a logical platform and many of the applications that support the analysis are written for this environment. However, there has been feedback from the commercial community to suggest that the expense of hardware and software in this environment is prohibitive. Therefore, this project has invested resources in the development of PC-based applications.

The next concern is the one of data-base structure, integrity, management, and visualization. I have come to understand that an environmental assessment is as much a problem in information management as it is in analysis. Increased effort in this project is being invested in these areas with emphasis on Geographic Information Systems (GIS) and data exchange between different GIS systems.

The need for active regulatory participation in the early stages of technology development has also been identified as an concern. Within the decision-analytic framework, the site-characterization technologies are being evaluated with respect to their ability to answer a regulatory question. If there are any ambiguities in the question, the answer is also ambiguous.

All the concerns given in this section are part and parcel of one large concern - communication. An environmental problem presents some unique challenges for technical staff. There are a large number of stakeholders with whom we must communicate effectively including program managers, regulators, technical staff in other disciplines, and the public. There are three separate problems that this project is actively trying to solve that are associated with the communication concern. The first is access to the stakeholder. Just as an example, consider protocol. Protocol dictates that technical staff supporting a program communicate with the project manager who then informs the program manager who then discusses the problem with the technical project officer who informs the technical program officer who reports to the deputy assistant acting secretary. The second is the form of the communication. For example, a technical paper is a form of communication. It is a totally inappropriate form for the vast majority of stakeholders. Each of the stakeholders must be addressed in the most appropriate manner. This project is investing resources in visualization, color graphics, animation, and desk-top publishing in order to reach each of the stakeholders effectively. The third is the language barrier. Technical staff do not speak "program management" or "public" effectively. For example, within the framework of this project, uncertainty can be defined as Shannon's Informational Entropy

$$H = -\sum_{i=1}^{n} p_i \ln p_i$$

This definition represents one of the outstanding intellectual achievements of this century, fully specifies uncertainty, profoundly affects the mathematics of the approach, and is entirely meaningless as a form of communication with all but a few stakeholders. However, the vast majority of people understand the concept if it is communicated as "Murphy's Law".

## BENEFITS

I mentioned, in passing, the economic incentives of this approach to the technology evaluation at the Fernald site. There are four major questions that are answered by the methodology: Where do I send the bulldozer? If I clean up this region but not that one, how certain am I that I'm not missing something? Would more samples help me reduce the area I need to clean up, or at least reduce the risk that I'm making a mistake? What are the economic consequences of each of the decisions I have just made? These questions are generically applicable to virtually every site investigation. I do not believe that current practice adequately answers these questions for the decision maker. I believe that better answers to these, and related questions, have the potential to reduce the current and future costs associated with environmental remediation. Current costs can be reduced by site characterization programs that, by design, provide the information upon which decisions will be based. Future costs will be reduced because the risk of failure has been minimized.

Given the nature of the problem, technical achievement alone provides no benefit. Political, social, and economic objectives that must also be met. Consider geographic information systems and graphic user interfaces, GIS's and GUI's, respectively. Neither is a technical necessity. Both are becoming essential communication tools. A GIS, in its ultimate form, allows instantaneous access to information to all stakeholders in a form that, with some effort, can be made readily understandable. The same can be said for the potential of GUI's. Reducing the time it takes for information to propagate through a program has direct economic consequence. Presenting information in a format that can be understood by all stakeholders has direct political consequence.

In the end, the evaluation of technologies for the characterization of uranium-contaminated soils presents challenges that are not unique. Quantifying the value of site-characterization data is a common geotechnical problem. The worth of any individual measurement is a common problem. Communicating the results of site characterization to the decision makers is a common problem. The approach taken by this performance-assessment task will demonstrate a possible solution to these problems.

ACKNOWLEDGMENTS

I would like to acknowledge the support and guidance of Kim Nuhfer (FERMCO), Anthony Armstrong (ORNL), and Mike Malone (DOE, HQ). This work was sponsored by the U. S. Department of Energy, Office of Technology Development, under the Uranium in Soils Integrated Demonstration Program.

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