Innovative Technology
Summary Report

DOE/EM-0491

Smart Sampling™

Subsurface Contaminants
Focus Area

Prepared for
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INNOVATIVE TECHNOLOGY
Summary Report

Smart Sampling™

OST/TMS ID 162

Subsurface Contaminants
Focus Area

Demonstrated at
Sandia National Laboratories
Albuquerque, New Mexico
Mound Environmental Management Project
Miamisburg, Ohio

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications."

TABLE OF CONTENTS

SECTION 1

SUMMARY

Technology Summary

Problem

Site characterization efforts at many contaminated sites across the United States (U.S.), especially at U.S. Department of Energy (DOE) sites, have provided sufficient information to produce fairly robust estimates of the overall nature and extent of soil contamination, but not enough to optimize remedial designs to target only those zones or areas requiring cleanup.

Costs for characterization alone can represent a significant portion of the overall cleanup costs. Optimization of the characterization process to maximize the effectiveness of and minimize the costs of remediation is needed. Tools to assist with evaluation of alternative remedial designs and setting of remediation goals are also needed.

How it Works

SmartSampling™ is a risk-based, goal-oriented process that provides an objective and quantitative framework for

1) evaluating and improving alternative remediation designs and

2) direct mapping of risk levels and cost alternatives . The process provides graphical tools to focus negotiations among site owners, regulators, and stakeholders to set remediation goals, using information on the economic consequences of various risk levels. SmartSampling™ quantifies the tradeoffs between accepting various levels of risk and associated remediation costs.

SmartSampling™ supports cleanup decision makers who must agree on the cleanup goal and the level of risk to accept in deciding on a remediation plan.

SmartSampling™ recommends optimal locations of additional samples to be collected and analyzed to complete site characterization. This can reduce remediation costs and uncertainty. SmartSampling™ explicitly assesses costs associated with alternative remediation plans.

At each step of the process, the stakeholders and the regulators are shown the consequences of decisions regarding both the action level (tied to a human health risk level) and the acceptable level of uncertainty in economic terms. The process considers the costs of characterization, treatment, or disposal of contaminated material and failure to meet design or compliance objectives, along with the uncertainties in the various costs, to evaluate design trade-offs that are likely to minimize the total cost of remediation.

Potential Markets

SmartSampling™ can be used at any hazardous or radioactive waste site where negotiating parties must decide to what level to clean the site and what technologies to use to clean the site. SmartSampling™ can be used in conjunction with site investigation programs to optimize future sampling plans and design of the site remediation systems, targeting various cleanup goals.

Advantages Over Baseline

The baseline against which SmartSampling™ is compared is the traditional site investigation approach, which consists of multiple phases of site investigation before a remedial design can be implemented. Extended negotiations regarding cleanup goals are also a component of the baseline process. Advantages of SmartSampling™ include:

- Improved remedial designs as better information is provided on various remedial options and the system of choice can be optimized to ensure maximum efficiency at minimum cost;
- Definition of the risk associated with over- or under-design of the remediation system; and
- the creation of probabilistic remediation maps (Figure 1),

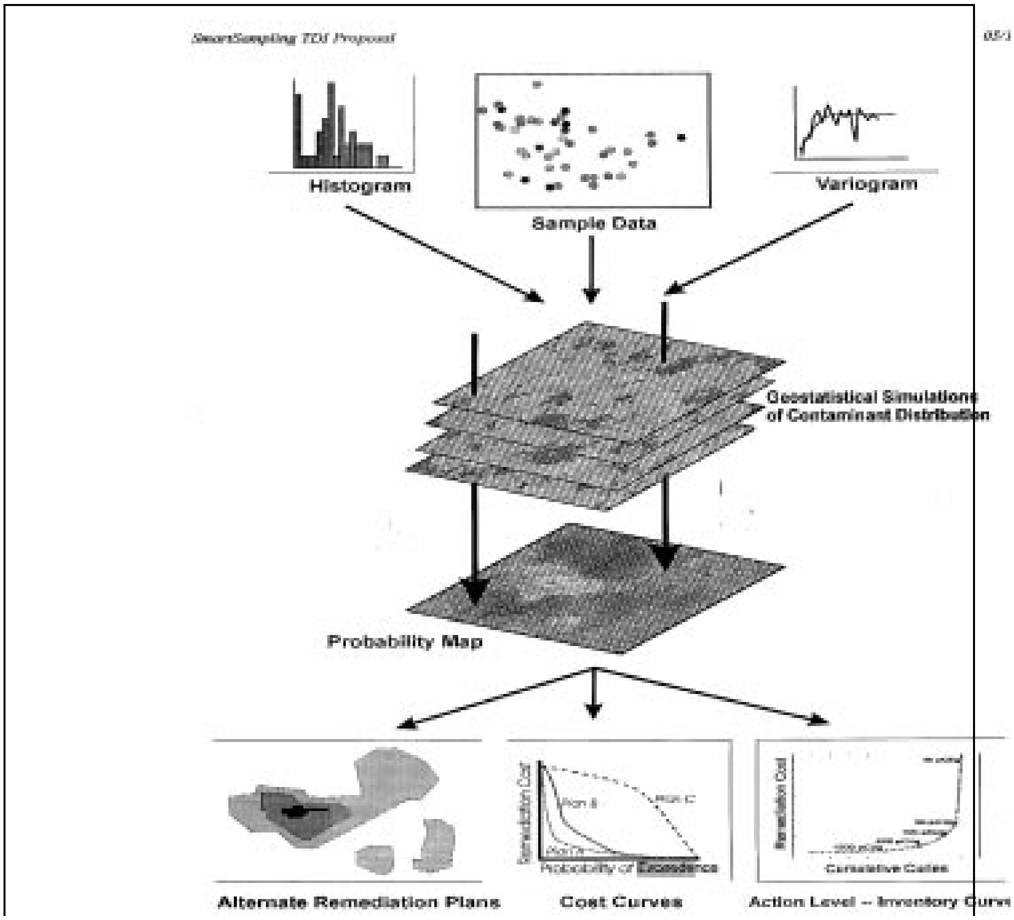

Figure 1. Example of probabilistic remediation map

Demonstration Summary

The SmartSampling™ method has been demonstrated on a number of projects since 1992, and it is ready for large-scale deployment. Demonstration efforts have included the following.

- Real-time, field-based uranium detectors were evaluated as part of the DOE Uranium-in-Soils Integrated Demonstration program in 1993 at the Fernald Environmental Management Project

(FEMP). Advanced geostatistical simulation techniques were combined with an economic objective function, described in the literature as Hydrogeologic Decision Analysis, to determine the economic worth of the data returned by each detector with respect to a remediation decision.

- A case study was conducted in 1996 of nitrate and herbicide contamination in both the unsaturated and the saturated zones over a 150-km^2 area in Oregon.
- SmartSampling™ was demonstrated in 1996 to evaluate the nature and extent of lead contamination at a site at Sandia National Laboratories (SNL). The results were presented to the Albuquerque (New Mexico) Citizen's Advisory Board (CAB) and the New Mexico Environment Department (NMED). As a result of the SmartSampling™ analysis, DOE, NMED, and the CAB agreed to remediate the site to a higher remedial action level, based on an industrial land-use scenario, which resulted in multi-million dollar cost savings.
- SmartSampling™ was demonstrated as a retrospective evaluation of plutonium contamination in Release Block D at the Mound Environmental Management Project (MEMP), Miamisburg, Ohio.
- SmartSampling™ has been and is now being demonstrated in conjunction with cleanup of a plutonium spill that contaminated part of the historic Miami-Erie canal, adjacent to the MEMP site. This application is unique in that SmartSampling™ is being used to address two issues (volume minimization and use of field-screening measurement methods in regulatory certification) and because the project reports to a core team comprising a representative from DOE, Ohio Environmental Protection Agency (EPA) Office of Federal Facilities Oversight, U.S. EPA Region V, and local citizens. Three sections of the canal underwent the SmartSampling™ process. The excavation plan resulting from this work called for removal of 95% of the plutonium at a cost of $67,000, whereas the original plan called for removal of 97% of the plutonium at a cost of $108,000.
- SmartSampling™ is currently being used at the DOE Idaho National Engineering and Environmental Laboratory (OU7 & OU8) and will be used at the DOE Rocky Flats Environmental Technology Site, the DOE Hanford Site (200 Area), and a Navajo Nation site.
- More information on SmartSampling™ is available at www.nwer.sandia.gov/sample.

Contacts

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference # for SmartSampling™ is 162.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

SmartSampling™ is a process that defines remediation as an economic investment to achieve regulatory compliance with appropriate clean-up standards at the lowest possible cost.

- This cost minimization appropriately balances remediation and characterization dollars, while accounting for costs (fines, penalties, etc.) that would be associated with regulatory failure to remediate the site properly.
- This cost minimization can be expressed quantitatively in a decision-analysis framework as

$$C_{\text{TOTAL}} = \sum_i \left[C_{\text{SAMPLING}} + C_{\text{REMEDIATION}} + P_f \, C_{\text{FAILURE}} \right]_i ,$$

  where C is the site-specific cost and P_f is the probability of failure. Economic failure can occur through either 1) the treatment or removal of soil predicted to be contaminated but that is actually clean or 2) the failure to remove contaminated soil, which can lead to regulatory fines, loss of credibility, and remobilization of contaminants.

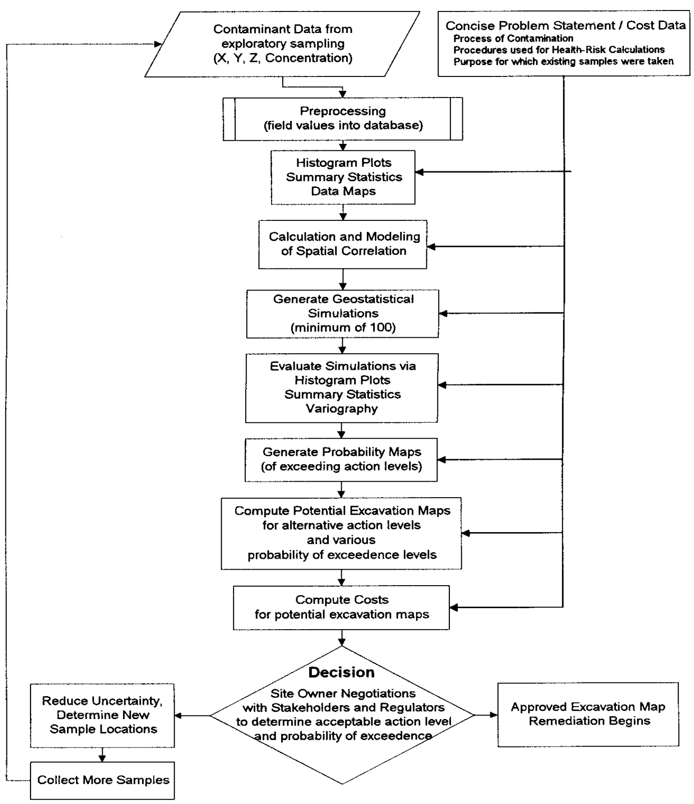

Figure 2. SmartSampling™ process flow diagram

- Advanced geostatistical techniques, such as interpolation and Monte Carlo simulation, are used to calculate the probability of failure under site-specific conditions
- SmartSampling™ is an environmental application of technologies and methodologies, such as those described above, developed to address spatial sampling problems faced in oil and gas exploration, mineral exploration, precision agriculture, and a host of other common geotechnical applications (Figure 2).
- SmartSampling™ combines economic risk analysis and spatial geostatistical simulations to provide a technically defensible basis for waste minimization and cost reduction.

Process/Operations

SmartSampling™ consists of six steps described below and shown in Figure 2.

- Create Histogram – From data obtained on contaminant concentrations at sampled locations, SmartSampling™ generates a histogram to display the known distribution of contaminant concentrations.
- Generate Variogram – A variogram is generated to quantify the spatial correlation that between pairs of samples. In geostatistics, the differences in values between pairs of samples will decrease as their proximity to each other increases. Smart Sampling applies spatial correlation algorithms to sampled values to predict values at unsampled locations. A variogram is a graphical display of this correlation.
- Perform Geostatistical Simulations – SmartSampling™ uses the histogram, the sample values and locations, and the variogram to perform geostatistical simulations. Many models are generated to show likely concentrations and distributions of the contaminant of interest across a site. Each model accounts for all known information and is equally plausible in predicting concentration and distribution at unsampled locations.
- Create Probability Maps – SmartSampling™ averages all the modeled values and maps them, showing the likelihood that the true contaminant value at any unsampled location exceeds the selected action level. Probability maps provide insight as to the most productive and cost-effective alternatives for remedial design, and they quantify the risks associated with each alternative.
- Generate Excavation Maps – SmartSampling™ generates excavation maps from the probability maps by marking for cleanup those cells with the selected probability of containing soil that exceeds the action level.
- Create Cost Curves – Cost curves show how costs are affected by decisions about action levels and probability of exceedence. They help decision makers clarify their options and understand the economic tradeoffs among various combinations of action levels, more characterization sampling, and negotiated levels of uncertainty.

Technical components of the SmartSampling™ process are described in further detail below.

- Geostatistics involves the study of data that exhibit spatial correlation (autocorrelation). Many variables or phenomena of interest in earth science exhibit relatively similar values when observed at two nearby sample locations. Furthermore, the degree of similarity typically can be demonstrated to decrease as the distance between two measurements increases.

- *Geostatistics*, given a set of relevant observations, provides a quantitative means of describing and applying such spatial correlation to the prediction of values at unsampled locations. The variogram (Figure 3) is defined as

$$\gamma(h) = \frac{1}{2N(h)} \sum_{1}^{N(H)} (Z_x - Z_{x+h})^2 ,$$

where Z_X is the value of a measurement of an attribute, *Z*, at a spatial location, *x*; Z_{x+h} is a measurement of the same attribute, *Z*, at a different spatial position, *x + h*, located at a vector distance, *h*. The vector distance, *h*, typically refers to a class of separation distances, all of which are approximately *h*. Statistically, the expression for γ is similar to that for a variance, except that in the case of a simple variance, the squared term compares each value of the variable with its mean (average or expected) value. In effect, $\gamma(h)$ provides a quantitative description of statistical variability as a function of the distance between sample locations.

Note: because *h* is a vector quantity, separation distance can consider annular relationships between sample pairs such that the description of spatial correlation can be anisotropic and stronger in one direction (along bedding in sedimentary rocks) than in another (perpendicular to bedding in the same example). Also, the computed (sample) variogram typically is fitted by some convenient mathematical expression, which allows computation of the degree of similarity or dissimilarity for any desired separation distance and/or direction.

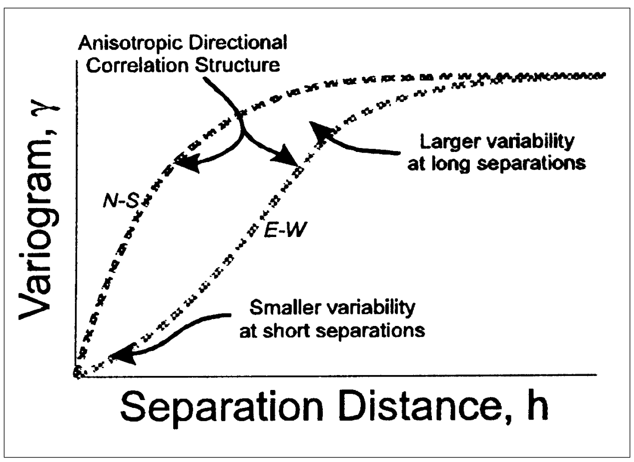

Figure 3. SmartSampling™ Variogram

- *Interpolation techniques* are commonly used throughout engineering and the sciences to develop estimates of particular attribute values corresponding to some other controlling variable for which direct measurements are not available using some set of measurements deemed relevant to the process at hand. In a spatial context, estimation is commonly used to predict the value of some earth science property, such as contaminant concentration, at an unsampled location given some set of surrounding measured values. The most frequently used spatial interpolation algorithms include nearest-neighbor polygons, inverse-distance-to-a-power weighting, and kriging.

  Virtually all numerical interpolation algorithms may be thought of as computing estimated values as a weighted average of a neighborhood of measured values. A hallmark of all interpolation algorithms is smoother estimated models (i.e., exhibiting less variability than do the data used to create the model). A corollary of this smoothing effect is that, unless negative weights are permitted, the maximum and minimum interpolated values cannot fall outside the range of the input values. In studies of contamination, this corollary amounts to a presumption that the existing, finite set of characterization samples have been "fortunate" enough to sample both the highest and the lowest actual contamination values at the site.

- *The Monte Carlo simulation technique* is a well-established modeling methodology that is intimately tied to the concept of addressing uncertainty in complex systems. The concept is quite simple: one is required to evaluate some parameterized mathematical description of behavior for a complex system in the presence of uncertainty as to what the exact values of those parameters should be in light of some goal-oriented objective.

  — For example, will an earthen dam stand without failing given that one knows precisely neither the maximum flood discharge of the river nor the minimum in-situ mechanical strength for the specific fill used for the dam under all moisture conditions? Attempting to predict exactly what the greatest possible flood will be for a given drainage-basin geometry, climate scenario, etc., one may choose to generate a variety of “plausible” values for both flood discharge and mechanical properties and to evaluate the design consequences of these various values given the working mathematical description of dam performance. The expectation is that although a finite likelihood of dam failure remains, the probability (given a specific design) is small enough to be accepted as reasonable.

  The following critical concepts are implicit in a *Monte Carlo* analysis.

  — First, expected conditions are not the principal interest. Dams do not fail under “usual" conditions of material strength or rainfall. Engineering consequences are generally the result of atypical extreme members of the plausible range of values for a variable.

  — Second, the approach implies that, no matter what is done, some finite, acceptable risk that the system will fail to perform as desired will always exist.

  — Third, analysis leads to a reasonable, empirical approximation of the underlying probability distribution function of the actual physical system.

  — Applied to the issue of soil contamination cleanup, the technique of spatial simulation is designed to generate a large number of plausible synthetic contaminant fields (Figure 1), all of which reproduce the measured values and the degree of variability and spatial correlation exhibited by the available measurements of soil contamination. Because all of these synthetically generated possible contaminant fields are equally likely, the multiple stochastic realizations can be processed to yield an empirical estimate of the likelihood, given a set of nearby measurements, that the true contaminant value at any unsampled location exceeds a stated threshold value.

  — Mapping of empirical probability estimates can yield significant insight as to the most productive and cost-effective alternatives for remedial design and quantify the risks associated with each alternative. Furthermore, this approach enables one to estimate the relative benefit of investing effort into additional sampling in a specific area in hope of reducing the volume of material to be treated or removed versus the cost of simply removing the material and moving on to the next site. In each case, short of treating or removing all material at a contaminated site, some finite probability exists that cleanup activities will fail to remove all contamination. However, the proper use of spatially-based *Monte Carlo* simulation will provide relatively objective, quantitative criteria for determining the point of diminishing that is acceptable to all involved parties.

SECTION 3

PERFORMANCE

Demonstration Plan

Background and Site Description

SmartSampling™ was demonstrated during 1996 at an environmental remediation site at SNL in Albuquerque, New Mexico. Site 91, also known as the “lead flyer site”, is relatively flat with small amounts of desert vegetation; the surficial geology is composed of alluvial sediments. Tests conducted at Site 91 between 1979 and the late 1980s consisted of approximately 13 detonations using 100,000 pounds of lead. The nature of the explosive shots was such that large amounts of lead were vaporized and then dispersed across the site by aerosol deposition. Large, identifiable chunks of lead were manually removed from the site before site characterization sampling.

Initial site characterization, begun in 1992, consisted of sampling along four transect lines arranged radially with the intersection of the sampling transects at ground zero for several of the explosive shots.

- The nominal sample spacing along the transects was 20 ft. Additional samples were obtained in the northern and eastern portions of the site on a grid with a 33-ft spacing. These characterization efforts resulted in 299 samples.
- All samples were composites representing the average contamination between the ground surface and a depth of 6 inches over a 10 ft × 10 ft area.
- Additional sampling to greater depths during 1995 indicated that most of the lead was contained in the upper 6 inches of the soil at the site.
- A suite of 22 follow-up samples was obtained in early 1996.

Remediation Objectives at Site 91

Outside stakeholders, organized as a CAB, and the NMED have been involved in negotiations with DOE concerning the future of Site 91. The baseline cleanup goal for a residential land-use scenario, as determined by pharmokinetic modeling by the U.S. EPA, was an action level of 400 ppm for lead. Contaminated soil (soil determined to have a lead concentration >400 ppm over a 10-ft-sq remediation panel) would be disposed of in a landfill.

Both parties were interested in the costs associated with the baseline remediation goal and possible alternatives to the baseline goal and the costs corresponding to those alternatives. Discussions between the three parties led to consideration of an alternative future land-use scenario, which would have a preliminary action level of 2000 ppm. DOE, NMED, and the CAB requested quantitative estimates of remediation costs to examine the economic consequences of a decision for each of the two action level alternatives.

Results

Remediation Maps

Remediation maps were created from the probability maps by applying an acceptable probability of exceedence across the probability map and remediating each cell that exceeds that probability (Figure 4). Note the large difference in the size of the areas requiring remediation both between the two action levels and between the two acceptable probabilities of exceedence at either action level.

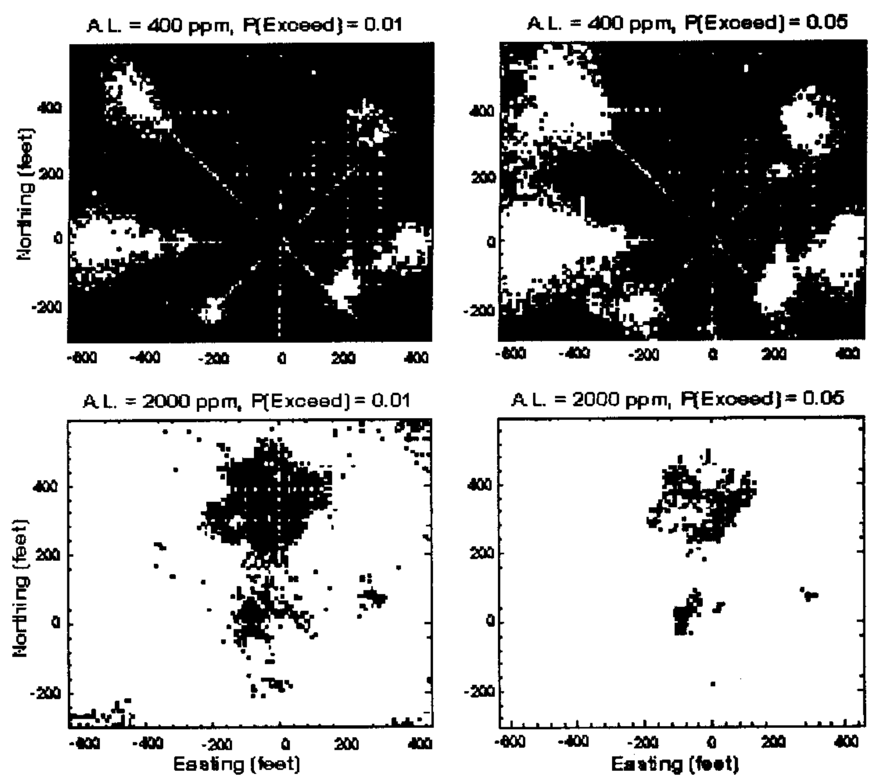

Figure 4. Remediation maps for the 400- and 2000-ppm action levels for acceptable probability of exceedences of 0.01 and 0.05

Model Validation

Locating second-phase or follow-up samples is an important issue for regulatory acceptance (confirmation samples) and a critical step in minimizing waste volume. Generally, follow-up sample locations are determined either by minimizing the total costs or uncertainty about the decision point (action level) or by choosing the locations that provide the greatest "worth" of the collected data.

Twenty additional samples were collected at Site 91 within the simulation domain to validate the geostatistical model. The additional samples were taken at essentially random locations that were chosen to check the reproducibility of the original samples. At every additional sample location, the sample value is compared with the distribution of concentrations at that location created through geostatistical simulation. Figure 5 shows this comparison.

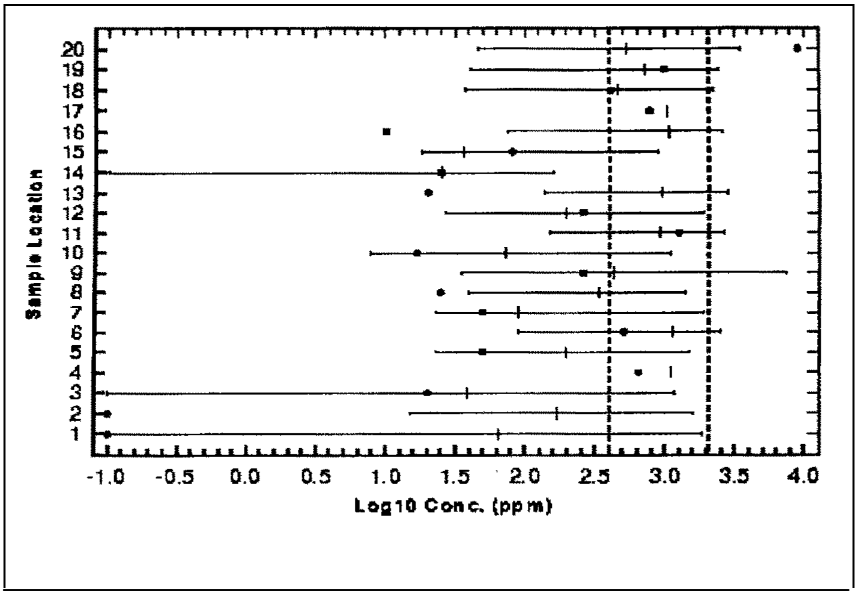

Figure 5. Comparison of sample value to the distribution of concentrations at a given location created through geostatistical simulation

The variability of the 20 distributions of lead concentration created through geostatistical simulation varies markedly by location. This variability in the width of distributions is due to the proximity of a new sample location to an original sample location. In two cases (Sample Locations 4 and 17), the new samples were obtained at the same location as earlier samples. The simulated distributions at these locations are composed of a single value.

The actual positions of the sample values within the simulated distributions give some sense of the accuracy of the model. However, the accuracy of the remediation decisions made, based on the model, is of the most importance. Two types of poor remediation decisions may be made:

- false positives, in which uncontaminated soil is cleaned up unnecessarily, and
- false negatives, for which contaminated soil is incorrectly classified as uncontaminated and left behind at the site.

Of these two mistakes, the false negatives are the more serious in terms of safeguarding human health and are often subject to regulatory penalties. Conversely, the costs of the false positives are only the costs of the unnecessary remediation.

For each of the 20 additional samples, the accuracy of the remediation decision is examined for the four remediation maps shown in Figure 3. Table 1 summarizes the results of the remediation decisions. The remediation maps based on the geostatistical simulations are quite effective in preventing false negatives. This result is advantageous to both the regulator (fewer locations are deemed to be clean when, in fact, contaminants are present) and the site operator (the chances of having to pay fines based on the regulator discovering areas of contamination within areas that were declared to be clean are small).

Table 1. Accuracy of the decisions at the 20 additional sample locations

Action level (ppm)	Acceptable P(exceed)	Number and percentage of correct decisions	Number of false negatives	Number of false positives
2000	0.01	15 (75%)	1	4
2000	0.05	17 (85%)	1	2
400	0.01	7 (35%)	0	13
400	0.05	8 (40%)	0	12

Summary

As a result of the SmartSampling™ analysis at Site 91, the three parties concurred to remediate the site to the 2000-ppm action level with an agreed upon 0.05 probability of exceeding the action level at any remediation panel.

The economic analysis comparing the two action levels, presented in Section 5, shows the difference in remediation costs between the 400- and 2000-ppm levels to be approximately $6.6M. The capability of SmartSampling™ to correlate costs directly with alternative action and probability levels was crucial in discussions with state regulators and local stakeholders to achieve an acceptable remediation level with respect to human health and remediation costs. Thus, DOE saved $6.6M as a result of the revised action level.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

- The current baseline for site characterization involves various intrusive sampling and analysis or non-intrusive analysis techniques. Initial site characterization efforts at many sites within the DOE complex have provided sufficient information to produce fairly robust estimates of the overall nature and extent of soil contamination, but not enough to allow accurate remedial designs for specific sites without grossly excessive conservatism and wholesale excavation or other treatment. Therefore, current baseline plans contain provisions for significant further assessment sampling targeted to support more precise remedial designs that can be contracted in relatively final form.

Technology Applicability

SmartSampling™ is widely applicable across the entire DOE complex, because it is a process that can be used at any site requiring characterization and remediation of contaminants. It is not a product that is tied closely to a specific contaminant or engineered structure. The conceptual and analytical tools of SmartSampling™ provide the framework within which site-specific information and requirements are displayed for evaluation and decision.

- SmartSampling™ is applicable to any measurable contaminant in soils.
- SmartSampling™ can be applied as an objective mechanism for determining the optimal locations for additional samples to reduce life-cycle remediation costs and reduce the risk that undetected contamination is left in place.
- SmartSampling™ can be applied to reduce the number of certification samples after a remedial action has been performed.
- SmartSampling™ can:
  - — lead to the generation of more rigorously defensible, risk-based remediation plans for a site, and/or
  - — aid in the quantitative evaluation of other, alternative remedial designs, such as those that might be proposed by a regulatory agency or a community action group.

Patents, Commercialization, Sponsor

SmartSampling™ uses public domain technology to create a process for site characterization to support remedial design and operation. SmartSampling™ was developed by SNL with support from DOE's Office of Science and Technology. It is currently not commercially available.

SECTION 5

COST

Methodology

The essential first step in SmartSampling™ is to state the site's characterization in terms of an economic objective function:

$$C_{\text{TOTAL}} = \sum_i \left[C_{\text{SAMPLING}} + C_{\text{REMEDIATION}} + P_f \, C_{\text{FAILURE}} \right]_i \, .$$

As the function clearly illustrates, the purpose of SmartSampling™ is to minimize the total cost of the remediation as a function of site-specific costs and contaminant distribution. SmartSampling™ evaluates the trade-offs between the cost of treatment or disposal, characterization costs, and penalties for non-compliance to define the least-cost design alternative. Cost savings can accrue from minimization of waste volume through additional characterization, more efficient design of the sample numbers and pattern as a function of site-specific conditions, and design of sampling programs to minimize the likelihood of a programmatic failure where regulatory penalties for false negatives are both expensive and highly likely.

In truth, the consequences of the additional assessments cannot be costed accurately into the future until the assessment itself has been completed. The following illustration (Site 91 at SNL) is an example of potential cost savings as a result of using SmartSampling™.

Cost Analysis

At the SNL Site 91, the baseline cleanup operation, based on a residential land-use scenario, involved removal of contaminated soil (soil determined to have a lead concentration >400 ppm over a 10-ft-sq remediation panel), and disposal in a landfill. An alternative industrial land-use scenario involved removal of contaminated soil with a lead concentration >2000 ppm over a 10-ft-sq remediation panel) and disposal in a landfill. Remediation maps were created for each action level (400 and 2000 ppm; see Section 3). A unique cost is associated with each remediation map that was created.

Cost Conclusions

At Site 91, the estimated disposal costs for either scenario are $545/yd^3, and each $10 \times 10 \times 0.5$-ft cell has a remediation cost of $1000. For any acceptable probability of exceedence at any action level, a remediation map can be created and the associated cost of remediation graphed as a function of the probability of exceedence. Figure 6 shows the costs of remediation for Site 91 as a function of probability of exceedence.

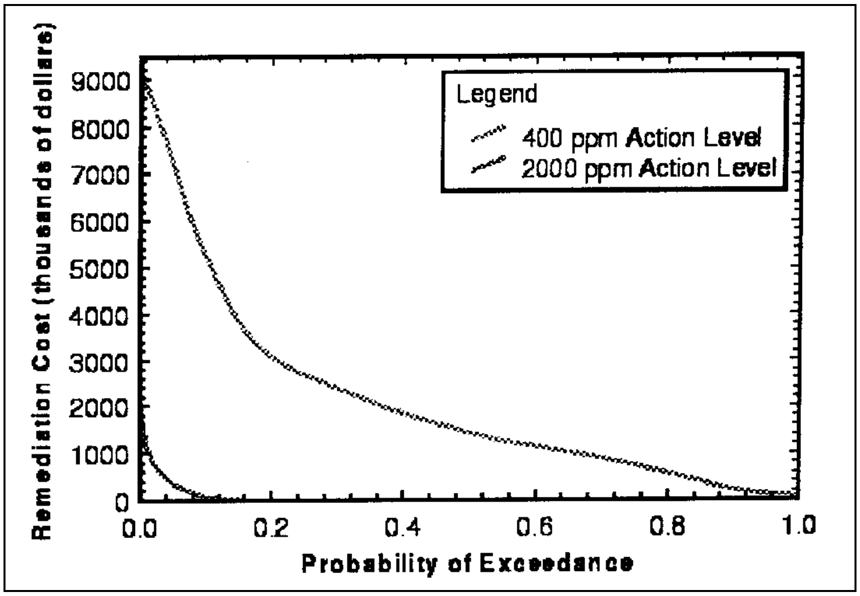

Figure 6. Cost of remediation for Site 91

At an acceptable probability of exceedence equal to 0.05, the cost savings created by designating the site as having an industrial future land-use scenario (action level = 2000 ppm) versus a residential future land-use scenario (action level = 400 ppm) are approximately $6.6M ($400K versus $7M). Also note the steep decrease in remediation costs afforded by only incremental increases in the acceptable probability of failure. For example, the figure shows that an increase in the acceptable probability of exceedence at the 400-ppm action level from 0.01 to 0.05 results in a decrease in the remediation cost of roughly $2M. At SNL Site 91, the cost of the SmartSampling™ Analyses was $10K, which helped to generate a savings of $6.6M. The use of SmartSampling™ at any site is predicated on an assumption that there will be a return on investment.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

Regulatory agencies typically require confirmation or verification sampling to be conducted after a remedial action has been completed for a site. Such confirmatory sampling can involve large numbers of samples and can represent a major cost item in the life-cycle budget for an individual site. Typically, locations for verification samples are determined on a purely random basis, and the total number of samples required is generally developed using traditional statistical methods that assume the spatial independence of the individual samples.

SmartSampling™ offers an objective, quantitative mechanism for reducing the number of certification samples required through more efficient placement of verification sampling by focusing attention on the locations within a certification unit that are most likely to contain residual contamination given either pre-cleanup sampling or some set of informal field-screening measurements. It is recommended that the DOE site owner work closely with the regulators to demonstrate the benefits of SmartSampling™, as has been done in New Mexico and Ohio.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

Because SmartSampling™ can reduce the number of field samples required for thorough site characterization, the potential exposure of workers to hazardous materials is reduced substantially.

Community Safety

The risk-based and goal-oriented framework of SmartSampling™ provides an objective mechanism for quantifying the relative risks incurred by leaving untreated contamination in place across a number of different contaminated sites. Therefore, the risk of exposure to the surrounding community is quantified further.

Environmental Impact

Because SmartSampling™ does not involve direct field operations, this assessment technology has no negative impact. However, because the number of field samples may be reduced as a result of SmartSampling™, a direct environmental impact results. In addition, the environmental concern about the potential for leaving untreated contamination in place is reduced.

Socioeconomic Impacts and Community Reaction

- The economy of the region should not be affected by SmartSampling™.
- SmartSampling has limited exposure within the general public; however, public support is expected to be obtained because characterization costs and the probability of leaving untreated contamination in place are reduced.

SECTION 7

LESSONS LEARNED

Implementation Considerations

- Preliminary, valid sampling data are required before SmartSampling™ can be implemented.
- SmartSampling™ explicitly acknowledges the futility of attempting to predict exactly the true value of a spatially-distributed variable at an unsampled location. Accordingly, emphasis is shifted away from predicting some estimated value(s) and placed instead on the likelihood that the true value at any unsampled location exceeds some stated action level (or set of levels).
- In SmartSampling™, remediation designs can be determined only after explicit, quantitative consideration of the level of uncertainty in making a remediation decision at a specified action level. This consideration results in a remediation plan that the site operator, the regulators, and third-party stakeholders can defend because all of these parties have been involved in determining the acceptable level of uncertainty.
- SmartSampling™ facilitates stakeholder consideration of the effects of uncertainty through generation of cost curves that show quantitatively the economic trade-offs among various combinations of action levels, continued programs of delineation sampling, and acceptable levels of uncertainty that all contaminated materials will, in fact, be identified and removed successfully.
- SmartSampling™ provides objective, goal-focused, quantitative criteria for locating additional follow-up samples, including samples taken using either field-screening or EPA-certified measurement techniques. Determining the optimal location for these samples is framed as a "data worth" problem. The worth of the data is defined as the economic benefit of collecting each sample minus the cost of that sample. Samples have positive economic worth only if the reduction in remediation costs provided by that sample is greater than the cost of taking it. SmartSampling™ allows for the use of several algorithms to determine sample locations with the greatest potential worth.
- SmartSampling™ was developed to be compatible with the probabilistic regulatory risk-analysis tools developed by EPA, DOE, and the Nuclear Regulatory Commission (NRC), ensuring that no technical or conceptual barriers to the deployment of SmartSampling™ exist as a new generation of regulatory risk-assessment tools enter the system.

Technology Limitations and Needs for Future Development

- SmartSampling™ does not address human health risk directly. The process allows the stakeholders and regulators to designate acceptable human health risk level(s) as action levels. SmartSampling™ then uses the designated action levels to generate potential remediation maps for a final decision. This process should be deployed according to site-specific information.
- SmartSampling™ describes contaminant distributions in relation to probabilities and costs and incorporates assessment methods that are not yet described in regulatory guidance documents. Successful deployment requires that the regulator and the concerned citizen understand the process and have access to both the tools and "neutral" expertise. Substantial time and effort should be invested to gain acceptance of the technology and, in doing so, to generate the experience and language required to bring probabilistic approaches into accepted guidance materials.
- SmartSampling™ training for site personnel should be presented as a formal curriculum tailored to site-specific applications and the ongoing consultation, design, and analysis services of project members until site personnel can perform the process independently. SNL has prepared a training course for the U.S. Geological Survey recently.

Technology Selection Considerations

The selection of SmartSampling™ as a supplemental tool for the analysis of data to maximize remedial effectiveness at the lowest cost is independent of site geology and contaminant type. The major reasons for selecting SmartSampling™ are as follows:

- more potential information is extracted from a set of sample measurements than by current modeling techniques,
- optimal locations are identified for additional samples that may reduce actual remediation costs and reduce the risk that undetected contamination is left in place, and
- remediation costs are generated for each identified action level.

APPENDIX A

REFERENCES

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