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INFORMAL REPORT

Use of Noninvasive Geophysical Techniques for the In Situ Vitrification Program

Volume 3: Discussion and Recommendations

**Nicholas E. Josten
Steven T. Marts
Glen S. Carpenter**

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USE OF NONINVASIVE GEOPHYSICAL TECHNIQUES
FOR THE
IN SITU VITRIFICATION PROGRAM
VOLUME 3: DISCUSSION AND RECOMMENDATIONS

Nicholas E. Josten
Steven T. Marts
Glen S. Carpenter

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Idaho National Engineering Laboratory
EG&G Idaho, Inc.
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VOLUME 3: DISCUSSION AND RECOMMENDATIONS

Approved by:

WE Harrison

W. E. Harrison, Manager
Geosciences Unit

Date:

3/6/91

Prepared by:

N. E. Josten

N. E. Josten

Date:

3/6/91

Reviewed by:

T. R. Wood

T. R. Wood
Technical Reviewer

Date:

3/6/91

ABSTRACT

In situ vitrification (ISV) is a waste pit remediation technology that can potentially eliminate the need for pit excavation. The ISV program at the Idaho National Engineering Laboratory (INEL) funded this study to evaluate geophysical techniques that might be useful for performing detailed screening of the materials, soil conditions, and local geology of waste pits targeted for remediation. The evaluation focusses on a specific set of characterization objectives developed by ISV engineers. The objectives are based on their assessment of safety, environmental, and cost efficiency issues associated with the ISV process. A literature review of geophysical case histories was conducted and a geophysical survey was performed at the INEL simulated waste pit so that the evaluation could be based on demonstrable results. The literature review shows that all the ISV objectives are theoretically achievable because they involve physical properties (such as electrical conductivity, density, or magnetization) that can be sensed by geophysical instruments. However, most of the ISV objectives require substantially higher resolution than is achieved in typical waste site investigations, or than has been demonstrated by researchers using state-of-the-art techniques. The survey at the INEL simulated waste pit yielded useful, qualitative information on subsurface materials and boundaries; but quantitative information, such as depth, size, or composition of buried materials, was subject to significant uncertainty. For ISV, the usefulness of geophysical characterization depends both on the capabilities of geophysical methods and on an assessment of the amount of uncertainty that is acceptable. Based on a preliminary assessment of these factors, the location of trench boundaries and detection of massive metallic objects are the important achievable objectives using current technology. Other ISV objectives are either not routinely achievable, or cannot be achieved with satisfactory confidence levels. A peer review of this report substantiated these conclusions but stressed that conventional geophysical methods are not designed for the high level of characterization sought by ISV and that continued research is needed.

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VOLUME 3: DISCUSSION AND RECOMMENDATIONS

INTRODUCTION

This document is the third volume of a three volume report to evaluate geophysical methods for the detailed characterization of waste pits. The study was funded by the In Situ Vitrification (ISV) Program to support the ISV remediation technology being developed at the Idaho National Engineering Laboratory (INEL). Geophysical waste characterization is being considered as a means to generate subsurface information that will enhance the efficiency and cost effectiveness of the ISV technology. Volume 1 documents the results of a broad-based literature review conducted to assess the capabilities and limitations of geophysical methods in common use and to identify promising new technologies. Volume 2 contains the results of geophysical surveys conducted at a simulated waste pit, and Volume 3 presents recommendations for the effective use of geophysical methods to support ISV.

BACKGROUND

The ISV process utilizes electric current to vitrify waste pit soils and waste materials in place, eliminating the need for excavation and handling of potentially hazardous materials. Four electrodes control an electric current that induces melting beginning at the ground surface. As vitrification progresses, the waste mass subsides and the volume of pit materials is reduced, forming a vitreous mass that serves to contain hazardous materials that remain.

Full-scale testing of ISV will be performed at the Subsurface Disposal Area (SDA), which has been the primary repository for hazardous waste at the INEL since about 1952. Historical records, compiled from various sources beginning in 1975, contain the principal source of information on the types and locations of buried materials at the SDA. Although valuable, these records are incomplete and potentially inaccurate.

Geophysical techniques are an independent source of information on the buried waste. This volume summarizes the capabilities and limitations of geophysical methods for providing information on waste pits. The summary is drawn from the results of a literature review conducted to assess the state-of-the-art in geophysics and from direct testing of several key geophysical tools at the simulated waste pit. These activities are discussed in detail in Volumes 1 and 2 of this report. In addition, an acoustic tomography experiment conducted during the intermediate scale ISV test in June 1990 and a geophysical survey of Trench 27 at the SDA in December 1990 contributed valuable site-specific information for this evaluation.

EVOLUTION OF ISV OBJECTIVES FOR GEOPHYSICS

The initial objective of this study was to assess the usefulness of geophysical methods in obtaining subsurface information that could be used to (a) screen sites before implementing ISV, (b) monitor the progressing ISV melt and provide feedback information to help adjust the process, and (c) evaluate the post-melt mass to determine the degree to which contaminants have been contained. A detailed list of specific characterization objectives was compiled by the ISV Program engineers and is contained in Volume 1, Appendix A of this report.

As reported in Volume 1, many of the detailed ISV objectives for geophysical characterization were found to be unprecedented in the geophysical literature. The direct tests performed at the simulated waste pit (reported in Volume 2), and other work at the SDA, showed that some of the objectives could be met, but the interpretations of the geophysical data will always be subject to some amount of uncertainty. During the course of the work, the Geosciences Unit and the ISV Program discussed the ISV objectives as part of a Quality Improvement (QI) process aimed at refining and prioritizing the objectives using the preliminary results of the geophysical methods assessment.

For each objective, the QI process was based on three questions: (a) Why is this information important to ISV?, (b) What would be the consequences to ISV if this information could not be obtained?, and (c) What are the alternatives? Through this process, the relative importance of the various ISV objectives was determined, and the amount of uncertainty that could be tolerated in meeting those objectives was gauged. The uncertainty element, which is due to the inherent ambiguity of geophysical interpretations, was an important factor in evaluating the usefulness of the geophysical information. The refined set of ISV objectives presented in this report were determined by comparing the confidence levels required by ISV for decision making with the confidence levels obtainable from geophysical interpretations.

SAFETY AND EFFICIENCY ISSUES FOR ISV

The ISV remediation concept has many potential advantages. A safety advantage of ISV is that it eliminates the need for direct handling of large volumes of free hazardous materials. An economic advantage of ISV is that the need to relocate hazardous materials can potentially be eliminated. To maintain these advantages, ISV must not create new safety hazards and its operation costs must be minimized. Once the technological feasibility of the ISV concept has been demonstrated by full-scale testing, ISV will be carefully scrutinized from a safety and an economic standpoint for application at uncontrolled waste disposal sites. Safety and cost-effectiveness issues will depend in part on the type of waste materials and pit environment targeted for remediation.

Important ISV safety issues include explosion risks resulting from the interaction of the melt with flammable or pressurized waste materials and environmental risks from volatilizing hazardous chemicals because of the intense heat of the process. There is also some risk that the containment of hazardous material by the vitrification process could be incomplete, making the vitrified mass a lingering hazard to the environment and unsafe to handle. Safety issues are subject to strict regulations and, in general, very little risk is tolerated. Unless it can be proved beyond a reasonable doubt that a hazard does not exist, the ISV process must be engineered to handle any hazard.

In situ vitrification economic issues relate to cost efficiency, including the cost of system downtime or unnecessary runtime. Although the risk of these occurrences is an unavoidable part of implementing ISV technology, incomplete knowledge of subsurface conditions will contribute to the problem. Examples of ISV cost-efficiency issues include the unnecessary vitrification of nonwaste areas from poorly known waste boundaries and loss-of-control of the ISV process when the electrodes encounter massive metallic objects or large void spaces in the subsurface. In contrast to safety issues, cost-

efficiency issues are primarily business concerns: risk is accepted but must be minimized.

The fundamental difference between safety and cost-efficiency risks emphasizes the importance of the uncertainty factor when judging the usefulness of geophysical information. Because of the high level of subsurface detail required to adequately address many safety concerns and because of the low tolerance for uncertainty, it is unlikely that geophysics methods can be a major factor in addressing safety issues. However, in the area of cost efficiency, geophysical methods can contribute important information that can be used to decrease cost risks.

GEOPHYSICS AND ISV

Geophysical instruments have been developed to sense a variety of material properties. The tools evaluated during this study include those that depend on magnetization, electrical conductivity, electrical permittivity (dielectric constant), acoustic velocity, and density. For typical waste forms, these properties can vary by many orders of magnitude as in the case of magnetization, or by less than one order of magnitude, as in the case of density. In practical terms, dependent on the physical properties of the waste, some materials may be detectable even when present in small quantities, some may be detectable only when very large amounts are present, and some may not be detectable at all.

Some basic questions must be answered to assess the usefulness of geophysical methods for providing the various types of information needed to support ISV: (a) Will a target of interest produce a measurable geophysical signal? and (b) To what extent will a measured signal be uniquely diagnostic of that target? These questions depend on factors that are specific to the particular target, such as size, shape, or composition, and on factors that are random, such as the target's burial depth and the amount and type of interference created by nearby objects. Both groups of factors contribute uncertainty to the process of interpreting geophysical data.

Geophysical methods may be subdivided into potential field methods and propagation methods. Magnetic, electrical, and gravity methods are potential field methods. These methods utilize measurements of the energy fields created by objects to locate and identify subsurface targets. Ground penetrating radar and seismic are propagation methods. Propagation methods transmit waves into the subsurface and observe the returning waves reflected off subsurface materials. The nature of uncertainty for determining target parameters such as size, shape, and depth differs for potential methods versus propagation methods.

Uncertainty Factors for Potential Field Methods

The material properties of interest for magnetic, electrical, and gravity methods are magnetization, conductivity, and density, respectively. Values for magnetization and conductivity vary over a wide range and the myriad of common waste materials can essentially be divided into two categories, metals and nonmetals. Magnetic and electrical methods are invaluable for detecting even small amounts of buried metal but have virtually no sensitivity to other waste materials or to differences between types of metal. The exception is that the combination of magnetics and electrical methods can be used to distinguish ferrous from nonferrous metals. By contrast, the density of most waste materials varies only over a small range. Consequently, gravity measurements measure the bulk or average density of all the materials within the volume of investigation. Unless a target object is very large or has an extremely high or low density with respect to the surrounding medium, it will be unresolvable using gravity.

For potential field methods, the size, burial depth, and material properties of an object can affect the strength of the geophysical signal in similar ways. Thus, although differences in signal strength may be used in an attempt to differentiate between a drum and a pipe, without prior knowledge of the depth to the target and the material of which the target is composed, it will be impossible to determine which factor is actually responsible for the observed signal. In theory, the signal is influenced by these factors in different ways, but in practice, these distinctions cannot be characterized for waste objects. This difficulty is due in part to theoretical responses that can only be calculated for extremely simple objects.

Multiple objects within the volume of investigation of a particular geophysical sensor cause anomalies to overlap and can make it difficult to resolve individual objects and establish boundaries between objects. For potential field methods, the primary interference effect is simple superposition of the individual fields. However, particularly for electromagnetic induction methods, there can be interaction between closely

spaced objects that produces complex secondary effects. Anomaly interference is less severe for shallow objects and more "focused" methods (i.e., methods that produce sharper anomalies from a stronger dependence on the distance between the sensor and the target). (This is the principle behind the increased resolution of magnetic gradient measurements compared with magnetic total field.)

The shape of a buried target is an important diagnostic feature that can be used to identify waste materials. Large scale shape information can be deduced from the length to width ratio of particular anomalies and the amount of symmetry that an anomaly exhibits. Small-scale shape information is difficult to derive from potential field data because of the smoothing effect that results from measuring the field at distances that are large compared to the size of the object. Nettleton (1971) compares this effect with the masking effects of a heavy snow:

Features on the ground which are immediately recognizable under a thin snow cover become more and more rounded as the snow gets deeper until their effect becomes only rounded bumps on the surface.

Uncertainty Factors for Propagation Methods

For seismic methods, propagating waves are reflected from interfaces between materials with contrasting acoustic velocities. Acoustic velocities for earth materials at the SDA range from about 1000 ft/s for soils to greater than 10,000 ft/s for basalt. For ground penetrating radar, reflections occur from interfaces between materials with contrasting electrical permittivities. Relative permittivities for waste pit materials range from 1 for air to 81 for pure water. Except for metallic waste, which produces very strong radar reflections, the permittivities for common waste pit materials depend mainly on their water content. For both seismic and radar methods, reflection strength is proportional to the magnitude of the contrast at an interface.

Very strong radar reflectors, metals for example, can prevent penetration of waves into the material beneath them.

The effect of target size on seismic and radar data is different than for the potential field methods. Propagation methods work essentially on a minimum threshold basis where all targets above a certain size can be resolved equally well, but targets below that size become progressively more difficult to resolve. The threshold size depends on the wavelength of the propagating wave. For acoustic methods, wavelengths are normally in the range of 1 to 3 m. Radar wavelengths range between 0.3 to 1.5 m.

For the propagation methods, signal strength decreases with distance as a result of attenuation. The propagating signal experiences continuous attenuation along its travel path down to a target and back. At some point, the returning signal becomes too small to measure. Attenuation is more rapid for the high frequency, short wavelength signal components. Attenuation also depends on the properties of the propagation medium. In particular, attenuation can be extremely rapid for radar waves traveling through conductive soils.

Interference effects are difficult to categorize for propagation methods. In waste pit investigations, there are two important effects. First, in the presence of multiple irregularly shaped targets, waves can be scattered in all directions. In this situation, waves that have been scattered from objects off of the line of investigation can return and be recorded along with the waves returning vertically from the line of investigation. The off-line signals create noise that can obscure otherwise interpretable reflections or create false reflections. A second interference effect results when waves pass through zones having irregular velocity distributions, such as a mass of waste. Signals that return from a uniform reflector below the complex mass can be extremely difficult to correlate and quantify because the overall wave paths vary greatly, dispersing the returned signal.

The ISV objectives for geophysical characterization are all subject to some uncertainty from the factors previously described. When interpreting geophysical data, it is important to consider the question of uncertainty. In particular, it is essential to consider the decisions that may be based on the geophysical information and the amount of uncertainty that is acceptable, as well as what the alternatives may be. For example, in planning ISV remediation for the SDA, historical records currently provide the only basis for designing and controlling the ISV process. The uncertainty associated with these records is probably best characterized as unknown. In this case, the potential for simply reducing this uncertainty may be adequate incentive for conducting geophysical surveys.

CAPABILITIES AND LIMITATIONS OF GEOPHYSICS FOR ISV NEEDS

The discussion of specific ISV geophysical characterization needs follows the revised set of objectives generated through the QI effort. These objectives are discussed below beginning with items having the greatest potential for geophysical contributions. The reason for each need, the recommended geophysical approach, and an assessment of the uncertainty associated with the recommended approach are included.

Trench Boundaries

The boundaries that are important to ISV include the vertical and horizontal limits of the buried waste. Detailed knowledge of these boundaries can be used to (a) develop a program for the number and location of ISV setups required to remediate a targeted pit and (b) stop the ISV process when vitrification has progressed completely through the waste mass.

Strategies for delineating the horizontal pit boundaries include direct detection of the excavated boundary using radar or inferred detection by mapping the location of metallic waste (or other waste visible with radar) and drawing a boundary to enclose these areas. Recent radar work at the SDA has shown that horizontal excavation boundaries are detectable and can be determined with an uncertainty of about ± 1 ft.^a Detection tends to be intermittent, however, and closely spaced radar traverses will be required to develop the redundancy needed to achieve this accuracy. For inferred boundaries based on the limits of metallic waste, there will always be some risk that nonmetallic waste may occur outside the interpreted boundary. Historical records may prove useful for evaluating this circumstance at the SDA. At the simulated waste pit, boundaries drawn on the basis of magnetic and electromagnetic data were accurate to about ± 1 m (see Volume 2 of this report).

a. Unpublished research results of N. E. Josten and S. T. Marts, EG&G Idaho, Inc., Idaho Falls, Idaho, 1991.

At the SDA, the lower extent of buried waste will be close to the top of basalt bedrock, which is potentially mappable with radar or seismic methods. Radar and reflection methods can potentially provide high resolution images of the basalt surface from data collected in the undisturbed areas between the pits and trenches. Waves propagated through waste materials will be subject to high noise levels, making it difficult to interpret depth to basalt directly beneath waste pits. Of the three methods, refraction seismic is probably least affected by this form of noise but will have limited ability to resolve detailed fluctuations of the bedrock surface. Radar, reflection, and refraction have all been used for bedrock mapping at (or near) the SDA. The results of this work are inconclusive regarding the accuracy of depth estimates because the surveys are not tied to well control.

Detection of Massive Metallic Objects

When the ISV melt zone encounters a massive metallic body in the subsurface, melt control can be lost from electrical shorting through the object or inability to induce melting of the object. Precise melt control is needed to ensure that the waste is thoroughly incorporated and contained. Metals are routinely detectable by magnetic and electrical methods. Thus, at a minimum, these methods could be used to select areas having little or no subsurface metal. The long-term solution will require that "massive" metallic objects can be differentiated from other metallic objects. This judgement may be made based directly on the magnitude of the observed anomaly or by attempting to determine the shape of the disturbing object.

Breiner (1973) presents a nomogram relating magnetic anomaly amplitude to volume of metal, which could be used in principle to identify massive objects. This approach could be customized for the material types, amounts, and depths that are of interest to ISV. While relatively straightforward to apply, this technique has multiple sources of uncertainty that will create a large gray area between anomalies from massive objects and anomalies from nonmassive objects. For example, the exact material composition and its depth will not typically be known or a single anomaly may be difficult to objectively isolate

from interfering features so that it can be analyzed. An additional limitation is that magnetic data will detect only ferrous metals. An electrical analog to the magnetic approach might be attempted but will require a slightly different definition for "massive" since electrical signals depend on the target surface area, rather than the volume. Despite these limitations, the technique may be useful in combination with historical records as a means to search for specific objects.

The shape of a subsurface object could also be used to make a judgement concerning its potential effect on ISV process control. If radar can penetrate to the depths of interest and clearly image an object's upper surface, it might be possible to identify the object from its shape, particularly if historical records provide a basis for identification. However, radar has performed poorly in tests at the SDA and simulated waste pit. Magnetic and electrical methods may also be effective, if less direct, for obtaining shape information. The symmetry of an anomaly, its size, and the ratio of length to width can be used to determine waste object shapes. The uncertainty associated with this approach must be judged on a case-by-case basis.

Void Spaces

A downward progressing ISV melt can collapse into large voids, resulting in loss-of-process control or shut down of the system. Large open voids are unlikely to occur at the SDA and small voids (e.g., between and within stacks or piles of waste material) are essentially undetectable. However, geophysical methods may be useful for detecting the presence of large tanks or drums, which could collapse during melting and create problems similar to open voids.

Tank and drum anomalies can be detected by magnetic, electrical, and radar methods. If clear radar data can be obtained, it will be possible to identify tanks and drums by their shape. Identification of tanks or drums from electrical or magnetic data can be based on characteristic anomaly patterns

and will be subject to the same uncertainty as described above for massive metallic objects. This uncertainty can be reduced through use of historical records. From experience and by making use of theoretical models of typical drums and tanks, it will become possible to recognize the types of anomalies produced by these objects.

Waste Type Within Containers

Certain types of waste materials create the potential for explosions or release to the environment during ISV melts. At the SDA, these types of materials have been containerized and buried for many years without proper documentation. The use of geophysical techniques to identify waste materials within buried containers is subject to two major difficulties: (a) Many important waste materials have no distinct geophysical response (e.g., fluids, paper or wood) and (b) The waste materials in the containers often cannot be distinguished from the containers themselves (e.g., metallic waste).

Geophysical methods may be useful indirectly for this purpose, as a means to verify historical records. For example, a historical record stating the presence of organic solvents in 55-gal drums can be supported if the geophysical response for drums is observed. Soil gas analysis or gravity may be useful if volatile or extremely dense waste types are suspected. However, the routine application of these tools would be expensive and the information obtained is nonspecific about the quantity or exact location.

Usually, establishing the presence of a particular substance on the basis of geophysical methods alone is impossible. Interpretations of waste material type can be made but only with a large amount of uncertainty. Since this information concerns safety issues, this degree of uncertainty will likely be unacceptable.

Overburden Thickness

The soil overburden above a targeted waste mass is melted first. The volume of this initial melt must be adequate to sustain the melt as it progresses into the waste and to provide the pressure needed to contain volatiles. Overburden thickness may be determined from geophysical techniques by finding the depth to the shallowest detectable object in the waste pit.

Radar is potentially the most powerful tool to determine overburden thickness since it is able to detect a wide variety of materials and because the depth to target for radar data can be determined very accurately. If radar performance is poor, rough depth estimates can be made using magnetic or electrical data, but these estimates will relate only to metallic waste. If radar is ineffective, importing soil to ensure adequate overburden thickness may be the most efficient solution to the problem.

Soil Density/Porosity

High porosity zones within the soils adjacent to the advancing ISV melt provide potential migration pathways for volatilized contaminants driven out of the ISV melt. High porosity zones are often characterized by low density or low acoustic velocities. Gravity and seismic data can be used to estimate soil density or velocity, but the values generated from these data are average or bulk values for all materials within the area of investigation. Conventional surface seismic and gravity are not suited for the detailed delineation of small zones with high porosity.

Post-Melt Evaluation

After completion of the ISV process, the vitrified mass must be evaluated to determine the hazards, if any, still present and if contaminants could escape to the environment or make the mass unsafe for handling. Fractures induced during cooling of the melt create a potential escape route for contaminants. Acoustic tomography may be applicable to this evaluation if the

velocity of acoustic waves passing through the vitrified mass is dependent on the presence and amount of fracturing. An estimate of the velocity can be made using tomographic methods, but incomplete knowledge of the mass boundaries and the presence of nonuniform velocity conditions around the mass (such as nonvitrified waste) will probably degrade the estimate quality, making it unusable for evaluating the potential hazard.

RECOMMENDED GEOPHYSICAL PROGRAM FOR SCREENING ISV SITES

The geophysical program recommended for screening future ISV sites is described below. The objectives of the recommended program are to delineate the horizontal and vertical boundaries of the targeted waste, map the distribution of ferrous and conductive metals, identify anomalies that may indicate the presence of massive conductive objects, verify historical records, and identify and investigate any unusual items or anomalies. In addition to addressing these objectives, the proposed program will provide an opportunity for further evaluation of some of the more detailed ISV objectives.

A geophysical program for screening ISV sites should include

- Electromagnetic induction survey (EM31) on a 1-m grid spacing including measurements of quadrature and in-phase components.
- Magnetic total field and vertical gradient surveys on a 1-m grid spacing, using the lowest possible sensor elevation.
- Ground penetrating radar survey with radar traverses oriented perpendicular to historical trench boundaries and spaced at 1 meter intervals.
- Historical records compiled in a form that will enable them to be compared with geophysical data.
- Follow up of unusual geophysical anomalies or important historical record entries with appropriate geophysical surveys.

A geophysical program for evaluating depth to basalt should include

- Compilation of well control on depth to basalt in the vicinity of the ISV site.

- Seismic reflection and refraction surveys over an area surrounding the site large enough to tie control wells; reflection surveys should be confined to the undisturbed corridors around and between trenches containing waste.
- Ground penetrating radar surveys if they can penetrate to the basalt.
- Calibration surveys to determine the acoustic velocity and dielectric constant for the site soils as needed to convert time records to depth.

The deliverable products from these surveys should include

- Magnetic and electromagnetic data maps and profiles showing boundaries between zones containing different quantities and/or types of metal. Anomalies that may indicate the presence of massive conductive objects should be reported.
- Radar records with annotations showing interpreted pit boundaries, basalt reflections, and any objects that are identified as waste material. The locations of these features should be shown on a site map.
- Seismic records showing interpreted basalt features.
- Depth to basalt map showing all control points including well, seismic, and radar control.
- Map summarizing key elements of historical records.

RECOMMENDED RESEARCH DIRECTIONS

During the development and testing of the ideas presented in this three volume report, a number of promising geophysical research directions have been identified in the area of waste characterization. These ideas are aimed primarily at the difficult ISV characterization problems that remain unsolved at the current time. They are also aimed at an envisioned future ISV technology that includes an integral system for self-monitoring and adjustment of the process based on the subsurface conditions encountered. These ideas are described briefly below, along with suggestions for the scope of initial efforts.

Improved Radar Antennas

The potential high resolving power of radar methods has been largely unrealized in tests performed thus far at the SDA and simulated waste pit. The poor radar data are the result of the high conductivity clay rich soils that are typical of the INEL. If there is a solution to this problem, it will most likely be through improved antenna design. To initiate efforts in this area, all radar data collected at the INEL should be analyzed in terms of fundamental radar theory. Once the detailed nature of the problem is understood, it may be possible to propose antenna designs that could increase the effectiveness of radar for use at the INEL.

Geophysical Modeling

An inherent shortcoming of the potential field geophysical methods (magnetics, electrical, and gravity) is the difficulty in visualizing the relationship between a measured anomaly and the physical source of the anomaly, buried somewhere in the subsurface. The interpretation of potential field data is normally based on qualitative comparison of observed anomalies with theoretical anomalies for basic geometric objects. Consequently, conclusions tend to be qualitative and are difficult to communicate in straightforward terms.

Potential field mathematics is a well developed discipline, and much of the theoretical basis for the computation of theoretical anomalies for realistic objects is available. A pilot program could be aimed at developing basic algorithms for computer modeling of magnetic, electrical, and gravity anomalies from typical waste materials. A simple catalog of theoretical anomalies for the most common waste forms would be an important achievement toward improved interpretation of potential field geophysical data.

Improved Tomographic Imaging

The initial attempt to image an active ISV melt using surface to borehole tomography produced promising results.^a The data showed that the melt increased both in size and depth with time. To build a useful monitoring technology from this prototype system, it will be necessary to develop a higher resolution acoustic energy source and adjust the source-receiver configuration for more complete examination of the melt zone. These are relatively straightforward advances and could be implemented in time for the next ISV test.

Electrode Mounted Sensors

Surface geophysical methods often cannot resolve important details of the subsurface because these details are obscured by interference effects or are too weak to detect. In concept, sensors mounted directly on the advancing ISV electrodes could overcome these problems because the effect of subsurface materials can be measured as the sensor moves progressively closer to an anomaly source. In this way, it may be possible to continuously monitor the waste as it is encountered by the melt and to recognize potential problems in time to make adjustments to the process. Electrode mounted sensors provide an opportunity for an integral waste monitoring system as part of the ISV technology. The feasibility of this approach is worth studying. An initial

a. Unpublished research results of A. J. Witten and R. F. Selfridge, Oak Ridge National Laboratory, Oakridge, Tennessee, 1991.

effort could study the types of sensors that are needed and the environment in which they must operate.

Evaluation of Borehole Geophysical Methods

For many geophysical methods, resolution improves as the distance between sensor and target decreases. For situations where boreholes may be safely drilled, borehole geophysical sensors can be lowered to the depth of the waste, thus reducing the sensor to target distance. Additionally, the side view of a waste mass obtained from borehole measurements can complement the top view obtained from surface measurements. Combined, these methods may make it possible to characterize the shape and properties of certain waste configurations more completely. The usefulness of borehole geophysical methods can be evaluated by the same approach that was used for this report on noninvasive methods. An intriguing secondary objective of this study could be to evaluate the feasibility of a "safe drilling system" that uses geophysical sensors to detect hazards before they are encountered by the drill bit.

CONCLUSIONS

A great deal of information on buried waste pits can be derived from geophysical data, but this information is subject to the variable uncertainty inherent in geophysical interpretation. For the information to be useful in addressing ISV issues, the uncertainty must be acceptable. Many ISV safety issues require detailed, unambiguous information and for the most part cannot be addressed effectively with geophysical techniques. In situ vitrification cost-efficiency issues are more tolerant of uncertainty, and geophysical methods can contribute valuable information to help address these issues.

Based on the above consideration, and on the results of the literature review and the INEL site-specific testing that was conducted for this study, the geophysical program recommended for screening ISV remediation sites includes (a) detailed magnetic, electromagnetic, and ground penetrating radar surveys, (b) a seismic survey that is tied to well control, and (c) comparison of geophysical data with historical records. The geophysical data from these surveys will provide information that can be used to address the following ISV objectives:

- Location of horizontal and vertical trench boundaries
- Identification of massive metallic objects
- Location of potential void spaces associated with large fluid- or air-filled tanks or drums.

In addition, a number of promising research directions have been identified including improved radar designs, geophysical modeling, high-resolution acoustic tomography, electrode-mounted geophysical sensors, and borehole geophysical methods involving a possible "safe drilling system." Development of these ideas may lead to improved geophysical capabilities for supporting in situ remediation efforts. In particular, these research directions are aimed at the difficult ISV objectives that cannot be addressed effectively with current technology.

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