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Subsurface Barrier Verification Technologies

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ABSTRACT

One of the more promising remediation options available to the DOE waste management community is subsurface barriers. Some of the uses of subsurface barriers include surrounding and/or containing buried waste, as secondary confinement of underground storage tanks, to direct or contain subsurface contaminant plumes and to restrict remediation methods, such as vacuum extraction, to a limited area. To be most effective the barriers should be continuous and depending on use, have few or no breaches. A breach may be formed through numerous pathways including: discontinuous grout application, from joints between panels and from cracking due to grout curing or wet-dry cycling. The ability to verify barrier integrity is valuable to the DOE, EPA, and commercial sector and will be required to gain full public acceptance of subsurface barriers as either primary or secondary confinement at waste sites.

It is recognized that no suitable method exists for the verification of an emplaced barrier's integrity (see Needs Statement IS-9). The large size and deep placement of subsurface barriers makes detection of leaks challenging. This becomes magnified if the permissible leakage from the site is low. Detection of small cracks (fractions of an inch) at depths of 100 feet or more has not been possible using existing surface geophysical techniques. Compounding the problem of locating flaws in a barrier is the fact that no placement technology can guarantee the completeness or integrity of the emplaced barrier. This report summarizes several commonly used or promising technologies that have been or may be applied to in-situ barrier continuity verification.

Most methods presently being employed for in situ characterization of the subsurface can be defined as well logging technologies. This report gives brief discussions of some of the commonly used logging techniques and the limitation(s) of the methodology when used to verify grout continuity. These methods include well logging technologies such as; neutron logging, gamma logging, electrical resistance tomography, radio imaging method, ground penetrating radar, acoustic logging, seismic tomography, and thermal logging. Also discussed are tracer technologies including a promising new technology for characterization of the subsurface using perfluorocarbon tracers.

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1. INTRODUCTION

One of the more promising remediation options available to the DOE waste management community is subsurface barriers. Some of the uses of subsurface barriers include surrounding and/or containing buried waste, as secondary confinement of underground storage tanks, to direct or contain subsurface contaminant plumes and to restrict remediation methods, such as vacuum extraction, to a limited area. To be most effective the barriers should be continuous and depending on use, have few or no breaches. A breach may be formed through numerous pathways including: discontinuous grout application, from joints between panels and from cracking due to grout curing or wet-dry cycling. Subsurface barriers are a remediation option for many of the DOE defense sites including: Sandia, Hanford, INEL, ORNL, Fernald, and Rocky Flats. Barriers are also considered an important remediation option by the USEPA[1]. The ability to verify barrier integrity is valuable to the DOE, EPA, and commercial sector and will be required to gain full public acceptance of subsurface barriers as either primary or secondary confinement at waste sites.

It is recognized that no suitable method exists for the verification of an emplaced barrier's integrity (see Needs Statement IS-9). The large size and deep placement of subsurface barriers makes detection of leaks challenging. This becomes magnified if the permissible leakage from the site is low. Detection of small cracks (fractions of an inch) at depths of 100 feet or more has not been possible using existing surface geophysical techniques. Compounding the problem of locating flaws in a barrier is the fact that no placement technology can guarantee the completeness or integrity of the emplaced barrier. Several of the DOE Integrated Demonstrations (MWLID, BWID) and Programs (ISRIP) are investigating variations of permeation grouting and jet grouting to emplace grout barriers. Permeation grouting is plagued by short circuiting of the flow of grout which can leave large untreated areas. Jet grouting methods require straight boreholes and sufficient overlap of columns to maintain barrier continuity. Often the borehole wanders or the jet is partially obstructed by cobble or varying soil types, leaving a gap in the final barrier. Panel jet grouting may leave gaps between panels and/or at the junctions of horizontal and vertical barrier walls. Cementitous grouts are subject to desiccation and wet-dry cycling cracks. Additionally at the time of gel formation separations or "tears" may occur if localized settling takes place.

DOE has a need to develop/refine barrier verification methods to determine the existence, size and location of breaches in a subsurface barrier. After such determinations the effect of the breaches may be factored into the performance assessment of the waste site or more appropriately the breaches could be repaired (and the repairs qualified with the same technology). This report summarizes several commonly used or promising technologies that have been or may be applied to in-situ barrier continuity verification.

2. TECHNOLOGIES FOR SUBSURFACE CHARACTERIZATION

Most methods presently being employed for in situ characterization of the subsurface can be defined as well logging technologies. This report will give only brief discussions of some of the commonly used logging techniques and the limitation(s) of the methodology when used to verify grout continuity. We will also discuss a promising new technology for characterization of the subsurface using tracers.

2.1 Well Logging Technologies

Well logging began in the petroleum industries for locating oil and gas reserves. Logging quickly spread to other "mining" technologies including coal, uranium and water. Early logging techniques focused on electrical properties and has since broadened to include gamma and neutron radiation, acoustic, thermal and electromagnetic methods. Well logging can determine macro features such as formation boundaries, local features such as water content and micro features such as soil impurities or mineral contents. For barrier continuity verification the determination of local features is most important. Logging can indicate water saturation, porosity, thermal conductivity, and many other parameters that may be related to barrier performance and continuity. Good discussions of well logging technologies can be found in Hearst[2] and Ellis[3]. Well logging consists of a sonde (probe) attached to cable which is lowered into the borehole (see Figure 1). The sonde receives/transmits signals in the formation. The type of logging is determined by the particular sonde used.

All logging methods measure distortions in a transmitted signal. Each method transmits some "normal" signal and receives back a distorted signal. How the signal is distorted and the magnitude of the distortion is related to the property of interest. If the formation is homogenous then the received signal can be calibrated directly with no corrections for unwanted distortions. This is rarely the case. Subsurface formations are heterogeneous in macro, local and micro scale. All of these heterogeneities can cause distortions in the logging signal. It is often impossible to differentiate between two different types of "distortions" or formation features. As an example a thin grout lens may give a similar resistivity as some ungrouted cobble. This is one of the main reasons why logging technologies have limited use in barrier continuity verification. To be useful over a reasonable affected area requires correcting for unwanted distortions by solving partial differential equations relevant to each logging type and distortion type encountered. Additionally, logging techniques require many boreholes to provide full coverage of a barrier.

Well logging can however be very useful to determine barrier performance. Parameters such as porosity, water content, density and brittleness can be measured and/or monitored. This is the traditional use of logging technologies and the methods are well developed and suited for such use.

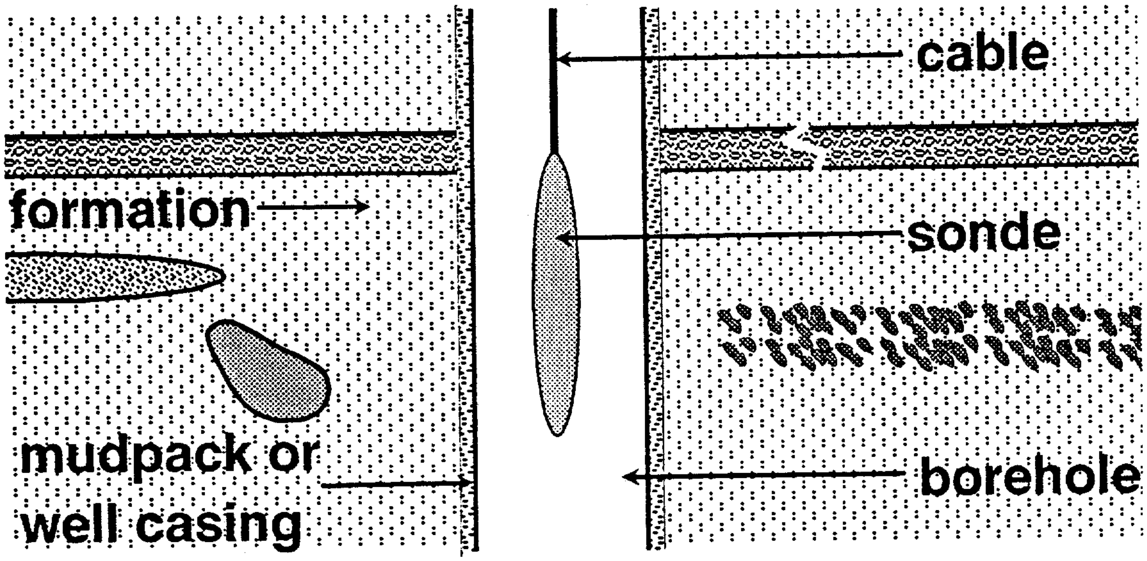

Figure 1. Well logging

2.1.1 Nuclear

Nuclear radiation can be utilized for subsurface characterization. There are many types of nuclear radiation including α, β, γ, and neutron. Alpha and beta particles are not deep penetrating in soil and rock formations and therefore have not been utilized for well logging. Gamma and neutron radiation have found wide scale use for formation characterization. Neutron logging has been extensively used to determine formation saturation and densities. Gamma rays are being used to determine subsurface compositions (minerals, contaminants, etc.). While these methods are valuable for mining and general characterization, they are of limited usefulness in barrier continuity determinations. The depth of penetration of radiation used in well logging is generally only 10 to 20 cm. With shielding and beam focusing, this may be extended but would still be less than 1 meter. The number of boreholes required may be prohibitive (one every meter at best). The nuclear methods are not currently capable of resolutions of fraction of an inch when the mean free path of the scanning radiation is a meter. Both neutron and gamma radiation logging methods are not well suited to detect fractures in a formation. Because nuclear decay is a statistical process only average values or bulk properties can be measured for the affected area. A fracture would simply raise or lower the average value of the parameter of interest.

2.1.1.1 Neutron Logging

Neutron well logging has become an important tool for estimating porosity and moisture content of a formation. Neutron logging is used to measure the hydrogen index I_h, which is defined as the equivalent volume fraction of fresh water containing the equivalent amount of hydrogen. Neutrons generally interact with atomic nuclei and therefore interactions are less frequent and neutron ranges are longer than other nuclear radiation. The most common neutron interaction is elastic scattering. Classical mechanics shows that the neutron is moderated more efficiently by nuclei with a mass similar to the neutron such as hydrogen and other low mass elements. There are two types or neutron sources; chemical and accelerator. Both of these sources produce fast neutrons and the logging type is usually distinguished by the detector type, either thermal or epithermal. Chemical sources produce neutrons with an energy of about 4 MeV. Accelerators produce neutrons with an energy of about 14 MeV. Chemical sources have the advantage of being cheap and reliable while accelerators have the advantage of being able to turn off the neutron source.

There are two common methods of measuring water content using neutron diffusion, the neutron log and the moisture gauge. An extended comparison of the two methods can be found in Hearst and Carlson[4]. Moisture gauges are sensitive to thermal neutrons and have an affected radius of 10 to 20 cm. Neutron logs measure thermal or epithermal neutrons depending on sonde configuration and have a measurement radius of 20 to 30 cm. Thermal neutron methods are used in fluid filled boreholes and are of little value in air filled borehole. Epithermal methods are preferred for air filled boreholes and can also be used in fluid or foam filled boreholes. Neutron methods are dependent on many different parameters such as; porosity, matrix, pore fluid, salinity, temperature, pressure, standoff, and borehole geometry. A complete mathematical solution incorporating all of these parameters is not feasible so numerical approximations are used and are field calibrated. Such approximations do not allow exact pictures of the subsurface but yield statistical equivalents that are averages over the affected range. Again the logging tool is very limited in affected area and is not very useful as a continuity verification tool. The inadequacy of neutron logging for barrier continuity verification has also been stated by Dwyer[5].

2.1.1.2 Gamma Logging

Gamma rays can be used in several ways to characterize a formation. Formation minerals contain naturally radioactive elements which can be detected by gamma spectroscopy. There are three major sources of natural gamma radiation; uranium, thorium and potassium. Detection of the characteristic gamma rays using spectral natural gamma logging can identify different mineral types and can determine the concentrations of these elements.

Interactions of gamma rays depend upon the atomic number of the matrix and the gamma energy. By exposing the formation to a source of gamma rays the density of the formation can be estimated. This type of gamma logging is γ-γ logging or density logging. Measurements using γ-γ logging utilize Compton scattering of gamma rays.

In-situ chemical analysis can be performed using gamma logging. Gamma ray exposure also results in the photoelectric effect and can be used to generate characteristic fluorescence x-rays. The energy of the x-rays is dependent on the atomic number of the incident matrix. Photoelectric effect interactions are the predominant interaction for gamma ray energies below 100 keV.

Gamma logging method are of limited usefulness for barrier verification. The range of gamma logging is only 5-12 cm. As mentioned for neutron logging the radioactive decay and interactions are a statistical process and are really only useful for bulk or average properties. It may be possible to detect components of a grout[6], but this would only indicate some grout in the local area not necessarily a homogenous, breach-free mix of grout and soil.

2.1.2 Electrical and Electromagnetic

The earliest form of well logging was electrical resistance logging. This type of logging measures the bulk property, resistivity of the formation. Generally, formation rocks are non-conductive and it is the pore waters that allow electricity to flow. The conductivity of the formation depends upon the quantity of water in the pore spaces and the ionic activity of the pore fluid which is a function of salinity. The resistivity is also highly dependent on temperature. Temperature affects the viscosity of the pore fluid which is directly related to the conductivity. Other artifacts will also affect the resistivity of a formation. Clays are strongly conductive and will enhance the ionic conductivity of pore waters. Minerals, such as sulfides, can increase the conductivity of the formation through electronic conduction. Even the geologic strike of the formation will affect the resistivity. Many formation rocks are anisotropic and conduct better in the planar direction than perpendicular to it.

Electrical resistivity logging requires a conductive coupling of the electrode to the formation. In boreholes where a non-conductive oil based mud or an insulating casing is used induction sondes must be used for electrical measurements. Induction logging uses alternating current and coils to induce an eddy current in the formation. The strength of the eddy current is measured with another coil and is proportional to the formation resistivity.

Electrical and electromagnetic logging techniques measure bulk properties of the formation and are not well suited for barrier verification. Depth of penetration of resistivity logging can be great (hundreds of feet) but spacial resolution is extremely poor. Induction devices have more limited ranges (about one meter) and also have poor resolution. Electrical cross-borehole tomography[7] and borehole induction logs[8] have been used to map affected areas of remediation and to determine grout penetration in soils [5], but these studies have been limited to general locations and could not be used to infer homogeneity of a barrier.

2.1.2.1 Electrical Resistance Tomography

Included in electrical and electromagnetic methods is electrical resistivity tomography (ERT) as developed at Lawrence Livermore National Laboratory. ERT will be employed at Fernald, Ohio to evaluate an in situ barrier placement[9]. ERT is a cross-borehole method for measuring electrical resistivity. It utilizes a series of electrodes in contact with the formation. Direct current is applied to a pair of electrodes and the resultant voltages across other pairs of electrodes are measured. The current is then applied to a different pair of electrodes and the voltages measured again. This process is repeated until all the combinations of electrode transmitter pairs are completed. The data is then processed using sophisticated tomographic methods and provides a map of the area between boreholes.

2.1.2.2 Radio Imaging Method

The radio imaging method (RIM) consists of a low frequency electromagnetic transmitter and a magnetic field receiver. The method can be used cross borehole or borehole to surface. By measuring the electrical conductivity of the formation details on moisture variations, fracturing and lithology can be inferred. Like ERT sophisticated analysis tools are required to interpret the data. RIM technology was used at the Chemical Waste Landfill at Sandia National Laboratory and was stated to be able to detect soil units of 0.5 meters[10]. Such resolution is still not quite accurate enough for barrier continuity verification although the method may be capable of finding leaks after water infiltration.

2.1.2.3 Ground Penetrating Radar

Ground penetrating radar (GPR) has been used to locate subsurface features such as old mine tunnels and buried waste [11] and is a surface oriented characterization tool, not a well logging device. It is included here since it is very similar in theory to RIM. GPR involves towing a radar antenna across a site along a set of grid lines spaced about one half meter apart. The transmitted radar is reflected back to the surface where a receiver picks up the perturbed signal. The resolution of GPR is poor under ideal conditions and the penetration of the radar is severely limited through clay layers. Formation features including water, rock, soil, plants, and buried man-made items result in strong radar absorbtion and reflection and a resultant high clutter in the signal. Depth and spacial resolution of GPR is greatly affected by the signal to clutter ratio.

2.1.3 Acoustic Logging

Acoustic logging has been said to be "almost unique among logging methods because far more information is available than can be interpreted"[1]. Acoustic waves are transmitted into the formation. The velocity and attenuation of these waves are affected by density, porosity, fracturing, pressure, pore fluid, temperature, and saturation. Two methods of acoustic logging can be used to map a formation, transmission or reflection. Transmission methods measure the velocity and/or attenuation of shear and compressional acoustic waves. Acoustic energy in the range of 20 kHz is transmitted from one borehole and the signal is received some distance away from the transmitter. Reflection methods generally operate around 500 kHz and measures the attenuation of the wave. The signal is reflected off of formation features and the transmitter and receiver can be in a single sonde. The higher frequency reflection methods have shown promise in the location of fractures.

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[1] Hearst, J., and Nelson, P., Well logging for physical properties, McGraw-Hill, Inc., 1985, p. 285.

Acoustic waves are well suited for measuring the elastic properties of materials and have been used in nondestructive testing of portland cement concrete for paving.[12] Researchers at BNL believe that acoustic measurements could be used to access cracks in barrier walls and to monitor the long term integrity of the barrier.[2] Inexpensive transducers could be emplaced in the barrier walls prior to solidification of the grout matrix. These transducers could then be used to look for fractures and gaps and to form a baseline acoustic signature of the barrier. The transducers could then be used in the future to recheck cracking and to compare the acoustic signature of the barrier. As mentioned earlier, there is often far too much information returned to the receiver in acoustic logging. Waves echo off the inhomogeneities of the formation and the echoes can further reflect. Acoustic techniques will be much clearer in the more homogenous grout media.

2.1.3.1 Seismic Tomography

Seismic tomography can be accomplished using surface or borehole probes. Seismic analysis uses low frequency acoustic energy pulses. Early petroleum explorations used explosive charges to generate the seismic pulse. Geophones then record the reflected waves as a function of time. The changes in the acoustic velocity of the seismic wave are dependent on the nature of the formation features. The low frequency of seismic logging allows great distances to be logged, e.g., hundreds of meters as opposed to several feet for other logging techniques. The drawback to seismic evaluation is the resolution. Resolution is strongly dependent on frequency; the lower the frequency the less resolved, particularly in the vertical direction. To "look" hundreds of meters into a formation results in a resolution of tens of meters.

Seismic tomography still represents one of the more promising of acoustic logging techniques. As refinements to the resolution are made, the deep penetration of seismic waves will prove valuable to subsurface investigations. Crosswell seismics were evaluated at the Mixed Waste Landfill ID and while found to be useful in locating general grout penetrations were not considered adequate for verifying continuity of a barrier [5]. In a study of high resolution seismic imaging of fractures in rock, Majer et al concluded that minor structures such as individual cracks were not detectable (at the frequecies they used)[13]

2.1.4 Thermal Logging

Thermal logging looks at the temperature variation within a formation. Temperature measurements are most often used to correct data from other logging techniques but thermal logging can be used to gather useful information about the formation. Thermal conductivity is affected by the porosity and pore fluid of the formation rock. Water filled porous rock will have

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[2]Conversation between J. Heiser and M. Zucker at Brookhaven National Laboratory April 1994.

lower thermal conductivities than solid rock and air filled pores will further lower the conductivity. Injecting cooler or hotter water into the formation will cause a thermal gradient to occur. Information about the porosity/water content of the formation can be obtained by observing the decay to thermal equilibrium.

Temperature logging can be used to track grouts in the subsurface. Measuring the heat of curing of cementitous or thermosetting grouts can be used to infer that grout has reached a certain area. This will not, however yield data on the continuity of the barrier. Thermal logging is best suited to indicating positive grout injection into the desired zone.

2.2 Tracer Technologies

A tracer is any substance that can be easily or clearly monitored (traced) in the study media. Tracers for soil studies can be radioactive or non-radioactive liquids, gases or solids. Tracer technologies can be used in transport/dispersion studies, leak detection studies and material location.

In transport and dispersion studies, tracers are used to tag a flowing medium to determine where that flowing medium is going and how it is being dispersed in a surrounding matrix. Example applications are transport and dispersion of pollutants in air parcels on a continental scale; transport and dispersion of injected fluids in petroleum reservoirs for enhanced oil recovery, and transport and dispersion of air within homes and commercial buildings for energy efficiency calculations. Typically, tracers for transport/dispersion are liquids and gases. They can be either radioactive or nonradioactive.

Leak detection studies use tracers to locate and estimate leak rates in various scenarios. These can be as simple as colored dyes used to visually locate cracks and holes in tanks or as complex as mass spectroscopy detection of helium to find leaks in vacuum systems.

Tracers can also be incorporated into a material (i.e. grouts) to allow tracking of the material through a media or along a pathway. Radioactive tracers could be incorporated into the barrier grout thus allowing non-intrusive detection of where the grout is placed. Chemical tracers could be utilized in the grouts but would have to be able to diffuse out of the grout to be detected by non-intrusive methods (e.g., gas sampling tubes).

In this section we will look at two types of tracer technologies: non-radioactive perfluorocarbon tracers for leak/breach detection and radioactive tracers incorporated into the grouts for determining grout location. Perfluorocarbon tracers have been proposed for use in barrier continuity verification.[14]

2.2.1 Perfluorocarbon Tracers

Brookhaven National Laboratory (BNL) has developed a host of perfluorocarbon tracers (PFT). These tracers were originally utilized in atmospheric and oceanographic studies and have since been applied to a great variety of problems including detecting leaks in buried natural gas pipelines and locating radon ingress pathways in residential basements.[15,16] Prior accomplishments in determining gas pathways in residential basements is readily applicable to barrier verification. The residential basements studied are essentially miniature "barriers" with vertical concrete walls and a horizontal concrete floor. Thus, PFT tracer technology should be directly applicable to barrier verification.

PFTs can be detected at extremely low levels. Parts per quadrillion are routinely measured. This allows detection of very small breaches in the barrier. A breach can be located by injecting a series of tracers on one side of a barrier wall and monitoring for those tracers on the other side. The injection and monitoring of the tracers can be accomplished using conventional low cost monitoring methods such as existing vadose zone monitoring wells or multilevel monitoring ports, placed using cone penetrometer techniques (e.g. Hydropunch). The amount and type of tracer detected on the monitoring side of the barrier will determine the size and location of a breach. It is easy to see that the larger the opening in a barrier the greater the amount of tracer is transported across the barrier. Locating the breach requires more sophistication in the tracer methodology. Multiple tracer types can be injected at different points along the barrier, in both vertical and horizontal directions (see Figure 2). Investigation of the spectra of tracers coming through a breach then gives a location relative to the various tracer injection points.

PFT technology consists of the tracers themselves, injection techniques, samplers and analyzers. PFTs have the following advantages over conventional tracers:

- Negligible background concentrations of PFTs in the environment. Consequently, only small quantities are needed:

- PFTs are nontoxic, nonreactive, nonflammable, environmentally safe (contains no chlorine), and commercially available;

- PFT technology is the most sensitive of all non-radioactive tracer technologies and concentrations in the range of 10 parts per quadrillion of air (ppq) can be routinely measured;

- The PFTs technology is a multi-tracer technology permitting up to six PFTs to be simultaneously deployed, sampled, and analyzed with the same instrumentation. This results in a lower cost and flexibility in experimental design and data interpretation. All six PFTs can be analyzed in 15 minutes on a laboratory based gas chromatograph.

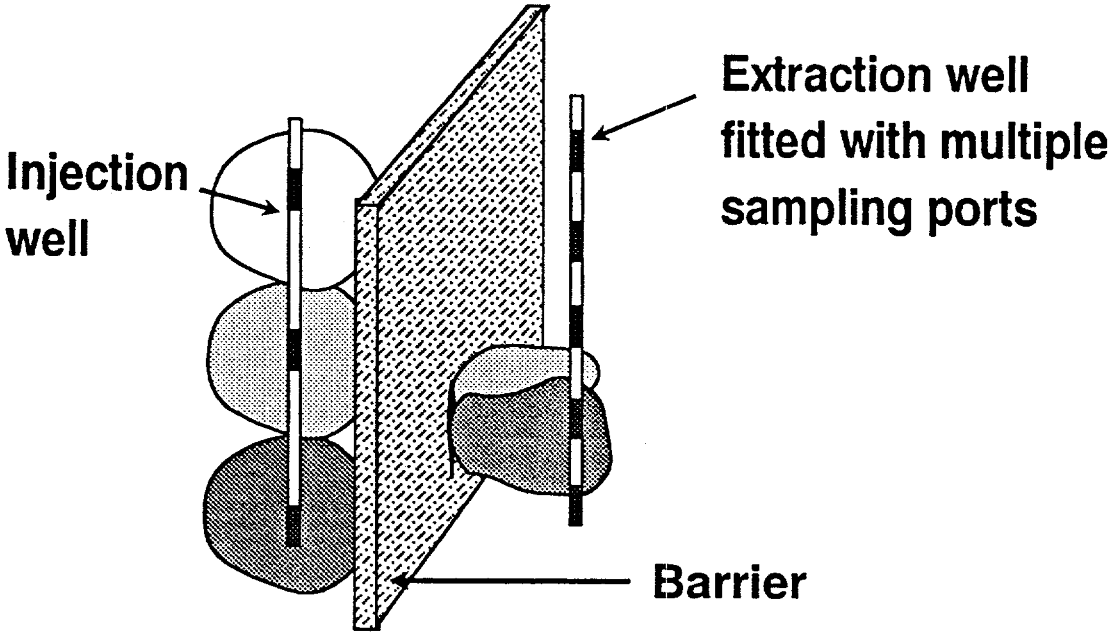

Figure 2. Perfluorocarbon tracer technology.

Typically, the PFTs are measured by a capillary adsorbent tracer sampler (CATS) which is a small cigarette sized glass tube containing a carbonaceous adsorbent specific for the PFTs. This sampler can be used dynamically (flowing a sample through the CATS) or passively (Opening only one end so as to allow the CATS to sample by diffusion). The passive mode allows a time integrated PFT concentration to be measured in a simple manner. The CATS are shipped back to the laboratory for PFT analysis. Several real-time PFT analyzers are available, one which detects four different PFTs per five minutes sample down to the ambient background of the PFTs in air. Another real time instrument can analyze PFT down to a part per trillion but cannot speciate the various PFTs.

One application relevant to barrier verification is the determination of radon flux into residential homes through cracks in the basement floor and surrounding subsurface walls.[15] This can only be achieved with a multitracer technology. One type of PFT source (with a calibrated emission rate, most often prepared as a permeation device) is buried outside a residence under study. Several other types of PFT sources are placed in the basement and the first floor of the residence. From a time averaged measurement of the various PFT concentrations in the basement and first floor and a measured radon concentration in these areas it is possible to calculate a radon flux rate into the home. This technique of using a reference source of PFT to estimate the source rate of a compound of interest has also been used to estimate

- The source rate of dioxin into a commercial building from surrounding contaminated soil[16]

- The rate of leaking gasoline from underground storage tanks at gasoline stations

- The rate of leaking dielectric fluid from subsurface electrical cables

Understanding mass transport through defects in barriers is central to the evaluation of barrier continuity. The migration of the tracers used in the experimental system will have to be analyzed using computer codes that predict the transport of the gas tracer through a porous soil and barrier with defects. Existing computer codes, such as TRACER3D, could be adapted as necessary for the problem.

PFTs may allow locating and sizing of breaches at depth and should have a resolution of fractions of an inch. The technology has regulatory acceptance and is used commercially for non-waste management practices (e.g. detecting leaks in underground power cables). This technology has been used in a variety of soils and will be applicable to the entire DOE complex as well as commercial waste sites. The major use of tracers will be to verify placement continuity of a freshly emplaced barrier and to re-check corrective actions that may be used to seal or repair a breach. It may also be useful to periodically check a barrier to determine the long term integrity of the walls. This would certainly be beneficial if a cementitous grout (portland based) barrier were used. Cementitous grouts are prone to cracking from various degradation modes including wet-dry cycling which is prevalent at many of the DOE sites (e.g. Sandia and Hanford). Tracers would allow determination of performance losses in containment over the life of the barrier.

2.2.2 Radioisotopes

Radioactive tracers can be used to locate grout after application. A short lived tracer is added to the grout prior to subsurface injection. Down hole detectors are used to measure the radiation emitted by the tracer. The tracer is generally a gamma emitter with a short half life. The short half life assures that the radioactivity will quickly decay away to innocuous levels. Multiple tracers and gamma ray spectroscopy tools have been used to determine the diameter and vertical extent of grout columns for grouting well bore casings[17].

The use of radioactive tracers is limited to locating areas of grout penetration. The detection of gamma energy in a local area indicates the grout has reached that area but tells nothing of the continuity of the grout formation. A grout lens several feet from the detector may give a similar spectrograph as a homogenous grout mix closer to the detector or as a thicker grout formation. Small (and perhaps large) holes and cracks would be invisible to present detection technologies.

3. CONCLUSIONS

Most subsurface characterization techniques have come from the petroleum and mining exploration industries. These technique are short ranged or poorly resolved or both. It does not appear that radiation based (neutron and gamma logging) techniques will be viable methods for subsurface barrier continuity verification. These methods, even if resolution were accurate enough would require a prohibitive number of boreholes to completely log the barrier. It would also be costly and time consuming to measure and analyze data from that many boreholes.

Acoustic/seismic logging methods have promise but must greatly increase resolution. As refinements to the resolution are made, the deep penetration of seismic waves will prove valuable to subsurface investigations. The use of embedded sonic transducers is a worthwhile area for further research. Such inexpensive transducers could then be used to look for breaches and to form a baseline acoustic signature of the barrier. The transducers could then be used in the future to recheck cracking and to compare the acoustic signature of the barrier.

Chemical tracers are an area that should prove valuable to subsurface barrier continuity verification. Perfluorocarbon tracers may allow locating and sizing of breaches at depth and should have a resolution of fractions of an inch. The technology has regulatory acceptance and is used commercially for non-waste management practices (e.g. detecting leaks in underground power cables). This technology has been used in a variety of soils and will be applicable to the entire DOE complex as well as commercial waste sites. The major use of tracers will be to verify placement continuity of a freshly emplaced barrier and to re-check corrective actions that may be used to seal or repair a breach. It may also be useful to periodically check a barrier to determine the long term integrity of the walls.

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