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NUREG-2151

Early Leak Detection External to Structures at Nuclear Power Plants

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ABSTRACT

Concerns about inadvertent releases of radioactive liquids to the environment from nuclear power plants have prompted consideration of ways to provide early leak detection in the subsurface external to the structures of the facilities. Approaches to this include the use of single-point sensors to detect changes in moisture content in the vadose zone. While many of these sensors are sensitive and relatively durable, they only interrogate about 1 liter of soil. Arrays of single-point sensors could provide adequate coverage of larger areas. Two-dimensional and three-dimensional geophysical methods provide information for much larger areas. These methods sense moisture or other parameters that may be related to leaks, such as changes in conductivity/resistivity, permittivity, or temperature. Use of cross-borehole geophysics may provide coverage of vertical planes of soil while horizontal boreholes (or horizontal tubes installed during construction) can be used to interrogate planes underneath areas of concern. Other techniques include detection of tritium in soil vapor and temperature changes using coaxial cables. Some of these methods can be made autonomous. The methods are critically reviewed and discussed with emphasis on practical application at nuclear power plants. The U.S. Nuclear Regulatory Commission (NRC) held a public workshop on February 15, 2012, to discuss many of these methods with experts and interested parties. Recommendations are made for NRC's Long-Term Research Program.

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1. INTRODUCTION

Between 2006 and 2010, nine nuclear power plants (NPPs) identified inadvertent releases of radioactive liquids to the environment (NRC, 2010). Several of these plants had multiple releases. Others had leaks that did not contain radionuclides. The U.S. Nuclear Regulatory Commission (NRC) maintains an historical listing of leaks of water containing tritium from power plants (NRC 2011, 2007). While none were determined to affect safety or human health, these leaks caused considerable concern on the part of some stakeholders, including Congressional, State, and local officials. The common approach to environmental monitoring external to facility structures, systems, and components (SSCs) is to use ground water wells. The drawback to this method is that the wells may be some distance from the leak and therefore are a very late indicator of contaminants entering the ground water. In addition, experience has shown that contaminants can move through unexpected pathways that may not be observed by wells. From this, it is clear that a means of providing early detection of leaks from subsurface pipes and structures, before contaminants reach the ground water, is desirable.

1.1 Objective

This report presents the results of a scoping study undertaken to identify and assess subsurface monitoring methods for detecting early indicators of leaks at new and existing NPPs, as well as proposed new reactor concepts (e.g., small modular reactors (SMRs)). A number of inadvertent releases from NPPs of liquids containing radionuclides prompted this study. This information will be used as input to decisionmaking for the Long-Term Research Program conducted by the NRC's Office of Nuclear Regulatory Research.

The scoping study focused on the feasibility of using sensors and monitoring techniques to promptly detect abnormal releases of liquids from the engineered facility SSCs to the surrounding subsurface environment (either engineered backfill materials or native materials). The objective was to study those sensors and techniques that could fulfill a critical inspection or monitoring need identified as early detection of a leak in close proximity to, but external to, SSCs (e.g., before it would be detected in a conventional monitoring well network). Such early detection of leaks may constitute an important element in any strategy for minimizing contamination during NPP operation and reducing the technical and financial uncertainties of decommissioning.

The regulatory driver is compliance with the proposed Title 10 of the *Code of Federal Regulations* (10 CFR) 20.1406(c) that requires operation of existing facilities in a manner that minimizes the introduction of radioactive materials into the site (including the subsurface). Early detection of leaks will be an important tool when implementing the Decommissioning Planning Rule to assess the need to remediate subsurface contamination, as discussed in Draft Regulatory Guide 4014, "Decommissioning Planning during Operations" (NRC, 2011). Early leak detection would facilitate decommissioning and remediation such that the site could be returned to unrestricted use at license termination. Related to this, the amended 10 CFR 20.1501(a) explicitly includes the subsurface in requiring surveys to evaluate residual radioactivity at the site.

1.2 Approach

The approach to early leak detection is to monitor the subsurface (especially the unsaturated zone) for moisture, radionuclides (especially tritium), temperature changes, or other indicators of leaks from nuclear facilities. Methods of interest include (1) detection of anomalous water content of soils surrounding SSCs, (2) radionuclides contained in the leaking water or soil vapor, and (3) secondary signals such as changes in temperature or chemical conditions. Ideally the methods should be in situ, sufficiently robust to maintain their useful life over some years, and sufficiently sensitive that they provide an early signal of leaks. Detection systems may be most important in the vadose zone but some certainly have applications in the saturated zone.

1.3 Background and Regulatory Context

Discovery of inadvertent, unmonitored releases (leaks and spills) of radionuclide-containing fluids that have affected ground water at several operating and decommissioning power reactors over the past decade have resulted in substantial costs during decommissioning, led to considerable public concern, generated widespread media attention, and motivated both licensees and the NRC to initiate activities aimed at minimizing future incidents. The NRC's response to ground water contamination incidents at power reactor sites has been multifaceted. On July 10, 2006, the NRC issued Information Notice 2006-13, "Ground-Water Contamination Due to Undetected Leakage of Radioactive Water," which summarized its review of radioactive contamination of ground water at multiple facilities as a result of undetected leakage from facility SSCs that contain or transport radioactive fluids. The NRC instructed licensees to review the information for applicability to their facilities and consider actions, as appropriate, to avoid similar problems. The NRC also formed a Liquid Radioactive Release Lessons Learned Task Force (LLTF), composed of NRC staff members, to assess the inadvertent release of radioactive liquid to the environment at power reactor sites. The LLTF issued its final report on September 1, 2006 (NRC, 2006). The report included 26 recommendations for additional consideration by the NRC. Several staff recommendations urged development of guidance for early detection of leaks and for onsite ground water monitoring. Other recommendations urged review of NRC regulations regarding minimization of contamination (10 CFR 20.1406, "Minimization of Contamination") and adequate decommissioning funding (10 CFR 20.1501, "General").

In 2012 the NRC issued Information Notice 2012-05 (ML120410213). It addresses the sources and causes of recent abnormal, unmonitored releases of radioactive materials in liquids to the ground that could potentially migrate to groundwater. It summarizes NRC requirements related to radioactive liquid effluents, related information notices, provides some examples of recent abnormal releases, and identifies those plant systems and causes most frequently associated with these abnormal releases.

Proposed changes to NRC regulations for decommissioning planning (SECY-09-0042, "Final Rule: Decommissioning Planning (10 CFR Parts 20, 30, 40, 50, 70, and 72; RIN-3150-AI55," dated March 13, 2009) have recently addressed the last two points in the preceding discussion of LLTF recommendations. The proposed final rule adds 10 CFR 20.1406(c), which will require licensees to conduct their operations to minimize the introduction of residual radioactivity into the site, including subsurface soil and ground water. This rule also amends 10 CFR 20.1501 to require licensees to survey and evaluate residual radioactivity that may require remediation during decommissioning to meet the unrestricted use criteria of 10 CFR 20.1402, "Radiological Criteria for Unrestricted Use," including in subsurface areas, and to keep records of surveys of subsurface residual radioactivity identified at the site with records important for decommissioning. In conjunction with the proposed rule changes, NRC staff is preparing new guidance (Regulatory Guide 4.22). These rule changes and regulatory guides will augment existing regulations (10 CFR 20.1406(a) and (b)) and guidance (Regulatory Guide 4.21, "Minimization of Contamination and Radioactive Waste Generation: Life-Cycle Planning") that address requirements for minimization of contamination for new facilities.

1.4 Relation to Ongoing Industry Initiatives

The Nuclear Energy Institute (NEI) has coordinated an industrywide response to the ground water contamination problem in the form of the Groundwater Protection Initiative (GPI) (NEI, 2007). The GPI identifies actions necessary for the implementation of a timely and effective ground water protection program. Among other actions, the GPI directs power plant operators to establish an onsite ground water monitoring program to ensure timely detection of inadvertent radiological releases to ground water. Through a staff requirements memorandum dated August 15, 2011, the NRC has approved a recommendation not to incorporate the voluntary industry initiative on ground water protection into the regulatory framework. The Commission has directed that the staff should, instead, monitor the effectiveness of the industry initiatives.

Another industry initiative is the NEI Underground Piping and Tanks Integrity Initiative (NEI, 2010), which is intended to "provide reasonable assurance of structural and leakage integrity of in-scope underground and buried piping and tanks" with "special emphasis on components that contain licensed radioactive materials." The Electric Power Research Institute (EPRI) is actively examining issues related to ground water protection and leak detection. EPRI (2008) provides guidance for designing and implementing a ground water protection program that is specific to site hydrologic conditions and plant SSCs.

Recently the consensus standard American National Standards Institute/American Nuclear Society (ANSI/ANS) 2.17-2010, "Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Plants" (ANS, 2010), was published. This standard establishes requirements for evaluating the occurrence and movement of radionuclides in the subsurface resulting from abnormal radionuclide releases at commercial NPPs. This new consensus standard provides technical guidance and references for site characterization, mathematical modeling, performance assessments, performance confirmation monitoring, and information management.

Two recommendations put forward in ANSI/ANS 2.17 are particularly relevant to this report. Section 6.2.2 suggests that "Surface and subsurface resistivity arrays may be used for detecting subsurface changes in soil moisture content or electrical conductivity." Section 6.3 suggests the location of monitoring stations, stating that "monitoring locations shall be close enough to the locations where a release to the subsurface might occur to ensure that the source of the detected contamination is identified." While ANSI/ANS 2.17 is not a regulatory requirement, it does provide a certain expectation, as an industry standard, of a greater level of monitoring. The scoping study reported here identifies methods that might prove beneficial in realizing that expectation.

2. CHARACTERISTICS OF LEAKING SYSTEMS AND LEAKED FLUIDS IMPORTANT FOR LEAK DETECTION

Design of a subsurface monitoring network aimed at reliable early detection of radioactive liquid leaks requires adequate knowledge of the following:

- SSCs that store or transport liquids that contain radioactive material
- SSCs that have leaked in the past or have significant risk of leaking in the future
- construction details of SSCs that may influence the nature of leaks and the ability to detect them (i.e., SSC materials, depth of burial, backfill material)
- characteristics of the radioactivity-containing fluids that, when leaked into the subsurface, may be detected by a sensor (i.e., moisture, temperature, or chemical characteristics that differ from ambient subsurface conditions)

The hydrogeological setting of the SSC will be a very important aspect of leak detection. Leaks into the unsaturated zone provide more opportunity for early detection than those into the saturated zone. In addition, the location of leaking systems with respect to the water table may not be a static property because of water table fluctuations on various time scales.

For buried piping or below-grade structures, the properties of the backfill will be a significant factor in leak detection. However, with the exception of structural backfill around safety-significant SSCs, detailed information about the backfill used is generally not readily available.

The material properties of the leaking systems are extremely varied (e.g., metal tanks and pipes, concrete-lined metal pipes, polyvinyl chloride pipes, concrete sumps, and vaults). However, one useful generalization that can be made is that a large number of components are made entirely of metal or contain metal reinforcement. This will be a significant detail for some geophysical survey methods.

2.1 Structures, Systems, and Components

The LLTF report (NRC, 2006) describes a variety of specific cases of leaks from NPPs. The report points out that some of the components that leaked are not subject to surveillance, maintenance, or inspection. As required by 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” safety-related SSCs of NPPs must be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed. The regulations at 10 CFR 50.55, “Conditions of Construction Permits, Early Site Permits, Combined Licenses, and Manufacturing Licenses,” and the guidance in Regulatory Guide 1.26, “Quality Group Classification and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants” (NRC, 2007), define these categories and standards. No American Society of Mechanical Engineers (ASME) Code Class 1 and 2 components (the most important for safety) are buried. Class 3 and unclassified, nonsafety-related components may be buried and contain relatively low pressure, low temperature water and are not necessarily subject to inspection.

In addition, the LLTF report states that "Leakage that enters the ground below the plant may be undetected because there are generally no NRC requirements to monitor the ground water onsite for radioactive contamination." It is also clear from the LLTF report that it is very difficult to generalize about construction details of systems that have leaked or have the potential to leak. A recent presentation at the EPRI Groundwater Workshop (Coker, 2011; Riley, 2012) provides some details specific to buried pipe systems that have leaked in 2009 and 2010. (See Appendix A to this report and the NRC workshop slides at Agencywide Documents Access and Management System (ADAMS) Accession No. ML120541054 for additional information.) More than 25 percent of the reported leaks were from potable water systems. About 5 percent of leaks contained radioactive material. Also of special concern were the 7 percent of the leaks that occurred in safety-related systems, the 8 percent that contained environmentally sensitive fluids (e.g., diesel fuel), and those leaks that occurred in systems necessary for fire prevention. A detailed list of SSCs that store or transport radioactivity-containing fluids will vary from plant to plant, but several classes of SSCs that have leaked into the subsurface at NPPs or present plausible risks for leaks that may reach the subsurface are discussed below and summarized in Table 1.

2.1.1 Spent Fuel Pools

Several plants have experienced spent fuel pool leaks. In addition, it is plausible for components comprising the fuel pool cooling and cleanup systems to leak. Leaks and spills from the refueling water storage tanks have occurred at several plants. A few plants have also experienced leaks in fuel transfer canals. Thus, the entire system for managing water used in the refueling process should be considered with respect to leaks that may affect soil or ground water.

2.1.2 Cooling Water Discharge Systems

Cooling water discharge pipes and canals are often used for permitted discharges of radioactive fluids. Leaks along these lines have resulted in ground water contamination at several plants. In addition, cooling water may also become contaminated by primary to the secondary side leaks in steam generators (pressurized-water reactors) or condensers (boiling-water reactors).

2.1.3 Primary Cooling Water Treatment and Storage Systems

Primary cooling water (and in some cases secondary cooling water) is run through treatment systems (e.g., demineralizers) to remove impurities, including certain radionuclides. These systems and associated piping have leaked at several plants. Water used in the primary cooling system is stored in a variety of ways (e.g., condensate storage tanks, borated water storage tanks). Leaks from these systems have affected ground water at a number of plants.

2.1.4 Liquid Radioactive Waste Systems

Radioactive waste storage tanks and associated piping have leaked at several plants. Drains and tanks containing liquid waste from onsite analytical laboratories and other waste-handling facilities at nuclear power plants can also be a source of soil and ground water contamination.

2.1.5 Storm Drain Systems

There have been many recorded instances in which spills, leaks, and sump overflows have caused contaminated fluids to flow into storm drain systems. In some cases contaminated water was then discharged to a storm water detention pond. The detention ponds, as well as joints in drainage pipes, can introduce contaminated water into the subsurface.

2.1.6 Septic System Piping and Leach Fields

Septic systems are designed for sanitary disposal of waste water, and fluids containing radioactivity are not intentionally disposed of via septic systems. However, experience has shown that prohibited wastes are sometimes mistakenly disposed of in both domestic and industrial septic systems. Thus, it is plausible that accidental disposal of radioactivity containing fluids could happen, and such events actually have occurred at a small number of NPPs.

2.2 Small Modular Reactors

In some ways, SMRs may present a special case for leak detection technologies. Some of the major differences between existing plants and SMRs are size, inclusion of some systems and components within the pressure vessel, some advanced safety features, and, most importantly for our purposes, subsurface emplacement of the reactor containment. Many SSCs that are described above for existing plants can be expected to be similar in SMRs. For example, some tanks and waste-handling facilities will be at the surface and have the potential to leak into the vadose zone. New designs are expected to incorporate measures to minimize undetected leaks, in accordance with 10 CFR 20.1406(c) (e.g., pipe chases, avoiding buried pipe, and new pipe materials). However, a very large part of the facility may be underground, with some excavations being well over 100 feet deep. Installed systems for leak detection around these buried structures may be useful.

2.3 Potential Signals

2.3.1 Radioactivity

Appropriate selection of devices that measure radioactivity of sampled material can detect leaks of water-containing radionuclides. Remote detection of radioactivity in the subsurface is difficult, if not impossible, for tritium. However, in many cases, radioactivity may not be the optimal signal to use for leak detection. In many cases, tritium is the radionuclide of concern (or at least a leading indicator of leaks containing other radionuclides). Detecting tritium is sometimes very challenging because it is a weak beta emitter. In addition, most of the readily available radiation detection instruments provide point measurements and typically require analysis of samples taken from the subsurface.

2.3.2 Moisture

For SSCs located in the vadose zone, leaks will generate a moisture anomaly that may be detected by a variety of methods.

2.3.3 Temperature

In many instances the temperature of the leaking fluid may differ significantly from the ambient soil water or ground water. Thus, temperature anomalies in the unsaturated or saturated zone may be a basis for leak detection.

2.3.4 Chemistry

In most cases, the chemical constituents of the leaked fluid will be very different than that of the native ground water. In the case of primary-side cooling water, the concentration of dissolved solids may be much lower than native water. Certain chemical components (e.g., boron) may provide a “fingerprint” to distinguish the leak from native water. On the other hand, blowdown water or radioactive waste water may have a much higher total dissolved solids concentration than native water.

2.3.5 Geophysical Properties

Several of the properties of leaking fluid discussed above (moisture, temperature, chemistry) may also create changes in the bulk geophysical properties of the subsurface (e.g., electrical conductivity, dielectric permittivity) that can be detected by geophysical survey methods.

2.4 Challenges of Leak Detection

The objective of early identification of leaks external to SSCs presents significant challenges. One challenge is that the distribution of leaking fluid in the subsurface can take several general forms (e.g., plume morphology). In the case of coarser grained material, fluid will move downward in a relatively small area as if in a conduit. In other cases in which backfill is well sorted and contains more fines, fluid will be distributed over a larger area within the vadose zone. In reality, leakage will find areas where it is distributed in or on lower permeability materials, as well as preferential flowpaths. This is hypothesized to be the case in the tritiated water leak at the High Flux Beam Reactor at Brookhaven National Laboratory (Sullivan et al. 2011, Figure 2-4). Preferential flowpaths present the substantial challenge of detecting leak signatures under unknown flow and dispersion regimes.

The challenge in the vadose zone is to detect anomalous water content of soil. In some circumstances, such as under buildings or pavement, the soil may have dried and attained a relatively steady state of moisture content. Leak detection under this condition should be relatively easy. However, many areas will be subject to influx of precipitation and experience substantial and rapid changes in moisture content. The challenge then is to discern a leak from background moisture levels that can change rapidly. Discussions with EPRI have indicated that it is working on identifying characteristics of water from different systems based on chemical composition and other features to help identify sources of leaks. This approach may help distinguish natural from anthropogenic water inputs. With regard to radionuclide detectors, the ideal would be an in situ low-energy beta detection system that is sufficiently robust that it can be left in place. Alternatively, a probe that can be placed in a borehole would be useful, but in both cases very low detection limits are needed. Another alternative could be vapor collection/samplers that provide information at discrete depths. EPRI is exploring this option.

Another challenge is the need for interrogation under foundations of building or pads. There are several documented cases in which leaks took place inside buildings and were only detected when contaminants emerged in the ground water from under the building (e.g., the tritium plume from the High Flux Beam Reactor at Brookhaven National Laboratory). Cross-well tomography may be well suited for this application. Another possibility is the use of existing buried pipes to act as electrodes for geophysical survey methods to interrogate the subsurface beneath certain susceptible SSCs.

Table 1. Systems, Components, and Potential Leak Signals

System	Component(s)	Potential Signal(s)
Spent Fuel	Spent fuel pool Fuel transfer canal Heat exchangers Filters and demineralizers Piping	Radioactivity Moisture Temperature ≠ Ambient GW Chemistry ≠ Ambient GW
Reactor Water Cleanup	Filters Demineralizers Piping Storage tanks	Radioactivity Moisture Temperature ≠ Ambient GW Chemistry ≠ Ambient GW
Cooling Water	Blowdown/discharge lines	Radioactivity Moisture Temperature ≠ Ambient GW Chemistry ≠ Ambient GW
Liquid Radioactive Waste	Piping Storage tanks	Radioactivity Moisture Temperature ≠ Ambient GW Chemistry ≠ Ambient GW
Storm Water	Detention ponds Ditches Pipes and culverts	Radioactivity Moisture Temperature ≠ Ambient GW Chemistry ≠ Ambient GW
Septic	Pipes Leach field	Radioactivity Moisture Temperature ≠ Ambient GW Chemistry ≠ Ambient GW Microbes ≠ Ambient GW

GW = Groundwater

3. TECHNOLOGY DESCRIPTIONS

The focus of this report is not on detecting leaks in structures, such as pipe races, but rather on detecting the leaked liquid once it has left the SSC and entered the soil. The following paragraphs outline some of the characteristics that are important in leak detection.

The volume of soil that is interrogated by the leak detection method is a critical factor. In situ, single-point sensors are only able to access information from the relatively small volume of soil near the sensor—perhaps 1 liter (L). Consequently, the sensor must be in exactly the right place or part of a larger array to ensure that a leak is detected. Methods in which instruments measure moisture as they are moved up and down in a well (e.g., neutron probes) sample a somewhat larger volume—from a few centimeters (cm) to perhaps 15 cm into the soil over a distance from the ground surface to the water table. This method describes a vertical line that is constrained by well location. Assuming a 5-cm ring of soil interrogated and a 20-meter (m) depth to water, this method might interrogate about 500 to 1,000 liters of soil. Other methods (e.g., geophysical survey methods) can interrogate much larger volumes. For example, two passes of ground-penetrating radar (GPR) examines a volume of perhaps 20 m deep by 1 m wide by the length of the path (say 10 m), giving a volume of 200,000 L. In this case, the position can be moved as needed unless constrained by structures. The large volume sampled provides greater assurance that a zone of anomalous moisture in the soil will be detected.

The advantages of many methods that provide larger sampling volumes are offset because they often require well-trained personnel to conduct periodic surveys and to perform detailed analysis. In contrast, simple in situ point measurement of soil moisture can be automatic and essentially untended for relatively long times. While this sort of measurement needs little analysis, interpretation of causes and distribution of elevated moisture is not possible. The use of a network of in situ point sensors, since it provides better areal coverage, would help develop a clearer picture of changing moisture distributions.

A comparison of the various methods must consider the interpretation of the signal and its sensitivity, as well as the measurement uncertainty. Simple moisture detectors, assuming they are calibrated and working properly, provide relatively unambiguous data with measurement errors of about plus or minus 2-percent volumetric water content. More complex techniques such as those based on electromagnetic radiation (e.g., GPR) have similar errors (about 2-percent root mean squared (RMS) based on surface wave measurements) but are potentially open to several interpretations, with penetration depth varying substantially with moisture content and sediment texture. As a result, it is typically the case that some other method (e.g., neutron logging of a borehole) is needed to interpret geophysical signals. In addition, surface-based geophysical methods can be subject to electromagnetic interferences which may be prohibitive at an NPP.

Frequency of data taking is another important consideration. A traditional GPR survey, for example, is conducted in a campaign that provides an image of the subsurface at a single point in time. These types of methods would need to be repeated periodically (e.g., time-lapse surveys) to detect leaks. Other methods, especially those using in situ probes could provide frequent measurements, providing essentially real-time data. Related to this is the cost of staging periodic measurements with outside personnel as opposed to an in situ method that only needs a data logger system.

Based on this brief discussion, favorable attributes of a moisture-sensing system to detect leaks at an NPP include the following:

- The sampling volume should be large, especially in cross-section, or the area of concern is small.
- Measurements can be automated and interpretation is straightforward.
- Interferences are minimal.
- Sensitivity is adequate
- Measurements can be performed frequently.

This section briefly discusses the advantages and disadvantages of various methods for detection of moisture in soils, particularly with regard to their application to NPPs. For useful overviews of soil moisture measurement by various methods, consult Robinson et al. (2008a and b), Young et al. (1999), and the following Web sites:

- http://www.sjrwmd.com/floridawaterstar/pdfs/SMS_field_guide.pdf
- http://www.sowacs.com/sensors/tdr.html (the Soil Water Content Sensors and Measurement Web site)
- http://water.usgs.gov/ogw/bgas/ (the U.S. Geological Survey (USGS), Geophysics Branch Web site)

The paper by Robinson et al. (2008b) describes more methods than discussed in this report, such as large-scale airborne methods.

3.1 Single-Point Methods

While these small volume, single-point soil moisture methods only interrogate about 1 L of soil, they may be used effectively in several situations. They present several advantages, including making direct measurements of some parameter. (Most geophysical methods provide indirect measurements). These sensors can be used in areas where leakage tends to accumulate and be preferentially transported, such as in backfilled trenches. To overcome the disadvantage of interrogating a small volume, they can be assembled in arrays that provide much greater coverage. All of the methods discussed need to be placed into the soil to be measured, therefore soil has to be excavated to a selected depth in such a way that installation is possible. Wires and, in some cases, tubing need to be run to the surface. These methods may be installed when buried pipes are excavated for repair. Young et al. (1999) discuss the strengths and weaknesses of several of these methods.

3.1.1 Porous Block Sensors

The homogeneity, mineralogy, and structure of soil can affect measurement of moisture content by electrical properties, such as capacitance or resistivity. One means of solving this problem is to insert porous blocks containing sensors, typically a pair of electrodes, into the soil. The porous material equilibrates with soil moisture, and electrical properties can then be measured.

These electrical properties are a function of moisture content within the block, which is representative of soil moisture. Calibration is necessary for the specific soil being measured. Some time is required for the block to come to equilibrium as its wetting and drying profiles will likely be quite different from the soil. As a result, these methods do not respond well to sudden changes in moisture content. Some sensors use gypsum blocks so that dissolution of gypsum provides a consistent ionic strength solution, the quantity of which is controlled by soil moisture. These blocks can function for up to 2 years in situ. Other approaches use inert porous materials.

3.1.2 Tensiometers

Tensiometers measure the energy with which water is held by soil by measuring the difference in pressure between the soil and a saturated porous cup. Dry soil will exert more suction on the cup imparting a negative pressure inside the tensiometer. This is measured with a vacuum gauge or pressure transducer. Conversely, wet soil will exert a positive pressure. The range of useful measurements by tensiometers extends from about +100 kilopascals (kPa) to −160 kilopascals, having limited utility under dry conditions. However, this type of sensor typically provides the most precise measurements of the instruments under consideration. The measurement of soil suction needs to be calibrated for specific soils to obtain moisture content. Tensiometers need to be refilled with water periodically, although newer gel-type probes may need less maintenance.

3.1.3 Capacitance Probes

Capacitance probes provide an estimate of soil moisture (as volumetric water content) by an inferred measurement of dielectric constant (Starr and Paltineanu, 1998; Bosch, 2004). When the probe is installed in soil, the soil becomes part of an electric capacitor while the probe comprises another part, with soil moisture determined by time required to charge the system. Pure water at 25 degrees Celsius (C) has a dielectric constant of 80, while air is close to 1 and dry soil ranges from 4–10. As a result, this measurement, while affected by temperature and salinity, is mostly influenced by water content. The sensors need to be embedded in the soil and calibrated with site-specific soil; they can be connected to wireless data collection systems. A variety of configurations of capacitance probes exist, including two or more parallel rods attached to a probe head (Topp et al., 2008). Another configuration consists of one or more pairs of metallic, cylindrical rings separated by an insulator. These may be arranged on a rod that contains a number of sensors so that measurements can be made at several depths in a single hole, which can be several meters deep. This type of sensor reads a wide range of moisture content. Measurements are observed in an approximately 10-cm radius around each individual sensor. These multisensory capacitance probes are installed in an access tube, helping durability. Capacitance sensors have been extensively used in agriculture and appear to be robust. In fact some have been installed in a research field at the U.S. Department of Agriculture’s Agricultural Research Station in Beltsville, MD, for 10 years (personal communication to M. Fuhrmann from Y. Pachepsky, 2012). Commercial systems are available that allow many probes to be read frequently, and the data transmitted wirelessly. Some are capable of measuring temperature and conductivity as well as soil moisture.

3.1.4 Heat Dissipation Sensors

A porous medium containing air will heat up and dissipate a pulse of heat more rapidly than the same medium containing water. These sensors consist of a porous material, such as a ceramic, that contains a sensitive temperature detector and a small heater. The porous material, being in equilibrium with soil moisture, provides a defined medium for observation. A short heat pulse is applied and the temperature change is observed. The rate of dissipation of heat can be directly related to water potential. These sensors are commonly used and appear to be quite rugged.

3.1.5 Dual-Probe Heat Pulse Sensors

Another approach to detecting moisture is through determining specific heat of the combined soil and moisture (Campbell et al., 1991). Dual-probe heat sensors consist of two small parallel needles, one containing a heater and the other a thermistor. Knowing the quantity of heat delivered, the change in temperature, and the distance between the heater and the temperature sensor allows determination of volumetric heat capacity. From this and the specific heat of soil solids, the volumetric water content can be estimated. These probes tend to have a small bias toward greater water content; however, the response appears to be linear and corrections have been published (Basinger et al., 2003; Ochsner et al., 2003). The volume of soil interrogated is small. Depending on needle length and separation, the sensed volume will be a few tens of centimeters.

3.1.6 Psychrometer

A number of designs exist for these sensors, with a common basis in the use of the "wet bulb/dry bulb" method of measuring relative humidity. The sensor contains two thermocouples. One is sealed within the sensor and is the "dry" bulb. The other is contained in an air chamber formed within a porous medium, such as a ceramic that can come to equilibrium with soil vapor. One thermocouple measures the ambient dry temperature while the other measures the temperature as lowered by evaporation of moisture in contact with the thermocouple. The rate of evaporation, as determined by the temperature difference, can be related to relative humidity and therefore the moisture potential of the soil. These sensors are commonly used in research, especially for drier soils, and may not perform very well near saturation. While they can be left in situ for some time, these sensors often have the drawback of requiring maintenance, including replenishing the water supply. One design uses Peltier (thermoelectric) cooling to cool a thermocouple so that ambient moisture condenses on it in place. In this way, the single thermocouple provides the wet bulb and dry bulb measurement.

3.1.7 Time Domain Reflectometry

Time domain reflectometry (TDR) is an electromagnetic measurement of the apparent dielectric constant of a material. A probe is inserted into the material to be measured and the two-way travel time is measured of an electromagnetic pulse sent through the probe and reflected back to a measurement instrument. Moisture content is calculated based on the apparent dielectric constant (Topp et al., 1980). American Society for Testing and Materials (ASTM) Standard Method D6565, "Standard Test Method for Determination of Water (Moisture) Content of Soil by the Time-Domain Reflectometry (TDR) Method," describes moisture quantification in soil by the TDR method (ASTM, 2000). Robinson et al. (2003) provide a detailed review of TDR. Many commercial instruments and probes of various configurations are commercially available. Some of these can be automated, multiplexed to provide measurements at many points, and the data transmitted. TDR requires the use of probes with two or more waveguides. These range in length from a few millimeters (mm) with multiple probes on printed circuit boards (Ito et al., 2010) to several meters. The moisture content is averaged over the length of the probe. To obtain profiles with long probes, switching diodes can be used to separate sections of the waveguides so that specific segments of the probe can be made active or inactive. TDR senses a relatively small volume of material with a 1-m-long probe interrogating about 2 L of material.

A number of factors influence the calculated moisture content, but the accuracy of the time delay measurement and calibration are primary. TDR instruments should be calibrated with the specific soil to be tested. Attenuation of the returned pulse by high ionic strength soil solutions or by high clay content can limit measurements, but this effect, within limits, can be used to estimate electrical conductivity. Temperature influences measurement by changing the cable length and by decreasing the dielectric permittivity of water with rising temperature, leading to underestimates of moisture content (Gong et al., 2003).

3.1.8 Example of Arrays of Single-Point Moisture Sensors

The radioactive waste subsurface disposal area at the Idaho National Engineering Laboratory (INEEL) (Hubbell et al., 2005) provides an example of the use of arrays of moisture sensors. For deep observations (i.e., from 16 to 385 feet), advanced tensiometers were developed, which Hubbell et al. (2005) describe. For shallow measurements, less than 25 feet in depth, two types of sensors were used—combined soil-moisture, resistivity, and temperature (SMRT) sensors and direct-push Type B tensiometer (DPT) sensors. Ninety-five SMRTs were installed with 73 percent providing data, and 66 DPTs were installed with 52 percent providing data. Many of these were located directly in the waste to provide measurements of wetting/drying trends. The DPTs required periodic additions of water, and this disturbed measurements for at least several weeks.

Hubell et al. (2005) and Meyer et al. (2005) evaluated the performance of these various types of sensors and found that the advanced tensiometers were preferred for long-term monitoring because they provide data year round during both saturated and unsaturated conditions. (See Figure 1 for an example of data from a set of these instruments.) McElroy and Hubbell (2004) provide additional information on using these instruments to evaluate the conceptual model of the deep vadose zone. SMRTs were suitable for long-term monitoring and were preferred over the DPTs, but were affected by temperature variations. The DPTs required extensive maintenance and were not able to measure in the dry range of moisture conditions.

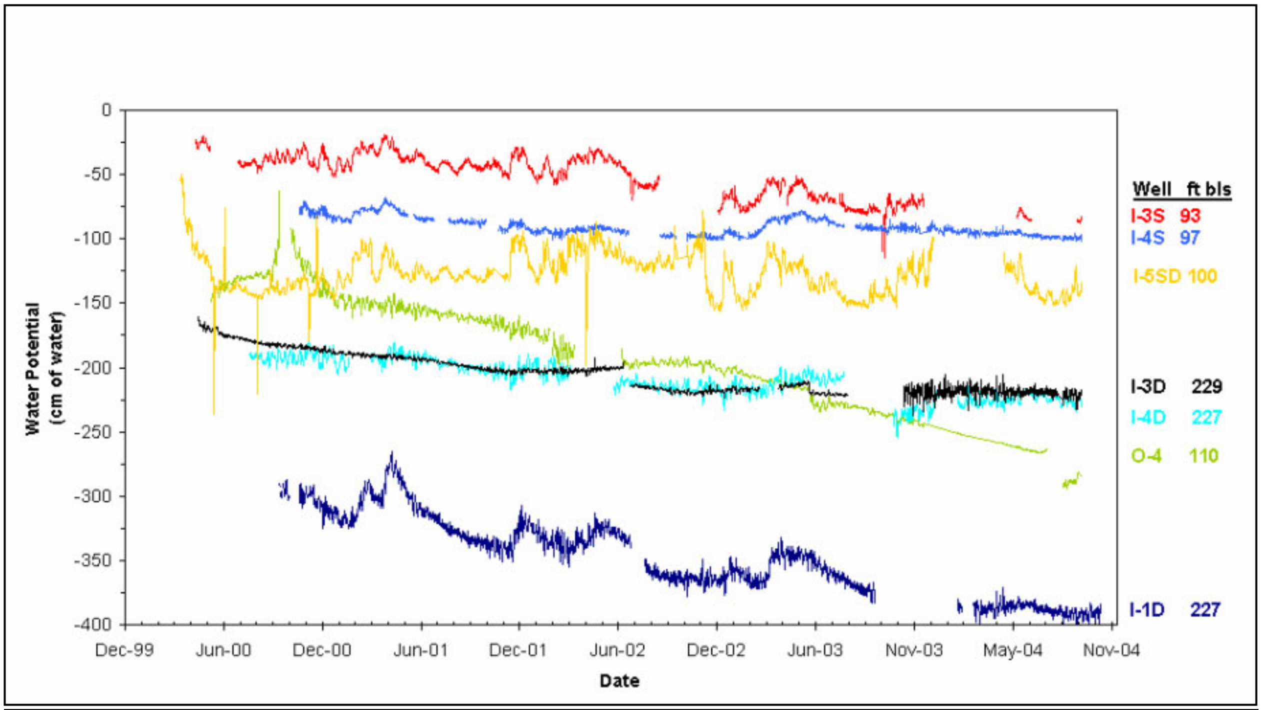


Figure 1. Data sets from advanced tensiometers showing long-term drying trends at different locations at INEEL (Hubbell et al., 2005)

3.2 <u>Two-Dimensional and Three-Dimensional Methods</u>

A number of methods, primarily geophysical, have been used to interrogate large volumes (relative to the small volume, single-point methods discussed earlier) of soil for moisture content and other parameters. Some of these can be used to generate data in a two-dimensional plane, while others can be configured to also provide three-dimensional tomographic information. The U.S. Environmental Protection Agency (EPA) provides useful background and describes many of these methods at http://www.epa.gov/esd/cmb/GeophysicsWebsite/index.html. Some of the configurations use probes or antennae at the ground's surface, while others are borehole to borehole or surface to borehole. Typically, vertical boreholes have been used, but horizontal boreholes or pipes installed during construction may present even more useful configurations.

Murray et al. (2005) reviewed and compared the state of the art of a variety of geophysical techniques that can be used to assess properties of the subsurface, such as stratigraphy, moisture content, porosity, permeability, geochemical properties, and flow patterns. The technologies reviewed are focused on those that would be most appropriate for use at the Hanford site and that are "minimally invasive," meaning that they can be installed at the surface (upper 1 foot of material), using preexisting monitoring wells, or can be installed in the subsurface with inexpensive techniques. Murray et al. (2005) evaluated the technologies on the basis of functionality, state of development, and costs, among other factors.

3.2.1 Electromagnetic Methods

Similar to the electrical resistivity (ER) methods discussed in Section 3.2.2, electromagnetic induction (EM) methods measure the apparent electrical conductivity (or resistivity) of a bulk volume of subsurface material (although using a different operating principle). In the EM approach, a time-varying current in the transmitter generates a primary magnetic field. Time variation of the primary magnetic field induces an electromotive force (EMF), which drives electromagnetic eddy currents in the subsurface. The decay of these eddy currents, which is governed by the subsurface electrical conductivity, generates a secondary electromagnetic field. The voltage measured in the receiver is proportional to the time rate of change of the secondary electromagnetic field. Thus, the receiver voltage can be related to the apparent subsurface electrical conductivity. Zhdanov and Keller (1994) provide a more detailed discussion of the underlying theory.

There are a wide variety of EM methods and several ways to classify them. Standard geophysics textbooks, such as Reynolds (2011), Sharma (1997), and Telford et al. (1990), provide an overview of the available types of EM surveys. EM methods may be classified according to the nature of source (i.e., controlled or uncontrolled), characteristics of the time-varying signal produced by the transmitter (i.e., time domain or frequency domain methods), and configuration of the transmitter and receiver. The following discussion will focus on controlled source electromagnetic methods (CSEM), since they are more appropriate for the application addressed in this paper. CSEM methods are defined as those which incorporate a transmitter device so that the user has control over the electromagnetic field transmitted. This distinguishes CSEM methods from those that rely on uncontrolled sources, such as natural electromagnetic fields or very low frequency radio signals. CSEM methods may be very useful for shallow subsurface investigations. CSEM methods can image deeper into the subsurface than ground-penetrating radar (GPR) and typically provide better resolution of small features than direct current resistivity (Everett and Meju, 2005). Similar to capacitive resistivity (CR) methods discussed in Section 3.2.2, CSEM methods do not require electrodes to be inserted into the subsurface and can therefore be mounted on a mobile platform, allowing for relatively rapid surveys of large areas. Everett and Meju (2005) and McNeill (1980a, b) discuss CSEM methods in more detail. In particular, Everett and Meju (2005) discuss techniques for dealing with noise in CSEM signals, which will be a concern at operating power plants.

3.2.1.1 Frequency Domain Electromagnetic Methods

In frequency domain electromagnetic methods (FDEM), the transmitter uses a fixed-frequency oscillating current. The amplitude and phase differences between the primary and secondary electromagnetic fields are then used, along with the transmitter-receiver intercoil spacing, to calculate an apparent soil electrical conductivity (or resistivity). An advantage of this approach is that equipment is available that allows one to select from multiple frequencies (typically ranging from 100 hertz (Hz) to 50 kilohertz (kHz)) to tailor the subsurface investigation to certain depth ranges and to avoid known noise sources. FDEM methods have proven to be well suited to rapid reconnaissance mapping of lateral changes in near-surface conductivity (Everett and Meju, 2005).

In practice, this approach is generally applied as terrain conductivity meters. Measurements are made in relative conductivity, and interpretation is qualitative and best applied to searching for anomalies. Surveys are conducted by moving a transmitting and a receiving antenna across the surface of the ground at a fixed distance to each other. Some systems are small enough that they can be carried manually along a transect. Measurements are taken periodically, perhaps every 20 feet. The depth of investigation depends on antenna spacing—a depth of 49 feet for 20-foot spacing and a depth of 98 feet for 40-foot spacing. An extensive bibliography of applications is available at http://www.dualem.com/abib.html, and at http://www.cflhd.gov/resources/agm/ . The technique has been used to map soil and ground water salinity in agricultural fields at depths of about 1 m (McNeill, 1980a). Other applications have included surveying subsurface acid mine drainage and saltwater intrusion in a coastal setting (see the EPA Web site cited above for additional information). Commercial systems are available.

3.2.1.2 Time Domain Electromagnetic Methods

In time domain electromagnetic methods (TDEM), the typical transmitter wave form is a rapid rise to a steady value followed by a rapid shutoff, as shown in Figure 2, with a cycle of about 1 millisecond. The transmitter current is sent through a large loop of wire (transmitter antenna) and induces an electromagnetic image that is propagated through the media above and below the antenna. As this image (Figure 3) moves through the medium, perturbations in conductivity generate eddy currents that can be measured at the receiver. A depth profile of conductivity can then be determined.

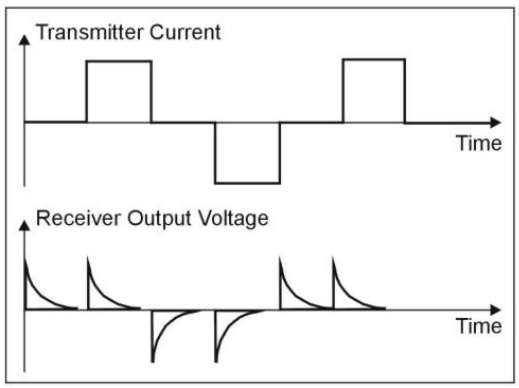


Figure 2. Transmitted and received signals from TDEM instruments (U.S. Army Corps of Engineers, 1995)

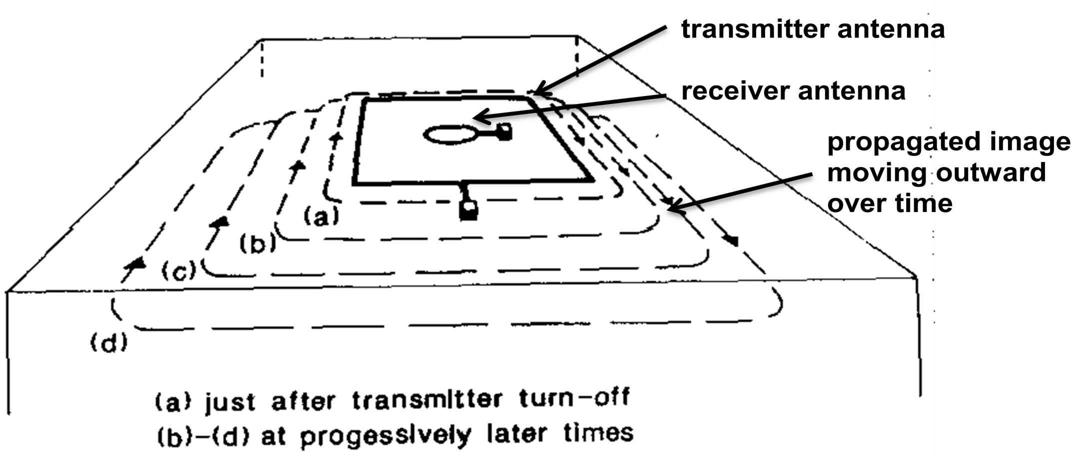


Figure 3. Schematic of TDEM process showing the transmitter and receiver antennae and the EM image propagating away from the transmitter antenna over time (U.S. Army Corps of Engineers, 1995)

The advantage of this approach is that the relatively weak secondary magnetic field is measured during the transmitter off time. In addition, various transmitter and receiver configuration and spacing combinations may be used to image depth zones of interest to a particular application. The transmitter antenna is generally a square that can have dimensions of perhaps 50 or 100 m. A single measurement may require about 100 microseconds, and perhaps 1,000 measurements are stacked to provide usable data. The depth to which conductivity measurements can be made depends on the current used in the transmitter, antenna size, and the material being interrogated. However, depths of 100 m or much more can be assessed. Surface or aerial surveys can be conducted to develop one-dimensional, two-dimensional, or three-dimensional images of the subsurface (Everett and Meju, 2005). Induced interferences from power lines present a problem as does the presence of metallic objects not only in the subsurface but the surface as well.

3.2.1.3 Ground-Penetrating Radar

Ground-penetrating radar (GPR) is a geophysical survey method that uses radiofrequency electromagnetic radiation (40–1,500 megahertz (MHz)) to detect objects and changes in soil properties. Transmitting antennae in contact with the ground produce an EM signal. Receiving antennae observe the direct or reflected signal, from which the time delay and intensity can be determined. This imaging technique uses differences in wave velocities of returned signals that are a function of the dielectric constant of the subsurface media, which in general, is related to the moisture content of the medium (e.g., soil). (See Huisman et al. (2003) for details about the method and a variety of applications.) In addition to moisture content, GPR can be used to determine the electrical conductivity of the medium by measuring the attenuation of the radar signal (Lane et al., 2004).

The typical configuration for GPR is an antenna array at the ground surface. This configuration is used to search for buried objects or to assess the moisture content of agricultural soils. The antennae are moved to produce readings over a large volume. Spacing of antennae can be important, and an initial test of antenna configuration is common during a survey. Another configuration has been tested in which the antennae are located down wells several meters apart (Alumbaugh et al., 2002). Figure 4 illustrates several configurations for downhole GPR. These same arrangements can also be applied to some other geophysical methods.

GPR is of interest because it appears to be sufficiently sensitive to changes in soil moisture such that it could readily observe anomalous moisture zones in the soil. The RMS error in volumetric water content taken by tomographic GPR is estimated to be 2–3 volume percent (Alumbaugh et al., 2002). Grote et al., (2003) reported the RMS for 29 estimates as between 2.2 and 1.5 volume percent. Use of site-specific soil moisture and texture measurements to calibrate GPR is necessary for high-quality measurements.

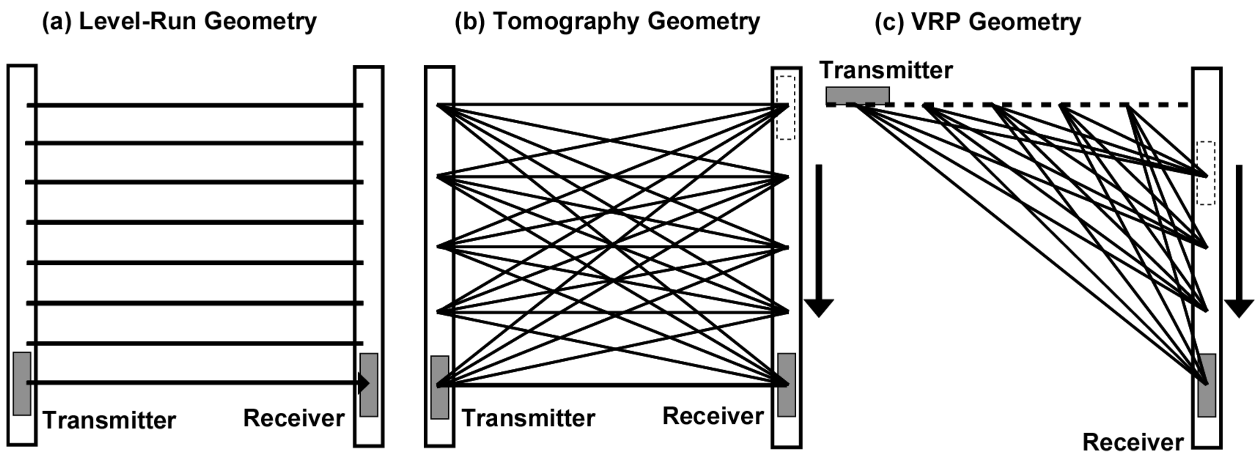


Figure 4. Three configurations for downhole GPR (Lane et al., 2004). Level-run geometry is also called "zero-offset." VRP geometry refers to vertical radar profile geometry. These configurations can also be used with some other geophysical methods, such as resistivity profiles or tomography.

The volume sampled by GPR depends on a number of factors that include antenna configuration; the frequency of use; and the texture, homogeneity, and moisture content of the soil. Under ideal (dry, homogenous) conditions, penetration depth can be up to 30 m, but more commonly depths are only a few meters. Nevertheless, this method can describe a plane that covers a substantial area. Several scans spaced 1 m apart can interrogate a large volume of soil with a measurement error of about 2–3 volume percent.

A serious limitation of GPR, especially for surface-deployed systems, is that it is subject to electromagnetic interferences. This is not necessarily an issue for many applications, but at a power generation plant it could in fact limit the use of this method.

In cross-borehole GPR, the antennae are placed down boreholes to sample a plane between two wells. This has several advantages, including shielding from electromagnetic interference and the ability to interrogate to greater depths than surface methods. In the downhole mode, GPR can be used in two ways (Lane et al., 2004). One approach, the zero-offset profile, produces simple measurements of average moisture content at discrete depths. With this technique, the transmitter and receiver (in different wells) are moved simultaneously so that they are at the same depth, providing a simple measurement of travel time on the line between the two antennae (Binley et al., 2001). The other approach uses sets of ray paths between receivers and transmitters at different depths. This computationally intense method is used to generate tomographs. Alumbaugh et al. (2002) compare the moisture content from cross-borehole GPR and neutron probe for five wells. In most cases, the general trends of moisture content with depth are similar for the two methods. The GPR system tends to average out local peaks that are observed by the neutron probe. However, in this case the resolution of GPR could be improved by smaller intervals.

Cross-borehole GPR can be applied to horizontal subsurface wells to observe vertical moisture movement in certain suspect areas. Because the cross-borehole approach is used in a fixed location in a periodic monitoring mode, the soil could be well characterized and the time series of measurements would be available for comparisons, making interpretation easier. This method is especially sensitive to signals from dense materials, such as pipes in the subsurface.

As a result, while this method may be good for finding pipes, the signal from them may mask subtler signals from changing moisture content.

3.2.2 Electrical Resistivity Methods

Electrical (direct current) resistivity methods have been widely applied in fields such as mining, oil and gas exploration, construction, water resources engineering, and ground water remediation (Telford et al., 1990). Many of these applications have focused on the measurement of subsurface water content. In its most elementary form of application, the ER method comprises propagation of an electrical current between two electrodes ("current" electrodes) inserted at the ground surface, while information on the induced electric field is obtained by measuring the voltage between a second pair of electrodes ("potential" electrodes) also inserted at the ground surface The applied current and the resulting measured voltage, together with knowledge of the electrode spacing and arraignment, allow determination of the bulk resistivity of a subsurface soil volume. Resistivity measurements can be conducted in a variety of configurations. Useful information can be obtained from time series of voltage values, or data can be used to generate images. These can be relatively simple two-dimensional interrogations of a plane through the subsurface to much more complex three-dimensional or tomographic imaging techniques that require sophisticated computational analysis. For three-dimensional imaging, electrical resistance tomography (ERT) is a method that calculates the subsurface distribution of ER from a large number of resistance measurements made from electrodes on the ground surface or in boreholes, or both, to produce images of vertical or horizontal sections. Depending on the application, resistivity variations can then be related to geology, subsurface moisture content, porosity, temperature, and pore fluid chemistry.

For soils comprised of sands and silts (i.e., negligible clay and organic fractions), bulk soil resistivity will be directly proportional to the soil solution resistivity and vary inversely with porosity and saturation (i.e., inversely with volumetric water content). The soil solution resistivity is, in turn, a function of ion concentration, ion type (since different ions have different mobilities), and temperature. One should note that, because the soil solution resistivity depends on ion concentration, it is often interrelated with soil moisture content. For example, as a soil dries (moisture content decreases), the dissolved ions become more concentrated in the soil solution that remains and the soil solution resistivity decreases.

Seasonal to daily fluctuations in temperature and moisture may cause resistivity variations greater than 50 percent of mean values. For example, the resistivity of frozen sand or silt is extremely high since ion mobilities are reduced to near zero. However, in spite of the significant natural temporal variability, the spatial patterns of soil resistivity are often remarkably stable. Even small weight percentages of clay and organics can have a significant influence on resistivity because clay minerals and organic matter often coat the surfaces of sand and silt particles, reducing bulk soil resistivity by providing exchangeable ions that lower solution resistivity.

For leak detection at NPPs, ERT methods can be used to detect changes in subsurface conditions rather than precise measurement of water content. Several different changes in the subsurface conditions associated with a leak could produce detectable changes in bulk soil resistivity in the soil volume affected by the leak. Soil moisture change (for leaks above the water table) is one obvious signal that could be detected. The challenge with respect to soil moisture changes will be differentiating between natural soil moisture changes and those caused by leaks. In this regard, looking at changes in spatial patterns of soil moisture rather than focusing only on a time series of moisture measurements at a point or in a small volume will be beneficial. Time-series data will be useful, but only after a sufficient length of record has been collected to determine natural patterns and establish correlations with other observations, such as local precipitation events.

If the concentration or type of dissolved ions in the leaking fluid differs significantly from the ambient soil water, then there may be an observable change in bulk soil resistivity. This type of change should be detectable whether the leak has occurred above or below the water table. Similarly, if the leaking fluid differs significantly in temperature from ambient soil water, it may produce detectable changes in bulk resistivity.

A variation on the ERT method that may have applications at NPPs is cross-borehole ERT (e.g., see Daily and Owen, 1991; Binley et al., 2002). In cases in which electrodes cannot be left at the surface, two or more boreholes can be drilled on either side of the structure. Electrodes are installed at several depths in the boreholes and computerized control provides an array of measurements. A two-borehole arrangement will allow for a two-dimensional image of the subsurface. Three or more boreholes will allow for a three-dimensional survey, but these are computationally very intensive. The acceptable distance between boreholes can be limited by signal attenuation and may be only a few meters.

Using electrodes to contact the ground is called "galvanically coupling." Another approach, discussed later, is termed "capacitively coupling," in which electrodes are not inserted into the ground but can be moved over the surface. Capacitive coupled resistivity (CR) is a geophysical technique designed to extend the scope of the conventional methodology to environments in which galvanic coupling is notoriously difficult to achieve, such as pavement, dry soils, or snow/ice cover (Douma et al., 1994; Kuras, 2002; Kuras et al., 2006). CR systems use a capacitive-coupling approach to introduce electric current into the ground and to measure potential differences at the soil surface. This capacitive-coupling is accomplished using the capacitance of an antenna (commonly a coaxial cable) to couple an alternating current (ac) signal into the ground (Geometrics, 2001). Existing CR systems use a fixed, high-frequency ac current (10–20 kHz) to induce an ac current in the soil (Allred et al., 2008). In this way, no direct contact is needed between the instrument and the ground. Essentially, a large capacitor is formed by the coaxial cable and the soil surface. The metal shield of the coaxial cable is one of the capacitor plates, and the soil surface is the other capacitor plate, with the outer insulation of the coaxial cable acting as the dielectric material separating the two plates. The system transmitter applies ac to the coaxial cable side of the capacitor, in turn generating ac in the soil on the other side of the capacitor.

With regard to the receiver, a similar phenomenon occurs, except in reverse. The ac in the soil charges up the capacitance of the coaxial cable, which is measured to determine the potential difference (voltage) generated by the electric current within the soil (Allred et al., 2008). The transmitter and receiver are usually deployed in a dipole-dipole configuration in which the transmitter and receiver are placed in line and separated by an integer number of dipole lengths (Geometrics, 2001; Allred et al., 2008). By using line electrodes with different lengths and changing the separations, it is possible to vary the penetration depth, which can extend down to approximately 20 m (Geometrics, 2001) The CR methodology allows the use of towed sensor arrays, thus enabling the rapid collection of high-resolution resistivity data. Tomographic imaging is possible using such datasets acquired with moving arrays (Allred et al., 2006; Kuras et al., 2007).

Resistivity measurements, as mentioned earlier, can be set up with lines of electrodes at the ground's surface or with electrodes inserted at discrete depths in the subsurface (electrodes have been developed for direct push-hole boring techniques). Resistivity survey techniques that take advantage of existing subsurface infrastructure (e.g., steel-cased wells, metal pipes) by using them as current electrodes are a recent advance that may prove useful at NPPs (Ramirez et al., 1996; Calendine et al., 2011). ER measurements can be conducted from systems that consist of an electrode array and associated electronics that can be towed along the ground surface behind a small vehicle, allowing rapid measurement along transects without the need to insert and remove electrodes. These are continuous resistivity measurement techniques that use either galvanic contact or capacitive-coupling approaches. It is likely that electromagnetic interference may be a problem for this approach, but in an NPP environment this type of survey may be appropriate for use away from paved areas (e.g., for long effluent discharge lines). Paved areas (e.g., concrete, asphalt, gravel) will clearly pose difficulties as will very dry surface soils. In addition, winter conditions (e.g., ice-covered, snow-covered, or frozen ground) may prevent sufficient galvanic contact for the method to work properly.

3.2.3 Some Approaches for the Use of Electrical Resistivity Methods for Leak Detection

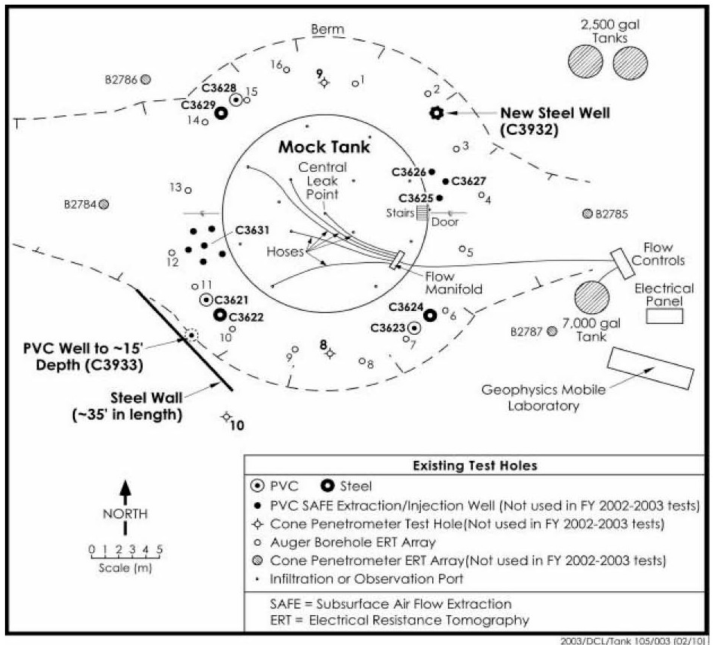
The following examples illustrate approaches that may be used for leak detection. Some are based on presentations and discussions that occurred during the NRC's Workshop on Early Leak Detection, held on February 15, 2012 (see the abstracts in Appendix A to this report and slides from that workshop at http://pbadupws.nrc.gov/docs/ML1205/ML120540481.html).

3.2.3.1 Leak Rate and Volume Detection on a Tank Farm

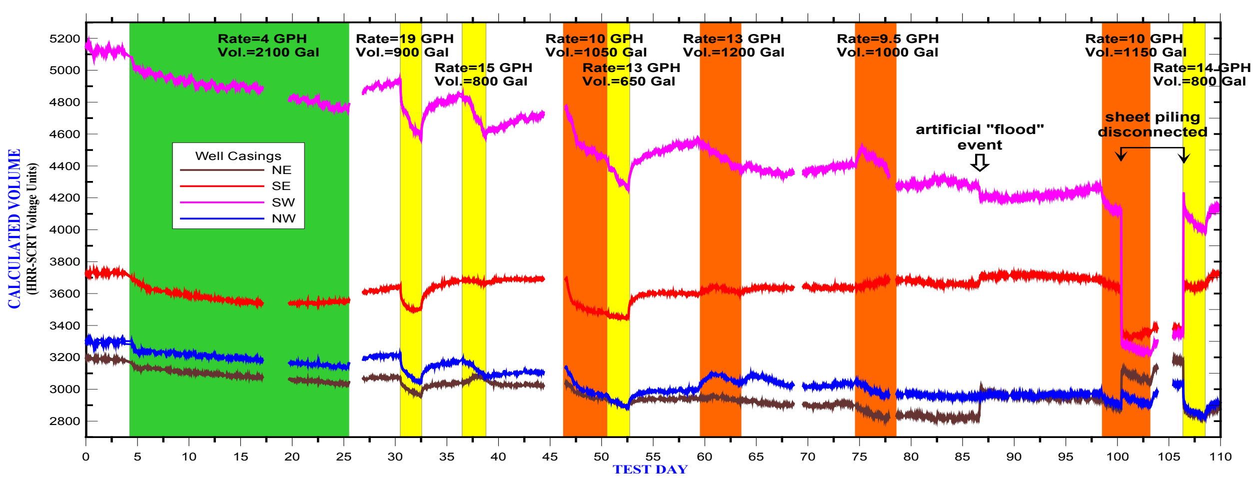
As part of the Hanford work to address leak detection, monitoring, and mitigation (LDMM) from high-level waste (HLW) tanks, researchers subjected six technologies, five of which are geophysical, to preliminary field testing. Evaluations of these methods (Bratton, 2002) are based on the results of field work on a mockup of a tank with simulated leaks. This report also discusses the maturity of the techniques and describes various projects using the methods.

Rucker (see Appendix A to this report and the presentation slides) presented results of ER measurements for tests conducted at a mock tank, as well as subsequent tests at actual tank farms at Hanford. These sites include buried pipe and other infrastructure. Figure 5(a) shows the configuration of the mock tank; note the different locations and arrays of electrodes for ER. Water injection took place from a well screened at 20–30 feet below ground surface at rates that ranged from 4–16 gallons per hour. Some methods use steel wells as electrodes; others use electrodes that were emplaced by cone penetrometer. Figure 5(b) shows data for the tests in terms of leak volume (in gallons) based on conversions of voltages using the high resolution resistivity-steel casing resistivity technique (HRR-SCRT). Leaks were readily detectable by this method and both leak rate and volume could be estimated. Later tests detected leak rates as low as 2 gallons per hour; typical leak volumes were about 1,000 gallons. Figure 5(b) presents four data traces for measurements made using the four steel well casings around the tank (indicated in Figure 5(a)) as potential electrodes. The injection well or the tank itself was used as the excitation electrode. This method does not provide spatial information for leak location but is sensitive to volumes and rates.

Later tests at the Hanford HLW tank farms were conducted to assess the ability of geophysical monitoring systems, especially ER methods, to detect leaking HLW and to function in an industrial setting. Figure 6 (Calendine et al., 2011) shows the effects of a number of events and environmental changes from August 2010 to January 2011. Particularly interesting is the effect of cathodic protection on the noise level of the signal compared to a short interval when the protection was turned off. No leaks were detected during this period.



(a)



(b)

Figure 5. **(a) Plan of Hanford mock tank and the locations of wells used as electrodes and (b) After Rucker, 2012, data from the four wells showing volumes of leak tests (derived from voltages). Leak rates can be determined from the slopes of voltages.**

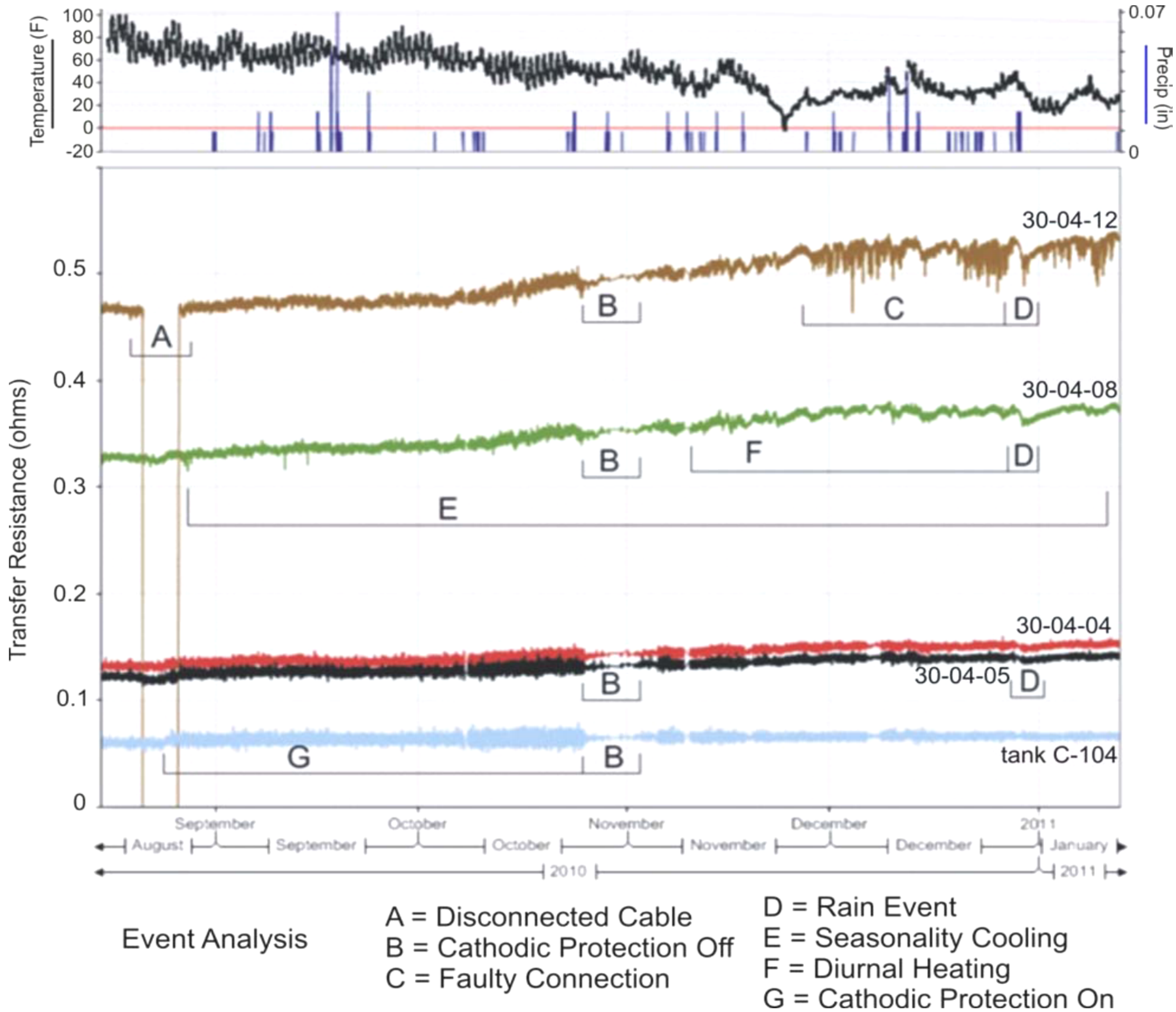


Figure 6. Analysis of various events for resistivity monitoring of Tank C-104 at Hanford for about 5 months. Of particular interest is the difference in the data when cathodic protection is on and when it is off (Calendine et al., 2011).

3.2.3.2 Moisture Location, Imaging, and Impact of Buried Pipes

Perhaps the most NPP-relevant example of using ERT for leak detection is the Hanford Tank Farm (Rucker et al., 2008; Calendine et al., 2011; Johnson, 2012), at which an ERT-based program for monitoring and leak detection has been deployed since 2004. Many of the challenges presented by the industrial nature of the Hanford site (e.g., extensive subsurface piping, grounded electrical infrastructure, cathodic protection), as well as natural features such as diurnal and seasonal fluctuations in temperature and soil moisture, are similar to those that might be expected at a NPP. The problem of drilling in an infrastructure-rich location can be overcome by using existing steel monitoring wells as long electrodes (Rucker et al., 2012). ER imaging techniques can provide detailed spatial information on subsurface electrical properties. For leak detection, this technique can be applied in time series and examined for differences in moisture content. Figure 7 illustrates infiltration of rainwater into the subsurface at

Hanford, WA, over a 9-week period. Also shown is the surface array of electrodes used to generate the data.

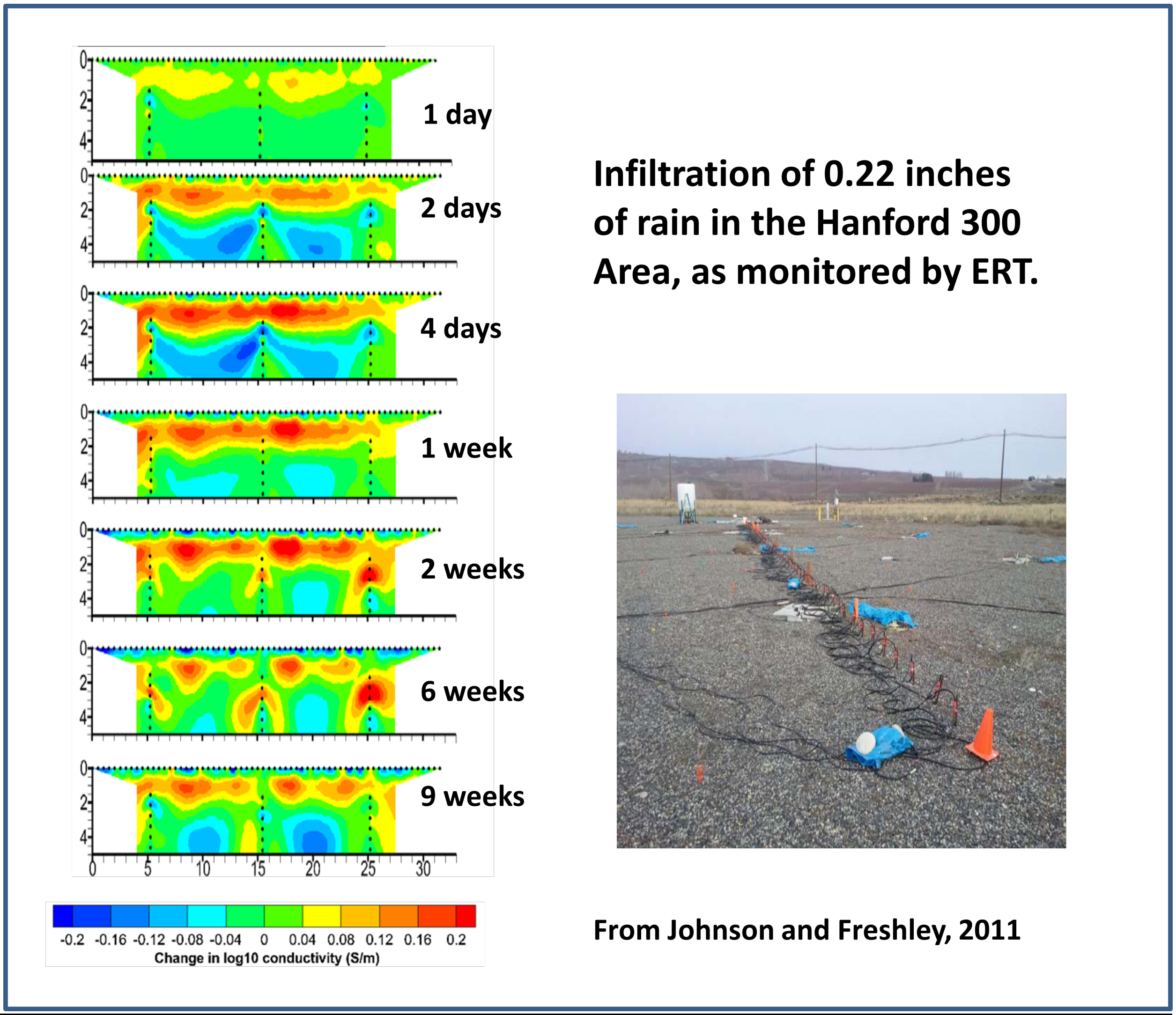


Figure 7. **ERT showing infiltration of rain over a 9-week period at the Hanford 300 Area. Also shown is the array of electrodes used for the ERT. Dimensions are in meters.**

Figure 8 shows the results of ERT used to determine changes in soil moisture as a result of a desiccation process intended to retard the transport of technetium-99 under old liquid waste discharge cribs at Hanford. The waste was an aqueous solution high in nitrate salts providing a target of high (180 microsiemens per centimeter) electrical conductivity. Nitrogen is injected into the subsurface through a well and then extracted from another well 15 m away, carrying moisture with it. Imaging indicates that moisture is removed from zones of high permeability, but is retained in stringers of finer grained sediment. Images were autonomously produced twice per day and show a growing area of lower soil moisture over time.

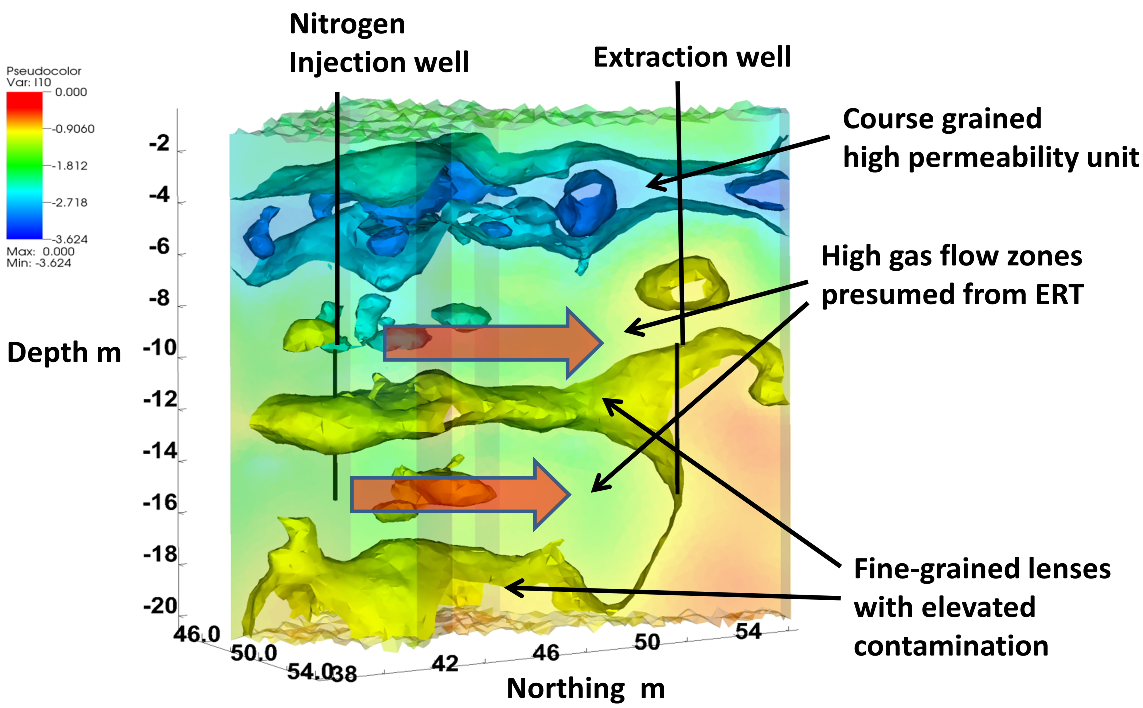


Figure 8. **ERT-derived subsurface monitoring for the vadose zone desiccation at the Hanford B-C cribs (Johnson et al., 2012)**

ERT now can be run autonomously and frequently. Advances such as computer-controlled multielectrode systems greatly simplified the task of conducting surveys along long transects or large grids. Electrodes can be installed in cement and have been used for 11–12 years. A soil moisture monitoring system has been installed at a site at Hanford, WA, where a treatability test for moisture removal is underway. A variety of soil moisture and water potential probes are used, as well as cross-hole GPR and daily ERT surveys. The ERT system consists of 15 electrodes in each of nine wells, giving daily images at submeter resolution (personal communication, Tim Johnson and Mike Truex, March 7, 2011).

At the Brandywine Superfund site in Maryland, remediation of volatile organic compounds (primarily trichloroethylene) used bioaugmentation to degrade the contaminants. As part of the monitoring system, an autonomous time-lapse ERT (downhole and surface electrodes) system was used that automatically acquired field measurements, managed and processed the data, and provided images. This system gave near real-time results showing the distribution of 1,000-gallon injections of molasses into the subsurface to stimulate microbial degradation of the volatile organic compounds (http://water.usgs.gov/ogw/bgas/estcp/bioremed-monitor.html, Versteeg et al., 2010).

3.2.4 Nuclear Magnetic Resonance Sensing

Magnetic resonance surveys (MRS) measure the magnetic resonance response of protons in bulk water molecules after excitation by an ac current that induces a change in magnetic field. Unlike other geophysical methods that are indirect methods with nonunique interpretations (e.g., they can be influenced by variations in mineralogy, temperature, conductivity of the solid, and ionic strength of the ground water), MRS is a direct measurement of the presence of bulk protons. Typically this means water, although organic fluids and hydrocarbons also respond to MRS. Lubcynski and Roy (2004) discuss the theory of the process; USGS also provides additional information at http://water.usgs.gov/ogw/bgas/mrs/. The one commercial instrument, the NUMIS system, is described at www.heritagegeophysics.com.

Briefly, bulk protons normally align themselves to the local magnetic field of the earth. Using a loop of electric cable (often a square from 20–150 meters on a side) on the ground, an ac pulse is applied that indices a magnetic field that realigns the protons. The frequency of the pulse is important and needs to be tuned to the Larmor frequency, which is a function of the local strength of the earth's magnetic field. When the excitation current is turned off, the protons return to their original orientation, and this signal is measured in the same loop of wire. Two components of the signal are used for interpretation; amplitude indicates the number of protons excited and thus the water content and the decay rate which indicates the pore size (Vouillamoz and Legchenko, 2010). Faster decay rates result from frequent collisions of water with the solid phase (small pores); even faster rates (i.e., less than 30 milliseconds) indicate water bound to the solid (e.g., in clays). These fast decay times are typically filtered out so that only free water is detected.

MRS can interrogate a large volume of soil and can provide information on both the vadose and saturated zones. The volume is a function of antenna size; for a 100-meter antenna, the volume analyzed is about 2 million cubic meters. Depth of analysis is 1 to 1.5 times the antenna length; field experience indicates that the depth of shallow, horizontal strata can be placed with an accuracy of about 1 m. Sensitivity of the method for water content is not clear, but typical graphic data show variation of water content of about 1 percent. Usually MRS data are interpreted as one-dimensional models of water content versus depth. A two-dimensional tomographic inversion is reported to provide more accurate data than the one-dimensional approaches (Hertrich et al., 2007).

This method is susceptible to electromagnetic noise from a variety of sources (Lubczynsi and Roy, 2004). Such sources can be both natural and artificial and include lightning strikes (some at a large distance), noise from power lines, ground cables and working electrical machinery, and conductivity of subsurface media. Interference may be especially problematic when it is close to the Larmor frequency.

3.2.5 Fiber-Optic Distributed Temperature Sensing

Distributed fiber-optic temperature sensing (DTS) systems are commonly used to detect leaks in pipelines for oil, gas, and brines (Nikles et al., 2004) and for fire detection. Recently these systems have been applied to a variety of near-surface hydrologic processes, including measuring the positions and dynamics of lake thermoclines, determining energy exchanges at stream/atmosphere interfaces, and finding underwater springs where ground water flows into river water. In other cases, they have been used to detect illegal discharges into sewer lines (Hoes et al., 2009). Down-borehole and mining applications include detecting locations of water flow into wells and mines and temperatures in oil wells. Selker et al. (2006) offer several examples.

With DTS methods, temperatures are commonly measured in 1-m increments over many kilometers (km) to an accuracy of 0.1 degree C. Greater spatial and temperature resolution are possible with longer integration times and better lasers and detectors. The fiber-optic cables used for temperature detection are the same as used for telecommunications; no sensors along the cable are needed. Temperature and distance measurements are obtained by measuring scattered light from a laser pulse. Distance is determined by timing scattered light returns. Raman scattered light is shifted slightly in wavelength from the original pulse. The returned scattered light contains both Stokes (lower frequency) and anti-Stokes (higher frequency) components. The amplitude of the anti-Stokes component changes as a function of temperature while the Stokes component does not. As a result, temperature can be determined from the ratio of the Stokes and anti-Stokes peaks. Tyler et al. (2009) provide useful observations on applying and deploying DTS systems.

Measurement of temperature may apply directly to leak detection, assuming that the temperature of the leaking water differs from ambient temperatures and that the sensor is close enough that the difference is still measurable. However, slow leaks or those at ambient temperatures may not have a clear thermal signature. Direct measurement of moisture content by DTS has been attempted by measuring changes in soil thermal properties as a function of moisture content. Conceptually, this is a standard approach to soil moisture measurement at single points, but the distributed sensor system allows large areas to be assessed. One attempt used diurnal temperature differences of a shallowly buried cable to determine soil moisture (Steele-Dunne et al., 2010). This attempt was not especially successful. However, an active DTS method can be used in which a heat pulse is applied to the soil and the response of temperature over time is observed. Laboratory tests have been conducted in a sand column measuring 0.61 m x 1.46 m using 31.5 m of fiber-optic cable. This commonly used type of cable contained, in addition to the two optical fibers, stainless steel strands, which were used as an electrical resistance heater (Sayde et al., 2010). By heating the cable in a short pulse and then measuring the change in temperature over time, the moisture content was calculated.

DTS has been used to assess the location and quantity of ground water discharging into the subsurface of water bodies. This approach may have application in assessing ground water discharges to water bodies close to nuclear facilities, where the ground water may contain contaminants. USGS has demonstrated the use of a fiber-optic distributed temperature sensor in evaluation projects (http://water.usgs.gov/ogw/bgas/fiber-optics/) for freshwater and estuarine systems. For example, at Waquoit Bay, MA, the contrast of temperature between bay water (16–29 degrees C) and ground water (11 degrees C) was used to assess input of freshwater to the bay. A 1.3-km-long cable was used and was deployed in a grid pattern of 60 m x 80 m. Measurements were taken at about 1-minute intervals over a 2-week period (Day-Lewis et al., 2006).

Discharge of uranium-bearing ground water to the Columbia River at the Hanford site has been investigated by a combination of DTS and continuous waterborne electrical imaging (CWEI) methods. The purpose of these investigations was to define specific locations where ground water discharges to the river. Data generated by DTS using four cables, each laid parallel to a 1.6-km section of the river showed cool water anomalies during summer when the river was warmer than the ground water and warm water anomalies when the river was colder than the ground water (Mwakanyamale et al., 2012). These anomalies are only observed at the low river stage (which varies diurnally by control from a nearby dam) because the elevated water stage actually drives water back into the bank. DTS was able to indicate ground water discharge locations using a two-dimensional, time-frequency analysis with 4-day periods (see Figure 9). CWEI was used to determine changes in lithology under the river, as well as to estimate specific surface area normalized to pore volume of the different geologic units outcropping under the river. The combined methods showed that ground water exchange with river water is strongly controlled by the thickness of the transmissive lithological unit, with the exchange being focused at springs that are sometimes controlled by paleochannels (Slater et al., 2010).

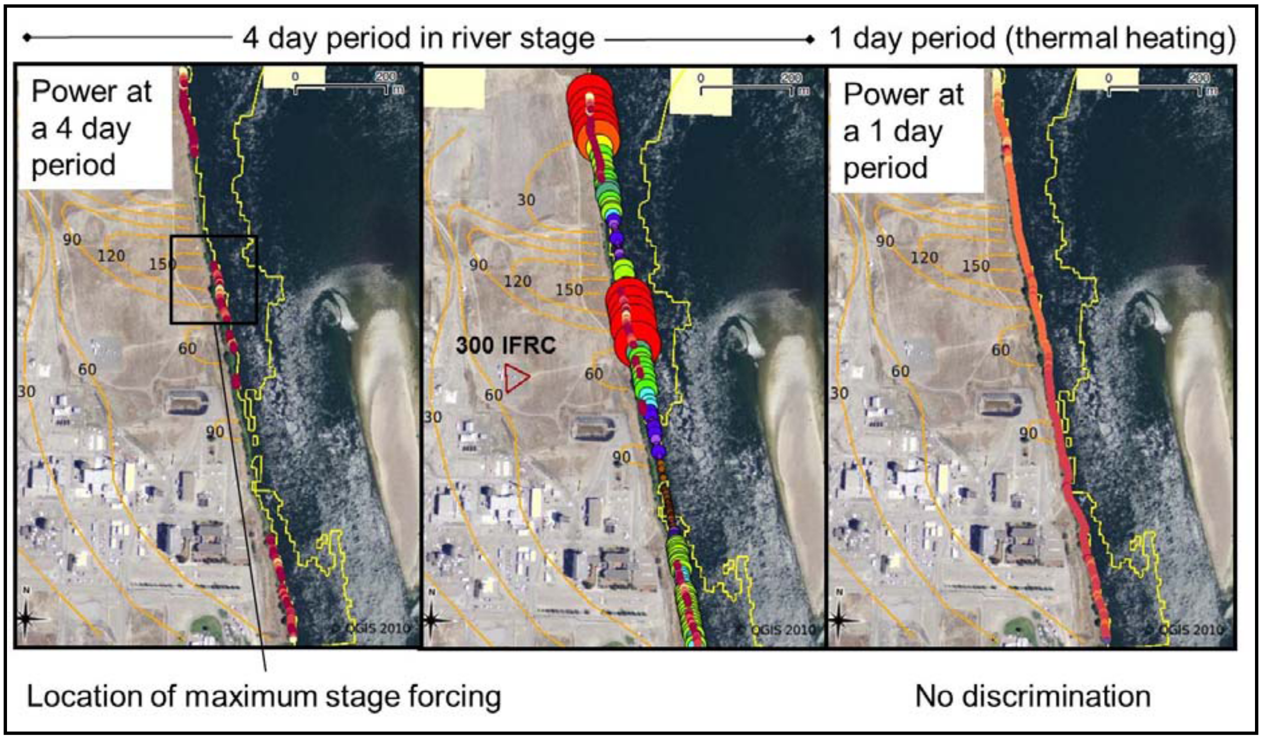


Figure 9. Transform analysis at two periods. The 4-day period shows strong correlation between stage changes and focused exchange of ground water with river water, while the 1-day period shows no discrimination (Slater et al., 2011). The central panel shows the thickness of transmissive layers where ground water exchanges with river water.

3.3 Nuclear Methods for Water Content

3.3.1 Neutron Probe

This well-developed technology is often used to provide reference measurements of soil moisture against which other methods are compared. ASTM Standard Method D6031, "Standard Test Method for Logging In Situ Moisture Content and Density of Soil and Rock by the Nuclear Method in Horizontal, Slanted, and Vertical Access Tubes," is a standard test method that includes thermal neutron moisture content and bulk density by backscattered gamma rays (ASTM, 2010). The instrument operates by emission of fast neutrons from a sealed source that are slowed (thermalized) by elastic collisions with atoms in the ambient environment. Hydrogen atoms are by far the most effective (although boron, cadmium, iron, and chlorine can interfere to some extent because of their high cross-sections for neutrons). Typically water contains by far the greatest quantity of hydrogen in soils; in the absence of hydrocarbons, the flux of thermal neutrons is proportional to water content of the soil.

This is a downhole method. The instrument consists of two parts—the downhole probe and the counting system. The probe contains a sealed source of fast neutrons, typically a mixture of americium-241 and beryllium powder, with activities of americium-241 ranging from 30 to

100 millicurie. Alpha particles interacting with beryllium produce fast neutrons that range in energy from 2 to 10 million electron volts. The probe also contains a detector that observes thermal neutrons but not fast neutrons. The counting system remains at the ground surface and contains electronics and power supplies

The method is used with a cased borehole. Aluminum casing is essentially transparent to neutrons, but steel is also acceptable. As little air gap as possible between the casing and the probe is desirable. The casing must be in direct contact with the ambient soil. The sensing volume of the method is greater than many other methods, with a radius of 10 to 40 cm, depending on moisture content providing an interrogated volume at each point of as much as 100 L (ASTM, 2010). An essentially continuous set of measurements can be conducted down a well. The accuracy of volumetric water content measurements is about plus or minus 0.005 $ft^3/ft^{3.}$ For high precision information, site-specific soils with known moisture content should be used for calibration.

3.3.2 Gamma Ray Attenuation

Gamma-rays passing through a heterogeneous earth material are adsorbed and scattered by the materials. The degree to which a collimated beam of gamma rays is attenuated by a given thickness of material depends on the energy of the gamma rays, the bulk density of the medium, and the elements of which it is comprised. This method therefore requires a source of monoenergetic gamma rays and a detector with the sample between the two. This means that the source and the detector are lowered into separate but nearby boreholes. Two source radionuclides (typically containing on the order of 100 millicuries) are commonly used—cesium-137 at 661 kiloelectron volts (keV) and americium-241 at 61 keV. The detector (e.g., a sodium iodide detector) must be able to distinguish between the two energies. This method is often used in the laboratory because it does not disturb the soil and has high precision; it is infrequently used in the field because of the high activity radionuclides and the inconvenience of needing two boreholes.

4. DETECTION METHODS FOR RADIONUCLIDES

While this report thus far has focused on the detection of moisture as a means of early detection of leaks in the subsurface, detection of anthropogenic radionuclides can be a more direct and sensitive indicator of leaks from NPPs. The radionuclide that has been most frequently observed at leaks has been tritium, although comparatively small amounts of other radionuclides, such as cobalt-60, strontium-90, and cesium-137, have been observed in soil and water as a result of leaks. A few radionuclides, tritium, iodine-129, and carbon-14, are sufficiently volatile that they can be observed in soil gases (ANS, 2010). Tritium (half-life of 12.35 years) is the radionuclide of interest because it is the radionuclide that most readily migrates in the subsurface and therefore can be a leading indicator of other contaminants.

The typical method for tritium quantification in water is by liquid scintillation counting of samples in a laboratory instrument. This method is based on detection of light emitted by a scintillator material when the material is excited by beta radiation. Standard analytical methods (i.e., ASTM D4107, "Standard Test Method for Tritium in Drinking Water" (ASTM, 2008)), state that, with appropriate instrumentation, sample size, and count times, the detection limit for tritium is less than 1,000 picocuries per liter (pCi/L), with the maximum contaminant level for tritium in drinking water being 20,000 pCi/L. The method stipulates chemical treatment and distillation of a water sample. The distillate is collected, added to scintillation fluid, and then counted.

However, a variety of other methods have been developed for tritium detection, some of which are for surface contamination and others for analysis of gases or liquids. In some cases, silica gel is used to sorb moisture from vapor samples for tritium analysis. Typically, moisture is desorbed from the gel, collected, and analyzed by liquid scintillation counting. Many flow-through systems have been developed using any of a number of scintillator materials, such as some organic crystals or coatings (with anthracene producing the most light), plastics, cerium-activated lithium glass, calcium fluoride doped with europium, yttrium glass, and yttrium silicate. Some flow-through systems mix liquid scintillation fluids with the water to be analyzed. If the approach is taken to test water samples for tritium, then several commercial systems are available that provide flowthrough cells (Marsh et al., 2007) with detection limits of about 100,000 pCi/L.

In another approach, helium-3, the stable daughter of tritium can be analyzed by mass spectrometry and the ratio of helium-3 to helium-4 is used to indicate the presence of tritium. This method requires sampling of soil vapor into pressurized gas sample "bombs" and relatively sophisticated analytical methods.

Our interest is in situ methods. Radionuclide detectors should have the following characteristics ideal for this application:

- They should to be able to detect low-energy beta emissions (i.e., tritium).
- They need to be sufficiently robust that they can be left in situ for long periods or provide measurements of the subsurface remotely.
- They should be able to interrogate large volumes of soil or soil vapor.

In addition, correction for background radiation is necessary, and the use of expendables such as gas is undesirable. Of the many types of radionuclide detectors, few if any have all of these characteristics. Because of the low-energy beta radiation of tritium (average of 5.6 keV with a maximum of 18.6 keV), remote detection is not possible. The material to be counted must be very close to or in contact with the detector material since the range of beta rays from tritium is about 6 micrometers in water. Most detector systems consist of electronics that are too delicate and expensive to be considered for in situ use in soils. Moreover, for detectors placed in the soil, the volume of detection is very small. As a result, options for early detection of tritium leaks into the subsurface are limited; they seem to be constrained to sampling and analysis of the subsurface material and to downhole methods.

4.1 In Situ Tritium Vapor Detection

Since tritium is generally in the form of tritiated water and is volatile, one approach to maximizing the volume of material sampled from the subsurface is to have an array of gas sampling boreholes in the vadose zone connected to an air pump, a manifold, and then to a detector. Sampling could be automated to rotate among the wells. Vapor is fed through the manifold to any one of several commercially available systems designed for tritium detection in air. These detectors, typically ionization chambers or proportional counters, have detection limits of about 1,000 pCi/L and have reference chambers that provide compensation for background radiation (Marsh et al., 2007). A common problem with these detectors is retention of tritium (a memory effect), especially on organic materials in the system. Selection of materials can help, as may providing the capacity to heat susceptible portions of the system. However, it is not clear how well tritium in ground water becomes distributed to water vapor in the subsurface.

Olsen et al. (2000) sampled tritium in moisture from soil vapor in two areas at Hanford, WA, underlain by extensive tritium ground water plumes. While the ground water contained 117,000 pCi/L, tritium in the nearby soil vapor was below the detection limit of 240 pCi/L. This suggests that soil moisture is dominated by the downward transport of moisture from precipitation; tritiated water vapor does not move upward. However, analysis of helium-3, the daughter of tritium, using the ratio of helium-3 to helium-4 indicated substantial enrichment of helium-3 that increased with depth. This suggests that sampling soil vapor may not be very useful for tracking tritium ground water plumes, although this method may be useful for tritium that is entering the vadose zone and is moving downward.

4.2 Down-Well Tritium Detection

Canadian nuclear facilities have used passive tritium samples. A glass vial half full of water (or a 1:1 water/glycol mix) is positioned in a sampling location, which could be in a well in the vadose zone. The vial has an opening in the cover to allow tritiated water moisture to diffuse into the vial and to come to equilibrium with the liquid. After about 1 month, the liquid is sampled and counted by liquid scintillation. This method is falling out of favor because it has been found to have extremely variable results.

Detectors that can be used down a borehole are an option. Several detectors of tritium are designed for downhole applications. A commercially available system, Model SSS-33DHC from Technical Associates (Canoga Park, CA), has a detector sonde that is lowered down a borehole while other electronics remain at the surface. The downhole system pumps water through filters and deionizers and then through a flow cell containing scintillation crystals coupled to photomultipliers. Data are then sent to the processor unit above ground. The lower limit of detection is 1,000 pCi/L in a 30-minute count. This instrument is designed for water analysis only. A variation puts only the pump system downhole, and it can detect 1 microcurie per liter (µCi/L) in a 20-minute count and 0.135 µCi in 3 hours. Product literature states that these instruments can be used in continuous operation and that they are "not influenced by other radionuclides."

Recently, researcher at Idaho National Engineering Laboratory developed a downhole beta detection system (Akers et al., 2010). Skorska et al. (2010) reports the results of an evaluation of the proof-of-concept detector, as well as a subsequently enhanced detector. This detector has a diameter of 1.906 inches, a length of about 19 inches, and a 12-inch length of the scintillator section. This system is designed for beta detection. It has a demonstrated sensitivity to technetium-99 at 1.2 picocuries per gram for a 3-minute count time. The counting system is able to discriminate between technetium-99 and strontium-90 (Figure 10), but it has not been demonstrated for the much lower energies of tritium. It can be used in water as well as in air.

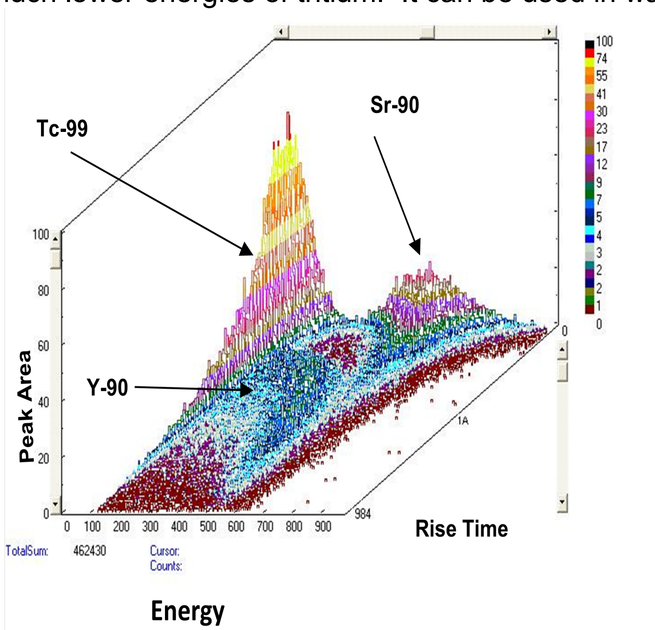


Figure 10. Output from detector tests showing separation of counts from technetium-99, strontium-90, and yttrium-90 (Akers et al., 2010)

This system is in the development stage and requires demonstrated ability to detect tritium and to discriminate between tritium and soil background radionuclides.

Work conducted for the U.S. Department of Energy at Mc Dermott Technologies (Berthold and Jeffers, 1998) investigated the development of a tritium detector based on the use of fluor-doped optical fibers. U.S. Patent # 5793046 was filed. The low-energy beta particle emitted by tritium is completely absorbed by coating materials typically used on radiation-detecting fibers. With this system, however, a polystyrene fiber has a thin coating of fluorescent material which is in direct contact with water containing tritium and therefore is able to interact with beta particles. The light generated can then propagate down the fiber to a photomultiplier tube. This work was stopped after the initial phase because of detection limit challenges, as well as questions about the stability of the coatings.

Recently, a fiber-optic tritium detector was developed (Jang et al., 2010) that consists of a scintillator in the form of a 10-mm-diameter disc, a bundle of 40 plastic fiber-optic cables feeding into a photomultiplier tube, and an amplifier which is read by a LabVIEW system. The scintillator was a 0.1-mm-thick disk of Gd_2O_2S:Tb in optical epoxy (1:1 by volume). The optical fibers were 1 m in length. The system was tested with metal hydride/tritium sources containing 0.05, 0.2, and 0.4 curies of tritium. The response of the detector to the different sources was linear, but count rates and efficiencies are not given. Nevertheless, the feasibility of coupling a scintillator and fiber optics for observing low-energy beta rays was shown.

Several other approaches to detection of tritium have been published and may provide the basis for useful means of subsurface detection. One is the use of avalanche photodiodes. Willms et al. (2005), at Los Alamos, developed a device for measuring tritium surface contamination that is capable of measuring down to 1,000 disintegrations per minute per 100 square centimeters, which is a free release limit. To obtain these detection limits, count times were very long and no window was used between the sample and detector. This work follows from earlier use of PIN diodes as detectors for x rays.

Researchers at Savannah River (Hofstetter and Wilson, 1992) developed a system for continuous monitoring of tritium in effluent. This system consists of a U-tube analysis cell containing plastic scintillator beads (0.1 mm in diameter) and a commercial (Berthold) radio-High Pressure Liquid Chromatography system using two photomultipliers as detectors. To minimize fouling and interferences, it was necessary to clean up the effluent with complex inline water treatments. A detection limit of 800,000 pCi/L was obtained for a 10-minute count and 300,000 pCi/L for 1 hour.

5. DISCUSSION

Table 2 compares the methods that can be used to monitor for early signals from leaks in the subsurface at NPPs. It includes methods for measuring moisture content, temperature, and tritium vapor. However, as discussed below, challenges are associated with many of these methods, especially the geophysical techniques using electromagnetic signals. While many technologies are available to detect and quantify the moisture content of soil, their practical application, especially at large complex facilities, is not necessarily straightforward. The following sections discuss some assumptions and observations that may apply to attempts to provide early leak detection at NPPs.

5.1 <u>Comparison of Single-Point Methods</u>

Several methods of measuring soil moisture lend themselves to being installed for long-term applications. These methods, although they only interrogate small volumes, could be used in specific areas where leaking water will accumulate or be channeled. For example, they could be emplaced into backfilled trenches during construction or repair work. Durability is the key requirement for these sensors. Sensitivity seems less important since changes of moisture content in a confined space would likely be rapid and readily apparent. Placement even within a constrained area could be important, and sensors should be positioned at the lower interface of backfill and native soil.

Since these sensors would be inaccessible, they cannot require maintenance (such as periodic addition of water) and should have low failure and degradation rates. TDR probes and perhaps capacitance probes seem to provide these characteristics, although there is no experience with in situ sensor functionability beyond about 10 years.

As part of the work to identify technologies that may be applied to treating wastes in the deep vadose zone of the central plateau at Hanford, WA, in situ sensors were identified as an important tool in determining moisture conditions in the vadose zone. Truex et al. (2011) evaluated in situ moisture sensors for use in field applications to desiccation as a remediation technology. These researchers conducted two laboratory experiments with a large flow cell into which a variety of sensors were installed—thermistors for soil temperature (evaporative cooling), heat dissipation units for soil matric potential between −0.1 and −5 megapascals, thermocouple psychrometers for soil matric potential between −0.2 and −8 megapascals, dual probe heat pulse for water content, and humidity probes for relative humidity. In the flow cell, moist soil was dried by air injection and extraction after which water was reintroduced. All sensors detected the passage of a desiccation front, but the thermocouple psychrometers and dual probe heat pulse sensors could not be reactivated upon rewetting.

5.2 <u>Comparison of Two-Dimensional and Three-Dimensional Methods</u>

In many circumstances, methods that interrogate large volumes of the subsurface provide a great advantage over point measurement techniques. The use of vertical cross-borehole methods that allow interrogation of a “panel” or plane of subsurface material has several advantages. The area interrogated between wells is consistent in location and solid material characteristics. As a result, measurements repeated over months and years can be used for simple comparisons instead of needing more complex analysis. In this configuration, the plane that is interrogated could be below a suspect area and therefore very likely to intercept moisture. Downhole arrays can be permanently installed, can be set up with wireless communications, and are out of the way of plant operations. In some cases, existing monitoring wells can be used. These boreholes do not need to be finished wells; polyvinyl chloride casings are used and, for some methods, 2-inch inside diameters are acceptable. Perhaps more advantageous is the possibility of using horizontal boreholes, especially for new construction. In either configuration, a simple analysis, rather than a complete imaging process, should be able to detect change.

The use of boreholes has limitations. First, locating the boreholes in appropriate areas could be difficult, not only because of the uncertainty in suspect areas but also because of the presence of subsurface pipes and cables that would preclude drilling. This is a concern at NPPs but drilling is often done, albeit with care to avoid infrastructure and with sufficient justification (personal communication; Zigmund Karpa to M. Fuhrmann, February 15, 2012). There is a limited distance between boreholes at which signals can be detected as a result of attenuation by the solid medium. Typically this separation distance is between one and two times the depth of the borehole.

Electromagnetic interference at an NPP is expected to be intense because of the operation of generators, motors, electrical cables, switches, and galvanic corrosion protection for underground pipes. This may preclude the use of some surface-based electromagnetic systems, such as MRS. However, EM noise comes in many forms, geological and cultural, with causes ranging from distant lightning strikes to the coherent noise from power lines (Everett and Meju, 2005). Fortunately, some EM methods are tunable so that they use only a small segment of the EM spectrum. In this case, it may be possible to use parts of the spectrum that are relatively free of noise or to filter out the interference. Surveys of a site can be conducted to assess the degree of interference. In addition, downhole methods provide some shielding from electromagnetic interference, but it is not clear whether this shielding effect is enough to allow use of these methods. Combining the two approaches may be effective. Figure 6 illustrates the influence of cathodic protection on resistivity measurements. Segment B is a period when cathodic protection at a tank was turned off. The signal is much less noisy than it is with it on, but the noisy signal still allowed detection of rain events (Calendine et al., 2011).

Challenges exist in identifying moisture movement resulting from precipitation as opposed to leak detection. Combinations of methods may allow better discrimination by sensing conductivity, temperature differences, and tritium, as well as moisture. In addition, techniques will be needed in which the site-specific behavior of natural processes (precipitation) can be "learned" so as to differentiate between leaks and infiltrating precipitation.

Of the methods shown in Table 2, DTS is consistently noted as favorable. As described earlier, this technique is primarily intended for temperature sensing but can be adapted for moisture sensing. Nevertheless, for many reactor systems, leaking water may provide a temperature signal. The sensor for DTS is a cable that can be very long; as a result it can be arranged as needed to provide coverage of an area. As discussed earlier, these systems are commercially available and configured for a variety of applications, including detection of leaks and fires.

The use of an array of single-point sensors has also been rated favorably on a consistent basis. While point measurement methods can in many cases provide high precision measurements of moisture content, they suffer from a lack of areal continuity. Typically they measure moisture in a volume of about a liter. However, arrays of point measurement instruments may be useful in small, well-defined areas that are especially subject to leaks. Many of these methods can be automated and permanently installed. Computer-controlled arrays of sensors (e.g., ER or TDR) have been used for extended periods (in excess of 10 years). They can be easily installed in simple boreholes with wireless communications. On Table 2, in the row entitled “Arrays of single-point sensors,” the topic of “Adequate Sensitivity” is marked with “F ?.” While the sensitivity of the sensors themselves is very good, sensitivity of the entire array is a different matter and will depend on sensor spacing.

As discussed earlier, ER can be used in a downhole zero-offset configuration for detection of changes in moisture content. This differs from ERT because of the shorter pathway (see Figure 3) between transmitter and receiver (when compared to tomography) and better signal to noise ratio. ER systems can be installed in the subsurface and operated for long times. Data computation is much simpler in the zero-offset configuration than in tomography, as well. Because of these differences, Table 2 treats zero-offset ER, which is the most favorably rated geophysical method, separately from ERT.

HRR-SCRT has been demonstrated with mock leak tests at Hanford; Table 2 rates this method highly. This time-lapse method seems to be sufficiently sensitive to low flow rate subsurface leaks (a few gallons per hour) that it is interesting for industrial applications. Calendine et al. (2011) discuss the method’s application to long-term monitoring, including data required for a complete data set, anthropogenic changes, factors causing false positives, and automation of a leak detection system.

Cross-borehole ERT and tritium vapor analysis both are rated as favorable, but in each case there are substantial unknowns associated with the method’s applicability to leak detection at NPPs. For tritium vapor detection, a topic of considerable interest to EPRI, a key issue is the volume of soil from which vapor is drawn. This will likely be site specific and is subject to gas movement through preferential flowpaths that may draw low activity vapor from unintended areas, such as along well casings. Analytical equipment for continuous tritium detection is commercially available and has been in use for years for air monitoring. Most require a gas supply and appear to be sufficiently sensitive for application to leak detection. However, the partitioning of tritium between the vapor and the liquid and solid phases in the subsurface may need to be better understood to inform models of contaminant migration.

Cross-borehole ERT is also a well-developed technology that has been applied to a variety of sites, primarily in the area of geochemical remediation where near continuous and autonomous monitoring was done. It is possible that ERT using surface probes will suffer from EM interference to such an extent that it is not useful. Downhole ER methods are less prone to anthropogenic interference than many other methods; however, it is not clear if the technology, in its downhole configuration, will be usable in the presumed high EM interference environment of an NPP. A limitation to cross-borehole ERT is the need for wells that are within a few meters of each other. Both cross-borehole ERT and tritium vapor analysis have promise, but are likely to require additional development specific to the question of leak detection. This report further addresses this issue in a later section.

MRS is a relatively new means of assessing moisture content noninvasively. While it is very sensitive to EM interference, such that the presence of local powerlines or distant lightning strikes present problems, there is a downhole Nuclear Magnetic Resonance tool that could be less subject to interference. As a result, while surficial configuration appears to be inappropriate for leak detection at NPPs, it may be possible to use another configuration.

GPR, like ERT, can be configured for surface or downhole interrogations, or a combination of the two. Surface-based methods are probably seriously affected by EM interference, but the downhole approach may be less degraded. Of the two cross-borehole configurations, tomographic imaging does require sophisticated computer processing, while the zero-offset (or level-run) approach is much simpler. This latter technique appears to be well suited to provide change detection information. However, GPR systems are not suited to continuous or autonomous operation, requiring skilled operators and complex data processing. GPR techniques may also have particular difficulty overcoming the presence of infrastructure.

In summary, the methods that appear to be most applicable for early leak detection are DTS, arrays of a single-point method, tritium vapor sampling with real-time analysis, and cross-borehole zero-offset ER. One method is primarily for temperature, one is for tritium, and two focus on moisture content (but may also be used for temperature and fluid conductivity). Combining these methods lend themselves to a more robust monitoring strategy by using methods that interrogate different properties. This allows a double check of anomalous signals or may allow identification of the leaking pipe system.

Table 2. Comparison of Large-Volume Interrogation Methods

F = favorable U = unfavorable ? = more information is needed

Method	Subject to EM Interference	Subject to Physical Interference[1]	Autonomous	Continuous Operation	Adequate Sensitivity[2]	Installed[3]	Simple Interpretation[4]	Comment
Cross-hole GPR tomography	F ?	F	U	U	F ?	U	U	Subject to EM but downhole may shield
Surface GPR	U	U	U	U	F?	U ?	U	Sensitive to EM interference
Cross-hole zero offset GPR	F ?	F	U	U	F	U	F	Subject to EM but downhole may shield
Cross-hole ERT	F ?	F	F	F	F ?	F	U	Subject to EM but downhole may shield
Surface ERT	U	U	F	F	F ?	F	U	Sensitive to EM interference
Zero-offset cross-hole ER	F ?	F	F	F	F	F	F	Higher S/N than ERT Less subject to EM
Magnetic resonance	U?	F	U	U	F	U	?	Very sensitive to EM
EM methods	U?	U	U	U	F	U	?	Some methods tunable to avoid noise
DTS	F	F	F	F	F	F	F	Only detects temperature in areas where cable is placed
Tritium vapor	F	F ?	F ?	F ?	F ?	F	F	Volume sampled is not clear. H-3 or He-3?
Array of single-point methods	F	F	F	F	F ?	F	F	
High-resolution resistivity	F?	F?	F	F	F	F	F	May be able to use existing wells (SCRT)

1. Interference may be caused by the presence of pipes and other materials or structures at the surface, such as pavement, or at depth.
2. Sensitivity consists of two parts: spatial resolution and ability to observe the analyte.
3. For the column entitled "Installed": F = can be permanently installed at site or U = must be deployed for each use.
4. Method does not require expert interpretation of data.

5.3 <u>Other Uses of Techniques of Interest to the NRC</u>

Some of the geophysical methods described previously could be applied in a proactive approach to identifying pathways that leaking water would take in subsurface systems. This method, suggested by John Lane of USGS (personal communication J. Lane to M. Fuhrmann, September 30, 2011), entails the use of a geophysically identifiable tracer (e.g., salt water) introduced at an area of interest, perhaps a structure that tends to leak. Geophysical methods would be used to follow this tracer as it moves through the subsurface. In this way, flow rates, dispersion, and preferential pathways could be identified. Using this approach, optimal locations and screen depth for monitoring wells could be established. This approach would be especially valuable for sites with large areas of underground infrastructure and backfill that may provide unexpected pathways for leaking water. The concept of using electrical imaging to follow a saline tracer was explored in a tracer release in an experimental tank (Slater et al., 2000).

Aside from detecting leaks at NPPs, the NRC has several other applications in which the techniques discussed in this report may be useful. The presence of water, changes in its concentration, or its movement through a system can be key indicators of performance of waste disposal systems. Engineered cover systems for low-level radioactive waste trenches, for waste incidental to reprocessing, and for the very large covers for uranium mill tailings disposal facilities are intended to manage water intrusion into the waste. This may be done by limiting infiltration of precipitation, enhancing and controlling runoff, and providing for evapotranspiration. Understanding the behavior of these covers is an important factor in assessing the long-term performance of these disposal systems. Many of the methods outlined in this report can be applied to determining the behavior of moisture in covers and how that behavior changes over time. Especially interesting are methods that allow large volumes of material to be interrogated in a horizontal plane. This can allow identification of areas with higher and lower permeabilities. High resolution arrays of vertical sensors within the covers can provide information on fluxes.

Several of the techniques discussed here are currently used to monitor the integrity of earthen berms and dikes. They are used to provide periodic, autonomous measurements through wireless communications systems of the water content or phreatic surface within earthen dams. This is important to the NRC for several reasons. At some NPPs, berms are used to channel and impound cooling water supplies. At others, earthen dams on water bodies upstream of NPPs have the potential to be an issue for flooding. As a result, their integrity may need to be monitored.

5.4 <u>The Infrastructure Problem</u>

The problem of subsurface infrastructure (e.g., pipes) interfering with geophysical methods is substantial but is being addressed as these methods mature. The greater density and electrical conductivity of metal pipes present problems for radar and electrical methods. Resistivity methods, which are the most commonly used for leak detection, determine changes in the resistance of the flow of current within a medium. While soil is relatively resistive, moisture and salts (e.g., from waste leakage) will decrease the resistivity, and this difference can be detected and models used to produce two- and three-dimensional images of their distributions. However, the presence of a pipe made of steel will perturb these measurements such that any other data are masked by the intense signal of the pipe. Rucker et al. (2012) discuss this problem for work done at a Hanford tank farm. Johnson also discussed this problem at the February 15, 2012, workshop (see Appendix A to this report and the workshop slides at ADAMS Accession No. ML120540481). Figure 11 is a synthetic modeling exercise illustrating the effect of a pipe on ERT results assuming the use of surface electrodes. This result occurs because the ERT models are not able to simulate the behavior of the pipe, the model meshes are too small to incorporate the pipe, the very large contrast in resistivity causes numerical instability in the models, and smoothing constraints are inconsistent with reality (Johnson, 2012). However, interference from infrastructure can be reduced by using electrodes that project below the infrastructure. The use of monitoring wells as long electrodes allows the distribution of some of the current beneath the infrastructure. Problems are associated with this approach since vertical resolution is lost when using a well as an electrode and lateral coverage is limited (Rucker et al., 2010; Rucker et al., 2012). However, coverage and resolution can be improved by using wells as electrodes in combination with surface electrodes positioned away from the infrastructure or by using subsurface electrodes emplaced at discrete depths using direct push techniques. It may be possible to use the pipe itself as an electrode. Advances in computational capabilities, models, and understanding of the behavior of various configurations of electrodes have rapidly improved plume detection capabilities (Rucker et al., 2012).

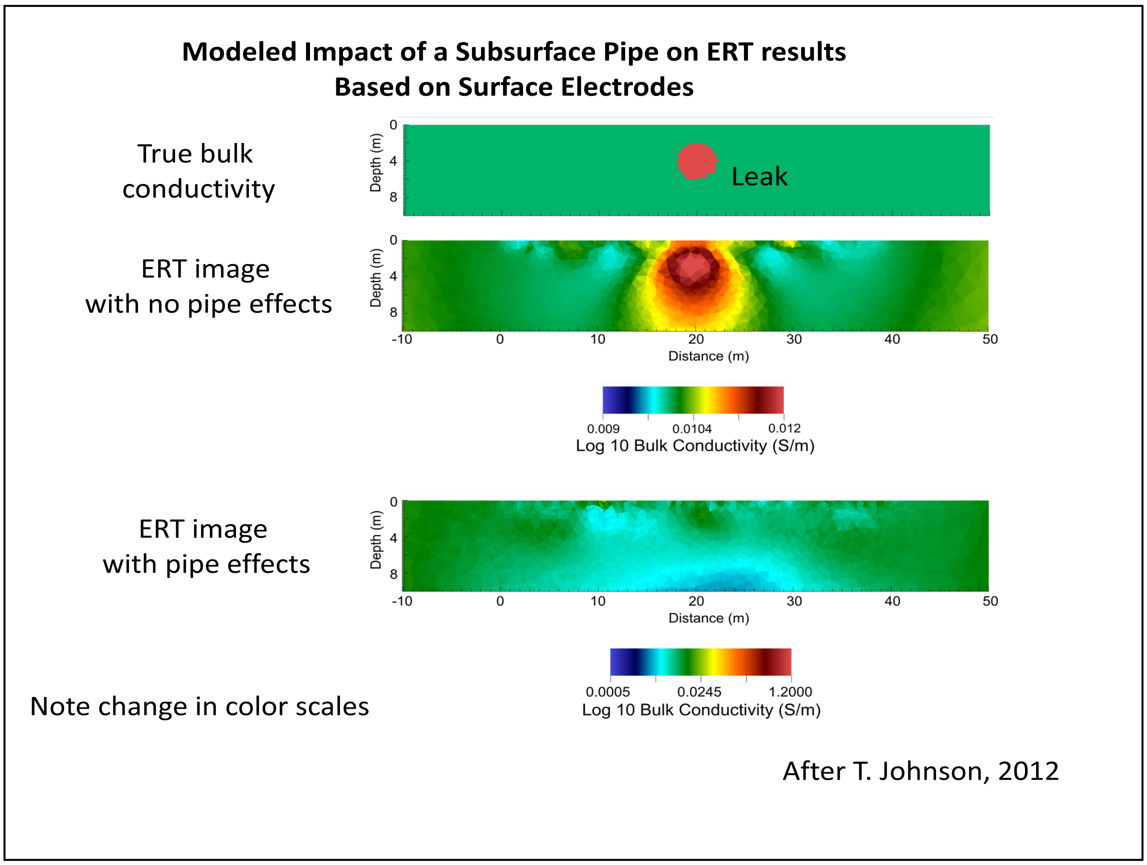


Figure 11. Modeled response of ERT detection of a leak with the absence and presence of a pipe.

6. LONG-TERM RESEARCH RECOMMENDATIONS

Table 2 suggests that the following large volume methods are the most applicable for early leak detection:

- DTS
- array of single-point methods
- high-resolution resistivity
- zero-offset cross-hole ER
- tritium vapor sampling with real-time analysis

Each of these methods is worth further investigation, to a greater or lesser degree, through the long-term research program. Of these methods, only DTS has no "?" notations on the table, indicating that this technique could be applied, as it exists, with some confidence that it will perform as expected. In fact, this technique is commercially available and is used for leak detection along pipelines. Additional information is needed for each of the remaining four methods.

The use of single-point small volume probes has application in certain areas, such as backfilled trenches. These sensors are well developed and some, such as TDR probes, have been used in situ over periods approaching 10 years. For the "array of single-point" method, there is a question of sensitivity. As discussed earlier, each probe (such as TDR probes) can have very good sensitivity for moisture content. However, the emplacement of the probes, particularly their spacing and number, will determine how readily a leak will be detected. An assessment of the area that needs to be interrogated and the number and arrangement of probes will be application specific.

Analysis of tritium vapor from the subsurface is envisioned as a real-time method in which sampling locations are periodically pumped by a computer-controlled system to an almost autonomous tritium detector. The detector and pumping control portions of this system are routinely available. The questions rest in achieving adequate sensitivity and knowing exactly where the vapor originates. Are there preferential flowpaths that short circuit the collection process? Are mechanical ways needed to ensure that a volume of soil vapor is obtained from its intended location? How much pumping is optimal? How readily does tritium partition from ground water to the vapor phase? Does it also become associated with the solid? Does tritiated water vapor segregate in the subsurface because of the mass difference with light water? How can measured concentrations of tritium in water vapor be modeled to assess concentrations in ground water? These questions are beyond the scope of this report and laboratory and field programs may be required to resolve them.

For moisture detection, zero-offset cross-hole ER is perhaps the simplest version of ER geophysical methods (Figure 12). While it appears that this method has advantages over other geophysical techniques, several unknowns are associated with its use for routine monitoring at an NPP. While this approach is the least affected by anthropogenic EM interference, the expected variety and intensity of interferences still may challenge the method. Sensitivity is also a question, primarily because of EM interference. Spatial sensitivity can be controlled by vertical spacing of electrodes, which can be as close as every 10–20 cm. As mentioned earlier, one issue is the optimal spacing of wells; distances may need to be fairly close together and this spacing is a function of the depth of the downhole array of electrodes.

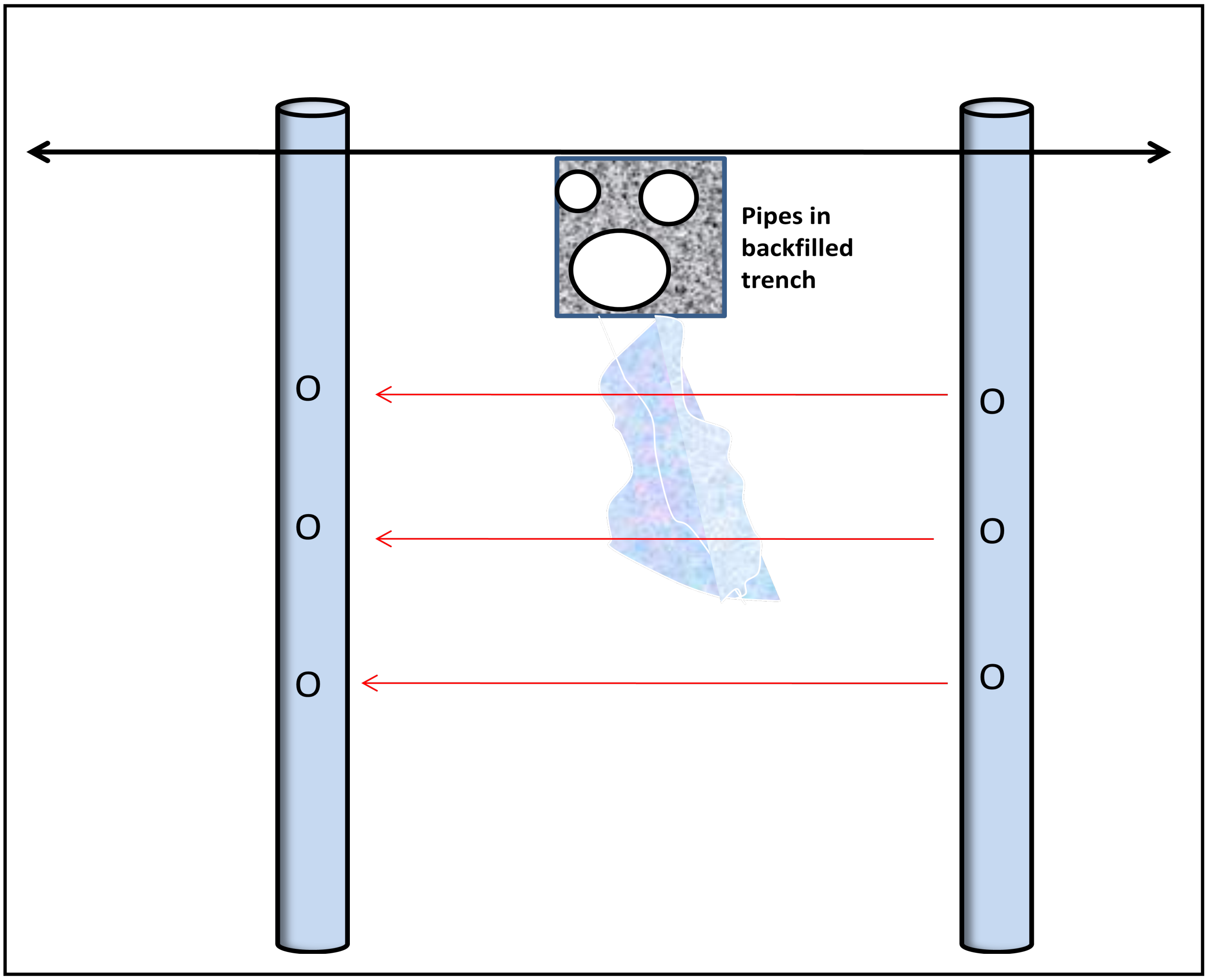


Figure 12. One approach to using zero-offset ER monitoring

Any moisture sensing system will have the problem of trying to distinguish between leaks and natural moisture infiltration. As a result, the system will need to be able to assess the difference in behavior of moisture during the two types of events. It is thought that a monitoring system could "learn" the difference in behavior of moisture through a neural network or other similar techniques (F. Day-Lewis and T. Ferré to J. Kanney, personal communications February 15, 2012). One system, developed at Argonne National Laboratory and known as the multivariate state estimation technique (MSET), is a software system for real-time process monitoring. While the system appears to be focused primarily on equipment monitoring, it may be applicable to the question of changing moisture regimes. A second function of MSET is its ability to detect anomalous sensor readings that indicate failure of the sensor (www.ne.anl.gov/codes/mset/#nuclear). Both issues, EM interference and discrimination of leaks versus rainfall, will require some research activity to resolve.

Some of the moisture measurement methods discussed are well developed and commonly used. Others are relatively new. Nevertheless, few if any have been used at NPPs. None have ever been applied to leak detection at NPPs. Consequently, a number of questions about these techniques and their application to NPPs may need to be explored, perhaps with a long-term research evaluation, before any decision can be made about their usefulness. General points about leak detection at NPPs that would need to be considered include the following:

- Leak detection for an entire plant is completely impractical. The possibility exists to install detection systems in local areas but these areas need to be defined. The NRC lessons-learned reports are helpful. EPRI has developed a procedure to rank specific systems for risk of leaks and to determine the characteristics of those leaks. It is available as a software package (BPWORKS).

- The complexity of NPPs may limit the installation of boreholes and other detection system equipment. This complication leads to a question about the optimal configuration and distance between wells for downhole applications and for surface electrodes.

- The electrical environment of an NPP may seriously affect many moisture-sensing systems, especially geophysical methods. It is unclear if this interference will be dampened in the subsurface and if galvanic pipe protection will also interfere. As a result, it will be important to assess the extent that the electrical environment interacts with selected methods of leak detection. Some methods can be tuned to certain frequencies that avoid interference. Survey instruments are available to allow sites to be checked before any field deployment.

It is likely that these conditions are location and plant specific. As such, it will be necessary to perform some onsite tests to provide a better understanding of the benefits and limits of the various methods.

Based on the discussion above, a research program will likely be needed to properly assess the feasibility of early leak detection methods. While much of the burden of proof should be placed on utilities, it is also necessary for the NRC to have sufficient independent information that a reasonable judgment can be made about the value of early leak detection methods. In addition, some of the moisture detection methods are applicable to evaluating processes at other types of sites of interest to the NRC, including the long-term performance of earthen covers for low-level waste and uranium mill tailings. Some of these methods also have the potential for monitoring the integrity of dams.

An initial assessment should consist of a feasibility study based on modeling of simple scenarios of leak propagation. Generic soil properties and parameters can be used to model water distribution under varying leak conditions based on evidence from the LLTF report (U.S. Nuclear Regulatory Commission, 2006) and on engineering properties of backfill materials. The modeling should be used to determine how sensors might be arranged and distributed for optimal effect. This initial study should also evaluate interferences generated by an operating power plant.

A second stage of investigation will be necessary to ascertain the utility of various methods under different conditions of leaks. We envision this to occur in several steps:

(1) The first step would involve the conduct of a systematic set of field test-bed experiments to assess the sensitivity of methods with respect to changing conditions of leak volume, backfill types, liquid conductivity, temperature, and background EM noise.

(2) Next, the selected methods would be installed at a power plant for tests following EM noise surveys.

(3) Finally, geophysical methods would be used to follow a tracer (e.g., salt water) that is introduced to some area of concern. This approach could be used to assess the pathway of leaking water from a specific structure to allow proper positioning of monitoring wells.

It would be beneficial to collaborate with several organizations for these tests, including EPRI, USGS, and universities. It should be possible to arrange a test-bed location locally, perhaps at the Agriculture Research Station in Beltsville, MD.

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APPENDIX A

Abstracts from the February 15, 2012, Workshop

Interagency Workshop on Monitoring for Early Detection of Underground Leaks at Nuclear Facilities

This appendix contains the abstracts for the presentations made at the workshop. Also included is the contact information for the speakers, as well as links to most of the presentations. This latter information is provided at the following web site:

http://pbadupws.nrc.gov/docs/ML1205/ML120540481.html

An Agencywide Documents Access and Management System (ADAMS) accession number is provided after each abstract title. Paste this number (e.g., ML120541054) into the search box on the U.S. Nuclear Regulatory Commission ADAMS Web page and it should take you to the presentation. Unfortunately, we were unable to post the slides for the talk by Karen Kim of the Electric Power Research Institute because of copyright issues, but please contact her, or any of the other speakers, for more information.

ABSTRACTS

Interagency Workshop on Monitoring for Early Detection of Underground Leaks at Nuclear Facilities

February 15, 2012

Underground Piping and Tanks Integrity Initiative (ML120541054)

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The nuclear power industries Buried Pipe Integrity initiative will be described. The goal of the program is reasonable assurance of structural and leakage integrity of in-scope piping and tanks with special emphasis on components containing licensed material. Information will be presented on the principal buried systems of nuclear power plants and a summary of the leaks that have occurred in different systems. Observations of causes of these leaks, the materials involved, and their recent frequency will be discussed.

Key Concepts for Early Leak Detection and Technical Questions (ML120541066)

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Early detection of leaks from nuclear facilities could provide substantial benefits if leaks are detected close to structures, systems, and components before fluid reaches the water table. Methods that may be useful for early leak detection have been briefly described and evaluated in a draft NRC white paper entitled, “Monitoring for Subsurface Leaks at Nuclear Power Plants: External to Structures.” We have focused on detection and distribution of moisture and tritium, but other parameters, such as conductivity and temperature, are also important. Some moisture sensors that are commercially available and durable are able to interrogate small soil volumes (about 1 liter) but could be arranged in arrays to attain greater volumes. Others, such as continuous downhole neutron probe moisture measurements interrogate a greater volume (e.g., several cubic meters) but are limited to soil borings. Other methods, primarily geophysical, can assess electrical properties from which moisture distributions, conductivity, and temperatures may be determined. These methods can interrogate large volumes of the subsurface, hundreds to thousands of cubic meters. Real-time downhole beta detection and tritium in soil vapor are also described. The practicality of using these methods in the environment of different nuclear facilities will be the focus of this workshop and will be valuable input to the final white paper and to the NRC’s Long-Term Research Program.

Soil Physics of Leak Detection Using Geoelectrical Methods (ML120541082)

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Electrical geophysical methods are sensitive to changes in pore fluid composition and moisture content of porous media. These methods therefore offer opportunities for imaging and monitoring of leaks from storage and containment facilities. The direct detection of an existing leak from a single resistivity survey may be complicated by the fact that electrical resistivity is a property that depends on multiple chemical and physical properties of a soil. However, the monitoring of time-lapse changes in resistivity associated with the transport of leaking fluids is likely to provide more confirmatory evidence of a leak. In theory, it may also be possible to estimate leak volumes or concentrations of a constituent in the leak from petrophysical relations relating resistivity to moisture content and/or chemical composition of the pore fluid. However, such petrophysical relations are inherently uncertain and likely to be spatially variable. Therefore, the transformation of resistivity to quantitative descriptors of the leak composition should be treated with caution. Despite these limitations, numerous successful applications of the detection of leaks from landfills and chemical storage facilities have been documented in the geophysical literature. These examples offer insights into the potential for electrical geophysical methods for monitoring and early detection of underground leaks at nuclear facilities.

http://www.ncas.rutgers.edu/lee-slater

Industrial Applications of Real-Time Electrical Monitoring (ML120541098)

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The three main objectives for leak detection and monitoring are to determine onset, rate, and location. The electrical resistivity geophysical method has been shown to be the most promising in meeting these objectives because resistivity is highly sensitive to changes in saturation and concentration of ionic constituents. Unfortunately, resistivity cannot be directly measured and instead is required to be indirectly determined by (1) electrical current transmitted into the earth to create an electrical field, (2) voltage measured at multiple locations, and (3) the resulting dataset inverse modeled to create the spatial distribution of resistivity over the domain. In our work, we have shown that all three steps can be used to address the leak detection objectives, provided sufficient temporal detail exist to discern minute changes in any measurement. Additionally, the electrical current and voltage data can be evaluated in real-time to help reduce time in determining the leak parameters. We showcase a couple of leak detection examples from mining and nuclear industries, where infrastructure and sources of noise are prevalent. Lastly, we provide information on the long-term leak detection program in place at Hanford to monitor underground waste storage tanks.

www.hgiworld.com

3D Time-Lapse Electrical Resistivity Imaging: Field Examples and Application Potential for Leak Detection at Industrial Sites (ML120541124)

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Recent developments in autonomous, multichannel electrical resistivity data collection hardware have enabled monitoring of subsurface processes with high resolution in space and time in terms of the bulk electrical conductivity alterations governed by those processes We give several examples of how three-dimensional time-lapse electrical resistivity tomography (ERT) has been successfully used to monitor a variety of subsurface processes, including surface infiltration, groundwater-river water interaction, subsurface bioremediation, and subsurface desiccation. ERT monitoring also has potential for imaging changes in subsurface conductivity caused by leaking infrastructure within industrial environments. However, this application is problematic because of the deleterious influence infrastructure has on ERT measurements, which is usually referred to as “noise.” In this talk we investigate the influence electrically conductive buried pipes have on ERT data. We show that in the presence of pipes and under typical conditions, ERT data are likely to be sensitive to leak-induced changes in subsurface bulk conductivity, and therefore can be used to image leaks with the appropriate modeling approach. We then show how typical ERT imaging algorithms break down in the presence of infrastructure because they are not designed to accommodate the sharp electrical conductivity contrasts in both space and magnitude arising from electrically conductive infrastructure. We show with a synthetic example how this problem may be rectified by explicitly modeling the infrastructure and allowing for sharp contrasts within the imaging algorithm. Finally, we discuss computational requirements of such an approach and the corresponding feasibility in commercial applications.

https://inlportal.inl.gov/portal/server.pt/community/inl_science_focus_area_project/700/sensing

Fiber-Optic Distributed Temperature Sensing:
Theory and Application to Monitoring Problems (ML120541137)

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Fiber-optic distributed temperature sensing (FODTS) is an emerging technology with potential for diverse applications in hydrology, petroleum geoscience, reservoir management, and geotechnical and environmental engineering. Depending on instrument settings, FODTS can measure temperature at high spatial resolution (approximately 1 meter), high precision (approximately 0.1 degree Celsius), and high frequency (about every minute) along cables up to several kilometers long. Higher resolution, precision, and frequency are possible using specialized cables and/or instrumentation or setting tradeoffs between resolution, precision, and sampling frequency. Laser light is transmitted down one or more fiber-optic cables, and backscatter is analyzed to estimate temperature all along the cables. Although FODTS technology has been commercially available for over a decade, recent decreases in instrument costs and expansion of capabilities have led to much wider use. Common applications include studies of ground water/surface water exchange, snowpack monitoring, dam/levee seepage, and leak detection in pipelines. This presentation reviews FODTS technology, instrument capabilities, case-study applications, and the potential for monitoring leaks at nuclear power plants and associated infrastructure.

http://water.usgs.gov/ogw/bgas/fiber-optics/waquoit.html

Finding Leaks Using Hydrogeophysical Data and Numerical Models
(ML120541140 and ML120550567)

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Geophysical methods are capable of providing high-resolution images of a specific geophysical attribute of the subsurface, which may reflect spatially variable, but stagnant geological features, time-dependent changes in fluid content and fluid properties, or a combination thereof. To successfully use such images for leak detection and specifically for predicting the system behavior in support of risk assessment, it is essential to (1) unravel the various factors that contribute to the variations in the geophysical attribute, (2) relate the geophysical attributes to hydrogeological properties that affect flow and transport, and (3) reduce ambiguities, nonuniqueness, instabilities, and other inversion artifacts. These issues are typically resolved (in part) by choosing an appropriate geophysical method with optimized measurement configuration, inverting the data using regularization techniques, and eventually transferring the geophysical image to a hydrogeological model using some petrophysical relationship. This approach can be enhanced by performing a joint inversion of geophysical and hydrogeological data using a flow and transport simulator that is coupled to a geophysical forward code within an optimization framework. The main contribution of hydrogeological modeling is that (1) additional data can be included to constrain the inverse problem, (2) regularization is based on physical rather than somewhat arbitrary geometrical criteria, and (3) the parameters determined are more directly related to features and processes that are of interest for leak detection and ultimate contaminant transport prediction. We will discuss the role that flow and transport simulations may play for early detection of underground leaks at nuclear facilities and the advantages and limitations of a joint hydrological-geophysical approach for characterization of the subsurface and monitoring of contaminant movement.

Assessing the Likely Value of Geophysical Data (ML120541144)
http://pbadupws.nrc.gov/docs/ML1205/ML120541144.pdf

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Geophysical methods offer unprecedented opportunities to image subsurface structures and to monitor temporal changes in property distributions. The methods range in their resolution, coverage, and sensitivity. But all are subject to limitations because of their indirect nature. A previous talk highlighted the importance of understanding and defining petrophysical relationships and properties. Others have shown the importance of selecting a geophysical method that is sensitive to processes of interest and then designing a survey to make the best use of the instrument's spatial sensitivity. Finally, we have heard about the value of combining process and geophysical instrument models to perform coupled hydrogeophysical interpretation. In particular, we have seen the value of added context that results from interpreting direct and geophysical data in a common framework. All of these concepts and approaches must be considered when designing monitoring networks for specific applications. I will present an approach that allows for assessment of the likely value of proposed direct and indirect (geophysical) measurements in the context of all known site information and in the context of user-defined cost or risk functions. We refer to the approach as the Discrimination/Inference to Reduced Expected Cost Technique (DIRECT). I will present a simple contaminant treatment example in the talk in the hopes that it will be useful for the general discussion of designing monitoring networks.

https://sites.google.com/site/tyferre/

EPRI Project on Advanced Technologies for Groundwater Protection: Automatic Tools and In-Situ Sensors for Groundwater Monitoring

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In 2011, the Electric Power Research Institute investigated technologies for the automatic and in situ detection of ground water contamination in monitoring wells. Such an automatic technology would facilitate the early detection of ground water contamination. EPRI assessed the state of science and technology for detecting radiological and nonradiological (e.g., chemical and physical parameters) signatures in ground water to identify technologies that would be applicable to nuclear power plant implementation. These technologies were assessed for their maturity, ability to detect tritium at levels typically found in the environment and at nuclear power plants, ability to detect nonradiological signatures that can be correlated to a potential leak or spill, and the functional capabilities of the technology. An EPRI Technical Report will document the results of this study.

Sensors for Tritium Detection (ML120620402)

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The presentation covers the state-of-the-art measurement techniques for detecting tritium in underground water at a nuclear power plant. Routinely used sampling techniques and the need of a real-time continuous monitoring system are discussed. Recent developments in sensor and sensing technique for tritium detection are also highlighted, and future research needs are suggested.

APPENDIX B

Participants in the February 15, 2012, Workshop

Interagency Workshop on Monitoring for Early Detection of Underground Leaks at Nuclear Facilities

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same as above

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Concerns about inadvertent releases of radioactive liquids to the environment from nuclear power plants have prompted consideration of ways to provide early leak detection in the subsurface external to the structures of the facilities. Approaches to this include the use of single-point sensors to detect changes in moisture content in the vadose zone. While many of these sensors are sensitive and relatively durable, they only interrogate about 1 liter of soil. Arrays of single-point sensors could provide adequate coverage of larger areas. Two dimensional and three-dimensional geophysical methods provide information for much larger areas. These methods sense moisture or other parameters that may be related to leaks, such as changes in conductivity/resistivity, permittivity, or temperature. Use of cross-borehole geophysics may provide coverage of vertical planes of soil while horizontal boreholes (or horizontal tubes installed during construction) can be used to interrogate planes underneath areas of concern. Other techniques include detection of tritium in soil vapor and temperature changes using coaxial cables. Some of these methods can be made autonomous. The methods are critically reviewed and discussed with emphasis on practical application at nuclear power plants. The U.S. Nuclear Regulatory Commission (NRC) held a public workshop on February 15, 2012, to discuss many of these methods with experts and interested parties. Recommendations are made for NRC's Long-Term Research Program.

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