A Review of Ground-Water Monitoring

Issues, Strategies, and Technologies

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Executive Summary

This report is submitted in response to the requirements of Task 1 of Contract NRC-04-03-061, Development of an Integrated Ground-Water Monitoring Strategy for Nuclear Waste and Decommissioning Sites.

Task 1 is a review of ground-water monitoring strategies with emphasis on:

- identification of performance indicators (*e.g.*, contaminant concentrations, water content in the unsaturated zone, and ground-water potentials in the saturated zone) of the hydrologic system being monitored;
- design and implementation of unsaturated-saturated zone monitoring programs;
- confirmation of PA modeling assumptions related to hydrologic features, events and processes identified in site characterization and critical to radionuclide transport within a Probabilistic Risk Assessment (PRA) context;
- spatial resolution and time frequency of monitored data collection;
- effectiveness and robustness of the strategy; and
- sources of uncertainties.

The key to any monitoring strategy will be deciding where, when, and what to monitor. These choices will depend on the nature of decisions to be made at the site (why to monitor), site characteristics, performance assessment sensitivities, and other considerations like capturing transient events. Then a choice will be made as to how to monitor. That's when access, sampling, and analytical technologies are called into play. Data management, analysis, and communication are over-arching aspects of the whole.

A systems engineering approach to monitoring is the recommended path forward. This would include a systems analysis of each site/system/subsystem/component and a matching of the site monitoring requirements to the performance capability of monitoring devices or systems. The systems analysis, done by a team of modelers, geologists, soil scientists, and hydrologists, should also reveal features, events, and processes that must be part of any PA modeling, as well as deficiencies in data that would result in uncertainties in the PA results.

A bibliography of over 330 references is included as a Microsoft Access database. This database will continue to be a work in progress during the course of the project. Key words are designed to allow selection of citations by the way their subject matter relates to why, how, what, and where of waste site monitoring issues.

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Development of an Integrated Ground-Water Monitoring Strategy for Nuclear Waste and Decommissioning Sites

Task 1: Review of Ground-Water Monitoring Strategies

I. Introduction

This report is a review of literature related to issues, practices, and research in ground water monitoring, mainly as these apply to performance assessment. Practices that have become routine through decades of use (*e.g.* monitoring well construction) are covered only in passing. Integration of unsaturated zone processes into ground water monitoring at waste sites is one of the active areas of research. In the past much unsaturated zone research was done to support agriculture, and contaminated site monitoring focused on the saturated zone. Integrating these two areas to develop monitoring strategies in support of performance assessments for current and future nuclear waste and decommissioning sites is the goal of this project.

The term "monitoring" connotes measuring some transient property of a site like water pH, or rainfall. The term "characterization" connotes measuring some intrinsic property of a site like fracture orientations, depth to bedrock, soil mineralogy, depth to static water level, or aquifer response to stress. In fact, characterization and monitoring represent a continuum, and the technologies used to measure them may be similar as well.

Monitoring to validate a performance assessment (PA) exercise may well include measurement of either transient or intrinsic site properties, or both. Although the focus of this project is underground water, there is no natural division between water, biota, soil, and vapors when the objective is assessment of contamination mobility and transport mechanisms.

The Nuclear Regulatory Commission (NRC) publication concerning PA methodology (NRC 2000) has general background on the PA process and White *et al.* (1990) reports recommendations of a group who deliberated the PA-related monitoring issues almost 15 years ago. Both have been useful documents. McCartin (2002) indicates that PA validation will be a continuing process during the lifetime of a disposal facility:

> "This required "performance confirmation" program would include *in situ* monitoring, and laboratory and field testing. Thus, NRC's licensing decision will be based on a comprehensive understanding of the overall behavior of the repository and its barriers that is supported by scientific information and data, and confirmed by an ongoing monitoring and evaluation process."

The SOW for this project outlines the following topics for Task 1:

- identification of performance indicators (*e.g.*, contaminant concentrations, water contents in the unsaturated zone and ground-water potentials in the saturated zone) of the hydrologic system being monitored;
- design and implementation of unsaturated-saturated zone monitoring programs;
- confirmation of PA modeling assumptions related to hydrologic features, events and processes identified in site characterization and critical to radionuclide transport within a Probabilistic Risk Assessment (PRA) context;
- spatial resolution and time frequency of monitored data collection;
- effectiveness and robustness of the strategy; and
- sources of uncertainties."

Rechard (2000) identifies several critical elements of performance assessment.

> "The overall process of assessing whether a nuclear waste disposal system meets a set of performance criteria is known as a performance assessment (PA), a term defined in 40 CFR 191. Similar to other risk assessments, a PA includes up to seven steps:
>
> - definition of performance criteria;
> - system definition and/or characterization;

- hazard identification and scenario development;
- probability evaluation;
- consequence evaluation;
- performance characterization and compliance assessment; and
- sensitivity analysis.

In general, a consequence evaluation (step 4) consists of (a) a dose–response assessment, which evaluates the response of a receptor (or system) to a hazard (or stressor), and (b) an exposure pathway assessment, which evaluates the exposure intensity of a hazard that reaches a receptor, *e.g.* a human. Because the main purpose of a PA is to serve as input to a social decision, it is an engineering analysis with constraints on time and resources specified by the decision makers (or tolerated by representatives of society). As with any scientific modeling or policy process, steps may overlap. More importantly, an analyst may need to cycle through several of the early steps when building an appropriate model. Hence, the steps are not always truly sequential. However, the discretization is useful as a means of describing the process and so is used here."

This project will focus on nuclear sites. Most of the information available for this report is directly related to DOE sites, and some comes from European publications. The DOE experience with radioactive waste is broad. Conceptually, there is no reason that fuel fabrication, dis-assembly and storage of spent fuel, and other parts of the nuclear cycle would be sufficiently different in the commercial world that it would invalidate conclusions drawn from a consideration of non-commercial facilities and activities. Some information gathered for the report was developed for hazardous, but non-radioactive, sites. Again there are generic issues that apply across waste constituents.

Many of the topics considered in this report have also been considered in other reports, and we have learned much while reading these. One of the best, capturing expert opinions through about 1989, is White *et al*. (1990). Each of these reports presents a facet of the bigger picture.

Our challenge has been to develop a perspective on the total issue of performance assessment and its validation in order to develop PA monitoring strategies. That challenge has not yet been met, being the subject of Task 2.

Online and literature sources contain predominantly two types of material – routine compliance monitoring reports and research papers. Compliance monitoring is almost exclusively based on sampling wells for ground water, and little new information was gleaned from these sources on reliability or applicability of new technology. Research papers have given some intercomparisons of devices for measuring, for example, soil moisture, but little on practical long-term applications of these devices, some of which are being migrated from other applications to environmental monitoring, and hence do have a performance history.

This report is divided into several sections. The bulk of the narrative concerns the six categories mentioned above as drawn from the project SOW. This includes material drawn from a literature review.

Appendix A is a brief discussion of some ideas for the development of an integrated ground-water monitoring strategy. It represents the approach to be followed rather than the details of what must be included. Appendix B is a bibliography of some of the materials gathered and reviewed. Appendix C is an overview of performance indicators gleaned from review of DOE low-level radioactive waste (LLW) PA documents and other sources.

Some of the references recommended in the Task 1 SOW are procedures or guides for sampling or well installation. We believe that this is pretty standard material. A number of states issue similar guidance and require monitoring well construction to conform to standards. Sampling and analytical QA are also pretty standard. Following the guides usually assures valid samples – but not always. Broken wells, leaking joints, driller malfeasance while not being watched, and other factors can contribute to questionable

subsurface data. At least for the time being, we do not plan to install wells or take samples, and some of us have experience with almost everything that can go wrong with a monitoring or characterization program, so we know to question data validity.

Innovative access and sampling technology continues to be developed by DOE, EPA, DoD and the commercial sector, and we will maintain an awareness of this as we proceed to develop a strategy in Task 2.

Models and modeling are an important part of the overall characterization, monitoring, and assessment process. We have not included a general review of models, but have referred to several in the following text. There are a number of published overviews, for example see Looney and Falta (2000) page 697, as well as published inter-comparisons, for example, Scanlon *et al.* (2002).

II. Background

Radioactive Wastes

The term "waste" in this report does not necessarily mean a formally prepared waste package or legally designated material. It may be used for any industrial or nuclear waste or constituent that, if released to the environment has the capacity to produce a risk to human health.

Waste and byproducts have been disposed at DOE and commercial sites in myriad forms and disposal systems. Most of this material poses little current risk, but the potential future risks to human health and the environment can be significant. Issues related to this material must be taken seriously by those who are responsible for the generation, transportation, and disposal of such wastes, including the NRC, DOE, the military, the nuclear power industry, medical facilities, and universities.

Highly radioactive nuclear byproducts or waste exist at every nuclear reactor, mostly in the form of spent nuclear fuel (SNF). Large amounts of waste from the production of nuclear weapons are present at DOE sites. Hanford and Savannah River have many

waste tanks containing fission and activation products from plutonium and tritium production. Other DOE sites, such as Paducah, have large volumes of waste from enrichment processes, including hundreds of thousands of tons of uranium hexafluoride ($^{238}UF_6$) that must be processed into a more stable form for ultimate disposal.

Radioactive materials stored or disposed at nuclear sites include different suites of radionuclides. (For example: U, Pu, Th, ^{90}Sr, ^{134,137}Cs, ^{3}H, ^{14}C, ^{60}Co, ^{99}Tc, ^{237}Np, and Rn.) Each has unique radiological, chemical and physical properties, making transport and risk estimations complex.

Low-level waste (LLW) is contained in everything from cardboard boxes to concrete vaults. The waste itself may vary from slightly contaminated laboratory apparel, to chemically or mechanically stabilized chemicals, to intensely radioactive sealed sources. Some mobile radionuclides in LLW have half-lives greatly exceeding the time when engineered barriers can reasonably be relied on to isolate waste from the environment. These include ^{14}C, ^{36}Cl, ^{99}Tc, and ^{129}I (NRC 2000).

Common waste disposal methods have included burial in trenches, auger holes, engineered structures and release to unlined seepage basins, cribs, and evaporation ponds - all of which introduce waste and water to the ground. An excellent summary and review of waste associated with defense programs is contained in DOE (1997).

Contaminant transport is initiated or carried out through processes including:

- ground water circulation in waste,
- surface water runoff of trench fluid overflows (USGS 1987),
- water infiltration through the unsaturated zone,
- water infiltration into waste repositories,
- diffusion of soil gas,
- uptake and redistribution by vegetation
- bio-turbation and translocation (*e.g.* by ants, gophers…)
- re-suspension of soil particulates

- atmospheric diffusion, dispersion, and deposition.

Remediation and site closure or decommissioning

Waste stored in the environment or facilities that have been decommissioned are subject to regulation which typically prescribes a limit to the release of materials to the accessible environment. Generally a waste site undergoes some sort of chemical and/or mechanical stabilization, then is capped or sealed to prevent exchange with the environment.[1]

Performance assessment is a process of evaluation to predict whether or not the as-built containment or remediation process will meet its low-release design objectives. Performance assessment monitoring is designed to evaluate specific indicator parameters that would test the validity of the assessment.

III. Performance Indicators

Performance indicators can be considered broadly in two categories. First is detection of fugitive waste or of a process, such as water flux, that would promote movement of waste. Second is site FEPs that would promote movement of waste. The second will be included in Section VII, below. (See also Appendix C.)

Water contact

Waste disposal sites are generally designed to keep water from making contact with or flowing through the waste. Water is reactive with some waste components, promotes biological activity, and can transport waste components in solution or suspension. These

[1] Several agencies or institutions have maintained on-line www databases of remediation, characterization and monitoring technologies. DOE has their TMS or Technology Management System at tms.em.doe.gov. This system can be queried for information on all DOE-funded environmental R&D from the past ten years or so. EPA supports a web-based environmental technology and methods site at www.clu-in.org.

water-involved reactions vary greatly depending on the waste form, the method of disposal and the packaging materials used.

Water can react directly with waste metals such as sodium, aluminum, lithium, uranium, or plutonium, releasing potentially explosive hydrogen gas and producing transportable ions. Water can also promote corrosion or degradation of containment devices or structures.

Water can promote biodegradation of organic packaging materials and produce organic or inorganic corrosive, complexing and solubilizing agents.

Contaminant Concentrations

Performance indicators that could detect leaking waste or undesired/unexpected water flux through waste are contaminant concentrations in ground water, surface water, the unsaturated zone, bulk soil, soil gas, and in overlying vegetation.

Ground Water

Perhaps the most common performance indicator is the concentration of contaminants found in ground-water. Once waste has reached the water table, transport of waste constituents in solution or suspension may be monitored through direct sampling of ground water. This is normally done through permanent wells, but can be done with direct-push technologies also (*e.g.* 'geo-probe').

Typically, samples are analyzed in the field for highly unstable parameters such as pH, alkalinity, redox potential, *etc.* Then they are stabilized, and transported to a laboratory for analysis for other constituents.

There are *in situ* chemical probes and sensors for many elements or compounds. These have a place in a monitoring strategy, but all are subject to maintenance and calibration

issues. For example, *in situ* fouling of membranes or electrodes through growth of bacteria or molds may reduce the effectiveness or change the response of some probes.

Water samplers for the unsaturated zone (*e.g.* suction lysimeters) have long been used in agricultural research to evaluate nutrient and pesticide movement in soils. A system in place at the Savannah River Site (SRS) is designed to sample soil water in order to detect radionuclide movement beneath or adjacent to LLW disposal vaults. The initial justification for this system was the fact that water at the water table was already contaminated from a long history of operations and LLW disposal nearby, and that any slight increment from the LLW vaults would never be detectable against the existing background (Joe Rossabi, personal communication, 2003, and Young et al., 2003).

Daughter products from decay of uranium, thorium, plutonium, tritium or other parent radionuclides may be more mobile, or may produce radiation that is more readily detected than the primary waste constituents. For example, ^{208}Tl, ^{214}Bi, and ^{241}Am are gamma emitters that may provide evidence for the presence of U, Th, or Pu, and ^{3}He can be used to detect tritium at depth.

Even though ^{90}Sr is not a gamma emitter, low energy gamma rays are emitted from some materials when irradiated by ^{90}Sr's beta radiation through a process called *brehmstrallung*. This radiation has been detected and used in monitoring programs at Hanford's high-level waste tank farm.

The presence of these radionuclides in the unsaturated and saturated zones may be detectable through well logging. Spectral gamma logging has been used for decades in the oil industry, has been adapted to environmental studies, and can provide identification and relative concentration information about radionuclides present around the well bore. Radiation sensors have been adapted to direct-push and other access technologies.

Soil Gas

While many radionuclides do not exist in the gaseous phase, several do partition between water and gas phases, including tritium (as tritiated water), ^{14}C (as $^{14}CO_2$ and other volatile carbon compounds), and the noble gases Ar, Kr, and Rn. Many RCRA constituents are volatile or semi-volatile, and are detectable in soil gas.

He-3 is produced by decay of H-3, and, as a noble gas, is mobile in soil. Helium and radon in soil gas and ground water have been used to prospect for uranium deposits. $^{3}He/^{4}He$ ratios in soil gas have recently been used by PNNL to trace a tritium plume at the water table.

Soil gas can be sampled and analyzed in a number of ways, and the term 'soil gas' is often applied to any soil constituents that got to where they are found in the form of a vapor. Thus hydrocarbons that are trapped in caliche and must be released with acid are treated as soil gas for the purpose of this discussion. The Gulf Oil Corporation used soil gas as an adjunct to petroleum exploration from 1934 onward, and there are a dozen or so vendors offering soil gas based exploration services in North America today.

In the late 1970s, the USGS reported detecting H_2S in soil gas above metal sulfide deposits by mass spectrometry. Attempts by Gulf Labs to duplicate this work indicated a potential for interference from ^{16}O-^{18}O diatomic molecules, but the possibility of detecting soil gas indicators of deep processes should be considered when developing monitoring strategies.

Other fluids

Some waste constituents may move without the assistance of water, including mercury, iodine, tritium, radon, argon, krypton and other waste components such as organic liquids.

Kerosene containing traces of t-butyl phosphate and uranium or plutonium (from the PUREX process) has been disposed at some sites. Carbon tetrachloride and other

halogenated organic solvents may represent issues at some waste or D&D sites. Biodegradation of kerosene will produce measurable methane in shallow soil gas and halogenated solvents, as well as their degradation products, are readily detectable in soil gas.

Surface Water

Surface water sampling may provide a method of locating preferred pathways of ground water. For example, sampling along a seep line, or of shallow subsurface water along a creek edge (where upwelling is expected) may provide more information that sampling the flowing stream.

Plants and Animals

Vascular plants can transport waste constituents, and may extend roots to significant depths to obtain water. Insects, especially ants and termites, and burrowing vertebrates can invade buried waste and may redistribute hazardous or radioactive constituents. An as yet unpublished report by Hooten *et al.*(2002) reviews the literature on bio-intrusion into waste.

Plants have been used in geochemical exploration for many years (Brooks, 1968). Phytoaccumulation of Cr, U, and Pu was the topic of a literature review by DOE's Amarillo National Resource Center for Plutonium (Hossner *et al.* 1998). The focus of this work was soil remediation, but plants that accumulate metals are also useful integrating samplers for detection of metals. Sagebrush (Erdman, 1981) and Fir (Dunn, 1980) are known to be useful for uranium exploration, and should also serve as indicators of actinides in ground water near waste sites. Andraski *et al*. (2002) used tritium concentrations in creosote (*Larrea tridentata*) to map tritium plumes in the unsaturated zone in the Amargosa desert.

Unpublished 1985 preliminary tests at SRS indicated that radionuclides could be detected in growth rings taken from pine trees and could date arrival times of seepage of materials from SRS seepage basins.

Water content in the unsaturated zone

The amount of water found in the unsaturated zone, or in engineered components of a disposal system can also be an indicator of the performance of a disposal system or the potential for transport in the unsaturated zone. Water can transport waste constituents downward and upward through infiltration, capillary action in the unsaturated zone, or fluctuations water table elevation.

For these reasons, much of the published work and research on waste site monitoring, especially in the western U.S., has focused on detection of water and assessment of water flux.

Water content can be estimated in a number of ways. Sampling and gravimetric analysis is probably the most robust, but may not be applicable for engineered covers or radioactive waste sites. Neutron probes are accurate once calibrated against gravimetric analysis (Evett *et al.* 2002). More remote methods that rely on electrical properties of soils (ERT, EM, GPR, TDR…) are sensitive to soil mineralogy as well as moisture content, but can provide good results once calibrated against gravimetric or neutron probe data. Gravimetric methods (*e.g.* thermal gravimetric analysis or TGA) can provide information about moisture that is tightly bound, or even incorporated in the structure of soil minerals. Tensiometers of various designs have been used for decades in agricultural applications, and are being applied to water content and flux measurements at waste sites.

Ground-water potentials in the saturated zone

Some existing LLW sites are at or below the water table. Examples can be found at Melton Valley, Oak Ridge National Laboratory (ORNL) where engineered barriers have been attempted to prevent shallow interflow from entering burial trenches; at Paducah where containers of U or UF_6 are buried in a landfill with the seasonal water table rising above the waste; and at Livermore Site 300 where interflow through a permeable zone channels water laterally into a landfill containing ^{3}H wastes.

Interestingly, there has been conflict between permitting groups in at least one state regulatory agency on landfill siting. The group in charge of surface water protection wants the landfills sited on top of hills. The ground-water protection group wants the landfill on the slope, where lateral flow is predominant and predictable, rather than on a ground water divide where flow direction is less easy to predict.

Any program intended to predict ground water flow and transport, and eventually risk and performance assessment, must have sufficient data to conceptualize the site hydrogeology. Any strategy to assure adequate PA monitoring must revisit the site characterization data, and test to be sure that monitoring trends in chemistry and water levels validate the conclusions of the initial characterization studies.

IV. Design and Implementation of Unsaturated-Saturated Zone Monitoring Programs

In a uniform isotropic world, ground water is monitored by establishing the slope of the water table and placing one well upgradient, one well to each side, and one well downgradient of a waste site. Generally, flow is assumed to be horizontal, and down the water table gradient. These conditions are probably never truly realized in nature especially at the scale of a waste disposal site. They are nevertheless, and unfortunately, implicit in many designs of ground water monitoring systems.

The assumption of uniform aquifer properties might be appropriate for a water resource study. Normally, water production wells are screened across all productive zones of an aquifer, so the quality and quantity of water produced follow properties of the entire productive thickness. Thus, at the scale of a regional aquifer, horizontal flow to producing wells may, in such cases be a reasonable assumption.

At the scale of a waste site, however, local subsurface heterogeneity controls the shape and extent of any plume emanating from the waste site and controls the zone of capture of monitoring wells. Furthermore, vertical flow may be important. (Hubbert, 1940). Design of monitoring systems at the scale of a waste or D&D site must therefore incorporate consideration of facility design and site characteristics. It is tempting to substitute a statistical analysis of well data that might be appropriate at a regional scale for geologic characterization at the waste site scale in design of a monitoring network.

Heterogeneity is not a statistical term, but is determined by geologic and pedogenic processes that are well defined in theory. Blindly attempting to model site heterogeneity using spatial statistics is a very risky process unless the controlling factors for the site are very well understood and sufficient site-specific data are available to bound the reasonable results of such modeling. Informed statistics, however, can go a long way in characterizing a site. There is currently a great deal of work underway to characterize petroleum reservoirs that will be directly applicable to the problem of characterizing waste sites. For example, detailed mapping and GPR at outcrops of the reservoir formation may be used to bound modeling based on seismic images of the formation at depth.

Saturated Zone

Location of wells in the saturated zone is an important component of designing a monitoring network for any waste site. The most effective monitoring network design for any given site is heavily dependent on the type of media through which the ground water will travel (i.e. sand, sands and clays, fractured bedrock, karst, fractured chalk).

Spruill and Candela (1990) propose that two different approaches can be used to design a monitoring network depending on the type of information required. In some cases one may be looking for quantification of typical concentrations in a given area and in other cases looking for potential problem areas.

One modeling program developed by Golder Associates in 1992 (MAP) has been used to develop a monitoring well network for landfills (Hudak 1998). The network begins with a simple design and then is further refined by shifting well locations to obtain a modeled 100% leak detection efficiency. This method uses only a two-dimensional analytical transport function with a uniform flow field and does not consider three-dimensional flows and or subsurface heterogeneities. Thus, it is perfect for a Flatlander's view of ground-water flow, and is not particularly useful. (See discussions below of MAROS, which performs similar analyses.)

Statistical tools have been applied to determine the number of wells and samples necessary to characterize properties of the aquifer and the water it yields (Ben-Jamaa *et al.* 1994). Their work applies to regional aquifers, but would not apply to areas as small as a waste facility. It might be possible to estimate a range of constituent concentrations from samples of a regional aquifer, then to spot probable anomalous values in data from a given well.

<u>Unsaturated Zone</u>

In the unsaturated zone, the monitoring objective is frequently detection of water. This can be done with tensiometers or with various geophysical methods that measure soil electrical properties related to moisture content.

A great deal of NRC-supported research has focused on unsaturated zone monitoring in arid climates. Work at the Maricopa site (Young *et al.* 1999) has evaluated trenches, islands, boreholes, and geophysics for monitoring. Borehole and surface geophysical methods offer flexibility because instrumentation can be replaced or maintained and boreholes can be advanced to depth, or can be angled beneath a waste site.

Work at the Apache Leap Tuff, the Las Cruces Trench and other sites has been reported in NRC, open literature and Intraval Project reports. Larsson *et al.* (1997) reported that data from the Las Cruces Trench were valuable for testing modeling against field results.

We will study results of these experiments as part of developing a draft strategy under Task 2.

Kung *et al.* (1991) present a study on the use of ground penetrating radar to improve monitoring of water quality in the unsaturated zone. They use GPR to define preferential flow paths of ground water in sandy soils by identifying coarse and fine sands. By collecting samples in preferential pathways using porous cups and/or wick pan samplers, they overestimated the potential for ground-water contamination.

Looney and Paquett (2000) present a case study discussing the importance of understanding and integrating unsaturated and saturated zone processes in the design of site characterization and monitoring. Horizontal up- and down-gradient wells placed to bracket the contaminant source in the saturated zone both missed a thin tritium plume at the top of the water table that had been detected in wells further down gradient.

Soil gas methods can be used to detect leaks or transport of volatile components and tracers, such as SF_6 can be incorporated into waste containers so that soil gas methods would detect a lack of container integrity (Pirkle and Price, 1984). Etched-Track Radon Monitors may be used to detect radon in soil gas and well water (Vasarhelyi *et al.* 1997). Tritium at depth can be detected by $^{3}He/^{4}He$ ratios in shallow soil gas (Olsen *et al.* 2002).

Bodvarsson *et al.* (2000) present a detailed review of flow and transport in the unsaturated zone. They tabulate all important flow and transport processes, each of which presents a challenge or an opportunity for monitoring. They note that heterogeneity in the unsaturated zone is poorly understood, and may confound modeling efforts.[2] From a strategic standpoint, a modeling strategy will have to be sufficiently robust to overcome the issues of heterogeneity and variability of properties.

[2] from Bodvarsson *et al.* (2000): "Heterogeneity is intrinsic to vadose zone soils, both porous and fractured media. Effects of heterogeneity in different scales in a porous or fractured medium on flow and transport processes currently are poorly understood in a multiphase, isothermal system. Until better understanding and more efficient modeling approaches to handling the heterogeneity

Some recent summary compilations of unsaturated zone issues, science, and technology include Looney and Falta, 2000, DOE/ID-10871, 2001, and NAS (HSEIH *et al.*) 2001. Each of these will serve as a rich source for input to rational strategies for monitoring.

Overview of performance monitoring considerations from NUREG/CR-5615

An especially rich source of information and ideas is White *et al.* (1990). The types of issues and the types of technology available to address issues in 1990 have not changed substantially, although many advances have been made in improved sensors, electronics, and computer tools. The following outline is adapted from NUREG/CR-5615 (White *et al.* 1990), Part II, "Performance Monitoring to Support Regulatory Decisions."

CR-5615 Contents

The document covers:

- Introduction and overview of PA monitoring for LLWDFs
- Monitoring objectives and approach
- Identification of physical monitoring parameters
- Monitoring techniques and instrumentation
    - Inspection during operational monitoring
    - Surface monitoring using traditional methods
    - SM using remote sensing and photogrammetric methods (we'd call this GIS today)
    - Subsurface hydrologic monitoring using tracers and *in situ* equipment
    - Subsurface physical monitoring using *in situ* equipment
    - Subsurface chemical monitoring
    - Subsurface monitoring using geophysical techniques
        - Surface and crosshole EM
        - Surface and crosshole resistivity
        - Surface and crosshole seismic
        - Nuclear logging techniques
- Monitoring with a representative test area

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problem are developed, reliable predictions using mathematical models will be questionable for real-world applications. In addition, there are many related issues, such as spatial and temporal scales of parameters, anisotropy, and hysteresis, which need to be better understood. It is apparent that a substantial amount of work remains to be done before the field scale physical processes of flow and transport in the vadose zone can be modeled with a high degree of accuracy and reliability."

- Analytical Approach
    - Planning,
    - Database,
    - Data Validation,
    - Analysis of data to answer specific questions
- Summary and conclusions

Two recent papers in Ground Water Monitoring Review by Kram, *et al.* (2001) cover DNAPL characterization technologies. The first paper deals with performance, and the second with costs and savings. Although the discussion is limited to one variant of each method (*e.g.* soil gas is only by direct push with samples at depth intervals) the study has some parallels in any monitoring or characterization. DNAPL chemicals (organic solvents) may be contaminants at legacy radioactive waste sites, and should be considered in the PA of such sites.

V. Confirmation of Assumptions Made for Performance Assessment Modeling

PA Input

Input to PA modeling typically includes a variety of properties, factors, and conceptual models to determine the dose to a hypothetical future human receptor:

- features, events and processes identified in site characterization and critical to radionuclide transport or dose assessment,
- waste content and inventory,
- waste packaging and containment,
- engineered barriers to migration,
- factors that degrade waste containment,
- hydrologic features,
- external factors such as climate, seismicity, and volcanism,
- soil structure, mineralogy, and chemistry,

- the characterization of biotic communities and their influence on contaminant transport,
- ground water chemistry, flow, depth,
- aquifer properties,
- human exposure scenarios,
- contaminant transfer factors, and dose conversion factors.

Each of these is estimated to some degree, but legacy waste sites and D&D sites generally have inadequate records of inventories, and present conditions may be difficult to measure. Estimation of inventories and extrapolation of geologic/hydrologic factors to the variation that might occur over time for each factor becomes a PA assumption. This project focuses on ground-water monitoring, and so waterborne contaminant transport, to the exclusion of regional seismicity and volcanism, biotic processes, and dose assessment.

One of our charges for Task 1 was to evaluate how monitoring programs have provided databases for confirming hydrologic system performance and PA model assumptions. Many sites have been monitored for over 20 years for regulatory compliance, and some for over 50 years as part of health protection program.

At the Savannah River Site, deep rock disposal studies conducted in the 1960s resulted in deep wells for which nearly continuous water level records were taken for decades afterward. In the 1990s, DOE funded the US Geological Survey and agencies within South Carolina and Georgia to install a large number of well clusters adjacent to SRS to understand regional flow patterns and interactions with surface hydrology. INEL (Wood, *et al.* 2000) has conducted a number of scientific hydrology investigations in addition to routine compliance monitoring.

A number of sites, both government and commercial, have installed monitoring systems to evaluate the extent of contamination and the efficacy of remediation, or natural attenuation of plumes. Data from this monitoring should provide a base for

understanding the site hydrologic systems - whatever the initial design of the monitoring was based on. There is certainly a wealth of data, but making firm statements about confirming PA assumptions or the details of the hydrologic system will have to be done on a case-by-case basis.

FEPs

In 10 CFR 61, part 50, NRC has identified characteristics of sites that might be conducive to siting of facilities. These include a geologic and hydrologic setting that present no undue hazards, and is simple enough to be characterized, modeled, analyzed, and monitored. Our concern is with geologic features, events and processes (FEPs) that control or influence water-borne radionuclide transport, and which are or can be identified as part of site characterization. Further, our concern is with techniques to measure, estimate, or evaluate these FEPs in such a way that our results can be useful to the PA process. The IAEA has also published some guidance on the same topic (IAEA, 1999). IAEA/NEA has published a database of FEPs that have been considered at nuclear sites in many countries (OECD/NEA, 2000). Some of those are important to include in a site conceptual model for PA modeling, and are also important in the design of a characterization or monitoring system. FEPs to be included in the PA must be evaluated on a site-specific basis, and confirmed in the PA validation process.

PAs, PRAs – Assumptions and Sensitivities

Performance assessment has, until recently been done deterministically, in the form of linked simulations by programs intended to simulate various subprocesses (*e.g.* waste package degradation, unsaturated zone transport, and saturated zone transport). Recent advances in computer simulation technologies, however, have provided tools for probabilistic performance assessment. One such software package is GoldSim (GoldSim Technology Group 2003).

NUREG/CR-6813 (Fleming and Nourbakhsh 2003) discusses some issues of PRAs as they have been applied to nuclear power plants. Several case studies are reported, and generically, the same problems occur with PRAs as with any modeling. Some FEPs were

dismissed from consideration for various reasons (*e.g.* incompetence, lack of critical data, lack or failure of procedures to guarantee collection of appropriate data). This raises the issue of developing strategies that are sufficiently robust that they can replace competent personnel – a tall order.

Our discussion of confirmation of PA modeling assumptions has so far focused on a sensitivity analysis, with follow-up to validate assumptions about those factors to which the model results are sensitive. This approach does not lead to testing FEPs that were not incorporated into the model since these cannot be evaluated for sensitivity.

John Tauxe has reviewed a dozen PAs prepared for DOE LLW disposal sites and has prepared a short list of factors to which the analyses are sensitive. Much of this work was done as part of an evaluation of relative performance of DOE mixed low-level radioactive waste disposal sites across the U.S. (DOE, 1996). Principal sensitivities are:

- time of waste degradation
- travel time from bottom of disposal site to the water table
- amount of dilution of recharge entering saturated zone
- travel time from entry into saturated zone to water well
- rate of biotic turnover for shallow buried disposals

Each of these is in turn related to characteristics of the waste form, or the local hydrology, geology, and ecology.

Summary

Each PA assumption, especially those to which the PA is sensitive should be addressed in the PA confirmation. To some degree this can be done by re-examination of characterization records, and to some degree confirmation monitoring will address these. For physical site features, confirmation monitoring may really be additional characterization to validate FEPs. For other PA assumptions, like water flux, the term monitoring is more appropriate.

VI. Spatial resolution and time frequency of monitored data collection

Sampling at a site can be distributed in time and space. For example, geophysical sampling methods respond to site properties over some volume. Soil and water samples taken and removed for analysis may represent only the point from which and time at which they are collected. Vegetation samples may integrate contaminant flux over time in the root zone of the sampled plant.

The important issue, from a strategic standpoint, is that the resulting data address the issue that the sampling is supposed to address. This concept also applies to 'real-time' sampling. Real-time does not have to be continuous in time - it could also mean triggered sampling that captures the first run-off from a site, or the first water through the unsaturated zone during snowmelt. What is important is that the sample provide useful information in a timely manner. True real-time sampling and analysis (instantaneous results) may be important for process monitoring under operating conditions, but probably not for environmental monitoring.

Geophysics

Geophysical methods can be point measurements such as gamma radiation in a well bore, or measurements that are affected by properties of a relatively large volume of earth, such as electrical resistance or impedance measurements, or seismic velocities. For average water content beneath a waste site, or for early detection of leakage of a conductive fluid, electrical methods should be ideal. In general, electrical methods such as EM and ERT have a depth resolution of about ±10% of the actual depth.

While geophysical methods can be applied without any subsurface data, interpreting the results is improved if independent information on geologic strata, properties, or structures can be obtained. For example, a single well can provide sonic velocities for seismic interpretation, or layer thicknesses and electrical conductivity for electrical or electromagnetic (EM) methods.

A number of geophysical methods such as ERT, TDR, GPR, TDEM, FDEM have been used to estimate water content. Ward *et al.* (2003) discuss comparisons with neutron probes in the 2002 Hanford Ground Water Report and conclude that EM methods can provide good water storage data after calibration for a given site against neutron probe data. Interestingly, although these technologies have been around for a number of years, specific instances of their application and comparison are still being reported as research by National Laboratories. In a strategic sense, this supports the case for qualified experts for the selection, application, and interpretation of subsurface measurement technologies.

Wells – Data Analysis

Statistics can also be used to examine data time series. If a well provides similar data period after period, then statistics can reveal the relation between variance and inter-sample time so as to allow selection of a safe interval. Of course, the peril of this approach is that extending the sampling interval will miss breakthrough or arrival of a plume.

This approach also ignores the possible effects of transient events such as heavy rain or even seasonal variation. A thorough monitoring strategy will account for transient effects. This is effectively handled in surface water sampling, which can be triggered by a rainfall event.

Real-time sensors may be appropriate for such things as leak detection. They could be solar powered, and set to transmit alarms if a measurement deviated from expected values. *In situ* sensors may be subject to loss of calibration because of bio-fouling, chemical fouling/corrosion, or other effects. It is known that cathodic or anodic protection can protect well screens from bio-fouling, which suggests a potential area of research for development of long-lived monitoring devices.

Geostatistical analysis of sample data.

With adequate analytical data, geostatistical analysis (*e.g.* kriging) can indicate the area or volume represented by a given well. The method is based on examining the correlation of measurements as a function of direction and distance. Geostatistics should only be applied by someone who understands both the method and the geology and hydrogeology of the site. For complex and poorly characterized sites, geostatistics may add critical insights into subsurface structure by revealing directional controls on correlations. Geostatistics can also be used to provide appropriate sampling design.

Data worth

Statistical analysis of the data provided by wells can provide an estimation of the need to monitor more or less frequently, or in more or fewer locations. The added value of an additional measurement to reduce uncertainty, or the loss from omitting a measurement can be quantified.

Purely statistical analysis, without careful consideration of the aquifer zone or other hydro-geologic details can lead to false conclusions, and may result in omitting critical wells from sampling. In fact, most such analysis has been done to justify economies in monitoring rather than to develop a thorough monitoring program.

MAROS

The computer program MAROS, developed for AFCEE, and under evaluation by other agencies including EPA seems especially useful for compliance monitoring networks in fairly simple geologic settings, and may have application to performance monitoring. This program evaluates trends, sampling frequency, and sampling locations and will recommend both deletions and additions to the well network or sampling frequency. The feature that spots areas of poor (statistically) plume definition and recommends additional wells is especially interesting (Aziz *et al.*, 2000).

VII. Effectiveness and robustness of the strategy

Effectiveness is a difficult issue. There are many standard approaches to monitoring that are presumed to be effective. For example monitoring wells, sample stabilization, and laboratory analysis are effective. Whether the well is in the right place is another issue – this requires that site hydrogeology and plume distribution be understood.

"Robust" is taken to mean effective in the face of impediments or complications. Some of the problems related to heterogeneous or poorly characterized (or poorly understood) sites might add considerable uncertainty to monitoring results. Point sources of data such as well or soil samples would be especially vulnerable. Volume-integrated sampling such as from geophysical measurements or from leachate collection systems would be less vulnerable to uncertainties resulting from site characterization deficiencies. The best solution for the issue of robustness is adequate site understanding and characterization.

PNNL has set up a web site (vadose.pnl.gov) on which they maintain reports on various unsaturated zone characterization and monitoring technologies they are trying. This is a useful site, and will continue to be useful as we evaluate technologies for application under specific site conditions.

As noted elsewhere, much of the technology for unsaturated zone characterization in the context of waste sites is being reported in research reports. Even though some of the technology has been used for agricultural research, mineral exploration, and/or site characterization, applications to monitoring or PA validation monitoring are generally new, and still being tested.

VIII. Sources of Uncertainty

Characterization, Monitoring, Sampling

The site conceptual model for any PA will be bolstered by data gathered and interpreted for site characterization. The fidelity of this model depends on the design of the initial

characterization, pre-operational, and ongoing monitoring programs, and on sampling (or analytical) and interpretation errors associated with these programs. Sources of some of these errors, and approaches to improving monitoring or characterization are the subject of a number of papers on optimization, and can be supported by computer programs like MAROS or the Smart Sampling programs from Sandia, or Visual Sample Plan (http://dqo.pnl.gov/vsp).

Careful design of a monitoring program for validation of the performance assessment model can reduce some of the uncertainties. This design will include a critical review and modeling of site characterization and monitoring data. Site complexity and heterogeneity and the natural variability of FEPs will contribute to uncertainty.

Performance Assessment Uncertainties

Sources of uncertainty for PA models include limited knowledge about: waste inventory, quantities as well as constituents, as-built waste containment structures, missed or poorly represented FEPs (Faybishenko *et al.*2000) and uncertainties in the performance of validation monitoring.

It is our opinion that the uncertainty (accuracy) of modern chemical analyses is small compared to the potential for sampling errors, especially in the unsaturated zone. Detecting leakage, and quantifying water and contaminant flux in the environment are both important for PA monitoring and for PA modeling.

Waste Inventory

Wastes at most defense legacy sites consist not only of radioactive materials, but also of solvents, metals, and other organic and inorganic compounds (mixed low-level radioactive waste, or MLLW). Currently operating LLW facilities are generally not permitted to accept MLLW. As noted elsewhere, DOE (1997) provides a good summary of waste types and locations for the defense uranium cycle.

Containment Structures

Waste and decommissioning sites include concrete structures, caps of various materials, concrete boxes or vaults, drums and other engineered structures as well as buried piping. For older facilities especially, the as-built details and the effects of aging on system integrity may be poorly known. There is a parallel here with PRA for operating facilities where the fidelity between site characteristics and the site model should be validated carefully.

> "In order to ensure model to plant fidelity, it is necessary that personnel with intimate knowledge of the plant and the procedures review certain aspects of the PRA such as system notebooks, operator action treatment, *etc.* Not only does this support PRA quality but it also facilitates PRA technology transfer to plant personnel and supports effective risk management. This has been done to varying degrees and even when done, is not always periodically updated." (Fleming and Nourbakhsh 2003)

Features, Events and Processes

A number of groups have compiled lists of site FEPs and scenarios under which these may be important (Guzowski, 1990, and Guzowski and Newman, 1993). Each geologic FEP represents a factor to be considered in a PA, and may be critical to site-specific monitoring plans.

INEL has published an exhaustive summary of unsaturated zone FEPs for which there is considerable uncertainty at INEL (Wood *et al.* 2000). This document reviews unsaturated zone investigations conducted at INEL between 1960 and 1999. It makes recommendations for programs to address issues with Spatial Variability, Data, Numerical Modeling, Conceptual Models, Source Terms, Geochemistry and Microbiology, as well as Organization and Communication.

Implicit in any computer model used to determine performance of a waste disposal containment system are a number of assumptions used to simplify site characteristics

(site FEPs). These assumptions can include external factors such as average annual rainfall and seasonal temperatures, as well as more specific characteristics of the surrounding media such as infiltration rates, hydraulic conductivity, and porosity.

Some of the FEP uncertainties include:

- changes in redox conditions along flow path,
- uncertainties in K_d, and the conditions under which it is valid,
- uncertainty in fluid-matrix interactions,
- possible chemical alteration of sediments from reaction with leaked fluids (Pruess, *et al.*, 2002),
- uncertainty in assumptions about dispersion, both horizontal, and vertical. Dispersion is often used as a proxy to account for flow controls.

These lead to changes in arrival times and peak concentrations to receptors.

An example of an event at INEEL is problems with water level mounding caused by recharge when excess water is diverted from a local river during high flows. Ground-water levels rising 10-60 feet must be included in the design of a conceptual model (Wood 1990).

Uncertainties in Performance Validation Monitoring

As with the development of the PA models there are uncertainties inherent in the validation monitoring for all waste disposal sites. Poor understanding of site hydrogeology may lead to inappropriate site selection for monitoring. Transient events such as rainfall or snow-melt, long-term climate, and infiltration rates may change drastically over time, making previous computer modeling obsolete and decreasing the validity of data gathered from sampling points devised based on original site assumptions.

Heterogeneity in general was noted above as a challenge for modelers. Spatial variability in unsaturated flow has been studied by Scanlon and Goldsmith, 1997, who conclude that playas focus recharge in some areas, rather than acting as evaporation pans.

Without (and maybe with) the most advisable monitoring locations for ground water, surface water, and the unsaturated zone it is very possible that a leak from the site will bypass any given sampling point (Looney and Paquett, 2000). For example, if one assumes ideal construction of a waste containment structure and then that structure fails at an unexpected point, any leaked contaminant may bypass ground-water monitoring wells and sampling points in the unsaturated zone. Failures of containment structures can be a result of chemical reactions taking place inside the structure or of geologic events such as earthquakes which may lead to weakening of the barriers.

Collection of flow-proportional samples may result in improved monitoring data quality and be more representative of releases (Huff *et al.*, 1997). This is easy to implement in surface water sampling (for example with paddle-wheel driven samplers), but problematic in ground water sampling.

In addition to these uncertainties, and often overlapping with them conceptually, is variability. Variability refers to the natural variability in a parameter such as porosity, for example. The distribution of porosity in value and space may be very well known, and hence have almost no uncertainty, but still may be highly variable. The state of the art in probabilistic analysis is just now starting to come to grips with how variability should be kept separate from uncertainty.

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Appendix A: Summary Notes on Development of Monitoring Strategies.

Waste and decommissioning sites fall into several categories requiring different approaches to monitoring. For example, legacy waste sites may be simple landfills, seepage basins or cribs, into which waste was placed in solid, liquid, or poorly containerized forms, and which have long since leaked waste into the environment.[3] In this case, some remedial action may be required and performance assessment becomes an assessment of the effectiveness of the remediation[4].

Decommissioning sites may never have been designed for long-term containment of residues (perhaps future ones will be), but were designed for a high level of environmental protection during operation, and should have some site characterization data. The characterization data were gathered to support design of the facility, rather than to support environmental monitoring, but there should be adequate data at many sites to support development of a strong approach to ground-water monitoring. Perhaps this leads to a criterion for which or how sites are to be de-commissioned. If data from pre-construction characterization are not adequate to design a robust monitoring system, then special requirements can be placed on the site before closure.

That immediately raises another issue. Closure and long-term monitoring of a site that no longer produces revenue is an invitation to divestiture and bankruptcy. NRC needs to get legislation passed to block this pathway to irresponsibility, or to establish a fund to support post-closure activities. It is in the best interest of the power industry to support such measures as a guarantee to the public of the long-term safety of nuclear power. Massmann and Freeze (1987) noted that pre-construction performance bonds are more effective than post-construction penalties in assuring quality results – this is another way to assure that bankruptcy is not a handy escape from the penalties of malfeasance.

[3] For example, in the SRS Burial ground, mercury was reputedly disposed in plastic bottles packed in paint cans.

[4] Remediation PA as a topic of research using a DOE field site was suggested by Jack Corey of SRS in response to inquiries to him about PA validation monitoring. Jack is currently acting as

Monitoring of legacy waste sites may be difficult because waste constituents are already loose in the environment. If the site is treated internally and then covered by an engineered cap, much of the monitoring will be similar to that discussed below for new sites, plus determination of the risk related to existing plumes. An example of such a site is the L-Oil and Chemical Basin at SRS. This basin received waste from drains in a facility used for reactor pump maintenance at the SRS L-Reactor. The basin contained significant amounts of ^{60}Co, and lesser amounts of U, Pu, Am, and other materials solvents and fission products. Remediation consisted of characterization of the depth of contamination, mixing the contaminated sludge and soil with a custom-designed grout to solidify it, then covering the site with an engineered cap. Monitoring remains as before – quarterly sampling of four water table wells around the basin, and the cap is inspected visually on a regular basis.

Legacy sites may also require site characterization to identify controls on water and contaminant movement. The continuum between characterization and monitoring is noted at the beginning of this report. Historical monitoring records can be used to understand plume development, movement, and dissipation at some sites, as well as hydrologic system responses to rainfall and other events, and thus place constraints on conceptual models used in a PA.

New sites will be designed to some sort of performance-based engineering standards. For example, a clay cap may have a performance requirement of 10^{-7} cm/s permeability (cm^3 of water/cm^2 of surface area per second). The cap will be built from some thickness of materials meeting that requirement in the laboratory, or in theory. Monitoring might include construction QA, and some way[5] to tell whether the performance requirements are maintained in a natural environment that may impose wetting-drying and freezing-thawing cycles that may cause fracturing or other deformation of the clay layer.

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liaison between SRTC and DOE's Office of Science. His DOE-HQ contact is currently Teresa Fryberger.

[5] *e.g.* integrated sensors or strain indicators

This leads naturally to a strategic approach to performance monitoring for all new sites. The containment system has performance requirements or objectives that lead to design requirements. The design will include sub-systems, which will include components, each of which contributes in some way to meeting the system performance requirements. It should be possible to design and incorporate integral monitoring devices for each component. For example, a plastic membrane could incorporate thin fiber optic or electric conductors whose continuity could be tested from outside the system without compromising the integrity of the system.

Monitoring beneath a waste site will require some sort of access technology[6] coupled with detection and monitoring devices. For new sites, the devices might be emplaced prior to construction. Chemical and/or geophysical sensors may be used, or water or vapor samples for *in situ* or offsite analysis may be appropriate. The determination of what is appropriate in a given case will be based on site characteristics, monitoring requirements, and performance capabilities of the devices.

Cost of monitoring should be a factor in final determination of monitoring requirements and should be estimated for all strategies considered in this project. A good approach to cost control might be through a combination of a cost/benefit analysis with the Data Quality Objectives (DQO process, to arrive at a consensus as to what needs to be measured and where and optimization to select frequencies, measurements and appropriate methods that meet DQOs at the best cost (Michael *et al.* 2000). Monitoring should not be a significant fraction of costs at operating facilities, but may be most of the cost during post-closure.

In summary, a systems engineering approach to monitoring seems to be the best path forward. This would include a systems analysis of each site/system (as outlined above)

[6] A large number of remediation technologies, including those for access, have been supported by DOE, EPA, AFCEE, and industry. Information on these is available in books, and online at a number of sites. A thorough discussion is beyond the scope of this review.

and then matching the site monitoring requirements to the performance capability of monitoring systems. The systems analysis, done by a team of modelers, geologists, soil scientists, and hydrologists, should also reveal FEPs that must be part of any PA modeling.

Visualization

The ability to visualize site FEPs and other data in three dimensions is highly recommended as an adjunct to implementation of a monitoring strategy into a site-specific monitoring plan and for communicating the plan to others. Visualization was one of the recommendations in Wood (2000) for aiding understanding of INEL unsaturated zone issues.

Subsurface modeling and visualization software has been developed for PC platforms. There are several target markets for this software, the largest being the petroleum exploration and development market, and a second being the mining industry. At the recent AAPG meeting we reviewed four PC-based packages, and eliminated two others because of cost. Costs range between $25k and $100k for the combined modeling and visualization capabilities. We have contacted (5/19/03) some mining software firms to get prices and demonstration versions of their software (*e.g.* Vulcan).

The figure below is one frame taken from a visualization of radioactivity distribution at a tank farm. Three-dimensional computer contouring alone indicates no significant contamination at the base of the modeled volume. Visualization reveals to the operator that the ‘hot’ wells do not extend to the base of the volume, whereas the ‘cold’ wells do extend deeper, and control contouring at that depth plane – so that there is still a real possibility that contamination extends below the depth of measurement at the ‘hot’ locations. This also calls into question the contouring method, which is probably on a plane-by-plane basis, rather than truly in 3-D.

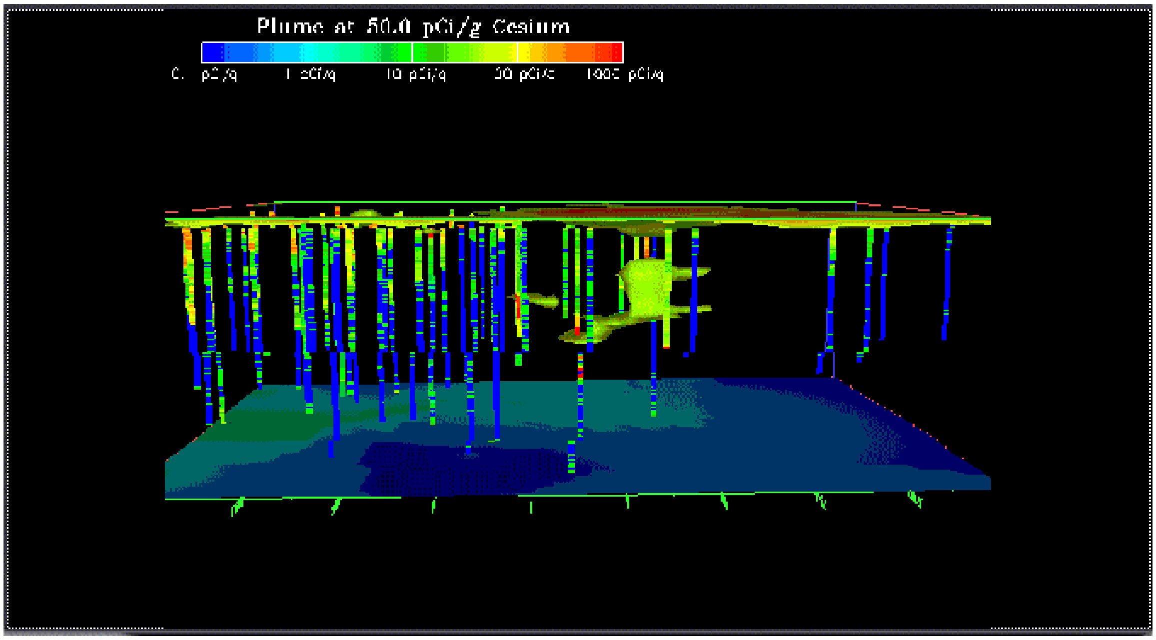

Figure: Quasi-3D contouring and solid rendering of Cs in soil. Note that ‘hot’ wells do not extend near base of volume modeled. (Apparent offsets in the wells are artifacts.)

Appendix B: Bibliography

This section has been incorporated into a Microsoft Access database, and can be searched by authors, key words, or full text search of titles and summaries. Key words have been chosen to classify the references into logical groups related to this project. There are over 330 references, which we have reviewed in hard copy or as portable document format (pdf) files.

WHY	**HOW**	**WHAT**	**WHERE**
Characterization	Access Technology	Logs	Surface
Data Management	Devices	ERT	Unsaturated
Data Quality/DQO	Ecological	EM	Saturated
Design	Geochemical	Tensiometers	Structure
Modeling	Geological	GPR	
Monitoring	Geophysical	Direct–push	
	Geostatistics	Lysimeters	
	Optimization	Neutron Probe	
	Performance	Horizontal drilling	
	Sampling	Bladder pump	
	Sensors	Trenches	
	Stds/Procedures	Biota	
	Uncertainties	Fiber optic	
		LONG LIST	

The table above is an example of the keywords used.

Appendix C: Performance Indicators Suggested by DOE LLW Performance Assessments

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A sampling of radiological performance assessments (PA) representing radioactive waste disposal sites across the DOE complex was reviewed for indications of potential site-specific performance indicators. Such indicators are limited to contaminant radionuclide fate and transport, and do not include dose assessment information. The following PAs for existing and proposed sites were reviewed:

Hanford Site (HS): 200 West Area Burial Grounds, Double-Shelled Tanks
INEL: Radioactive Waste Management Complex (RWMC)
NTS: Area 3 and Area 5 Radioactive Waste Management Sites (RWMSs), Greater Confinement Disposal (GCD) boreholes (part of the Area 5 RWMS)
LANL: Material Disposal Area G (MDAG)
ORNL: Solid Waste Storage Area 6 (SWSA 6) and the associated Interim Waste Management Facility (IWMF), Class L-II Disposal Facility (CIIDF)
SRS: East Area Vaults (EAV), Saltstone Disposal Facility (SDF), Hazardous Waste/Mixed Waste Disposal Facility (HW/MWDF)

Additional information, not from PAs, was reviewed for:

Rocky Flats Environmental Technology Site (RFETS)
Fernald Environmental Management Project (FEMP)
Portsmouth Gaseous Diffusion Plant (PGDP)
East Tennessee Technology Park (ETTP; former K-25 Plant)
Oak Ridge Y-12 Plant (Y-12)
Sandia National Laboratories' (SNL) Mixed Waste Landfill (MWL)

For the purposes of performance assessment, disposal sites fall into several overlapping categories. The most significant of these is the local climate: Humid sites and arid sites have fundamentally different hydrologic behaviors, resulting in potentially different ranking of performance indicators. At one extreme, typified by ORNL's SWSA 6, some wastes are disposed at and below the water table, with direct transport to groundwater and surface waters. This suggests that sampling of groundwater wells within or immediately adjacent to the disposal site would be an appropriate method of determining groundwater contaminant concentrations, a primary performance indicator for this configuration. At the other extreme, for example the RWMSs at the Nevada Test Site (NTS), depth to the water table is measured in hundreds of meters, and contaminant transport from near-surface disposals to the water table is not expected within thousands

of years, so sampling of the saturated zone is not likely to provide an adequate indication of performance. Sampling of the unsaturated zone in this case is also perhaps not fruitful, and in any case would be limited to the gaseous phase of the porous medium. The most appropriate performance indicator at the NTS sites is probably contaminant concentrations in the surface soils, which are expected to receive contaminants transported by plants and burrowing animals[7]. Intermediate examples include Idaho National Engineering Laboratory (INEL)'s RWMC and Los Alamos National Laboratory (LANL)'s MDA G, which are underlain by perched water bodies, providing appropriate locations for monitoring of contaminant concentrations as indicators of performance. Both of these also overlie aquifers affording large amounts of dilution, making the saturated zone less attractive as a location for monitoring contaminant concentrations.

Another category for discrimination between sites is that of disposal technologies. A common waste disposal configuration is shallow land burial (SLB), usually unlined pits or trenches, containing a variety of waste forms and generally capped within a few meters above grade. Examples include most of ORNL's SWSA 6 (as well as SWSAs 1 through 5), trench disposal at SRS, NTS' RWMSs, INEL's RWMC, burial grounds at Hanford's 200 West Area, and Sandia's MWL. Other structures effectively become SLB disposal, including impoundments intended to store liquids or intended to infiltrate liquids into the ground, and found at many sites in the DOE complex. These are typically closed in place, and so become SLB disposals. Shallow underground tank farms might also be considered SLB, such as those at Hanford and ORNL. Aboveground disposal structures are also found across the DOE complex, including tumuli at ORNL's SWSA 6, SRS' E-Area Vaults, and the disposal cell at FEMP. In consideration of NRC's interest of the decommissioning of contaminated facilities, this category might also include Hanford's abandoned plutonium reactors, commercial nuclear power plants, and the gaseous diffusion plants at Portsmouth, Paducah, and Oak Ridge. These facilities, generally built aboveground on concrete slabs of some sort, may provide additional opportunities for monitoring of performance indicators. For example, the Interim Waste Management Facility (IWMF) at ORNL, a tumulus design, was designed to collect water expected to infiltrate through the cap and make contact with the waste. If new facilities, such as nuclear power plants yet to be built, were to incorporate monitoring and entombment technologies into their design, our understanding of their performance should improve significantly.

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[7] It is not clear whether the scope of this project to develop a groundwater monitoring strategy is intended to include other contaminant transport pathways, such as that resulting from biotic activity. In many cases ground water monitoring alone will not capture the most significant release pathways, and contamination may "fall through the cracks". Maximum protection of human health and the environment, which is presumably our intended goal, should include evaluation of bio-intrusion/bioturbation.

A further discriminator for determining appropriate performance indicators at a site is the nature of wastes disposed. Long-lived, nonsorbing radionuclides such as ^{14}C, ^{99}Tc, and ^{129}I suggest different monitoring strategies from those for heavy metals (U and transuranics) or relatively short-lived radionuclides such as ^{3}H, ^{60}Co, ^{137}Cs, and ^{90}Sr. SRS has made this distinction by adopting different disposal concepts: Low Activity Waste Vaults, Intermediate Level Tritium Vaults, Intermediate Level Non-Tritium Vaults, and the Long Lived Waste Storage Building.

Combinations of these categories suggest different monitoring strategies. SLB disposal in humid environments with shallow water tables suggest the monitoring of groundwater at the water table and at discharge points to surface waters. SLB disposal in arid sites with perched water tables suggest monitoring of the perched water, and of the air phase of the porous medium, if volatile radionuclides such as tritium are present. Extremely arid sites, regardless of disposal technology, may not benefit from groundwater monitoring at all, instead requiring sampling of surface soils where biotic activity has dominated contaminant transport.

In some cases, the complex interaction of contaminant transport pathways suggests that focusing on a single medium (*e.g*. groundwater) may cause investigators to miss important mechanisms for release of contamination to the environment. For example, surface soils contaminated with plutonium at RFETS are entrained in the atmosphere and transported to nearby surface water reservoirs intended for drinking water.

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