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Title: Vadose Zone Monitoring Strategy

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1.0 INTRODUCTION

The vadose zone beneath the Hanford Site has been used to store radioactive materials and disposal of radioactive and hazardous wastes. The new mission of the Hanford Site is to remediate and restore sites contaminated by past waste management practices. Characterization and monitoring of the vadose zone is necessary to provide appropriate data, of suitable precision and accuracy, to guide fundamental decisions in waste management and environmental restoration. These decisions relate to operations, worker protection, public health and safety and ultimately to the priorities, techniques, cost and resources needed for environmental restoration of vadose zone soils contaminated by Hanford waste discharges. The quality of data collected as part of vadose zone monitoring (VZM) must meet the objectives of multiple operational and remediation/restoration program needs as well as meet the intent of federal and state regulations and DOE orders.

2.0 SUMMARY OF STRATEGY DEVELOPMENT

This paper outlines a strategy for identifying and quantifying data needed to characterize and monitor the vadose zone at the Hanford Site. A general description of the vadose zone is presented for background, followed by a strategy that addresses the formulation of requirements based on data quality objectives (DQO), instrumentation and development needs, and the integrated site management and implementation. Strategy development includes the following:

- Formulate/combine DQOs for multiple user needs considering the time and quality of the needed data for each user's present and future objectives
- Modify and upgrade existing gamma logging equipment/methods prior to development of new methods/instruments
- Adapt promising commercially available equipment/methods to Hanford Site VZM
- Develop VZM methods that acquire the needed data and satisfy the DQOs for radioactive and hazardous contaminant detection and transport characterization/modeling
- Phase activities to satisfy short-term characterization/modeling needs, intermediate term remedial action monitoring and long term verification monitoring
- Develop calibration in parallel with equipment/method development to satisfy precision/accuracy requirements and to support flow and transport modeling
- Modify borehole drilling and completion methods to optimize use of boreholes for data collection

- Emphasize geologic characterization so as to be able to correlate contaminant distribution and mobility with stratigraphy and distribution of geologic units.

3.0 VADOSE ZONE DESCRIPTION

The vadose zone is the volume of soils/sediments extending from the ground surface to the water table. Below the water table, all the voids (interstices/fractures) are filled with fluids, chiefly liquids. Above the water table, the voids are generally not filled with liquids; however, saturated zones may exist above a zone of lower permeability (e.g., a clay unit) in a perched zone. Pressure at the water table equals atmospheric pressure while pressure above the water table is less than atmospheric and fluids are generally held by capillary forces. Water in the saturated zone moves from areas of higher head (water level) to areas of lower head, where the total head is the sum of the pressure and the elevation head. Liquid also moves in the vadose zone where the total soil water potential is the sum of the soil water potential and the elevation potential. Liquid will not flow freely into a well or collection device in the vadose zone without applying suction; therefore, water is not extracted for human consumption or irrigation from the vadose zone.

3.1 FLOW

Liquids in the vadose zone move laterally and vertically and slowly infiltrate from the ground surface (or point of discharge in the vadose zone) to the water table. In the rain shadow of the Cascade Range, the semiarid climate of the Hanford Site provides little (estimates range from 0 to 10 cm/yr) natural recharge to the unconfined aquifer. The mean annual precipitation is 6.26 in. (15.9 cm). The vadose zone beneath the Hanford Site is up to 350 ft thick; i.e., the water table is deep below the ground surface. Infiltration of rainfall through the vadose zone may recharge groundwater under certain conditions, but infiltrating precipitation also provides moisture which facilitates the transport of contaminants in the vadose zone. Any contaminants in the vadose zone with low retardation coefficients (Kd) (e.g., ^{3}H, NO_3, ^{99}Tc) will advance through the vadose zone essentially with the advancing moisture. Contaminants in the soils are unconfined contaminant sources in the vadose zone and will move when there is adequate soil water energy gradient to result in transport. If liquids in the vadose zone infiltrate and recharge groundwater, the liquids and transported contaminants become part of the groundwater and move with it.

Groundwater moves from areas of recharge to points of discharge. The groundwater in the uppermost or unconfined aquifer beneath the Hanford Site discharges to the Columbia River, which is a source of municipal drinking water for communities downstream from the Hanford Site. Therefore, groundwater containing contaminants flowing to the Columbia River is a pathway for contaminant movement. Consumers of municipal water supplies extracted from the Columbia River are potential receptors of contaminants that reach the Columbia River. In addition, drinking water for the 400 Area of the Hanford Site is obtained from groundwater via extraction wells and is used by Hanford

workers as well as members of the public at the Fast Flux Test Facility visitor's center.

3.2 CONTAMINANT MOBILITY AND TRANSPORT

Contaminant behavior and transport in soils are affected by the volume of effluent discharges, the physical and chemical characteristics of the waste and its interaction with the soils, the volume of liquids in the vadose zone to facilitate chemical processes and transport, the characteristics of the soils and the lateral and vertical extent of the strata as they affect the movement of liquids through the vadose zone. In the past, artificial recharge from liquid effluent discharges has been as high as 10 orders of magnitude greater than natural recharge. Past monitoring of liquid effluent discharges has emphasized the radionuclide component of the waste, but at least some of the hazardous chemical component also poses risks and must be monitored. The hazardous component includes volatile organic compounds, which may exist in both the vapor and liquid phases, both of which must be monitored (e.g., acetone, carbon tetrachloride, toluene).

The greater the volume of discharges to a site, the greater the likelihood that the liquid exceeds the local field capacity of the soil (i.e., that which can be held by capillarity in the interstices without saturation and drainage to groundwater). In the natural state, Hanford soils generally contain less than 10% moisture (by volume), but this can vary with the season and the amount of evapotranspiration. Such low moisture contents severely restrict pore liquid sampling and certain extraction techniques. Sites that have been "armored" with gravel to prevent growth of vegetation and infiltration by burrowing animals have a greater likelihood of natural precipitation recharging the deep vadose zone and groundwater.

Interaction of the waste with the soil may result in sorption, desorption and/or precipitation depending on the character of the sediments and the waste. Any retardation can be affected by later discharges or chemical changes, which can lead to future mobilization or retardation at a different location and perhaps in a different chemical state. The interbedded sands, silts, and gravels of the Hanford vadose zone sediments and their varying unsaturated hydraulic conductivity leads to heterogeneous patterns of dispersal such that wastes disposed to the soils at one locality can spread laterally to soils beneath other facilities and potentially offsite.

4.0 STRATEGY

Cleanup or stabilization of vadose zone sites to which contaminants have been discharged and unconfined requires an understanding of the lateral and vertical extent of contaminants, the physical/chemical state of the contaminants, the physical/chemical properties of the sediments/rock, and their mobility and present toxicity/hazard. These data are required to define remediation and/or closure decisions and to demonstrate the efficacy of remedial actions during and after restoration. These needed data are acquired through characterization of the vadose zone; i.e., establishing a baseline of current conditions, and by monitoring changes to the baseline. The varying

4.2 MONITORING TECHNOLOGY

The VZM DQO will influence the type(s) of instruments to be used, the sampling geometries, and the monitoring frequencies after the baseline characterization has been completed. In the near-term, upgrades to existing equipment, methods and procedures are being/will be made to improve the data currently being collected. Acquisition of new tools and technology will be considered depending on the DQO and the dates when the data are needed. The adaptation of existing commercial technology to Hanford Site problems will be pursued through cooperative agreements with industry.

Geophysical logging in existing boreholes currently offers the most consistent and economic technology for VZM. Boreholes provide access for logging tools and provide some historic background, as many have been logged with present and older systems in years past. Because Hanford has so many boreholes, the subsurface is so difficult to get good data for, and "drilling" new bores into waste-site areas is so expensive, efforts have been concentrated on borehole geophysical techniques from existing boreholes.

4.3 INSTRUMENTATION

Currently, the Hanford Site utilizes three passive nuclear logging systems: (1) gross gamma-ray, (2) sodium-iodide spectral gamma-ray, and (3) germanium, spectral gamma-ray logging systems. Gross gamma-ray logging is used the most with more than 10,000 logging runs per year in support of tank farm leak detection. The sodium-iodide spectral gamma-ray system is in development and only one germanium spectral-gamma system is currently in use. The near-term, priority strategy is to continue the use of these remote sensing devices, supplemented where necessary with system/probe modifications and revised operating procedures to enhance data gathering as needed to support the DQO.

As with all gamma detection, gross gamma-ray logging detects gamma-emitting radionuclides with sufficient photon energy to penetrate well casing, but it cannot be used to identify radionuclide species. Gross gamma logging has been conducted in boreholes at the Hanford Site for more than 15 yr to screen for cumulative radioactivity. While the equipment is old, with minor upgrades, data quality can be improved. Such upgrades, including improving spatial resolution, calibration, and data management and analysis, can be made until new instrumentation is acquired. The advantages of gross gamma logging are that it is relatively inexpensive and fast. Improved gross gamma-ray logging will continue to be used where only total gamma activity is needed, for example tank leak detection.

Sodium-iodide (low resolution) spectral gamma logging provides information on the species of radioactive contaminant. The broad peaks provide relatively coarse energy-peak resolution for species identification but provide significantly more characterization data than the gross gamma system. Low-resolution spectral gamma logging will likely replace much or all of the gross gamma logging because of its higher signal-to-noise ratio and comparable cost and speed.

High-purity germanium (high-resolution) spectral gamma logging provides very sharp resolution of gamma-ray energies and permits specific nuclide

identification. With appropriate calibration, concentrations as well as identities of radionuclides can be obtained. This logging method will be used when characterization requires a high level of confidence and nuclide-specific information. It is anticipated that high-resolution logging saves characterization costs more than the previous methods. This logging system is slower than the low-resolution spectral gamma system. Three more systems are in procurement; one for vadose characterization and monitoring of inactive disposal facilities, and two are to support the tank farms leak-detection program.

Promising technologies that require some adaptation for application at the Hanford Site may be tested and implemented if they are shown to be improvements over existing methods. For example, techniques for determining moisture content and bulk density of formations in the subsurface through borehole neutron-neutron and gamma-gamma logging, respectively, have been used in the petroleum and mining industries. Adaptation of the neutron-neutron technique to measure the water content in the vadose soils, both the vapor in open pore spaces and the water molecules adhered to the mineral grains, would support contaminant migration mechanism and rate determinations at Hanford. Although these logging techniques have not been demonstrated to work in the large diameter (cased boreholes at the Hanford Site), modified versions of these tools might be used at Hanford if they support the DQO and show promise in making the measurements faster and cheaper than alternative methods. These and other industry adaptations will be pursued through vehicles such as a Cooperative Research and Development Agreement (CRADA).

Neutron capture/activation logging is a potential method for assessment of hazardous contaminants. The logging tool irradiates the material surrounding the borehole with neutrons and then surveys the material with a gamma-ray detector. Spectra collected by the gamma-ray detector contain signals from characteristic gamma rays that are emitted when neutron capture/activation interactions occur in nuclei of specific elements, including chlorine and nitrogen (constituents of many Hanford wastes), and hydrogen and oxygen. The elements can be identified and the concentrations deduced from the spectral data. This method can also be used to produce a continuous bulk geochemistry log. The development of this logging method for application at the Hanford Site will be considered.

Other geophysical tools and methods, especially electrical, have been and will continue to be considered. Table 1 is a summary assessment of technologies to be considered. Direct sampling of soil and vapors is also an important part of vadose zone characterization and monitoring and will be done where possible in existing boreholes using innovative sampling technologies.

4.4 ACCESS

For the depths required to monitor the vadose zone at Hanford, boreholes are required for placement of the sensors close to or in physical contact with the soil. The strategy is to maximize the use of the many boreholes at the Hanford Site; however, additional access may be needed in some currently undefined areas. The cone penetrometer and a recently tested casing driven with a pile driver provide subsurface access faster and cheaper than drilling boreholes. Such methods of access will be tested for applicability. Newly developed, sophisticated membranes with sensors or collectors embedded in them

can be placed in boreholes either temporarily or for long-term installation where measurements of soil-gas samples can be collected periodically. The perforation of existing boreholes to accommodate membrane techniques for placing sensors or collecting devices should be considered. An alternative to steel casing for new VZM boreholes should be pursued.

4.5 TECHNICAL COORDINATION

A Westinghouse Hanford Company (WHC) VZM technical coordination team will advise the various VZM programs. The team will be sponsored by upper management and will consist of technical representatives from each user of VZM data, WHC geophysics, WHC hydrogeology, and Pacific Northwest Laboratory geophysicists. The technical coordination team will discuss VZM methods/technology, technical problems, data and data management, and development of and changes to the DQO. The team will also make recommendations regarding operating procedures, equipment calibration, data management, equipment upgrades, and demonstration/development programs. Technical/logistic needs for VZM throughout the various VZM programs will be coordinated and appropriate funding for calibration, data management, and vadose zone plume monitoring will be sought. The team leader will be appointed by and will report to the manager of WHC geosciences. The regulators, U.S. Department of Energy, and outside technical experts may be invited to participate in team activities when appropriate.

Table 1. Technology Summary (Sheet 1 of 3)

Technique	Measuring	Advantages	Limitations	Comments
BOREHOLE NUCLEAR LOGGING (CURRENT, OR PLANNED FOR, ONSITE)				
Gross-gamma	Gross gamma-radiation count	Quick, inexpensive, in situ measurements, easy to calibrate	Provides only gross gamma radiation count. Provides no isotope identification	More sophisticated equipment is available. Limited use as lithology indicator at Hanford.
Low-resolution (NaI or CsI) spectral logging	Gamma energy spectrum from which specific nuclides can be identified	Specific radionuclides can be identified. Good detector efficiency	Spectral peaks are broad & may be difficult to interpret	Should replace much of the gross-logging. Some equipment on site.
High-resolution (HPGe) spectral logging	High-resolution gamma-energy spectral	Exact concentrations of gamma emitters can often be determined	Requires 4-in or larger diameter borehole. Lower detector efficiency	Most accurate in situ system available. One fully operational system onsite, three ordered.
Neutron Logging	Moisture level indicator (measures hydrogen)	Rapid, reliable, and accurate in some conditions	Requires 4-in or larger diameter borehole. There are no calibration standards at this time	May provide needed moisture data. A system has been identified to lease, test, and maybe purchase. Construction of calibration models is planned in the CRADA.
Gamma density	Bulk density	Supports porosity calculations	Very difficult at Hanford in cased holes/ unconsolidated sediments	Would strengthen porosity data & improve vadose moisture determinations. No known working system available at present for the Hanford environment.
Neutron activation	Nitrogen, chlorine, others (heavy metals)	A quick, in situ identification of chemical contaminants surrounding boreholes	Level of accuracy not yet known	System is being brought onsite. If proven effective, will result in a great leap forward for chemical assaying of the subsurface.
ELECTRICAL				
Resistivity	Fluids, clays, lithologic boundaries	Quick and inexpensive	Spatial resolution is coarse. Cultural interference (pipes, etc.) bad	Generally, values derived are too course for fluid transport modeling. May be good for gross outline of fluids under tanks and delineating major lithologic boundaries.
Electro-Magnetic	Fluids, saltcake	Quick and inexpensive	Spatial resolution is coarse. Cultural interference (pipes, etc.) bad	Generally, values derived are too coarse for fluid transport modeling. May be good for gross outline of fluids under tanks and delineating major lithologic boundaries.

Table 1. Technology Summary (Sheet 2 of 3)

Technique	Measuring	Advantages	Limitations	Comments
Borehole electrical methods	Clays and fluids	Quick, cheap, and gives vertical resolution to lithology	Must be non-metal casings	Could measure fluids or saltcake in the sediments.
Tomography	Fluids, clays, and saltcake	Same as above, saltcake	Must be non-metal casings	High-moisture zones, saltcake.
Radar	Fluids, clays, and soil layering	Can probably "see" saltcake	Depth of penetration is shallow	Moisture close to tanks. Tools are available for off-the-shelf purchase.
ACOUSTIC				
Reflection	Stratigraphic layering	Cheaper than drilling holes. Good vertical and horizontal resolution	Somewhat gross for some areas, usually 10% of depth	May be able to map caliche layer and expose "holes" in that layer and the first basalt layer.
Refraction	Velocity contrasts such as lithologic interfaces	Inexpensive and fast	Depth values are somewhat coarse	Maps stratigraphic interfaces and can provide velocity data for reflection surveys.
Borehole	Vertical density variations associated with acoustic velocity	Provides good vertical resolution of layering	Must have good acoustic coupling to the formation and generally, liquid-filled holes	Would map density layers, if they were of interest. Technique is unlikely to be of significant benefit in Hanford vadose zone.
VSP	Acoustic velocity profile around a borehole	Possibly could locate geologic anomalies	Must have good acoustic coupling to the formation. Steel casings can be bad	Provides velocity information for reflection-seismic work, and the ability to construct a 2- or 3-dimensional image.
Tomography	Harness/fluids	Gives much better picture	Would probably require new boreholes. Questionable through steel casing	May be of value mapping saltcake under inactive cribs, if it exists.
POTENTIAL FIELDS				
Gravity	Changes in gravity field due to lateral density changes	Very quick and cheap	Requires measurable density differences. Data are poorly constrained	Probably of not too much value at this time.
Magnetic	Changes in magnetic field due to lateral rock-type changes	Very quick and cheap	Data quickly becomes unusable if steel pipes are in the area	Of value mainly for identifying underground steel piping and ferro-metallic debris.

Table 1. Technology Summary (Sheet 3 of 3)

Technique	Measuring	Advantages	Limitations	Comments
COMMERCIAL OIL FIELD LOGGING				
Density	Bulk density	If it can be made to work, would be rapid and continuous measurement	Data from Hanford boreholes not valid at this time	Techniques for vadose logging are under investigation.
Neutron porosity	Saturated porosity, moisture indicator	Rapid in situ measurements	Does not produce calibrated data in vadose zone	Commercial logging company tools and techniques are to be adapted and tested in vadose environments at Hanford within the next year.
INSERTING TUBING, OR MEMBRANE, IN AN INVERTED MANNER INTO BOREHOLES (Requires perforation of the borehole casing)				
Sample Collection:				
(Gaseous phase)	Chemical analysis	Identify chemical contaminants	Requires access to the soils. Long turnaround time at lab	This would provide positive, in-hand samples. Has been used in holes being drilled.
	Moisture content	Determine moisture driver for contaminants	Requires open borehole	Logging may prove more accurate. Method may not be very effective.
(Liquid phase)	Chemical analysis	Positive, in-hand samples	Requires access to soils	True in situ volumes cannot be determined.