Field Test Bed for Vadose-Zone Monitoring Approaches – 20404

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ABSTRACT

In the Central Plateau at the U.S. Department of Energy Hanford Site, a large inventory of contaminants resides in unsaturated sediments within the approximately 100-meter-thick vadose zone, posing a potential continuing risk to groundwater. Vadose zone remedies used to address these contaminants will require performance monitoring to provide feedback during implementation and for long-term verification that remedial action objectives have been met. Passive approaches may also need long-term monitoring to demonstrate that the flux of contaminants from the vadose zone to the groundwater are below thresholds established to meet groundwater protection goals.

Collection of physical (e.g., groundwater or sediment) samples is a common method for identifying contaminant concentration distributions, but this approach is limited by the number of locations and the frequency with which data can be collected. In situ vadose zone measurements have evolved over the past few years to include key measurements of water content, soil water pressure, temperature, and chemical concentration. However, the current generation of sensors is designed for relatively short-term use in near-surface soils or sediments. Geophysical methods have been evolving but are also limited in that they have not been designed for the specific long-term vadose zone monitoring needs at the Hanford Site. Overall, monitoring under unsaturated conditions can be difficult due to the need to install and maintain instrumentation over a large area and depth and the need to identify preferential flow pathways due to geologic and chemical heterogeneities over long periods. Thus, a vadose zone monitoring test bed was initiated to address these challenges and identify cost-effective approaches for implementation and post-closure monitoring of the deep vadose zone. The monitoring test bed is expected to provide valuable field-scale information for the design of vadose zone monitoring systems.

INTRODUCTION

In situ vadose zone (VZ) remedies are generally designed to reduce the flux of contaminants from a source in the unsaturated zone to groundwater (GW) and are selected based on predicted plume behavior, often far into the future. Model predictions rely on data for parameterization and validation. Monitoring data can be applied to provide a technical basis for these predictions both prior to remedy selection and during remedy implementation to assess and optimize remedy performance, and ultimately site closure. These monitoring needs are relevant to the U.S. Department of Energy Hanford Site.

Under the arid conditions present at the Hanford Site, contaminant migration in the VZ is a slow process with timescales on the order of hundreds of years. A monitoring strategy that relies solely on GW sampling alone will likely be unable to provide the information needed to accurately predict long-term VZ remedy performance. Monitoring the long-term behavior of both the VZ and GW will be critical to implementing and validating cleanup strategies that use both active and passive (e.g.., monitored natural attenuation) remedies. VZ monitoring components include methods and technologies for directly and indirectly measuring moisture conditions and contaminant flux to groundwater, providing early-warning monitoring of unexpected or unacceptable deep VZ behaviors. Long-term monitoring technologies that minimize the need for permanent surface or subsurface infrastructure are preferred to minimize infrastructure degradation issues that will inevitably occur over the expected lifetime. A properly-designed active remedy might require years to decades for implementation but would be able to maintain stable low-flux conditions for much longer time periods (hundreds of years). Monitoring should be flexible to accommodate the variable frequencies and types of information that will likely be needed to more effectively contribute to different stages of the remediation process.

Monitoring technologies have seen many advancements recently and have been successfully demonstrated for a wide range of groundwater and VZ applications, including soil desiccation, surface barriers, and amendment infiltration/injections. Building on the recent advancements, a set of existing and emerging long-term VZ monitoring technologies were identified within the context of an overall monitoring strategy for the Hanford Central Plateau [1]. A test bed with multiple locations has been initiated in the Hanford Central Plateau to test a suite of VZ monitoring technologies that have the potential to meet Hanford's VZ monitoring needs.

DESCRIPTION OF METHODS

A test bed has been established at former VZ research test sites in the Central Plateau at the Hanford Site. The primary site, located in the 200-BC-1 operable unit cribs and trenches (BC Cribs and Trenches), is a former treatability test site for soil desiccation and is being used to test recent adaptations of existing monitoring technologies to the deep VZ.

Past practices at BC Cribs and Trenches have resulted in significant levels of technetium-99 and nitrate in the 107-meter-thick VZ. To date, this contamination has migrated to approximately 70 meters below ground surface (BGS). A second satellite site, located approximately 1 mile north of BC Cribs and Trenches, was developed to test leak-detection technologies that could be used to monitor tank waste retrieval operations, and is designated as the Mock Tank site. The Mock Tank site contains several metallic structures that are common to field settings at Hanford, including steel-cased boreholes and a full-scale Hanford single-shell tank. Since the presence of metallic infrastructure can interfere with the several geophysical monitoring techniques, the Mock Tank site will be used to test approaches for minimizing and/or removing these effects. Another satellite site is located at the Prototype Hanford Barrier, an evapotranspiration cover that uses a 2-meter-thick silt loam layer to reduce infiltration into the subsurface at the 200-BP-1 waste site. Surface barriers will likely play a major role in future remedies aimed at minimizing contaminant flux to groundwater at the Hanford Site.

As all are former field test sites, sensors and access boreholes to support geophysical logging are already in place and extensive site characterization has been performed. Moreover, the heterogeneous nature of the sediments in the VZ at both the BC Cribs and Trenches and Mock Tank sites makes them ideal locations for a monitoring test bed, with opportunities to identify preferential flow pathways. This paper will focus on the primary test bed site at BC Cribs and Trenches.

VZ monitoring methods to be tested at the field site include both geophysical and pore water sampling approaches. Geophysical methods can provide two- or three-dimensional monitoring information over time for variations in the parameters that have a measurable geophysical signature. Electrical resistivity tomography (ERT) has been well demonstrated at Hanford and seen more widespread use for subsurface surveys because the measured subsurface electrical properties are well correlated to important parameters, including pore fluid salinity and saturation. Low-frequency electromagnetic methods that measure the bulk electrical conductivity of subsurface materials in a manner similar to ERT will be used in conjunction with bulk electrical conductivity to refine estimates of both moisture and solute content. Seismic methods will be tested for soil matric potential measurements, another important parameter influencing fluid flow in the VZ. Monitoring of matric potential can provide a more sensitive means to quantify hydraulic changes that occur under very dry settings resulting from application of desiccation or surface barrier remedies.

In addition to geophysical methods, methods for collecting distributed borehole pore water samples will be deployed to provide direct evidence of contaminant migration, complementing the spatial and temporal information gained from geophysical surveys. In situ sensing includes point measurements of temperature, matric potential, and fluid sampling as well as distributed fiber-optic sensing. Advancements in sensing and sampling are actively underway and the testbed will allow for deployment of new technologies in later years. A new VZ smart borehole completion system is currently being developed at Pacific Northwest National Laboratory (PNNL) that allows for dense sampling of VZ pore water or gas, matric potential, temperature, and relative humidity in addition to an array of electrodes to enable ERT imaging. The system is designed for long-term survivability and uses no buried electronics or complex components.

Electrical Resistivity Tomography

Electrical resistivity (the inverse of electrical conductivity) quantifies how strongly a material opposes the flow of an electric current. ERT is an active-source geophysical method in which a low-frequency current typically is injected between two transmitting electrodes, and the resulting potential drop is recorded across two receiving electrodes (for review, see [2]). The spacing between the transmitting and receiving electrodes determines the volume of interrogation over which each measurement is collected. The bulk electrical conductivity of the subsurface has been widely observed to follow the empirical Archie's law [3] in low-clay-content, non-conductive sediments. Ohm's law forms the basis for simulating the applied currents and the potentials that arise for ERT. On the Hanford Site, electrical and electromagnetic methods have been used to image the distribution of contamination and monitor changes in moisture content and delivery of electrically conductive amendments [4, 5]. An example of the use of ERT for estimating moisture changes that occurred during the desiccation test in shown in Fig. 1.

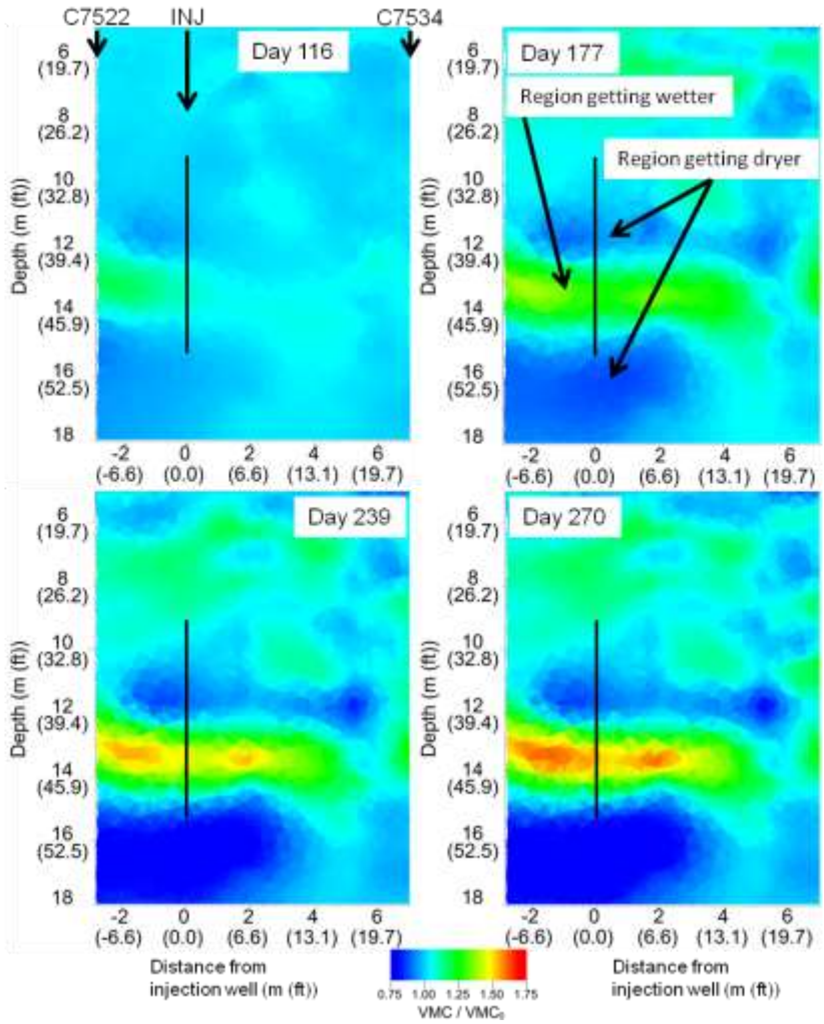

Fig. 1. ERT estimated moisture content changes during desiccation (after [6]).

Electromagnetics

Electromagnetic (EM) methods such as controlled source electromagnetics (CSEM) and ground penetrating radar (GPR) have been widely used for subsurface imaging in both near-surface and deeper environments [2], [7-10]. Low-frequency EM methods measure the bulk electrical conductivity of subsurface materials, similar to ERT. At high frequencies, EM methods (e.g., GPR) are also dependent on bulk electrical permittivity, which can be used in conjunction with bulk electrical conductivity to refine estimates of both moisture and solute content. On the Hanford Site, EM methods have been used to image the distribution of contamination and monitor changes in moisture content and delivery of electrically conductive amendments [10, 5].

CSEM is a widely used geophysical method for both near-surface and deep applications ranging from petroleum exploration to environmental characterization [7-10]. The method can be acquired using land, marine, or aerial configurations to estimate the bulk electrical conductivity of the subsurface. Similar to high-frequency (MHz) EM methods like GPR, lower frequency (Hz-kHz) CSEM measurements transmit EM into the ground that is sensed using a receiving device. Low-frequency methods use sources that produce relatively large electric and magnetic fields in conjunction with sensors that are able to measure the resulting magnetic fields induced in subsurface media.

The electrical conductivity of both aqueous solutions and bulk soil/rock also depends on temperature. The temperature dependence of bulk conductivity in the VZ depends on water content but is always monotonic so that a change in temperature will correspond proportionally with changes in bulk conductivity [11, 12].

Like ERT, CSEM is capable of imaging the distribution of bulk electrical conductivity, and if repeatedly acquired, changes in EC over time. CSEM can also be deployed at the surface, within a single borehole, or in cross-borehole configurations. Unlike ERT, CSEM does not require electrical contact with the ground and can be deployed within non-electrically conductive boreholes.

Seismic

Seismic attributes (velocity and attenuation) of geologic materials depend on the effective stress state that exists. Unsaturated systems consist of multiple phases, the solid matrix, and at least two fluids (typically water and air) and together determine the effective stress state. Changes in the relative fraction or stress of any phase can induce a corresponding change in effective stress [13].

It has been generally understood that the effective stress and therefore the seismic velocity depends on both moisture content and matric potential. For unsaturated sediments, matric potential has a dominant influence on the observed seismic velocity [14-16]. Seismic velocity of unsaturated, unconsolidated sediments as a function of effective stress for a range of sediment types has recently been demonstrated with excellent fits to the observations. Petrophysical models like this, along with repeat seismic surveys and overburden stress, can potentially be used to image the changes in the spatial distribution of matric potential. Under dry, low-flux conditions, like those that occur for surface barriers and desiccation, monitoring matric potential can provide a more sensitive means to quantify hydraulic changes [17].

In Situ Sensors and Fluid Sampling

In addition to providing direct information concerning processes that alter subsurface temperature, the temperature field data can also be used to correct geophysical properties that are temperature sensitive (Fig. 2). For instance, ERT-derived EC can be corrected to a standard temperature prior to using the ERT data for estimating volumetric water content. Subsurface temperatures can be measured using a number of sensing types, including thermocouples and thermistors. Thermistors are generally capable of increased precision, readily achieving absolute accuracies of better than 0.1°C.

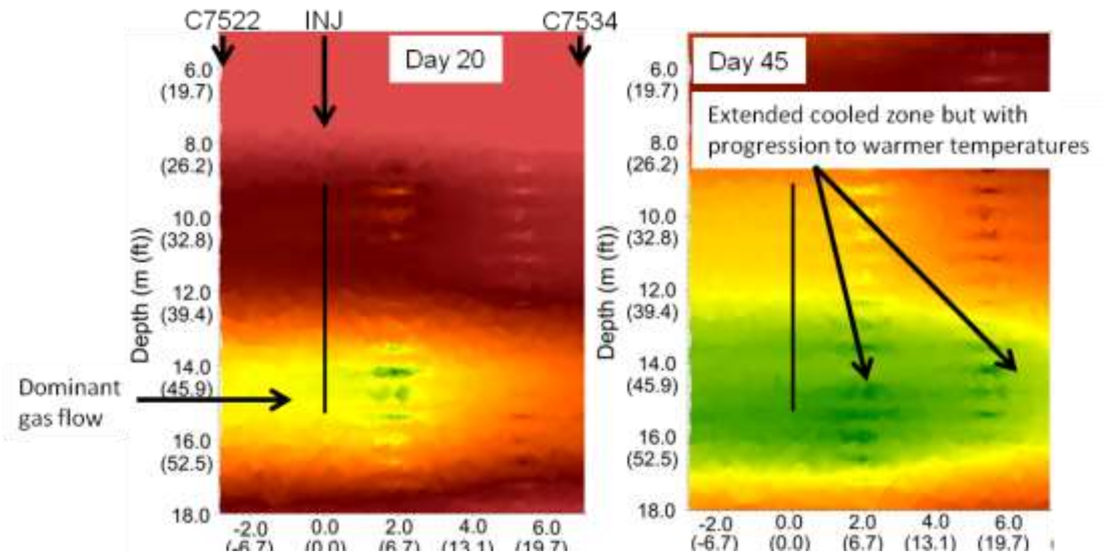

Fig. 2. Interpolated temperature response along the axis between the injection and extraction wells, indirectly showing desiccation through the evaporative cooling effect (adapted from [6]).

Matric potential is a key metric for VZ monitoring and is analogous to water level/pressure monitoring in saturated systems. Matric potential can be measured using several different sensors including tensiometers and heat dissipation unit (HDU) sensors. Tensiometers typically possess the greatest accuracy but cannot be used under very dry conditions (~-1 bar). The measurement range of an HDU (229-L HDU, Campbell Scientific, Inc., Logan, UT) is typically from -0.01 to -2.5 MPa (-0.1 to -25 bar) with an accuracy of 1 kPa [18].

Analogous to water sampling from saturated groundwater aquifers, pore water collection from the VZ can provide direct measurement of the aqueous constituents that are present. Pore water can be extracted from soil samples in the laboratory or in situ using various approaches. Commonly used methods include tension/suction porous cup and passive capillary samplers [19, 20]. A number of complications have been identified, such as clogging, pressure/duration dependent results, and adsorption of analytes or contamination by the sampler material. Common sampler materials are ceramic, stainless steels, fritted glass, fiberglass, and Teflon, and each has both advantages and disadvantages.

Since gas is always present in unsaturated systems, gas sampling also can provide important information on subsurface processes. VZ gas sampling systems are inherently simpler than pore water sampling. The simplest systems consist of a porous or mesh screen on the end of a tube that is buried in contact with the ground and attached on the other end with a sampling pump. Gas sampling is often used in conjunction with the injection of gas phase tracers that can be used to estimate field-scale permeability and gas transport.

Borehole Logs

Soil moisture content determination using neutron scattering probes has become a standard method over the past several decades [21]. Neutron probe borehole logs provide valuable information for both characterization and monitoring of changes that occur during VZ remediation. A neutron probe consists of a high-energy neutron source and thermal neutron detector. The concentration of thermalized neutrons is affected by both soil density and elemental composition. Elements that absorb neutrons are often in low concentration in the soil solid phase, and when clay content is also low, the neutron probe response is mainly affected by changes in moisture content. The volume of soil contributing to the measurement is much larger than that of many other moisture content measuring devices (e.g., time domain reflectometry) and is therefore more representative of field scale conditions.

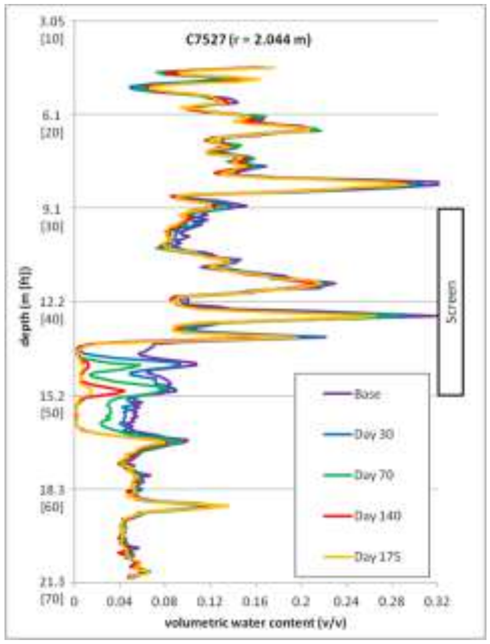

Fig. 3. Neutron probe soil moisture response to desiccation (after [6]).

As discussed above for ERT and electromagnetic geophysics applications, the bulk electrical conductivity can be a useful measurement for VZ monitoring. Electromagnetic conductivity can be obtained from a borehole logging tool to provide high vertical resolution of regions in the vicinity of the wellbore. When combined with a neutron probe log, it can potentially be used to estimate solute concentrations, and if repeat measurements are acquired, could also provide contaminant flux estimates.

Borehole logging requires no buried components other than a simple access tube for lowering the tools. Any repairs or maintenance can be performed at any time, an advantage for very long-term monitoring.

PROMISING TECHNOLOGY DEVELOPMENTS

Real-Time Cross-Borehole Imaging

ERT has undergone major advancement in recent years and has been successfully applied to monitoring a wide range of environmental applications that benefit from knowledge of subsurface bulk EC and changes that occur over time [4, 5]. One potential limitation of borehole-based ERT is the requirement that electrodes and cables be permanently emplaced during borehole construction. CSEM can also image bulk EC but only requires a simple PVC (or other non-conductive material) cased borehole and low-resistivity grout construction. Over the lifetime of the Hanford Site, degradation of such a borehole is less likely and suggests that further development of CSEM is warranted.

To this end, a real-time cross-borehole EM imaging system is currently being developed at PNNL. The basic design of the system is similar to [7] and is comprised of an array of EM source and receivers, as well as the associated data acquisition and control system. Each EM source is a coil/solenoid designed and constructed around an approximately 0.03-meter-diameter, 1.2-meter-long PVC tube, machined with threads and wound 400 turns using 18-gauge wire. Interior to the tube, ferrite beads are used to increase the magnetic permeability of the coil. The coil is powered from the surface using two transmitter designs: a sine wave signal generator (Model AMX 312, Pacific Power Source, Irvine, CA), and a time domain pulse generator (ZT-30, Zonge International Inc, Tucson, AZ). Two receiver designs are being investigated, the first receiver design being identical to the EM source transmitter. The second uses a fluxgate magnetic field sensor (Model 690, Bartington Instruments Ltd, Oxfordshire, UK). The fluxgate sensor has a range of +/- 100nT, frequency response from DC to 1kHz, and a noise level less than 20pT/√Hz.

Similar to ERT, an array of antennas are deployed within boreholes at a test site. Relay multiplexers are used to select individual antenna as either a transmitter or receiver. By using a number of transmitter/receiver configurations, sufficient data can be collected to image the subsurface electrical conductivity distribution. The data acquisition and control system is used to autonomously perform the survey.

Along with EM, a real-time cross-borehole seismic imaging could find use during the active phase of remedy implementation. One such system exists [22] that utilizes piezoelectric sources. The source strength of the system is unlikely to generate detectable signals for boreholes more than 10 meters apart in the unconsolidated sediments present at the Hanford Site. Higher energy seismic sources are being investigated for use in Hanford VZ monitoring.

Along with the physical system, PNNL has developed both an EM and Seismic forward modeling and inversion module within E4D for real-time imaging in addition to ERT.

Vadose Zone Borehole Monitoring System

Several sampler designs have been used to collect VZ soil pore water, which include both vacuum porous cup samplers and passive capillary wicks. Commonly used samplers are individually emplaced at a single depth and utilize a sampling tube that extends back to the surface, requiring relatively large fluid samples. Multi-level borehole sampling systems are commercially available for saturated conditions. These sampling systems were evaluated for modification and use for fluid sampling in the deep VZ.

A new multi-level vadose zone borehole monitoring (VZBM) system is being designed to provide for both small volume water and gas sampling in addition to tensiometer measurements at multiple depths along a wellbore. The system consists of casing sub-assemblies that incorporate a porous membrane in the wall of the casing and a wireline measurement and sampling tool.

PRIMARY TEST SITE INFRASTRUCTURE

The primary VZ test bed field site is located at the former deep VZ desiccation treatability test site conducted at the BC Cribs and Trenches Area. The 6 cribs and 20 trenches at this waste disposal site received about 110 million L of aqueous waste containing high nitrate and radionuclide concentrations, primarily from Hanford Site operations in the mid-1950s. The site contains relatively high concentrations of mobile Tc-99 contamination and is representative of VZ conditions found elsewhere on the Hanford Site.

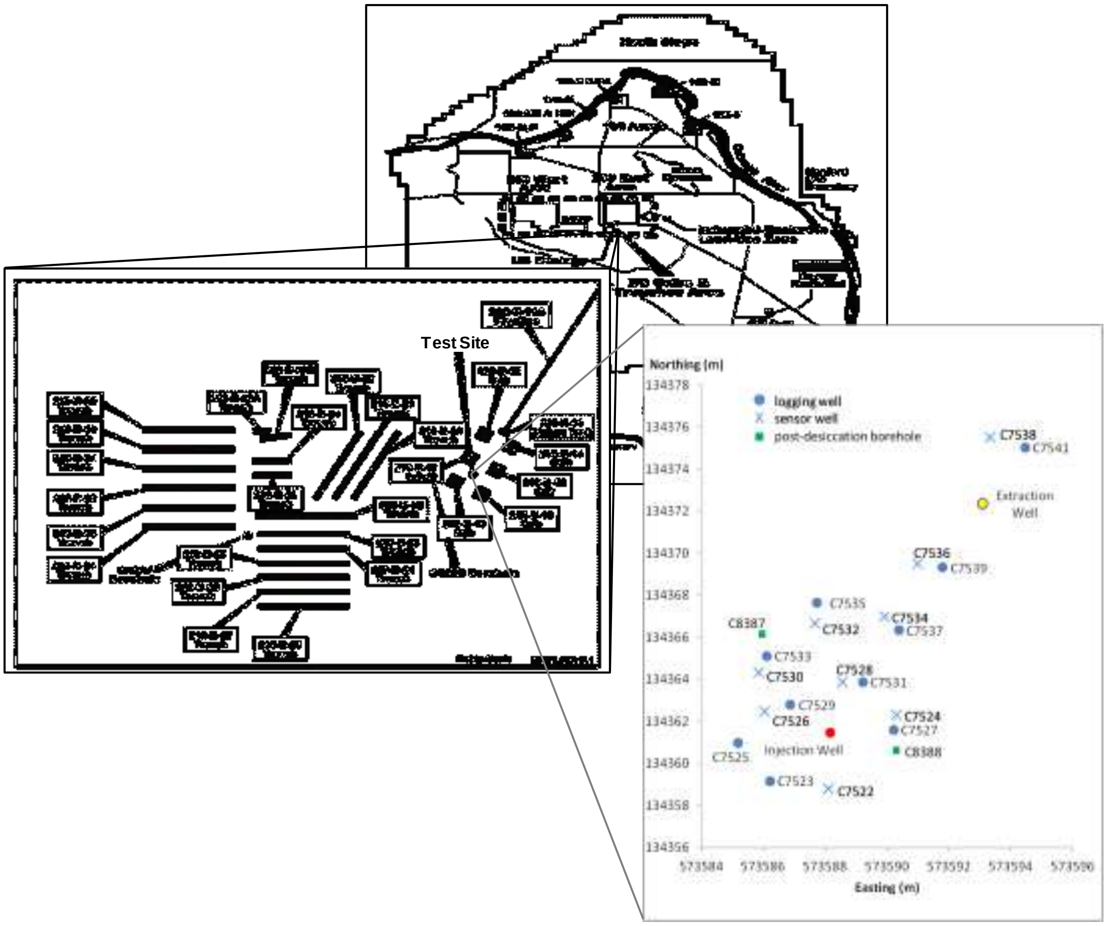

Fig. 4. Test site location in the BC Cribs and Trenches Area (inset, 200-BC-1 operable unit) of the Hanford Site (map) (after [23]) and location of test site logging wells, sensor boreholes, and post-desiccation boreholes for collection of sediment samples.

Several boreholes exist at the site and include two for gas injection or extraction, and 23 for monitoring (Fig. 2). The injection/extraction wells were constructed to a depth of approximately 60 feet BGS and monitoring boreholes to 75 feet BGS. A clustered monitoring approach was used whereby a borehole containing sensors, gas-sampling ports, and ERT electrodes was placed nominally adjacent to a sealed/unscreened 2-inch-diameter PVC cased borehole that can be used to conduct borehole logging and cross-hole borehole geophysical surveys. Sensor boreholes are constructed with alternating layers of 100-mesh silica sand and granular bentonite every 5 feet. Four intervals are placed nominally at 32, 37, 42, and 47 feet BGS to provide vertically discrete monitoring across the injection/extraction well screen interval and contain sensors for measuring matric potential, moisture content, and humidity, in addition to gas sampling ports. Thermistor temperature sensors are also placed every 2 feet from 10 to 70 feet BGS and electrical resistivity electrodes every 5 feet within the bentonite intervals of the borehole fill material.

Both the Prototype Hanford Barrier and the Mock Tank site also have existing monitoring and logistical infrastructure that will be leveraged for implementing monitoring filed tests at those satellite sites.

INITIAL FIELD TESTS

The former desiccation treatability test site is being redeveloped for use as a VZ test bed starting in Q1 of FY2020. Site infrastructure needs include a mobile office, onsite equipment storage, dry air and nitrogen injection system, monitoring equipment, data acquisition and control systems, and power to the site.

Similar to the original desiccation test, dry gas will be injected to induce changes to subsurface conditions that can be monitored with both new and previously tested methods. Unlike the original test that used nitrogen as the dry gas, the initial tests in 2020 will use ambient air that will be conditioned to a relative humidity less than 40% and temperature greater than 70 °C. Each of the monitoring methods described above will be deployed during the initial year of testing, with the exception of the VZBM.

CONCLUSIONS

Monitoring is an integral part of remedy selection and implementation and long-term stewardship. Analysis of groundwater well samples provides important information, but is of limited value for evaluation of VZ remedies. Advancements are being made in the use of VZ monitoring techniques to augment data collected in monitoring wells and provide enhanced information for remedy selection and implementation. Hanford Site remediation decisions rely on predictive models that accurately represent the real conditions at a given site and require field-scale monitoring data to achieve that goal. The use of VZ fluid sampling, borehole logs, point in situ sensors, geophysical approaches to characterize baseline conditions in the subsurface and to monitor changes that occur in response to the injection of gas phase tracers will provide the data inputs needed to verify or reformulate models, ultimately improving their predictive ability for validating remedy effectiveness. The new test bed will allow for testing of a broad suite of technologies and evaluate the role of each to an effective VZ monitoring strategy.

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