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Pacific Northwest NATIONAL LABORATORY

Advanced Monitoring Systems for Deep Vadose Zone Applications Interim Status Report

September 2018

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RD Mackley
VR Vermeul
RE Clayton
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BQ Roberts

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

The vadose zone within the Hanford Central Plateau contains large quantities of mobile contaminants that have not yet reached the groundwater. Deep vadose zone (DVZ) contamination is located below the depth of direct contaminant exposure potential, but may be a current and/or potential future source of groundwater contamination. Monitoring to observe subsurface processes and driving forces related to contaminant transport or to directly observe contaminant movement in the DVZ provide remedy performance information prior to contaminants reaching the groundwater and thereby are important elements of a remedy implementation.

Contaminant migration in the vadose zone at the Hanford Site is a slow process, spanning decades to hundreds of years. The use of groundwater monitoring alone may be unable to provide timely information to verify long-term remedy performance. Monitoring the long-term behavior of natural subsurface systems and the performance of remedial actions will be critical to implementing and validating cleanup strategies. DVZ 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 DVZ behaviors. Long-term monitoring technologies that minimize the need for permanent surface or subsurface infrastructure are preferred to avoid degradation issues that will inevitably occur over the expected lifetime. Thus, geophysical surveys are identified as important to vadose zone monitoring approaches. At early stages of active remediation, additional information will likely be needed to capture more rapidly changing conditions as well as more direct ground truthing measurements that go beyond geophysical data alone.

Monitoring technologies have experienced several recent advancements and have been successfully demonstrated for a wide range of groundwater and vadose zone applications, including soil desiccation, surface barriers, and amendment infiltration/injections. Building on recent advancements, a set of existing and emerging long-term DVZ monitoring technologies were identified within the context of an overall monitoring strategy for the Hanford Central Plateau. This report documents initial development towards a subset of promising DVZ monitoring technologies. In FY18, progress was made on development of a cross-borehole controlled source electromagnetic imaging system, characterization of seismic-matric potential relationships for Hanford sediments, and construction of a prototype multi-level vadose pore water sampling system.

Acknowledgments

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Acronyms and Abbreviations

CSEM	controlled source electromagnetics
DVZ	Deep Vadose Zone
EC	electrical conductivity
EM	electromagnetic
ERT	electrical resistivity tomography
GPR	ground-penetrating radar
HDU	heat dissipation unit
ML-DVZS	multi-level deep vadose zone sampler
NQAP	Nuclear Quality Assurance Program
PCAP	passive capillary sampler
PVC	polyvinyl chloride
RAY	Recharge Application sYstem

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1.0 Introduction

The vadose zone within the Hanford Central Plateau (e.g., 200-BC-1) contains large quantities of mobile contaminants (e.g., Tc-99 and nitrate) that have not yet reached the groundwater. To reduce contaminant fluxes to groundwater, surface barriers or in situ remedies may be applied, which will require effective monitoring strategies to monitor both active and passive approaches. Given that contaminant transport through the vadose zone to the groundwater can span tens to hundreds of years, groundwater monitoring will not be sufficient for confirming attenuation or remediation processes in the vadose zone (Strickland et al. 2018). Effective monitoring methods must therefore be configured to provide quantitative information over long time periods.

Monitoring provides parameters and data that serve as inputs for predictive models that are used for site decisions. When these data are used to build and update models, they reduce the uncertainty associated with model predictions. 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. Geophysical methods can be used to map the spatial distribution of contaminants and hydraulic conditions, and time-lapse approaches can also assess changes that indicate contaminant movement and recharge.

Both geophysical and pore water sampling approaches are identified as methods that can be applied to the deep vadose zone (DVZ). Low-frequency electromagnetic (EM) methods measure the bulk electrical conductivity of subsurface materials similar to electrical resistivity tomography. At high frequencies, EM methods 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. Seismic methods have been shown to be highly sensitive to soil matric potential, another important parameter influencing fluid flow in the vadose zone. Monitoring 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 are being developed to provide direct evidence of contaminant migration, complementing the spatial and temporal information gained from geophysical surveys. Vadose zone pore water sampling techniques are well established in near-surface settings, this effort has focused on adapting them for use in DVZ settings.

This document presents interim results on the deployment of promising monitoring technologies identified as part of an overall DVZ monitoring strategy for the Hanford Central Plateau as outlined in Strickland et al. (2018). The adaptation of the existing technologies to the DVZ takes advantage of expertise gained from monitoring of the Prototype Hanford Barrier, mock tank, 300-FF-5 polyphosphate injection treatability test, and the desiccation and uranium reactive gas sequestration field test sites.

2.0 Monitoring Context and Needs for the Central Plateau Deep Vadose Zone

2.1 Background

The Hanford Central Plateau is located in the middle of the Hanford Site (Figure 1), where historical chemical processing of irradiated fuels for recovery of plutonium and other materials occurred. Multiple types of waste discharges occurred to the environment, some of which caused the current vadose zone and groundwater contamination.

Figure 1 shows the location of the Central Plateau DVZ region relative to other Hanford Site features, including the Columbia River. Figure 2 shows the location of the sites within the DVZ region that were identified by the U.S. Department of Energy Richland Operations Office (DOE-RL 2008) as potentially containing significant quantities of contaminants in the DVZ. A majority of waste sites with DVZ contamination in the Central Plateau are assigned to the 200-DV-1, 200-EA-1, 200-WA-1, and 200-BC-1 operable units.

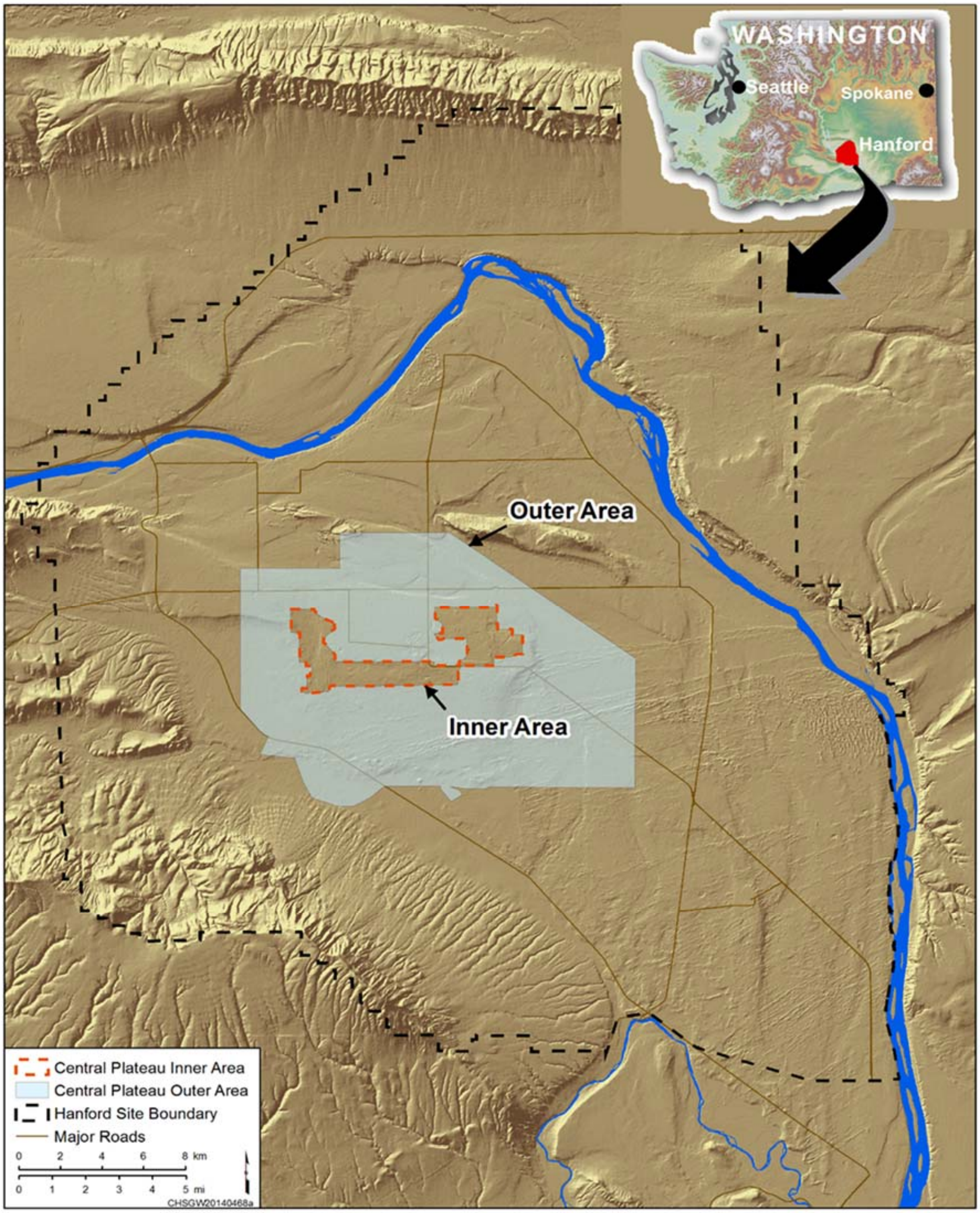

Figure 1. Hanford Site and Central Plateau location.

DOE-RL (2008) examined the available information on potential deep vadose zone contamination of technetium and uranium in partial fulfillment of Tri-Party Agreement Milestone M-015-50, *Submit a Treatability Test Work Plan for Deep Vadose Zone Technetium and Uranium to Ecology and EPA* (Ecology et al. 2018). The available information included disposal inventories, depth of contamination, and potential risk to groundwater (Eslinger et al. 2006).

Figure 2. Map showing source zone operable units within the Hanford Central Plateau Inner Area.

At many sites where liquid waste was discharged, the vadose zone is contaminated across the full thickness to the water table. Thus, monitoring approaches will need to consider potential applications for any of the depths and various DVZ hydrostratigraphic units present on the Hanford Site. This is illustrated conceptually in Figure 3.

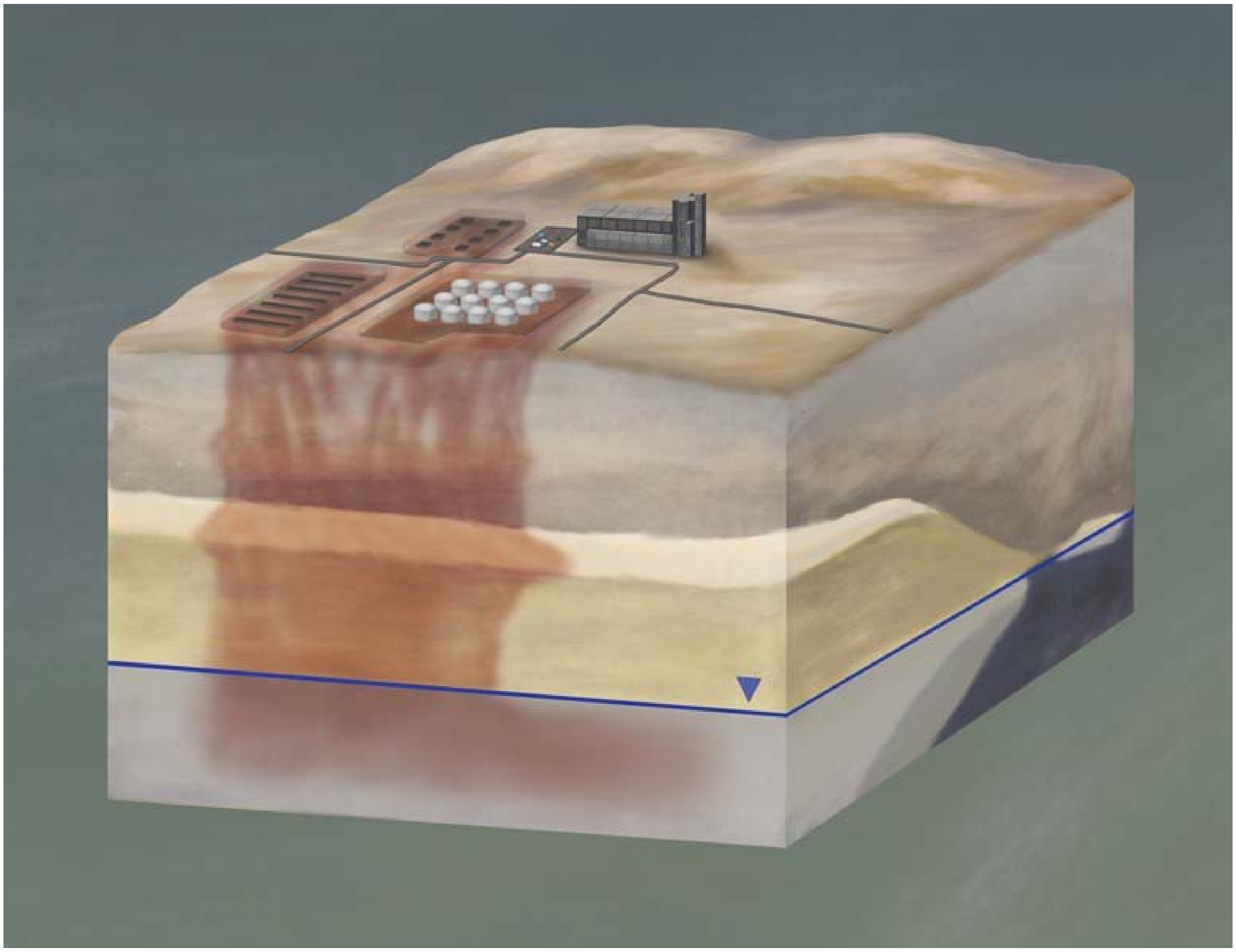

Figure 3. Conceptual view of the Hanford Central Plateau DVZ monitoring setting.

2.2 Coupled System Contaminant Dynamics

2.2.1 Vadose Zone and Groundwater Contaminant Transport

Physical transport processes such as advection, dispersion, and diffusion are critical to understanding contaminant transport in both the groundwater and unsaturated zone. However, several different processes control transport in the vadose zone relative to groundwater systems. First, a nonlinear relationship exists between water content/water potential and hydraulic conductivity. The nature of recharge at the water table and mixing of recharge water with groundwater are also important relative to the resultant groundwater contaminant concentrations. Finally, there is significant information about relevant biogeochemical processes due to their dominant roles in contaminant attenuation in groundwater systems, but due to the presence of a gas phase, they can vary significantly in the vadose zone.

2.2.1.1 Moisture Retention and Unsaturated Water Flow

The groundwater system pore space is saturated with water, but within the vadose zone, some gas (i.e., air) is present, resulting in the existence of three phases: solid and two fluids (water and gas). Common conceptual models of unsaturated fluid flow idealize subsurface materials as a group of effective capillaries and ignore the adsorptive effects. Capillary forces act on pore water in the vadose zone and impact fluid flow and water content distributions (Cohen and Mercer 1990; Hillel 1998). The capillary pressure is also commonly referred to as suction, tension, or matric potential.

Water content varies as matric potential changes and the relationship is termed the water or moisture retention curve (Figure 5). The capillary pressure generally increases nonlinearly with decreasing water content. Alternatively, capillary pressure generally increases with decreasing pore radius (or decreasing grain size). Thus, the largest pores drain first and water contents are generally higher for finer-grained materials. The last water to drain comes from the smallest pores. The dependence of the water content on the capillary pressure is a characteristic property of a soil. General properties of the characteristic relationship are dependent on soil texture, pore size distribution, and geometry. Two commonly used functions that describe the relationship between matric potential and saturation are given by Brooks and Corey (1964) and van Genuchten (1980).

Groundwater flow in typical subsurface materials generally follows Darcy's law (Darcy 1856). Groundwater flux is a function of the hydraulic conductivity and the hydraulic gradient. Water movement in the vadose zone can also be described with a version of Darcy's law that was modified by Buckingham (1907).

The primary difference for Darcy's law in the vadose zone is that the hydraulic conductivity is not a constant for a given porous medium. The unsaturated hydraulic conductivity is highly variable as a function of the water content. The relative water permeability of a given soil can change over many orders of magnitude with changes in saturation and can be estimated from the saturated hydraulic conductivity and water retention function (Burdine 1954; Mualem 1976) even under dry conditions (Webb 2000; Zhang 2011).

2.2.1.2 Recharge

Recharge is generally defined as the rate at which water enters an aquifer from any source. Recharge occurring across the Hanford Site Central Plateau is transmitted through the vadose zone to the underlying groundwater aquifer. All precipitation may not infiltrate (e.g., surface run-off), and all infiltrated water may not recharge the groundwater system (e.g., due mainly to evapotranspiration and vadose zone storage). The flux of water at depths below the influence of evapotranspiration can be used to predict future recharge. Recharge rates at the Hanford Site range from near zero to more than 100 mm/yr (Gee 1987; Fayer and Szecsody 2004; Rockhold et al. 2009) and primarily depend on surface soil and vegetation conditions.

2.2.1.3 Contaminant Attenuation

Contaminant transport is impacted by solubility, sorption, and degradation/decay processes that are a function of the contaminant properties and the biogeochemistry in the vadose zone. These processes are essentially the same as those presented and described in detail in the U.S. Environmental Agency's technical protocol for monitored natural attenuation of inorganic contaminants in groundwater (EPA 2007a,b, 2010; ITRC 2010) and described with respect to conceptual site models by Truex et al. (2011).

These processes need to be evaluated and considered in combination with the factors controlling water flux to the groundwater to estimate the contaminant flux to groundwater. Attenuation processes decrease contaminant concentrations or migration rates such that, over the long term, the combined impact is a cumulative contaminant reduction response that may be greater than the impact of any individual process.

3.0 Monitoring Technologies

3.1 Monitoring Relevant Vadose Zone Properties

Predictive modeling is needed for remedy decisions and optimization and requires site-specific information on geochemical and physical properties. One of the most critical features influencing future impacts to groundwater is the contaminant flux. Several properties influence flux to groundwater, including the spatial distribution of contaminant concentrations, permeability, porosity, moisture content, and matric potential. Information must also be acquired soon enough for timely decision-making in system response.

The ultimate goal of vadose zone remediation is to assure that contaminant mass flux is at levels where regulatory thresholds, such as groundwater maximum concentration limits, will not be exceeded. For some scenarios, including soil desiccation and surface barriers, contaminant flux is reduced by removing moisture from the subsurface, lowering the unsaturated hydraulic conductivity and water flux, which in turn reduces contaminant flux. One measure of satisfactory remedy performance is demonstrating that unsaturated hydraulic conductivity can be maintained sufficiently low using knowledge of soil texture and measurements of moisture or matric potential.

Sediment samples in the vadose zone provide detailed information on a wide range of properties (i.e., porosity, permeability, moisture content, and contaminant concentrations). This information is critical to the overall characterization and monitoring strategy but is limited to a discrete number of locations and discrete times. Continuous sampling methods and methods that cover broad spatial areas can be used to improve flux estimates. Monitoring methods described here can be used independently and in combination to provide data that improve understanding of vadose zone behavior. These methods include both point-scale sensors and geophysical methods that are sensitive to moisture content, matric potential, and electrical conductivity/salinity.

Technology adaptation for the DVZ include (1) design and construction of a cross-borehole controlled source electromagnetic imaging system, (2) identification of the relationships between seismic velocity and matric potential for Hanford sediments and (3) design of a multi-level vadose zone pore water sampling system.

3.1.1 Electrical and Electromagnetic Methods

Geoelectrical and EM methods have been widely used for subsurface imaging in both near-surface and deeper environments (Wilt et al. 1995; Peterson 2001; Binley et al. 2002; Zhdanov 2002). 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 (Johnson et al. 2010; Strickland et al. 2010; Truex et al 2013).

Controlled source electromagnetics (CSEM) is a widely used geophysical method for both near-surface and deep applications ranging from petroleum exploration to environmental characterization (Constable and Srnka 2007; Wilt et al. 1995). 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 ground-penetrating radar (GPR), lower frequency (Hz- KHz) CSEM measurements transmit EM into the ground that is sensed using a receiving device. Low-frequency methods utilize 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.

EM phenomena are governed by Maxwell's equations, which can be combined to produce vector wave equations (Helmholtz equation) for the electric and magnetic fields. Maxwell's vector wave equations are used to simulate the EM fields for both GPR and CSEM. A central aspect of any wave is the propagation constant, which can be decomposed into two key attributes: the phase and attenuation constants. The phase velocity can be determined from the phase constant and along with the attenuation influence the signal that is ultimately measured. For EM waves, the phase velocity and attenuation constant are functions of both the electrical conductivity and permittivity of the material through which the wave propagates.

At very low frequencies, the electric field can be approximated as the negative gradient of a scalar electric potential or voltage. Maxwell's equations can be simplified to produce the continuity equation describing the electric potential field that results from direct current electrical sources introduced into an electrically conductive material. The continuity equation forms the basis for simulating the applied currents and the potentials that arise for electrical resistivity tomography (ERT). The EM velocity depends on the electrical conductivity and permittivity of subsurface media as well as the frequency of the propagating wave. The material properties are seldom known so two commonly made assumptions are (1) the magnetic permeability is equal to that of free-space, and (2) the electrical conductivity is much less than the product of the frequency and electrical permittivity, often termed low-loss conditions. Under these conditions, the EM velocity only depends on the electrical permittivity.

The electrical permittivity of geological media is strongly dependent on moisture content because of the large difference between water and typical mineral components. The *apparent permittivity* can be determined from the observed velocity of an EM pulse propagating through the sediment/rock. The term *apparent permittivity* is used here to mean the permittivity value that is inferred from measurement of the velocity of an electromagnetic wave at a given frequency. Under low-loss conditions, it has been shown that the volumetric moisture content is a linear function of the square root of the apparent electrical permittivity and largely independent of soil texture (Topp et al. 1980; Ledieu et al. 1986; Topp and Ferré 2002).

The bulk (composite mixture of both sediment/rock and fluid) electrical conductivity (EC), inverse of resistivity, is a useful metric for characterizing the subsurface. EC is sensitive to several important variables influencing contaminant flow and transport, including pore-water solute concentration, moisture content, and soil texture (Slater and Lesmes 2002).

The bulk EC of the subsurface has been widely observed to follow the empirical Archie's law (Archie 1942) in low clay content, non-conductive sediments. The EC of both aqueous solutions and bulk soil/rock also depends on temperature. The temperature dependence of bulk conductivity in the vadose zone depends on water content, but is always monotonic so that a change in temperature will correspond proportionally with changes in bulk conductivity (Friedman 2005; Ruijin et al. 2011).

CSEM is capable of imaging the distribution of EC, 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. CSEM does not require electrical contact with the ground and can be deployed within non-electrically conductive boreholes.

3.1.2 Seismic

Seismic-based geophysical methods can provide estimates of moisture content and matric potential (including spatial distribution and temporal changes) in the DVZ. Seismic wave propagation is governed by elastodynamic theory. Stress, displacement, deformation, strain, and motion are central to the behavior of elastic/seismic waves. Elastic waves are stress/displacement waves. Unlike EM waves that propagate through isotropic media at a single velocity, elastic waves in solid media exhibit two velocities for different types of body waves (compressional and shear waves).

The mechanical properties that determine seismic velocities of geologic materials depend on the stress state that is applied. In general, as the overburden or confining stress (due to the weight of the overlying material) increases, so does the compressional and shear velocity. Since unsaturated systems consist of three phases – solid matrix and two fluids (typically water and air) – effective stress must be considered across all three phases (Terzaghi 1925). Effective stress is defined as the difference between confining stress and fluid pressure.

It has been generally understood that the effective stress and therefore the seismic velocity of sediments, depends on moisture content and matric potential (Brutsaert and Luthin 1964; Bishop and Blight 1963). Recent research has identified matric potential as a relatively large influence on the observed seismic velocity (Santamarina et al. 2001; Lu and Sabatier 2009; Whalley et al. 2012). Whalley et al. (2012) developed a model of seismic velocity as a function of effective stress for a range of sediment types and obtained excellent fits to their observations. A reformulation of this model along with measurements of seismic velocity and overburden stress can be used to estimate matric potential. Following a similar approach, seismic velocity tomography in unsaturated sediments may be used to image the spatial distribution of matric potential. Under very dry conditions, like those that occur beneath surface barriers and in zones of desiccation, matric potential is a better performance indicator than moisture content (Zhang et al. 2011).

3.2 Pore Water Sampling

Analogous to water sampling from saturated groundwater aquifers, pore water collection from the vadose zone 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.

Suction samplers utilize a porous cup or tube geometry that is placed so that its outer surface is in contact with soil. A partial vacuum is applied to the interior that causes pore water to be drawn into the device under the condition that the vacuum does not exceed the air entry pressure of the porous material (otherwise soil gas/air will be drawn in). A number of complications have been identified (McGuire et al. 1992) such as clogging, pressure/duration dependent results, and adsorption of analytes or contamination by the sampler porous material. Common sampler materials are ceramic, stainless steels, fritted glass, and Teflon, each possessing advantages and disadvantages. Adsorption/contamination is generally best for Teflon and fritted glass, followed by stainless steel, with ceramic having the largest effect.

Passive capillary samplers (PCAPs) are constructed by placing a wicking material (typically a rope made of many individual fibers) in contact with soil that introduces a hanging water column to create tension on the soil proportional to the length of the wick (Brown et al. 1986; Knutson and Selker 1994, Frisbee et al. 2010). Unlike suction samplers that require applying a vacuum to the device, PCAPs passively collect soil pore water. PCAPs have been shown to work well over a wide range of soil conditions but are ineffective at high matric potentials due to limitations of the amount tension that can be applied. Fiberglass is commonly used for the wick material and can affect the chemistry of the sample by adsorption and contamination of analytes by the wick material, similar to suction samplers (Goyne et al. 2000; Perdrial et al 2014). In general, constituents of the glass (e.g., Na, Si, B) can significantly affect the collected sample results, but a wide range of other analytes are unaffected.

Vadose zone pore samplers are typically used in shallow settings less than 10 m deep; however, a number of commercially available suction cup samplers are available that can be installed at depths as high as 70 m. The installation of currently available deep samplers requires that they be installed in a borehole that has been constructed using annular fill materials (e.g., sand or diatomaceous earth) with properties that are different the surrounding soils. Also, pore water samples are delivered to the surface via tubing that will limit the number of samplers that can be installed in an individual borehole. Like any buried device, maintenance of the subsurface components is limited.

Long-term collection of pore water samples at multiple locations/depths within the DVZ can provide data on the migration of a wide range of mobile contaminants and warrants further development towards application to the Hanford DVZ.

4.0 Monitoring Technology Development Efforts

4.1 Electromagnetic Methods

ERT has undergone major advancements 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 (Johnson et al. 2010; Johnson and Wellman 2013; Truex et al. 2013). 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 polyvinyl chloride (PVC) (or other non-conductive material) cased borehole and low-resistivity grout construction.

To this end, a cross borehole CSEM imaging system was designed and constructed. The basic design of the system is similar to that of Wilt et al. (1995) and is composed of both EM source and receivers, as well as the associated data acquisition and control system (Figure 4). The EM source is a coil/solenoid designed and constructed around an approximately 0.03 m diameter, 1.2 m long PVC tube, machined with threads and wound 400 turns using 18 gauge wire (Figure 5). Interior to the tube, ferrite beads were installed to increase the magnetic permeability of the coil. The coil is powered from the surface using sine wave signal generator (Model AMX 312, Pacific Power Source, Irvine, CA). Two receiver designs having differences in noise floor, number of magnetic field measurement components, and frequency range were implemented. The first receiver design is identical to the EM source transmitter. The second is a fluxgate magnetic field sensor (Model 690, Bartington Instruments Ltd, Oxforshire, UK). The fluxgate sensor has a range of +/- 100 nT, frequency response from DC to 1 kHz, and a noise level less than 20 pT/√Hz.

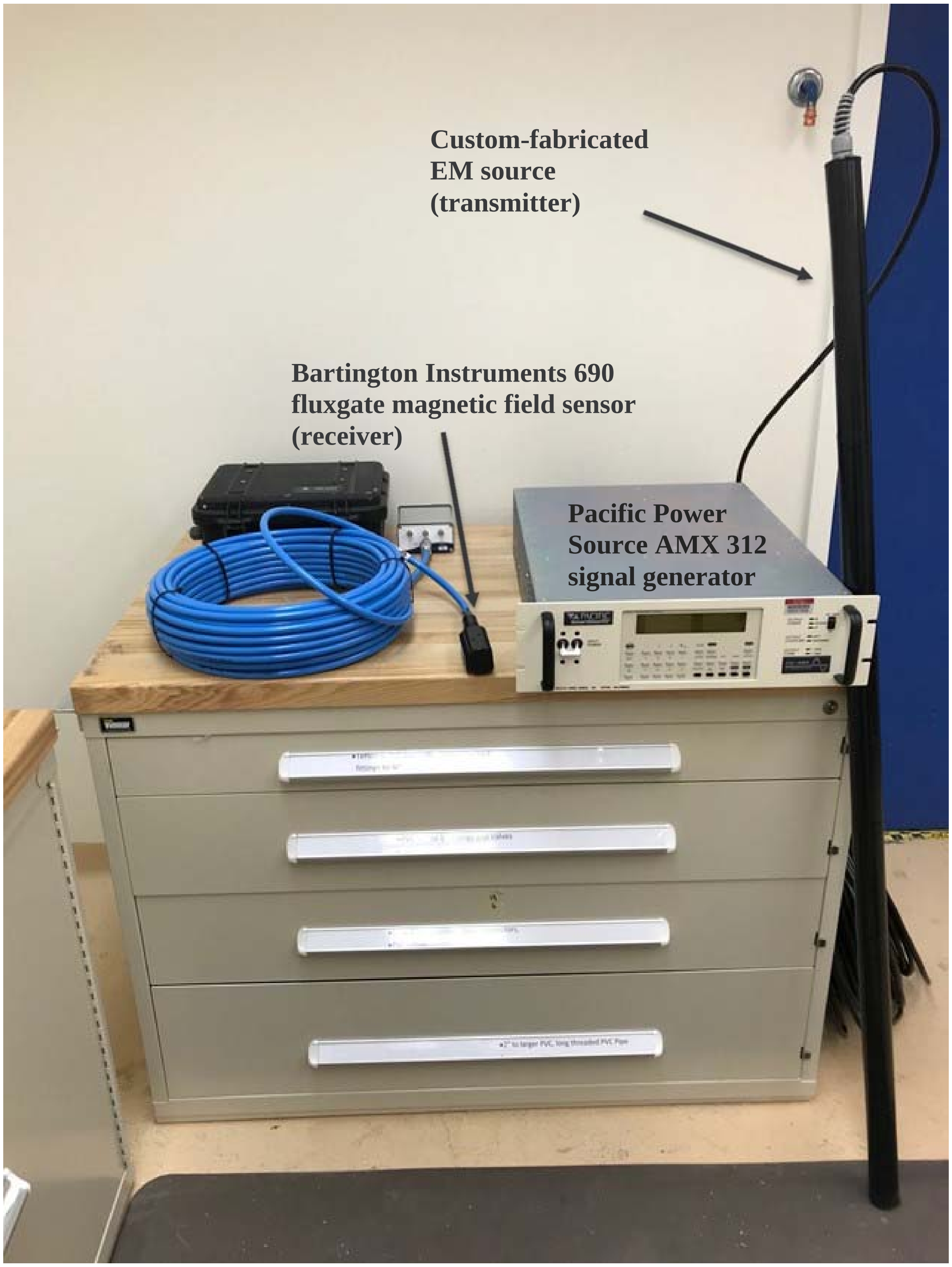

Figure 4. Developmental cross borehole CSEM imaging system.

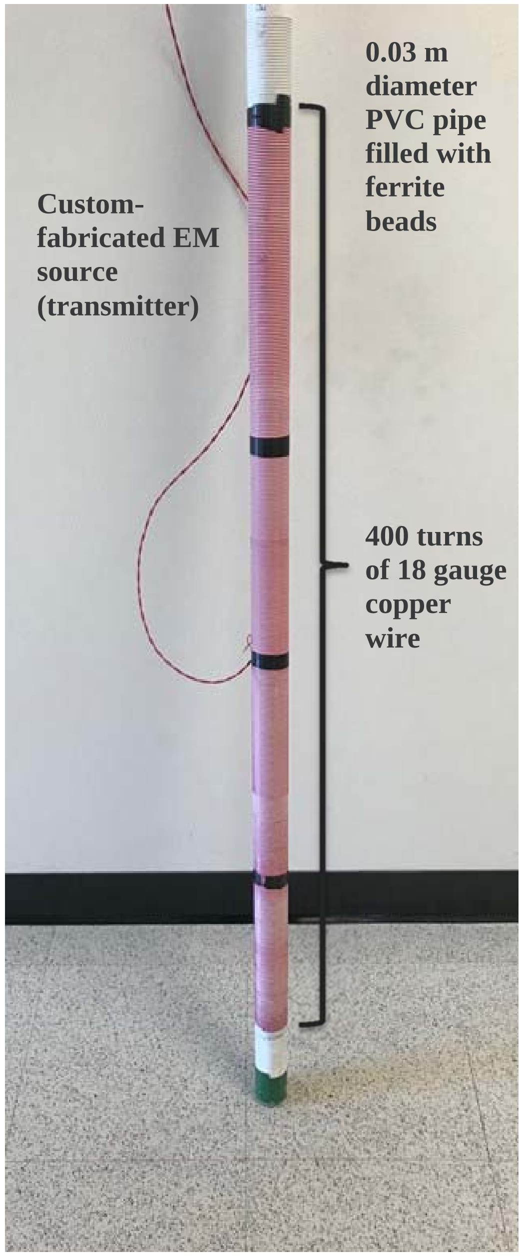

Figure 5. EM source (transmitter) showing the winding used in the design (with black protective jacket removed).

Construction of the cross borehole CSEM was completed in FY18 along with initial laboratory testing. Commercial cross-borehole CSEM systems are not available for sale and are intended for deep oil/gas reservoir environments. The pressure and temperature ratings required for such a system far exceed those for shallow environmental applications. The DVZ cross-borehole CSEM was designed with the flexibility for expansion with an array of three component magnetic fluxgate receivers for efficient EC imaging. Laboratory and field testing of the system is planned to evaluate the range and data sets that can be produced with this type of system.

4.2 Seismic Methods

Seismic-based geophysical methods can provide estimates of moisture content and matric potential (including spatial distribution and temporal changes) in the DVZ. Laboratory experiments were initiated in FY18 to determine the relationship between seismic attributes and both overburden stress and matric potential using sediment textures/formations typical of the Hanford Site. Seismic wave propagation attributes (i.e., velocity, attenuation) depend on moisture content, temperature, soil type/texture, as well as matric potential and overburden stress. Under very dry conditions, recent work by others has shown seismic velocity is very sensitive to soil matric potential (Santamarina et al. 2001; Lu and Sabatier 2009; Whalley et al. 2012).

A general relationship describing seismic velocity as a function of overburden stress and matric potential has been demonstrated for a range of sediments (Whalley et al. 2012). Using this relationship, measurements of seismic velocity and overburden stress can be used to estimate matric potential. With this approach, seismic velocity tomography in unsaturated sediments can be used to image the spatial distribution of matric potential, using site-specific information on Hanford sediments.

FY18 laboratory experiments focused on determining the relationship between seismic attributes and Hanford sediments (warden silt loam) under a range of imposed conditions. An apparatus was constructed to first saturate, then slowly desaturate the sample, while acquiring measurements of matric potential, temperature, and both compressional and shear velocity (Figure 6). In addition to changing matric potential and water content, the system could impose variable stress conditions. In this case, a range of lateral confining stress was applied and equal to the axial stress. Confining stress ranged from 20 to 80 psi for this set of initial experiments.

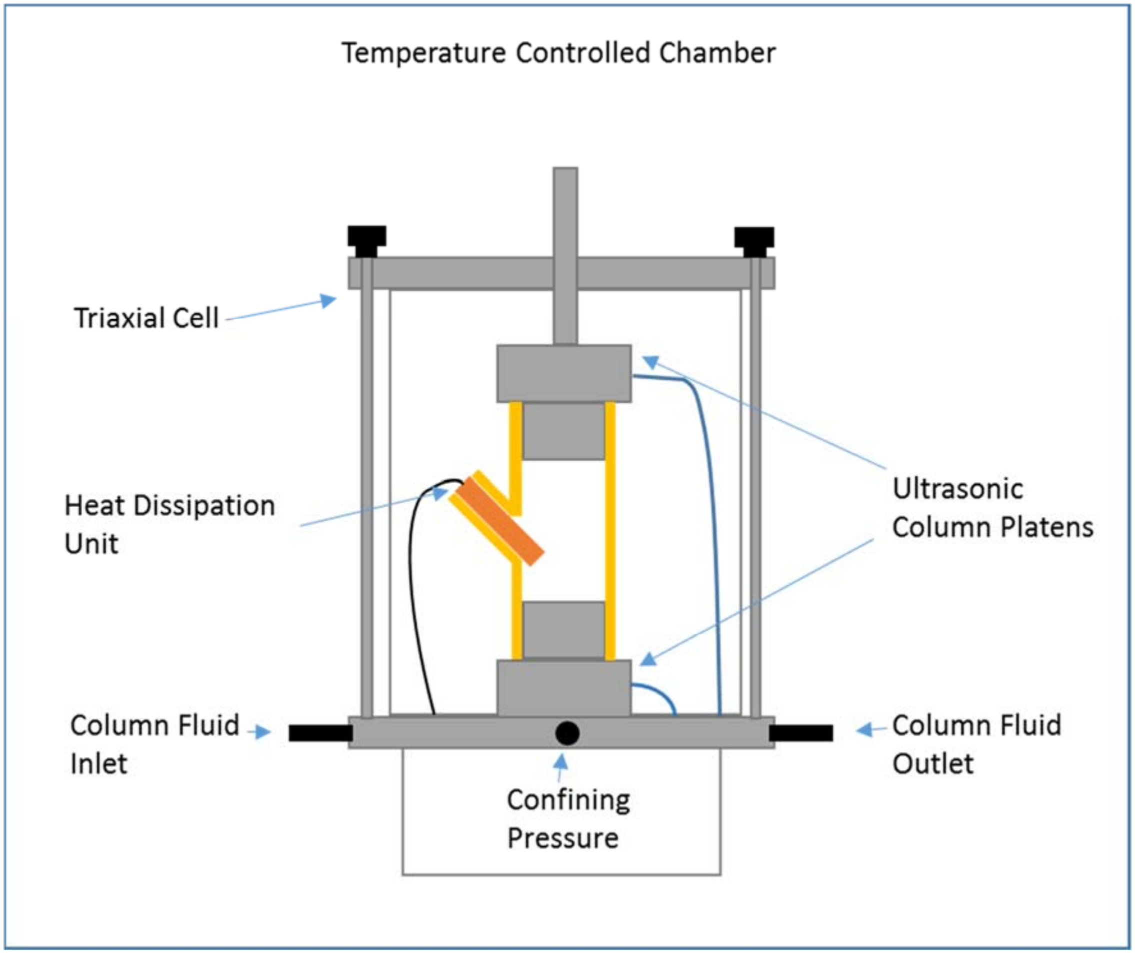

Figure 6. Schematic of apparatus for measuring ultrasonic velocity and matric potential.

Column platens with embedded compressional and shear wave transducers were used to both generate and measure elastic wave velocities at ultrasonic frequencies from 5 to 250 kHz (Figure 7). A ULT-200 ultrasonic velocity test system (GCTS Testing System, Tempe, AZ) was used to generate ultrasonic pulses and acquire the received signals.

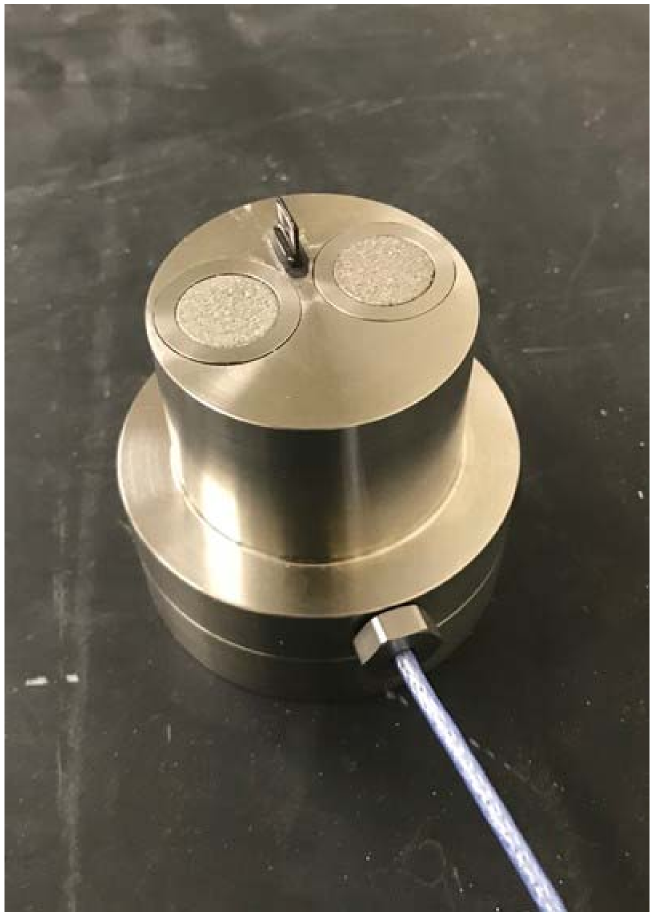

Figure 7. Column platen for mounting sediment samples and measuring ultrasonic velocities.

Matric potential and soil column temperature were measured using a heat dissipation unit (HDU; Model 229L Campbell Scientific Inc., Logan, UT). The 229L HDU is capable of measuring matric potential over a wide range and has been successfully used both in the lab and the field. The final assembly showing the installation of the ultrasonic column platens and HDU is shown in Figure 8.

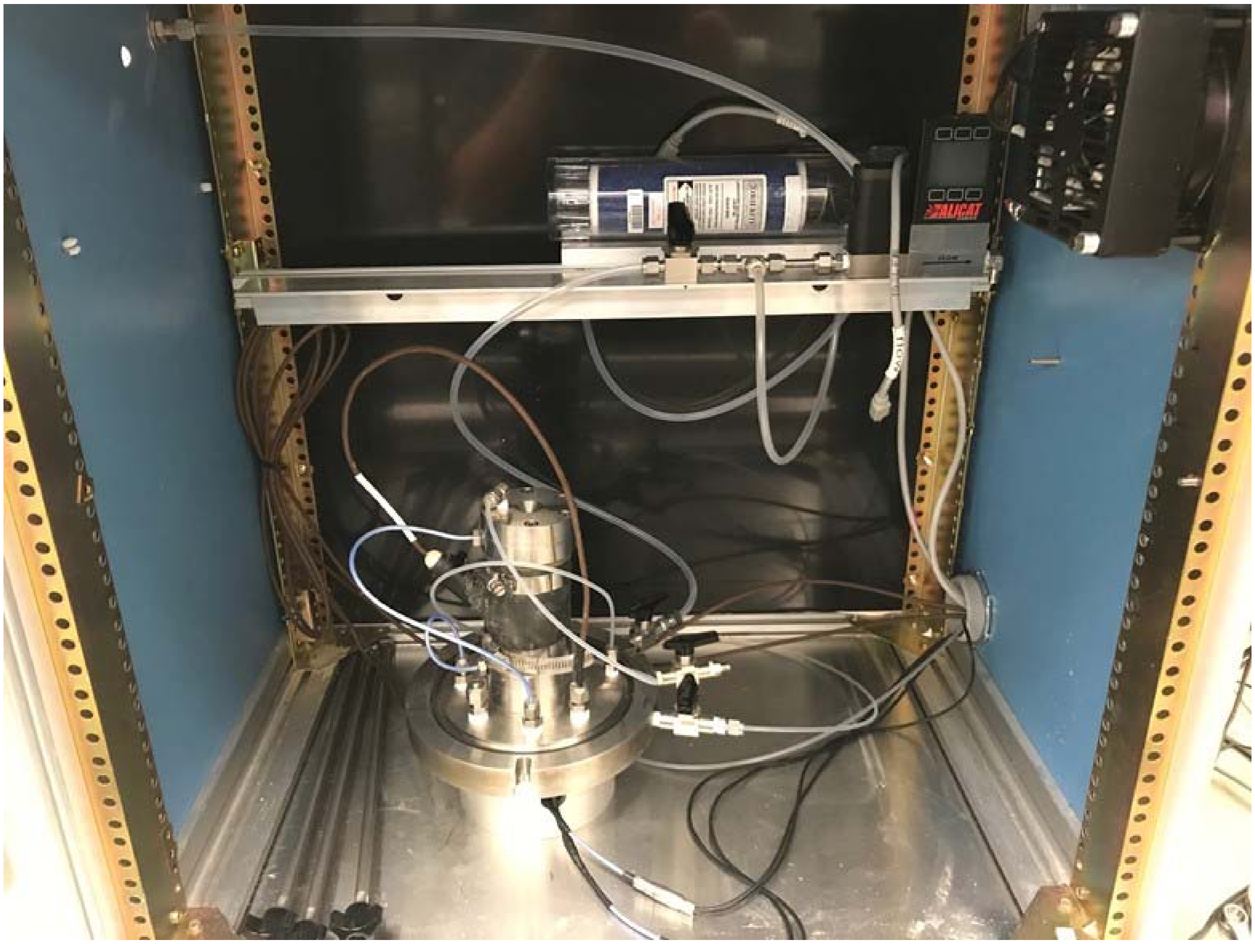

Figure 8. Column setup showing the installation of HDU and ultrasonic platens prior to seismic testing.

Samples were evaporatively desaturated, and at each desaturation step, confining pressure was varied. Matric potential and ultrasonic velocities were recorded at each step. Evaporative desaturation continued until very low final matric potentials were obtained, approximately 30 bar. Initial results for warden silt loam are consistent with published relationships (Figure 9). Additional relationships between seismic attributes and other Hanford sediments are needed for deployment in multiple soil types.

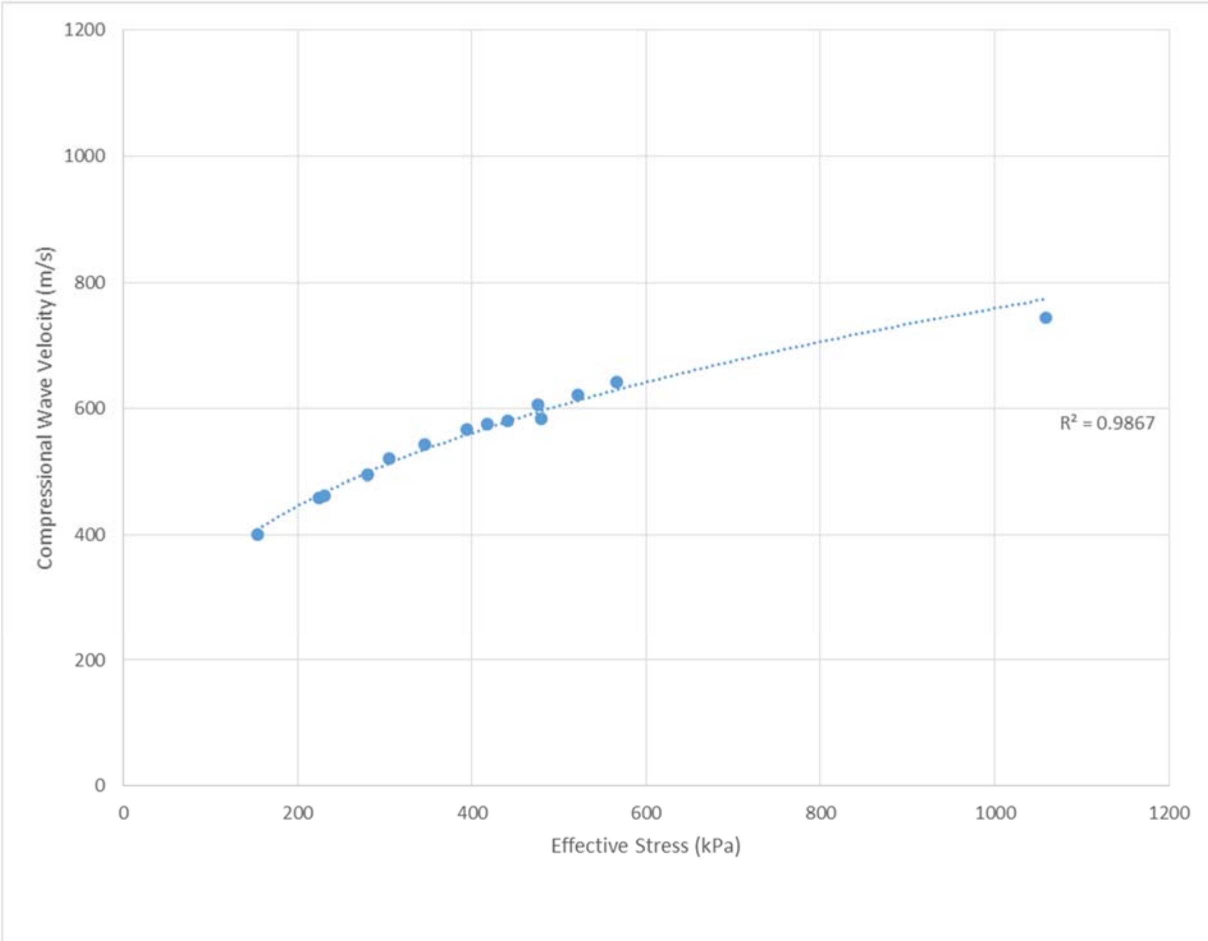

Figure 9. Seismic velocity data for Warden silt loam test sample (blue circles) along with fit using power law model for effective stress (dashed blue line).

4.3 Vadose Zone Multi-level Pore Water Sampler

A number of sampler designs have been used to collect vadose zone soil pore water, which include both vacuum porous cup samplers and passive capillary wicks (Litaor 1988; Jabro et al. 2008). Commonly used samplers are individually emplaced at a single depth and can provide a physical sample only at that location and time of collection for laboratory analysis. There are drawbacks to each type of sampler. Of particular importance is alteration of the chemical composition by sampling (McGuire et al. 1992). To meet the needs of the DVZ, multi-level borehole sampling systems originally developed for saturated conditions were adapted for DVZ conditions.

Two multi-level deep vadose zone samplers (ML-DVZS) designs were constructed, followed by the initiation of laboratory column tests for verification. Each sampler configuration utilizes a porous stainless steel membrane (Figure 10). To provide sampling at multiple depths along a wellbore, a modified multi-level sample acquisition system (Westbay Instruments; see Koch and Pearson 2007 for a review), which is generally used for collection of water samples under saturated conditions (Figure 11), was modified to interface with the suction sampling elements for unsaturated pore-water sample acquisition.

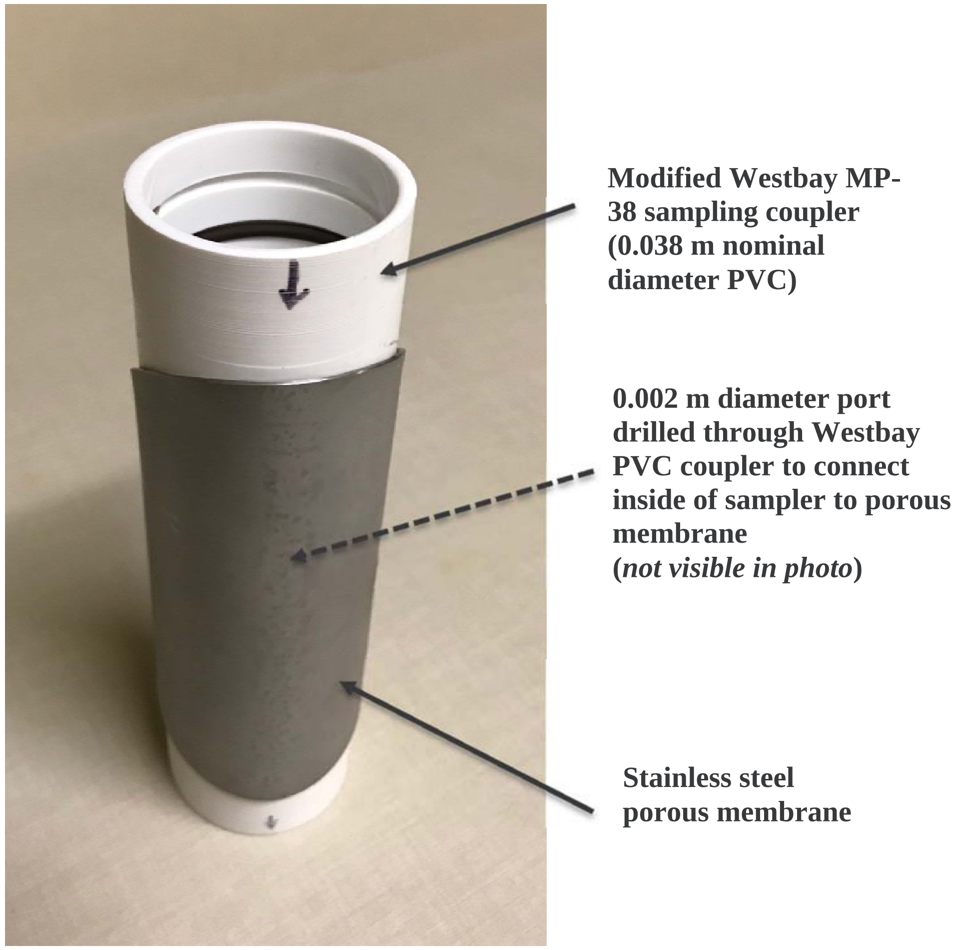

Figure 10. Custom-fabricated sampling element for use in the ML-DVZS.

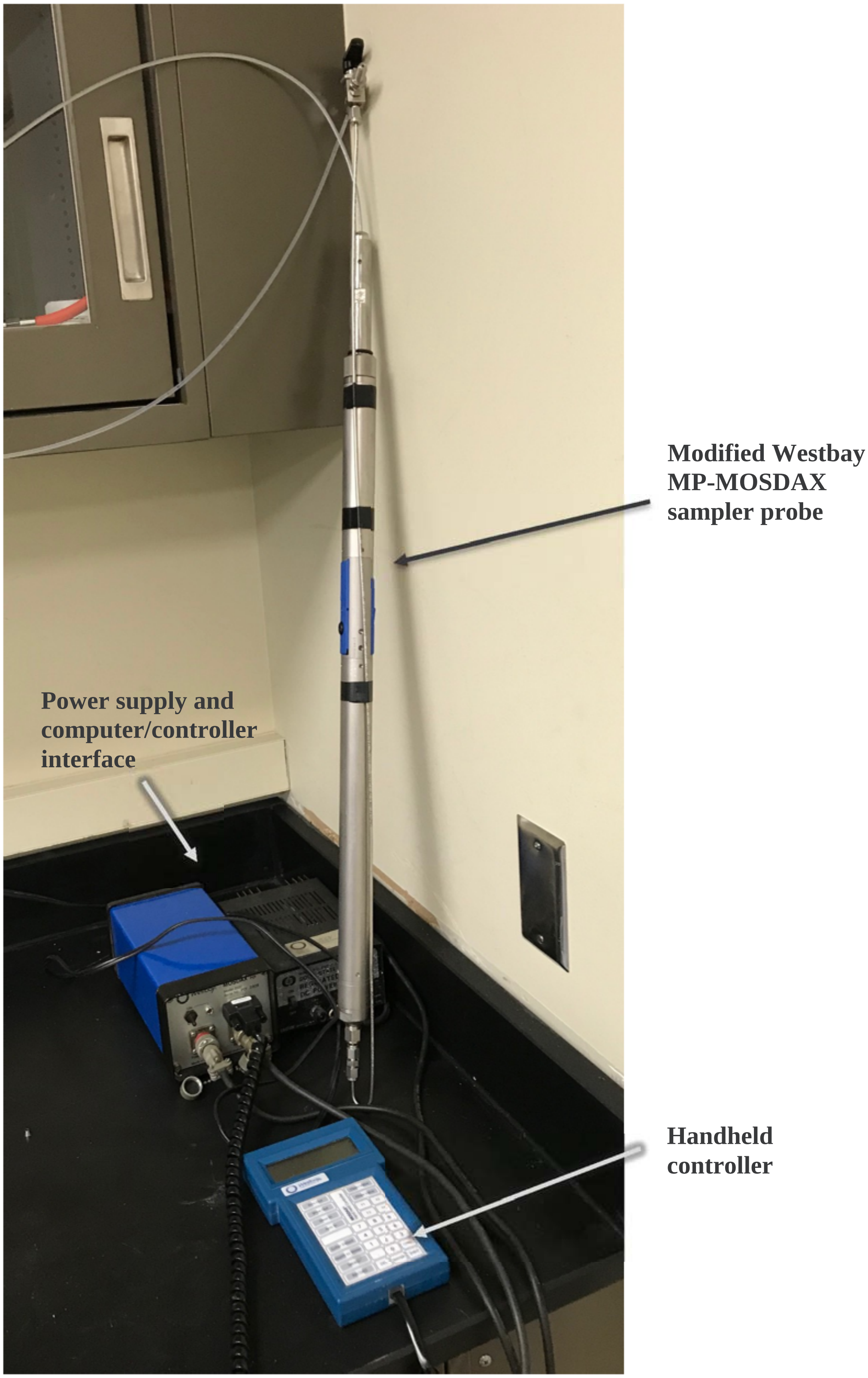

Figure 11. Components of the ML-DVZS acquisition system.

Prior to developing a full-field-scale design for an ML-DVZS capable of providing spatially and temporally discrete pore water samples under Hanford Site Central Plateau conditions, an initial assessment of pore water sampling elements and sample acquisition designs was performed at the bench scale. These laboratory-scale tests were needed to test different configurations under more controlled conditions and provide the design information needed to upscale the sampling system for full-field-scale application. Initial tests were conducted using a small-scale test cell that was developed to support an assessment of prototype pore-water sampling elements, and their use in conjunction with the sample acquisition system. Information from this testing will be the basis for selection of the preferred sampling element design(s) once the bench-scale tests are completed.

Following this assessment, promising pore water sampling element and sample acquisition configurations will be evaluated in intermediate-scale column experiments. To minimize column wall effects, these tests will be performed using large-diameter columns (~ 60 cm diameter [Figure 12]). In addition to the intermediate-scale columns, a Recharge Application sYstem (RAY) was also designed and constructed (Figure 13). The RAY is designed to be attached to the top of the intermediate-scale columns and is outfitted with an array of 36 solenoid valves and emitters that can be used to control the spatial and temporal distribution of recharge applied to the top of the column. The system is fully automated and controlled through a Campbell Scientific, Inc. data acquisition and control system. In addition to controlling recharge rates, the RAY can also be used to apply pulses of tracer that will be used to assess the ML-DVZS's ability to assess transport properties and track advancement of a simulated contaminant front.

The first packing of the intermediate-scale column will be conducted with the vadose zone sampling string in place. This approach will allow for an initial assessment that is not affected by possible drilling-induced sampling artifacts. Once this assessment has been completed, the intermediate-scale testing will then focus on evaluating the potential for drilling- and construction-related effects on pore water sampler performance. For this suite of tests, simulated boreholes will be drilled into the soil column and selected ML-DVZS will be installed in a manner that best replicates actual field-scale construction conditions in order to assess real-world implementation challenges. The effects of non-native completion materials will be evaluated by emplacing both native and non-native materials in the borehole annular space and comparing their effects on pore water sample collection. Each configuration tested will provide for hydraulic contact between the soil and the sampler and a means of collecting pore water samples at depth.

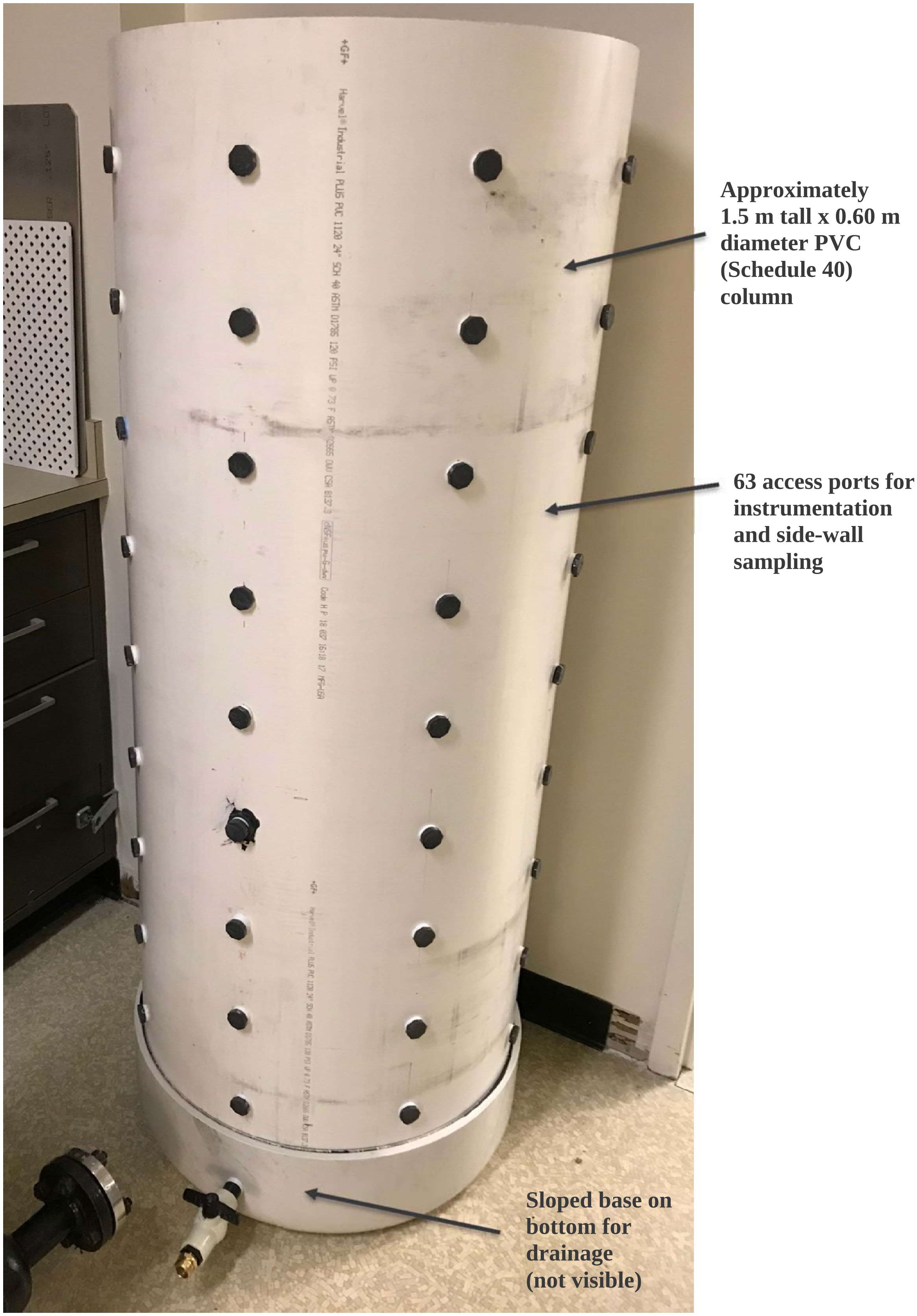

Figure 12. Large-scale column for testing of ML-DVZS.

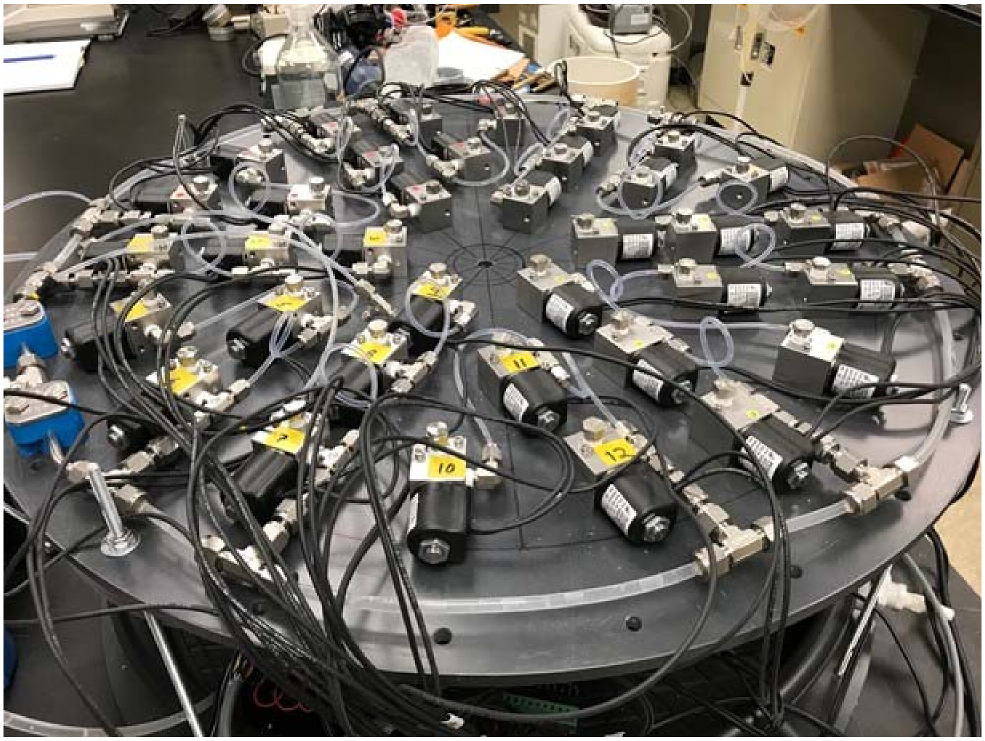

Figure 13. View showing the top of the Recharge Application sYstem (RAY) with its array of 36 solenoid valves. Valve-controlled spray emitters (not visible in photo) are located on the bottom of the RAY.

During the column experiments, a conservative tracer solution will be applied to the top of the column and pore water samples collected from ML-DVZS selected for evaluation. The effluent at the bottom of the column will also be collected. Pore water sampler performance will be evaluated by comparing solute concentration measurements collected using ML-DVZS, drainage water, and 1:1 soil pore water extracts on side-wall sediment samples (e.g., cores taken during advancement of tracer front). Construction of the large diameter columns, recharge application system, and instrumentation has also been initiated and is nearly complete.

5.0 Conclusions

Monitoring technologies have seen many advancements recently and have been successfully demonstrated for a wide range of groundwater and vadose zone applications, including soil desiccation, surface barriers, and amendment infiltration/injections. Building on the recent advancements, a set of existing and emerging long-term DVZ monitoring technologies were identified within the context of an overall monitoring strategy for the Hanford Central Plateau. This report documents initial efforts focused on adapting available technologies for application to the DVZ. These technologies included adapting a cross-borehole CSEM imaging system, establishing seismic-matric potential relationships for Hanford sediments, an constructing a prototype multi-level vadose pore water sampling system. Based on efforts to date, these technologies show promise for monitoring in the DVZ.

6.0 Quality Assurance

The results presented in this report originate from work governed by the Pacific Northwest National Laboratory Nuclear Quality Assurance Program (NQAP). The NQAP implements the requirements of the U.S. Department of Energy Order 414.1D, *Quality Assurance*, and 10 CFR 830 Subpart A, *Quality Assurance Requirements*. The NQAP uses ASME NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Applications*, as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

Two quality grading levels are defined by the NQAP:

Basic Research - The required degree of formality and level of work control is limited. However, sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

Not Basic Research - The level of work control is greater than basic research. Approved plans and procedures govern the research, software is qualified, calculations are documented and reviewed, externally sourced data is evaluated, and measuring instrumentation is calibrated. Sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

The work supporting the results presented in this report was performed in accordance with the *Basic Research* grading level controls.

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