COMPARISON OF THREE DRILLING TECHNOLOGIES TO CHARACTERIZE THE VADOSE ZONE, HANFORD SITE

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of ROCHELLE HALES HOLM find it satisfactory and recommend that it be accepted.

Chair

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Abstract

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A recently developed direct-push technology (hydraulic hammer rig) was used for vadose zone characterization to 36 m depth adjacent to a mixed-waste disposal site in the 200 West Area at the U.S. Department of Energy's Hanford Site near Richland, WA. The capabilities of the hydraulic hammer rig in terms of time required to reach target depths, depth of penetration, and ability to obtain representative soil samples were evaluated and compared to two other characterization techniques used at the site (Enhanced Access Penetration System and cable tool drilling) in similar geologic conditions. The hydraulic hammer rig technology took several hours to reach the Cold Creek unit calcic paleosol stratum versus days for the Enhanced Access Penetration System and weeks to months for cable tool drilling. The hydraulic hammer rig is an innovative and rapid vadose zone drilling technology with proven capabilities to penetrate, characterize, and sediments down to about 36 m depth without bringing soil cuttings to the surface.

PREFACE

This thesis was written in the form of a manuscript to be submitted to the Vadose Zone Journal (ISSN: 1539-1663); therefore, it was formatted in the style required by the Journal. This study was conducted while I was an employee of Vista Engineering Technologies, L.L.C., Kennewick, Washington. The study, which was conducted on the Hanford Site in south-central Washington state, was conducted under contract #DE-AC06-03NT41826 as a prime contractor to the U.S. Department of Energy. The manuscript will be submitted with co-authors, Dr. Wesley Bratton, Vice President of Vista Engineering Technologies, L.L.C., and thesis committee members Mr. Steven Smith, Mr. Kenneth Moser, and Dr. Mark Byrnes. Supplemental information is provided in the Appendices.

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COMPARISON OF THREE DRILLING TECHNOLOGIES TO CHARACTERIZE THE VADOSE ZONE, HANFORD SITE

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1. Abstract

A recently developed direct-push technology (hydraulic hammer rig) was used for vadose zone characterization to 36 m depth adjacent to a mixed-waste disposal site in the 200 West Area at the U.S. Department of Energy's Hanford Site near Richland, WA. The capabilities of the hydraulic hammer rig in terms of time required to reach target depths, depth of penetration, and ability to obtain representative soil samples were evaluated and compared to two other characterization techniques used at the site (Enhanced Access Penetration System and cable tool drilling) in similar geologic conditions. The hydraulic hammer rig technology took several hours to reach the Cold Creek unit calcic paleosol stratum versus days for the Enhanced Access Penetration System and weeks to months for cable tool drilling. The hydraulic hammer rig is an innovative and rapid vadose zone drilling technology with proven capabilities to penetrate, characterize, and sediments down to about 36 m depth without bringing soil cuttings to the surface.

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2. Introduction

Remedial investigation of the 200-PW-1 Operable Unit mixed-waste disposal sites in the 200 West Area of the U.S. Department of Energy's Hanford Site, near Richland, WA, utilized a graded approach to characterize the nature and extent of radioactive (plutonium and americium) and organic (carbon tetrachloride) contaminants in the vadose zone. Initial passive soil vapor surveys provided broad coverage to identify areas for a more focused and intensive investigation. One of the waste sites intensively investigated was the 216-Z-9 Trench. From 1955 to 1962, 132 000 to 477 000 kg of carbon tetrachloride (CCl_4) was estimated to have been disposed to the 216-Z-9 Trench along with high-salt, acidic aqueous wastes and organics wastes that included tributyl phosphate, dibutyl butyl phosphonate, lard oil, nitrate, americium, and an estimated 106 kg of plutonium.

Because of the significant radiological and chemical hazards present at the 216-Z-9 Trench, the only practical subsurface characterization methods are those that minimize or control airborne vapors and particles. Previous investigations have included cable tool drilling of boreholes and cone penetrometer testing (CPT) push holes (USDOE, 2006b). Because of the limited penetration depths (maximum of 35.4 m) historically achieved in the 200 West Area sediments by up to 36.3 metric ton CPT, a combined CPT and drilling technology – the Enhanced Access Penetration System (EAPS) – was developed especially for the 200 West Area and used to investigate several waste sites (Applied Research Associates, Inc., 2006). In 2005, a direct-push technology (hydraulic hammer rig [HHR]) was developed to provide vadose zone characterization at the Hanford Site Tank Farms (a collection of subsurface tanks that stored liquid waste from the historic processing of uranium and plutonium). After several modifications, an additional HHR was built to conduct vadose zone characterization at nine unique locations adjacent to the 216-Z-9 Trench (USDOE, 2007).

This study evaluated and compared nine HHR boreholes adjacent to the 216-Z-9 Trench against one cable tool borehole drilled on the south side of the Trench and four EAPS boreholes drilled at nearby waste sites in similar geologic conditions. These three different vadose zone characterization technologies were compared based on time to reach the Cold Creek unit (CCU) calcic paleosol stratum (a distinctive calcium-carbonate cemented layer at a depth of about 36 m depth), depth of penetration, and ability to collect representative vadose zone soil samples. The motivation for considering new drilling technologies for characterization of the subsurface was based on achieving a reduction in schedule time, project costs, waste management responsibilities, and potential for exposure of personnel to radiological and volatile organic contaminants. The investigation area adjacent to the 216-Z-9 Trench is shown in Figure 1. The hypothesis for this study was that the HHR is an innovative and rapid vadose zone technology capable of penetrating, characterizing, and sampling sediments from the ground surface down to the CCU in the 200 West Area at the Hanford Site, WA.

3. Overview of Site

The vadose zone in the 200 West Area adjacent to the 216-Z-9 Trench is approximately 67 m thick and is comprised of three main geologic units (Figure 2). The Hanford formation is the uppermost unit extending from the ground surface to about 33 m depth. This cataclysmic glacial flood deposit is composed of a heterogeneous mix of unconsolidated sediments that range from boulder- to silt-size particles. The CCU is present from about 33 to 36 m depth and is comprised of two distinct layers. The upper silt layer is about 2.5 m thick and the lower "caliche" layer (169 m elevation NAVD88) is about 0.5 m thick and varies from gravel, sand, and silt with a calcium carbonate cemented matrix. The lowermost vadose zone unit in the study area is the Ringold Formation which consists of a semi-consolidated silty-sandy gravel with lenses of gravelly to muddy sand (USDOE, 2006b).

Over the years, the more mobile wastes disposed to the 216-Z-9 Trench have migrated from the original disposal site into the Hanford formation and subsequently passed through the Cold Creek unit to the groundwater. The conceptual site model indicates CCl_4 is retained in thin, fine-grained (i.e., silt) layers of the Hanford formation. Significant concentrations of CCl_4 have been observed in a 61 cm thick silt lense at an average depth of 19.8 m below ground surface (bgs) in the vicinity of well 299-W15-46, which is south of the 216-Z-9 Trench (USDOE, 2007).

4. Hydraulic Hammer Rig

The HHR consists of a EuroDrill®, HD5012 percussion drilling system with a hydraulically powered mast and hammer mounted on a rubber tire backhoe (Figure 3). The EuroDrill® HD5012 is typically used for driving anchors and micropiles in civil construction projects[2], but was adapted by Energy*Solutions*, L.L.C., Richland, WA, for subsurface soil sampling on the Hanford Site. The HHR pushes steel rods, 6.7 cm outside diameter by 1.2 m long, into the vadose zone. The HHR rotating head operated at a rate of less than 10 revolutions per minute (rpm) during this study, although it is was capable of rotating up to 68 rpm. The rate was optimized to allow for maximum depth of penetration by moving the soil away from the rods using a fluted cone tip. The slower rate does not significantly disturb or heat the soil while the cone tip is being advanced, allowing representative soil samples to be collected for volatile organic analysis.[3] However, the HHR can only be used in unconsolidated sediments and the maximum depth of penetration was limited by the presence of gravel, cobbles, or highly-consolidated cemented geologic units (e.g. the CCU calcic paleosol in this study).

The HHR, as with most direct push technology approaches such as CPT, does not bring soil cuttings to the surface. This is important at mixed-waste sites where waste minimization is a high priority. The only soil brought to the surface using the HHR are depth-discrete soil samples obtained specifically for analysis purposes (USDOE, 2007).

Current published literature on sampling and characterization in radiological environments does not reference the HHR. Since July 2005, the original HHR has pushed vertical and angled boreholes adjacent to Hanford Site Tank Farms to successfully collect

[2] Personal communication with Mr. Joe Patterson, TEI Rock Drills, January 2, 2007.
[3] Personal communication with Mr. John Auten, Senior Drilling Engineer, Mavrik Environmental, January 28, 2007.

characterization data to a depth of 19.8 m bgs (USDOE, 2007). An early soil sampling test with the Tank Farm HHR tooling at the 216-Z-9 Trench failed due to the difficult geologic conditions dominated by sand, gravel, and cobbles present in the Hanford formation. As a consequence, sturdier tooling capable of penetrating and sampling to the CCU calcic paleosol stratum was designed and employed at the 216-Z-9 Trench, to approximately 36.6 m bgs. The objective of the testing was to collect sediment samples at multiple depths to evaluate contamination levels as deep as the top of the CCU calcic paleosol stratum. The boreholes drilled using HHR are labeled with a preceding “P” for push location and an identifying number in Figure 1.

The HHR pushed steel rods with a solid tip cone, solid tip soil sampler, or dual-wall retractable soil sampler. Initial sampling of the vadose zone sediments using the HHR was performed with a soil sampling system, which required a separate borehole for each soil sample collected. Later, a Mavrik Environmental dual-wall soil sampling approach was implemented to allow multiple soil samples to be collected from a single borehole (Figure 4). As depicted in Figure 4, the maximum gravel size that the probe will collect is limited to 1.7 cm with the dual-wall soil sampling approach. During application of the dual-wall system, the HHR outer rod was advanced in conjunction with a locked internal split-spoon soil sampler to the desired sampling depth. To collect a depth-discrete sample, the split-spoon sampler was unlocked above ground and material from the undisturbed formation was collected and retracted to the ground surface through the stagnant outer rods. A new sampler was then placed down the borehole outer rods at depth, locked into place, and the borehole was advanced until the next depth-discrete sampling interval was reached. The dual-wall sampling system significantly enhanced sample collection, although minor design modifications were required to the tooling to initially optimize the system. The HHR dual-wall system was used to collect depth-discrete vadose zone soil samples for volatile organic analysis (e.g., CCl_4) from up to 10 intervals in a single borehole. All boreholes were decommissioned in accordance with state regulations (USDOE, 2007).

In addition to obtaining depth-discrete soil samples, the HHR provided additional capabilities. For example, during the investigation near the 216-Z-9 Trench, slim-hole borehole geophysical instruments (less than 5.7 cm in diameter) were raised and lowered down the HHR rod for collection of geophysical logging data. These spectral gamma and neutron moisture logging surveys were performed inside the HHR rod to guide the selection of depth-discrete vadose zone soil samples, assess radiological hazards, prepare for extraction of borehole rods, and support sample management controls. One active soil gas sample was also collected and field measured for carbon dioxide, CCl_4, chloroform and water vapor. In addition, the HHR was also used to install three, 1.9 cm diameter, GeoInsight® soil vapor monitoring wells with a screen depth from approximately 19.0 to 19.5 m bgs. It took less than 6 hours for the HHR to penetrate to 19.5 m bgs and complete installation of each soil vapor monitoring well (USDOE, 2007).

5. Cable Tool Drilling At Well 299-W15-46

Well 299-W15-46 was drilled by cable tool drilling technology immediately south of the 216-Z-9 Trench (Figure 1). Using this method a cable tool drive barrel continuously removed soil from inside and ahead of the casing, then the drive barrel was brought to the surface and the soil cuttings were removed or disposal. Cable tool drilling can penetrate through the vadose zone, unconfined aquifer, and the underlying semi-confined aquifer and into the basalt bedrock. It is commonly used to drill groundwater monitoring wells and waste site characterization boreholes even in highly radioactively contaminated sites. Soil samples and characterization data may be collected with the cable tool drilling method throughout the entire vadose zone and deeper. However, the drilling method is relatively slow and it has the disadvantage that soil cuttings must be contained, sampled for waste characterization, and disposed at appropriate facilities.

At well 299-W15-46 the drill cuttings from 14.0 to 36.6 m bgs were classified as transuranic waste, which was expensive to dispose of and required workers to wear high levels of personnel protective equipment. During drilling, a temporary 34.3 cm outside diameter casing was used from ground surface to 36.3 m bgs, then 29.8 cm outside diameter casing was used to 61.2 m bgs. From 61.2 to 160.0 m bgs, the borehole diameter was decreased in stages to 10.2 cm. Depth-discrete vadose zone soil samples were collected and analyzed for CCl_4. Drilling was intermittently delayed due to CCl_4 and radiological contamination levels encountered that exceeded established control levels. The daily drilling rate was impacted by sample handling and packaging, the use of personnel protective equipment, and waste management concerns (Caron, 2005).

6. Enhanced Access Penetration System

In 2005, an innovative EAPS drilling technology, developed by Applied Research Associates, Inc., of South Royalton, VT, was used at six locations in the 200 West Area for characterization of the vadose zone. Four of the EAPS drilling locations (C4883, C4884, C4885, and C4886) in the vicinity (less than 500 m) of the 216-Z-9 Trench were selected for comparison in this study (Figure 1). The EAPS used a combination of independent drilling technologies, standard CPT direct push technology and air rotary drilling, to collect vadose zone gas samples for CCl_4 analysis. The system was designed specifically for the difficult geologic conditions in the 200 West Area of the Hanford Site and allows interchanging direct push and drilling methods within a given borehole to maximize depth and minimize drill cuttings (Applied Research Associates, Inc., 2006). Both a 7.3 cm diameter air rotary drill system and a smaller 5.1 cm diameter drill were used. CPT does not create drill cuttings, whereas both drilling approaches used pressurized air to cool the drill bit and lift soil cuttings to the surface. As soil samples were not collected at these boreholes, the lithology for nearby well 299-W15-45, located 45.4 m south of borehole C4883, and was used to interpret the EAPS site lithology. The lithology of well 299-W15-45 and well 299-W15-46 are similar. The CCU calcic paleosol stratum was at 38.1 m bgs in well 299-W15-45. This was approximately the same elevation that the CCU calcic paleosol stratum was encountered at well 299-W15-46.

7. Materials and Methods

Three drilling technologies were evaluated based on their ability and the time to penetrate the Hanford formation and reach the CCU calcic paleosol stratum. Furthermore, the capability to collect representative vadose zone material was compared. Although the Hanford formation is heterogeneous, by comparing the three drilling technologies within a small part of the 200 West Area, minimal variations of the formation were expected due to the close proximity of the boreholes. Therefore, the time and ability to reach the CCU calcic paleosol stratum would be more likely a function of each drilling method, rather than geologic differences in the sediments being penetrated.

The HHR depth data were obtained with a downhole tape measure which provided a bottom depth measurement to the nearest 0.3 m (USDOE, 2007). Depth data from well 299-W15-46, drilled using cable tool technology, was reported to the nearest 0.2 m (Caron, 2005). At the four EAPS boreholes considered in this study, depth was measured in real time as the head clamp was raised and lowered during drilling, and was reported to the nearest 0.3 m (Applied Research Associates, Inc., 2006). The maximum depth of penetration by cable tool drilling and EAPS was based on the scope of the investigations and was not necessarily limited by the technology.

The drilling time required to characterize the vadose zone by each technology to the CCU calcic paleosol stratum, including collection of vadose zone soil samples and other characterization data, was evaluated. The geologic units observed during the installation of wells 299-W15-45 and 299-W15-46 were representative of the geologic units encountered by the three drilling technologies in the study area. The CCU calcic paleosol was identified based on color, texture, and particle size from soil samples. The HHR drilling time included sampling and/or logging of the vadose zone, addressing radiological hazards, and was reported to the nearest minute. For the four boreholes installed using EAPS, start dates documented by the drilling personnel (Applied Research Associates, Inc., 2006) were compared to the time of the soil gas sample collected at the maximum depth of penetration by sampling personnel[4] to account for penetration time and all onsite support services. For the EAPS investigation, the penetration time to reach the CCU calcic paleosol stratum depth was based on the depth of this stratum in well 299-W15-45. The EAPS time to reach this stratum, including soil gas sample collection along the length of the borehole, was calculated to the nearest half work day. Soil samples were not collected as part of the EAPS investigation, although drill cuttings can be observed when the drilling tools are utilized. The penetration time to reach the CCU calcic paleosol stratum at well 299-W15-46, installed using cable tool drilling technology, included sampling and on-site support services for radiological concerns. The borehole log provided the actual time to reach the CCU calcic paleosol stratum, excluding delays encountered in drilling to upgrade personnel protective equipment, and was reported to the nearest day (Caron, 2005).

To determine if a drilling technology was able to collect representative soil samples from the formation, a thin silt lense at 19.8 m bgs was selected as a known and unique benchmark. Utilizing HHR and cable tool drilling technologies, depth-discrete vadose zone soil samples were collected. The visual analysis of vadose zone material obtained using either HHR or cable tool drilling allowed a qualitative comparison of the representative nature of the material collected at this depth interval. Slough, soil that has fallen back into the borehole during drilling, is not representative of in-situ conditions.

[4] Personal communication with Mrs. Doris Ayres, Fluor Hanford, Inc., June 19, 2007.

8. Results and Discussion

Time to CCU Calcic Paleosol Stratum

The HHR was able to successfully penetrate into the calcic paleosol stratum and collect a representative soil sample of the CCU calcic paleosol stratum at six of nine locations in an average of 6.3 h. The time to reach this stratum for each HHR borehole is presented in Table 1. The CCU calcic paleosol stratum is at approximately 169 m elevation NAVD88 (Figure 5). At P56, the HHR time to the CCU calcic paleosol stratum was 10 h, but this included neutron moisture logging throughout the borehole and vadose zone soil sample collection from 33.8 to 34.4 m bgs. Although this borehole took the longest time to reach the CCU calcic paleosol stratum, it was also the first HHR borehole after initial engineering modifications. At borehole location P51, the HHR time to the CCU calcic paleosol stratum was 5 h, and this included collecting a vadose zone soil sample between 36.3 to 36.9 m bgs. At P66, the HHR time to the CCU calcic paleosol stratum was less than 3 h, with no attempt to collect a vadose zone soil sample. At P67, the HHR penetration time to the CCU calcic paleosol stratum was 8 h, with an unsuccessful attempt to obtain a vadose zone soil sample, from 32.6 to 33.2 m bgs, due to a tooling malfunction. At P68, the HHR penetration time to the CCU calcic paleosol stratum was 6 h, with no soil sample attempted. At P69, the HHR penetration time to the CCU calcic paleosol stratum was 6 h, with no attempt to collect a vadose zone soil sample.

The time to the CCU calcic paleosol stratum by cable tool drilling at well 299-W15-46 is presented in Table 2. Cable tool drilling started on 7 Oct. 2003, and stopped 12 Nov. 2003 through 9 Mar. 2004 to allow an evaluation for health and exposure concerns due to radioactive material and volatile CCl_4 associated with the vadose zone soil. Total drilling time to reach the CCU calcic paleosol stratum was 91 days. The increased total time to this stratum compared to the HHR and EAPS boreholes was a result of the necessary use of personnel protective equipment for the management of soil cuttings and for soil sample collection and management (Caron, 2005). Cable tool drilling achieved sampling objectives in the vadose zone, but at a slower rate.

The time to the CCU calcic paleosol stratum for each EAPS borehole considered is presented in Table 2. The average time to reach the CCU by this method was 4.5 days. It should be noted the first borehole, north of the 216-Z-9 Trench at C4885, took 6 days to reach 45.7 m bgs, with decreasing time to depth for each respective borehole over the duration of the project.

The HHR can be used to permit rapid geologic and contamination characterization, and sampling of the vadose zone. The HHR was able to reach the CCU calcic paleosol stratum in substantially less time than cable tool drilling or the EAPS. In addition to engineering differences as described previously, a significant factor impacting the penetration rate was the relative need to address personnel health hazards and waste management issues. If drill cuttings were not generated, then radiological controls during drilling and the effort related to waste management of soil cuttings could be significantly reduced. The duration of drilling well 299-W15-46 using cable tool drilling can be tied to the volume of radiological soil cuttings. The shorter duration of the EAPS boreholes, compared to cable tool drilling, is associated with the decreased radiological concerns and smaller borehole diameter. The primary benefit of the HHR is the successful accomplishment of characterization objectives at radioactive and mixed-waste sites in the least amount of project time. An additional benefit is the elimination of soil cuttings that may need to be managed and disposed with significant reduction in operational costs associated with health and safety.

Depth of Penetration

The average HHR penetration was 34.0 m bgs, and the maximum penetration depth was 36.9 m bgs at P51 (Figure 5). The standard deviation of the depth of penetration was +/- 3.4 m. Borehole P55 was the first and shallowest borehole of the investigation with a penetration depth of 25.6 m bgs. During penetration at P55, engineering modifications were made to refine the sampling equipment. Excluding P55, the standard deviation of the maximum depth of penetration of the remaining boreholes was +/- 1.2 m.

The HHR penetrated 0.3 m into the calcic paleosol stratum at P51 and P56. In addition, the HHR was able to penetrate into the CCU and collect representative vadose zone soil samples at locations P66, P67, and P69, each less than 6.1 m from well 299-W15-46. At P66, P67, and P69, the CCU calcic paleosol stratum was encountered at approximately 35.5 m bgs, with approximately 0.3 m of this stratum collected at each location. The CCU calcic paleosol stratum was also reached at P68 at 35.1 m bgs. The HHR succeeded in reaching the CCU calcic paleosol stratum at 100% of the locations south of the 216-Z-9 Trench with the dual-wall sampling system (USDOE, 2007). However, the HHR was not capable of penetrating beyond the CCU calcic paleosol stratum, due to the dense and cemented nature of this unit. This property of the vadose zone material resulted in a maximum depth of penetration for the HHR in its current configuration to the CCU calcic paleosol stratum.

Well 299-W15-46 was drilled using cable tool to penetrate through the CCU calcic paleosol stratum. The CCU calcic paleosol was observed from 35.5 to 36.0 m bgs (Caron, 2005). Cable tool drilling was capable of penetrating through this stratum and into the bedrock at this borehole, but the regulatory controls associated with management of soil samples and drill cuttings was extensive. The large diameter casing used at well 299-W15-46 in the vadose zone was a factor that increased time and volume of drill cuttings, but was necessary to reach the underlying basalt layer at 160.0 m bgs.

The EAPS system penetrated through the CCU calcic paleosol stratum to 45.7 m bgs at each of the four locations, and drilling was stopped based on the investigation scope. The CPT was the preferred method of drilling from ground surface to 38.1 m bgs due to the lack of soil cuttings. Below 38.1 m, the radiological and volatile organic hazards associated with the vadose zone material significantly decreased permitting the use of air rotary drilling. However at this site, which was not radiologically contaminated, the CPT penetrated between 12.5 and 22.9 m bgs at which point the drilling system switched to the air rotary drill. This approach resulted in drill cuttings that were subsequently managed as hazardous waste. It was noted that the CPT needed further improvements to successfully penetrate the CCU calcic paleosol stratum. A more powerful down-hole hammer was considered necessary for the EAPS drilling technology to be applied successfully in the Hanford formation (Applied Research Associates, Inc., 2006).

The depth of penetration using HHR is limited by the degree of consolidation of the formation sediments. The CCU calcic paleosol stratum is a variably dense layer that the HHR was able to penetrate to, but not completely through. The shallow depth of penetration at the initial borehole, P55, can likely be attributed to inadequate design of the sampler, which was subsequently modified. Following design modifications, the HHR was able to penetrate, sample, and collect soil samples into the top of the CCU calcic paleosol stratum. The HHR penetrated to the engineered limits of the equipment. The HHR and the CPT portion of the EAPS system move vadose zone material with the probe with force to reach the desired depth, resulting in no soil cuttings. If the formation material cannot be moved, or if there is no porosity, there is no penetration of the formation. The air rotary portion of the EAPS and cable tool drilling technologies remove soil for the drill to penetrate, which takes longer and creates soil cuttings. The EAPS was limited by the capabilities of CPT, but was able to overcome this through the use of the air rotary drill to reach the investigation depth of 45.7 m bgs at the cost of producing soil cuttings.

Representative Vadose Zone Soil Samples

The vadose zone soil samples collected using the HHR were determined to be representative based on visual observation of color, texture, and particle size compared to the lithology from well 299-W15-46 (Caron, 2005). A potential limitation of sampling during cable tool drilling is that the top few centimeters of material collected may be slough. No slough was observed in any of the HHR soil samples collected using the dual-wall system, based on the lithology reported for well 299-W15-46. This is particularly important when collecting vadose zone soil for determining the presence and amount of potential contaminants.

A thin silt lense was found from 19.8 to 20.4 m bgs in well 299-W15-46 (Caron, 2005). The samples from HHR locations P66, P67, P68, and P69 were geographically close enough to well 299-W15-46 to permit a comparison to the soil samples south of the 216-Z-9 Trench from 19.8 to 20.4 m bgs (Figure 1). At P66, a silt lense was observed from 19.7 to 19.8 m bgs. At P67 the silt lense was observed from 19.8 to 20.0 m bgs. At P68, a silt lense was observed shallower at 19.2 to 19.4 m bgs. At P69, the silt lense was observed from 19.7 to 19.8 m bgs, approximately consistent with P66. The HHR collected representative vadose zone soils from a thin, laterally discrete, interval (19.8 to 20.4 m bgs) south of the 216-Z-9 Trench, which correlated with the lithology of well 299-W15-46. The visual analysis of vadose zone material obtained using either HHR or cable tool drilling qualitatively indicated the material was similar.

Further Studies

The capabilities of the HHR warrants further studies in a range of environments. While the HHR is designed to be used in unconsolidated sediments, its use in this study of a geologic formation with a wide range of grain sizes, from boulder- to silt-size particles, provided an especially challenging environment to evaluate this drilling method. A geologic formation lacking a highly-consolidated cemented stratum, such as a calcic paleosol, could have a greater maximum depth of penetration than found in this study.

Due to the lack of published literature on the application of the HHR technology, there is a need to evaluate its capabilities and limitations. In particular, studies are needed to evaluate its utility at non-hazardous waste sites where the absence of radiological and on-site support should increase productivity. The HHR also has the capability to drill angled boreholes, but further studies are needed to determine the penetration rate and depth capabilities of angled boreholes in comparison to vertical boreholes. The HHR also could be used for the collection of water samples.

Although the HHR may allow a relatively rapid penetration of unconsolidated vadose zone soil, a study of drilling technologies based on the cost of operation would be useful. These data would allow the comparison of costs associated with the drilling technologies presented in this study and other readily available technologies, such as GeoProbe® and traditional CPT, in hazardous and non-hazardous environments. Application of the HHR technology does not create soil cuttings, which significantly reduces the costs associated with the cuttings management and disposal, and the use of personnel protective equipment. Consequently, utilizing HHR for drilling projects, specifically at hazardous waste sites, may provide significant cost benefits.

9. Conclusions

This study presents a comparison of the time to reach the CCU calcic paleosol stratum at about 36 m bgs using the HHR, EAPS, and cable tool drilling technologies in similar geologic conditions. The relative ability to obtain representative vadose zone soil samples was also evaluated. Compared to the EAPS and cable tool drilling, the HHR allowed a more rapid penetration, including collection of vadose zone soil samples. The HHR technology took several hours to reach the CCU calcic paleosol stratum versus days for the EAPS and weeks to months for cable tool drilling. An additional advantage of the HHR was the elimination of soil cuttings, which are a significant project expense at a mixed-waste site. The latter characteristic significantly reduces health and safety issues associated with waste management and soil sample handling controls. However, a disadvantage of the HHR, compared to the EAPS and cable tool drilling, was the apparent limited capabilities to penetrate beyond the highly-consolidated cemented CCU calcic paleosol stratum. Vadose zone soil samples collected using the HHR were representative of the formation, as the technology prevents slough during sample collection.

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USDOE. 2006b. Remedial investigation report for the plutonium/organic-rich process condensate/process waste group operable unit: Includes the 200-PW-1, 200-PW-3, and 200-PW-6 operable unit. DOE/RL-2006-51, Draft A. USDOE, Richland, WA.

USDOE. 2007. Carbon tetrachloride dense non-aqueous phase liquid (DNAPL) source term characterization report addendum. DOE/RL-2007-22, Rev. 0. USDOE, Richland, WA.

11. Figures

Figure Captions

Fig. 1. Hydraulic Hammer Rig (HHR), Enhanced Access Penetration System (EAPS) Boreholes and Cable Tool Borehole Area of Investigation, 200 West Area, Hanford Site, WA.

Fig. 2. Major Geologic Units of the 200 West Area Vadose Zone, Hanford Site, WA (After Caron, 2005).

Fig. 3. Hydraulic Hammer Rig Direct Push Technology.

Fig. 4a. Mavrik Environmental, Dual-Wall Retractable Soil Sampler.
Fig. 4b. Soil Collected with Dual-Wall Retractable Soil Sampler at P67, 19.5 to 20.1 m below ground surface.

Fig. 5. Overview of Site Geology from the Ground Surface to the Cold Creek unit Calcic Paleosol Stratum (Caron, 2005 and Martinez, 2003) and Depth of Penetration at Each Borehole Investigated, 200 West Area, Hanford Site, WA.

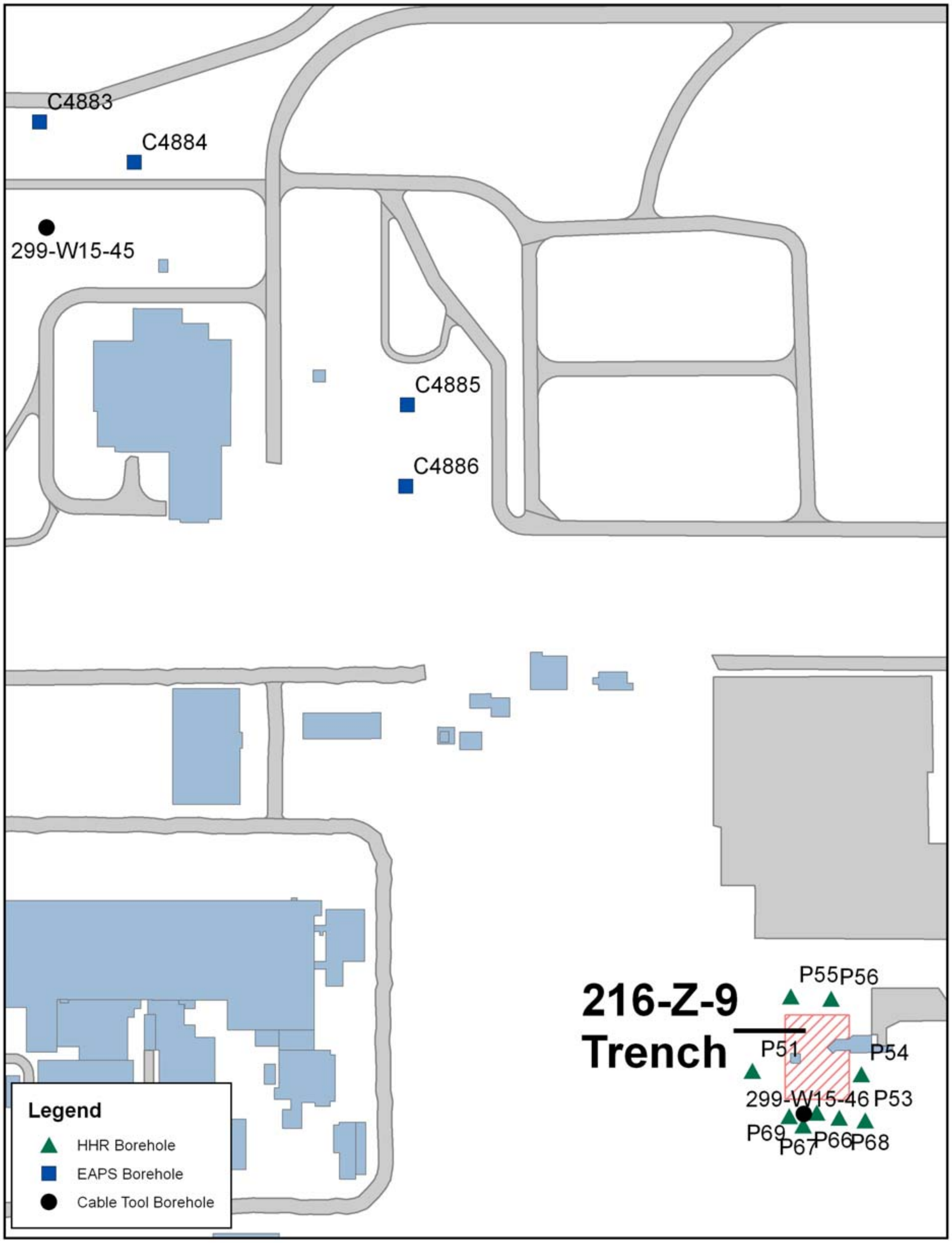

C4883
C4884
299-W15-45
C4885
C4886
216-Z-9
Trench
P55
P56
P51
P54
299-W15-46
P53
P69
P67
P66
P68
Legend
HHR Borehole
EAPS Borehole
Cable Tool Borehole

Figure 1.

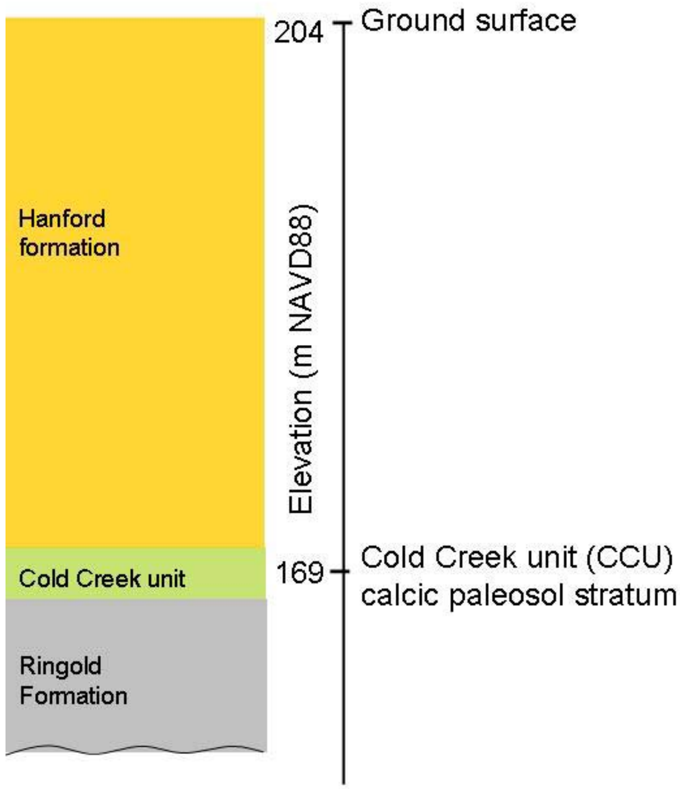

Hanford formation
Cold Creek unit
Ringold Formation
204
169
Elevation (m NAVD88)
Ground surface
Cold Creek unit (CCU) calcic paleosol stratum

Figure 2.

Figure 3.

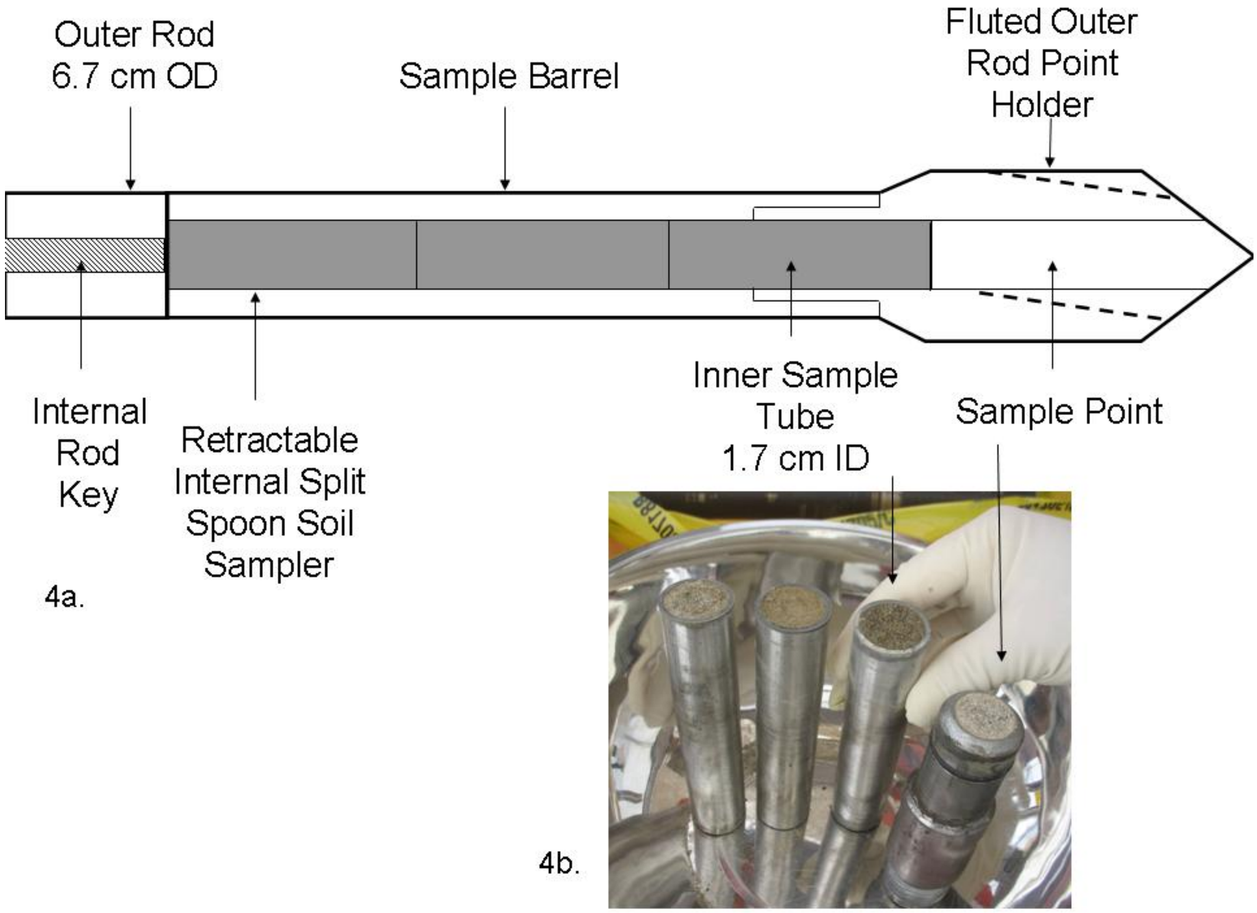

Outer Rod
6.7 cm OD
Sample Barrel
Fluted Outer
Rod Point
Holder
Internal
Rod
Key
Retractable
Internal Split
Spoon Soil
Sampler
Inner Sample
Tube
1.7 cm ID
Sample Point
4a.
4b.

Figure 4.

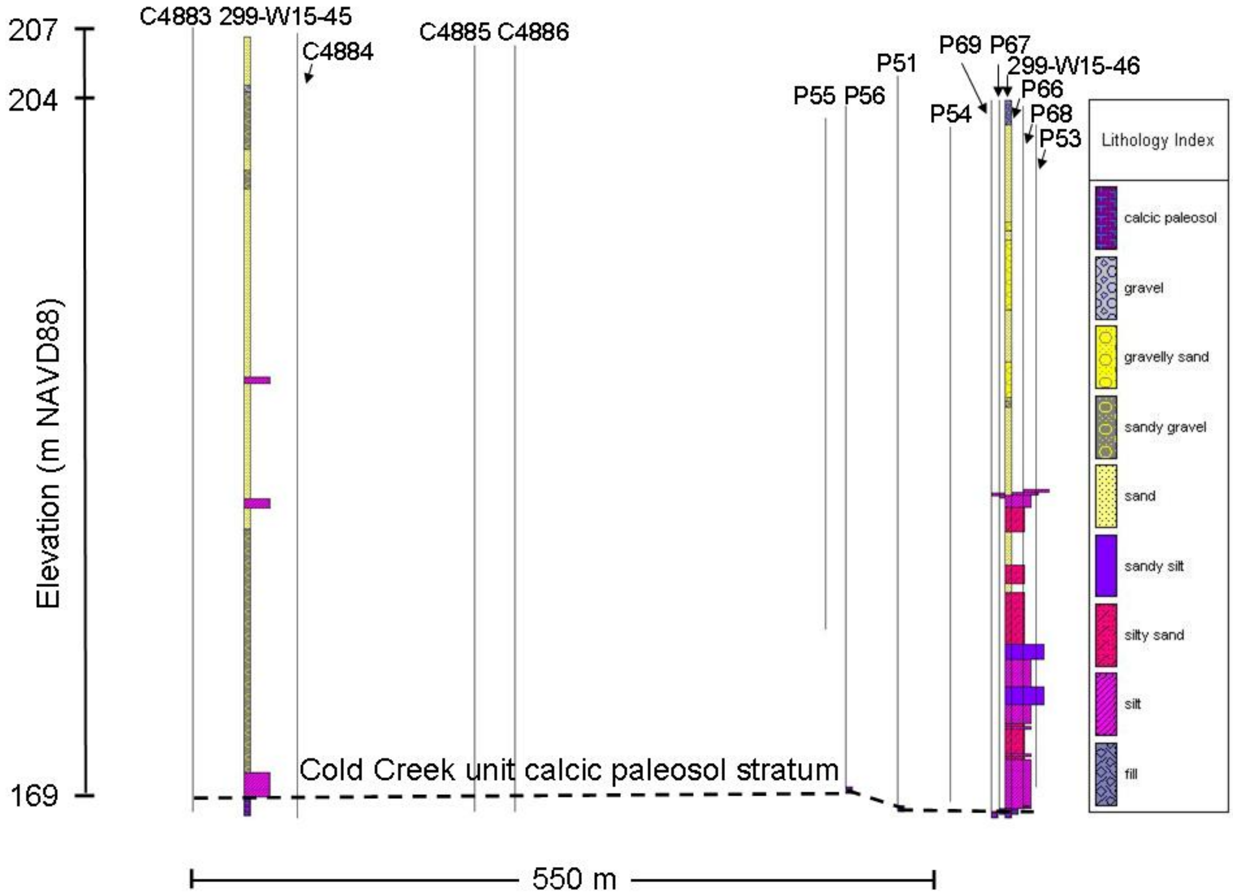

207
204
169
Elevation (m NAVD88)
C4883 299-W15-45
C4884
C4885 C4886
P55 P56
P51
P54
P69 P67
299-W15-46
P66
P68
P53
Cold Creek unit calcic paleosol stratum
550 m
Lithology Index
calcic paleosol
gravel
gravelly sand
sandy gravel
sand
sandy silt
silty sand
silt
fill

Figure 5.

12. Tables

Table Captions

Table 1. Time for the Hydraulic Hammer Rig to Reach the Cold Creek unit (CCU) Calcic Paleosol Stratum at Boreholes Investigated.

Table 2. Time for the Cable Tool and Enhanced Access Penetration System Drilling Technologies to Reach the Cold Creek unit (CCU) Calcic Paleosol Stratum at Boreholes Investigated.

Table 1.

Borehole Identification Number	Total Depth (m bgs)	Penetrated to CCU Calcic Paleosol Stratum	Time to CCU Calcic Paleosol Stratum
P55	25.6	No	NA
P56	34.4	Yes	10 h
P54	33.8	No	NA
P53	33.2	No	NA
P51	36.9	Yes	5 h
P67	35.7	Yes	8 h
P66	36.0	Yes	3 h
P69	35.9	Yes	6 h
P68	34.9	Yes	6 h

CCU = Cold Creek unit
bgs = below ground surface

Table 2.

Drilling Method	Borehole Identification Number	Total Depth (m bgs)	Penetrated to CCU Calcic Paleosol Stratum	Time to CCU Calcic Paleosol Stratum
Cable Tool	299-W15-46	160.0	Yes	91 d
EAPS	C4885	45.7	Yes	6 d
EAPS	C4884	45.7	Yes	3 d
EAPS	C4883	45.7	Yes	3.5 d
EAPS	C4886	45.7	Yes	5 d

EAPS = Enhanced Access Penetration System
CCU = Cold Creek unit
bgs = below ground surface

APPENDIX A

Global Positioning System surveys were performed by Vista Engineering personnel, with reporting by X, Y and Z in Washington State Plane Coordinates, south zone (North American Datum of 1983 and vertical datum NAVD88). The X, Y and Z were accurate to the nearest 0.3 m (1 ft). At each push location, the letter "P" to indicate a push, the location number, and a subsequent letter identified boreholes. For example, at location P51 the first borehole pushed was P51A and the second borehole pushed was P51B. All boreholes were vertical.

Table A1. Hydraulic Hammer Rig Field Locations, 200 West Area, Hanford Site (Page 1 of 2).

Hanford Site Well ID	HHR Push ID	Easting (m)	Northing (m)	Ground Elevation (m)	Depth (m bgs)	CCU Calcic Paleosol Stratum Observed
C5198	P51A	566729.5	135604.5	204.9	36.9	Yes
C5199	P51B	566729.4	135603.8	204.9	20.7	No
C5328	P51C	566729.8	135603.1	204.9	28.7	No
C5329	P51D	566729.4	135605.2	204.9	20.7	No
C5330	P51E	566729.3	135605.7	204.9	31.7	No
C5331	P51F	566729.2	135606.5	204.9	31.7	No
C5332	P51G	566728.5	135604.5	204.9	36.0	No
C5333	P51H	566728.6	135603.5	204.9	27.7	No
C5334	P51I	566728.4	135605.7	204.9	35.1	No
C5200	P53A	566777.1	135583.6	204.9	33.2	No
C5201	P53B	566778.6	135583.5	204.9	20.1	No
C5240	P53C	566777.9	135583.6	204.9	32.0	No
C5241	P53D	566776.6	135583.6	204.9	19.2	No
C5242	P53E	566775.6	135583.3	204.9	26.2	No
C5326	P53F	566775.2	135583.3	204.9	29.3	No
C5327	P53G	566774.6	135583.3	204.9	32.6	No
C5202	P54A	566775.5	135603.1	202.4	33.2	No
C5203	P54B	566775.5	135602.0	202.4	16.8	No
C5229	P54C	566775.5	135601.0	202.4	28.7	No
C5230	P54D	566776.5	135603.3	202.4	19.8	No
C5231	P54E	566776.5	135604.3	202.4	25.6	No
C5232	P54F	566775.3	135604.1	202.4	17.4	No
C5233	P54G	566776.4	135602.4	202.4	17.4	No
C5234	P54H	566776.7	135602.3	202.4	28.7	No
C5235	P54I	566777.2	135604.2	202.4	19.8	No
C5236	P54J	566777.0	135602.1	202.4	31.7	No
C5237	P54K	566773.8	135602.7	202.4	17.8	No
C5238	P54L	566774.1	135601.5	202.4	32.6	No
C5239	P54M	566774.6	135602.2	202.4	33.8	No
C5204	P55A	566745.7	135635.9	202.6	15.2	No
C5205	P55B	566746.3	135635.9	202.6	19.5	No
C5221	P55C	566746.6	135635.9	202.6	19.5	No
C5222	P55D	566746.8	135635.9	202.6	19.5	No
C5223	P55E	566747.5	135635.8	202.6	20.7	No
C5224	P55F	566745.7	135636.6	202.6	25.6	No
C5206	P56A	566762.9	135635.1	203.2	26.8	No
C5207	P56B	566762.4	135634.7	203.2	15.2	No
C5225	P56C	566761.7	135635.1	203.2	29.9	No
C5226	P56D	566760.9	135634.9	203.2	32.0	No
C5227	P56E	566762.4	135635.4	203.2	32.9	No
C5228	P56F	566761.9	135635.9	203.2	34.4	Yes
C5208	P66A	566756.7	135586.8	203.5	35.4	No
C5336	P66B	566755.8	135586.8	203.5	36.0	Yes
C5337	P66C	566757.0	135585.8	203.5	18.6	No
C4937	P66D	566754.8	135586.8	203.5	19.5	No
C5209	P67A	566751.0	135581.5	203.5	33.2	No

Table A1. Hydraulic Hammer Rig Field Locations, 200 West Area, Hanford Site (Page 1 of 2).

Hanford Site Well ID	HHR Push ID	Easting (m)	Northing (m)	Ground Elevation (m)	Depth (m)	CCU Calcic Paleosol Stratum Observed
C5335	P67B	566751.2	135582.9	203.5	35.7	Yes
C5210	P68A	566766.2	135584.9	203.2	34.9	No
C5339	P68B	566765.2	135585.9	203.2	35.1	Yes
C5340	P68C	566763.9	135586.4	203.2	19.7	No
C5211	P69A	566745.1	135585.4	203.5	34.9	No
C5338	P69B	566745.3	135587.1	203.5	35.9	Yes
C4938	P69C	566746.6	135587.0	203.5	19.5	No

Washington State Plane Coordinates, south zone (NAD83)
Vertical datum: NAVD88
Locations are accurate to the nearest 0.3 m (1 ft)
HHR = Hydraulic Hammer Rig
ID = Identification Number
CCU = Cold Creek unit
bgs = below ground surface

APPENDIX B

Well summary sheets for well 299-W15-46 (Caron, 2005).

Reference

Caron, M.E. 2005. Borehole summary report for well 299-W15-46 (C3426) drilled at the 216-Z-9 trench. WMP-26264, Rev. 0. Fluor Hanford Inc., Richland, WA.

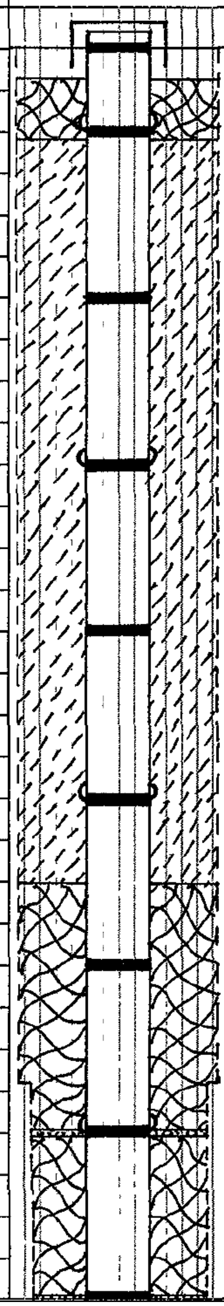
WELL SUMMARY SHEET

Start Date	10-3-03	Page 1 of 4	
Finish Date	5-3-05		
Well ID	C3426	Well Name	299-W15-46
Location	216-Z-9 Crib	Project	FY03 DNAPL Extraction Well
Prepared By	N. Bowles, Date 5/18/05	Reviewed By	L.D. Walker, Date 5/26/05
Signature	[signature]	Signature	[signature]

CONSTRUCTION DATA

Description
Protective 6" S.S Casing: +3.05' → 1.92'
Concrete Aggregate: 0' → 4.0'
Portland Cement Grout: 4.0' → 12.0'
Temporary Drive Casing: 13" C.S., 0' → 123.8'
Permanent Well Casing: 4", Sch. 5, 304/304L S.S. +2.05' → 209.53'
#8 Granular Bentonite. 12.0' → 100.4'
Portland Cement Grout: 100.4' → 129.1'
Temporary Drive Casing: 11" C.S., 123.8' → 200.9'
Natural Backfill/Sluff: 129.1' → 130.8'
Portland Cement Grout: 130.8' → 149.8'

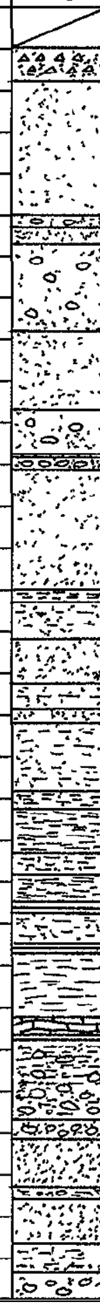
Diagram



GEOLOGIC/HYDROLOGIC DATA

Depth in Feet: 0, 25, 50, 75, 100, 125

Graphic Log



Lithologic Description
0-4': gravel drill pad
4-20': sand (S)
20-21.5': gravelly sand (gS)
21.5-23': sand (S)
23-34.5': gravelly sand (gS)
34.5-43': sand (S)
43-49': gravelly sand (gS)
49-49.5': sand (S)
49.5-50.5': sandy gravel (sG)
50.5-65': sand (S)
65-67': silt (m)
67-71': slightly silty sand ((m)S)
71-76.5': sand (S)
76.5-79.5': slightly silty sand ((m)S)
79.5-81': sand (S)
81-89.5': silty sand (mS)
89.5-92': sandy silt (sM)
92-96.5': silt (M)
96.5-99.5': sandy silt (sM)
99.5-102.5': silt (M)
102.5-103': silty sand (mS)
103-103.5': silt (m)
103.5-107.5': silty sand (mS)
107.5-108': silt (M)
108-108.5': silty sand (mS)
108.5-116.5': silt (m)
116.5-118': caliche
118-118.5: sand gravel (sG)

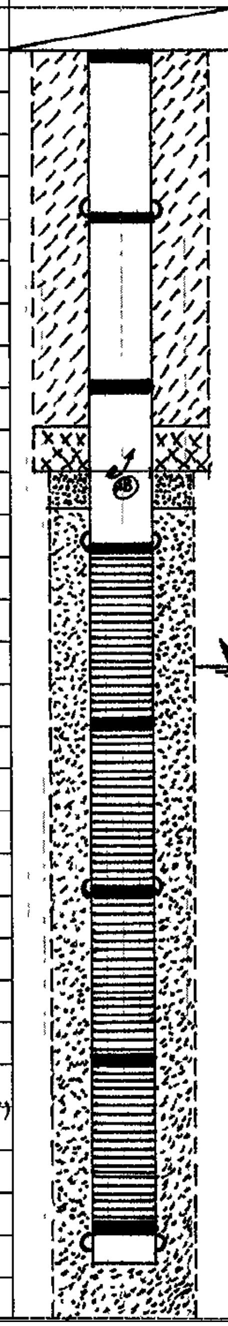
WELL SUMMARY SHEET	Start Date 10-3-03 / Finish Date 5-3-05	Page 2 of 4

Well ID C3426		Well Name 299-W15-46	
Location 216-Z-9 Crib		Project FY03 DNAPL Extraction Well	
Prepared By N. Bowles	Date 5/18/05	Reviewed By L.D. Walker	Date 5/26/05
Signature [signature]		Signature [signature]	

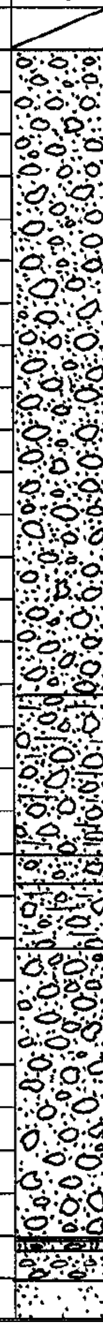
CONSTRUCTION DATA | Depth in Feet | **GEOLOGIC/HYDROLOGIC DATA**

Description	Depth in Feet
#8 Granular Bentonite 149.8' → 194.9'	150
1/4" Bentonite Pellets: 194.9' → 200.1'	175
Temporary Drive Casing: 9" C.S., 200.9' → 419.5'	
Colorado Silica Sand, 20/40 mesh: 200.1' → 204.0'	200
Colorado Silica Sand, 10/20 mesh: 204.0' → 300.2'	225
Wellscreen: 4", 304/304L S.S., Cont. Wire Wrapped, 0.020" Slot, 209.53' → 289.47'	250
Tailpipe/Sump: 4", Sch. 5, 304/304L SS., w/ welded endcap, 289.47' → 292.79'	275
Total Length of S.S. well = 294.84'	

Diagram:



Graphic Log:



Lithologic Description:

- 118.5-128': silty sandy gravel (msG)
- 128-131': sandy gravel (sG)
- 131-137': sand (S)
- 137-138': slightly silty gravelly sand ((m)gS)
- 138-143': sand (S)
- 143-147': slightly silty sand ((m)S)
- 147-227': sandy gravel (sG)
- Water Level = 222.69' (4/29/05)
- 227-245.5': silty sandy gravel (msG)
- 245.5-247.3': gravelly sand (gS)
- 247.3-257': silty sandy gravel (msG)
- 257-290.5': sandy gravel (sG)
- 290.5-291.5': sand (S)
- 291.5-293.5': gravelly sand (gS)
- 293.5-295.5': sandy gravel (sG)
- 295.5-303': sand (S)

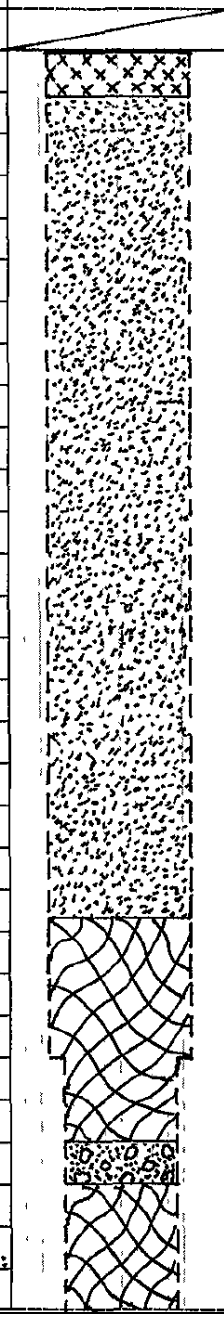
WELL SUMMARY SHEET

Start Date 10-3-03	Page 3 of 4
Finish Date 5-3-05	

Well ID C3426	Well Name 299-W15-46
Location 216-Z-9 Crib	Project FY03 DNAPL Extraction Well
Prepared By N. Bowles Date 5/18/05	Reviewed By L.D. Walker Date 5/26/05
Signature [signature]	Signature [signature]

CONSTRUCTION DATA

Description	Diagram
3/8" Bentonite Pellets: 303.2' → 306.6'	
Colorado Silica Sand, 10/20 mesh: 306.6' → 403.2'	
Portland Cement Grout: 403.2' → 430.3'	
Temporary Drive Casing: 7" C.S., 419.5' → 498.'	
Natural Backfill/Sluff: 430.3' → 435.25'	
Portland Grout Cement: 435.25' → 484.1'	



Depth in Feet: 300, 325, 350, 375, 400, 425

GEOLOGIC/HYDROLOGIC DATA

Graphic Log	Lithologic Description
	303-316.3': sandy gravel (sG)
	316.3-318.7': sand (S)
	318.7-328': sandy gravel (sG)
	328-329.5': sand (S)
	329.5-353': sandy gravel (sG)
	353-354.5': sand (S)
	354.5-364.3': sandy gravel (sG)
	364.3-369.5': sand (S)
	369.5-396.2': Sandy gravel (sG)
	396.2-400': silty sand (mS)
	400-417': sandy gravel (sG)
	417-440': silt (M)
	440-444': sandy silt (sM)

WELL SUMMARY SHEET

Start Date 10-3-03	Finish Date 5-3-05	Page 4 of 4

Well ID C3426	Well Name 299-W15-46
Location 216-Z-9 Crib	Project FY03 DNAPL Extraction Well
Prepared By N. Bowles — Date 5/18/05	Reviewed By L.D. Walker — Date 5/26/05
Signature [signature]	Signature [signature]

CONSTRUCTION DATA

Description

Natural Backfill/Sluff: 484.1' → 486.0'

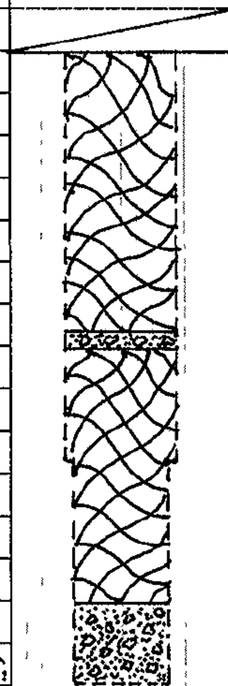
Portland Cement Grout: 486.0' → 516.'

Open Borehole Drilling: 498.' → 525.'

Natural Backfill/Sluff: 516' → 525.'

Notes:
- All depths are in feet below ground surface
- All temporary casing was removed from ground.

Diagram



GEOLOGIC/HYDROLOGIC DATA

Graphic Log

Depth in Feet	Lithologic Description
450	444-467': silty clay (M)
	467-473': silty sand (mS)
475	473-512': gravelly silty sand (gmS)
500	
	512-521.5': silty sandy gravel (msG)
525	521.5-525.': vesicular basalt
	TD = 525'

APPENDIX C.

Well summary sheets for well 299-W15-45 (Martinez, 2003).

Reference

Martinez, C.R. 2003. Fiscal year 2003 CERCLA groundwater monitoring well summary report. CP-16139, Rev. 0. Fluor Hanford Inc., Richland, WA.

WELL SUMMARY SHEET

Start Date: 03/26/03	Finish Date: 3/27/03	Page: 1 of 2	
Well ID: C4119		Well Name: 299-W15-45	
Location: N. of PFP \ ZP-1		Project: CY 2003 CERCLA G.W. well drilling	
Prepared By: Charlene Martinez	Date: 03/31/03	Reviewed By: L.D. Walker	Date: 4-8-03
Signature: Charlene Martinez		Signature: LD Walker	

CONSTRUCTION DATA

Description

11 3/4" ga 4/14/03 TEMP CSG TO T.D.

~~8"~~ 8" I.D PERMANENT carbon steel casing:
8" +4.0' → 233.19'

Portland cement grout:
0' → 10.2'

Granular Bentonite:
10.2' → 218.4'

Bentonite Pellets:
218.4' → 223.7'

10-20 mesh Colorado Silica Sand:
223.7' → 287.0'

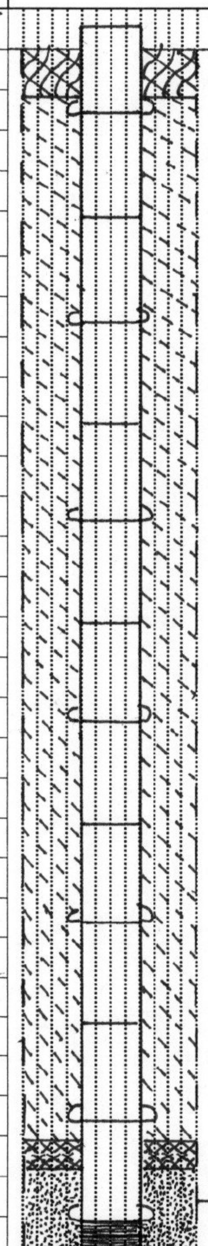
8" I.D SS 304 0.01 inch (~~0.20 cm~~ ~~0.02 cm~~)
cont. wire-wrap wellscreen:
233.19' → 243.2'

8" ID SS 304 0.02 inch
cont. wire-wrap wellscreen:
243.2' → 283.23'

All depths are in feet below ground surface:

All temporary casing removed from ground.

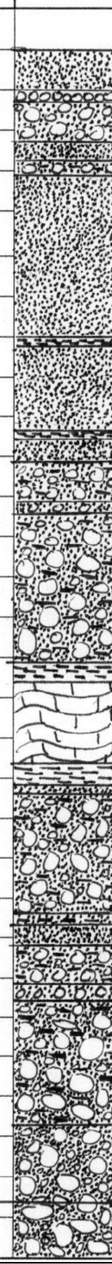
Diagram



GEOLOGIC/HYDROLOGIC DATA

Depth in Feet: 0, 40, 80, 120, 160, 200

Graphic Log



Lithologic Description

- 0-8' SAND (S)
- 8-9' GRAVEL (G) — Hanford @ 8' formation
- 9-18.5' sandy GRAVEL (sG)
- 18.5-22' SAND (S)
- 22-25' silty sandy GRAVEL (msG)
- 25-56' SAND (S)
- 56-57' SILT (m)
- 57-76' SAND (S)
- 76-77.5' SILT (m)
- 77.5-81' SAND (S)
- 81-89' silty sandy GRAVEL (msG)
- 89-91' sandy GRAVEL (sG)
- 91-121' silty sandy GRAVEL (msG)
- Cold Creek Interval @ 121' bgs
- 121-125' SILT (m)
- 125-142.5' CALICHE
- 142.5-145' SILT (m)
- 145-146.5' SAND (S)
- 146.5-172' silty sandy GRAVEL (msG) — Ringold Formation @ 146.5'
- 172-174' Silty SAND (mS)
- 174-178' SAND (S)
- 178-185' Silty SANDY GRAVEL (msG)
- 185-189' Sandy GRAVEL (sG)
- 189-215' silty sandy GRAVEL (msG)
- 215-239' Sandy GRAVEL (sG)

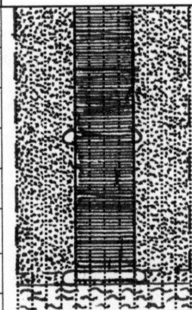
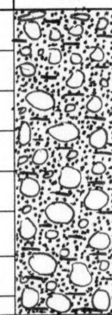
WELL SUMMARY SHEET

Start Date: 02/26/03
Finish Date: 3/27/03
Page: 2 of 2

Well ID: C 4119	Well Name: 299-W15-45
Location: n. of PFP/ZP-1	Project: CY 2003 CERCLA G.W. well drilling
Prepared By: Charlene Martinez — Date: 03/31/03	Reviewed By: L. D. Walker — Date: 4-8-03
Signature: Charlene Martinez	Signature: LD Walker

CONSTRUCTION DATA

GEOLOGIC/HYDROLOGIC DATA

Description	Diagram	Depth in Feet	Graphic Log	Lithologic Description
8" ID SS304 sump: 283.23' → 286.25'		240		239' - 292.1' silty sandy GRAVEL (msG)
muddy backfill: 287.2 → 292.1'		280		
				TD = 292.1' bgs
				Static G.W. => 229.6' bgs (03/28/03)
		320		
All depths are in feet below ground surface				
All temporary casing removed from ground				