IN PLACE MIXED CONTAINMENT SYSTEM DESIGN AND CONSTRUCTION AT A DNAPL SITE

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Abstract: The selection process, design, and construction of a source encircling containment wall to depths up to 90 feet are described. The selected remedy for the Source Area of Operable Unit 2 at Hill Air Force Base stipulated containment of the pure-phase trichloroethylene contamination. The physical setting was a primary factor in the selection of the remedial design approach and technology selection. The source area and dissolved plume at OU2 are located on a hillside that is the site of a former landslide of several million cubic yards in size. The in-place-mixed wall construction method was selected because of the irregular topography, small area of the site, and the requirement to reach depths of 90 feet below ground surface. Bench-scale compatibility studies were performed for the containment wall mix design on three commercial bentonite clays. The samples were subject to screening tests and long-term tests for evaluation of changed soil properties when exposed to the contaminated groundwater. The quality assurance testing during construction and the long-term performance monitoring of the wall are discussed.

INTRODUCTION

As a result of industrial processes for aircraft and missile maintenance at Hill Air Force Base, Utah, up to 110,000 gallons of waste chlorinated solvents were disposed at Operable Unit 2 (OU2). The waste solvents primarily consisted of trichloroethylene (TCE). Disposal of the solvents occurred between 1967 and 1975. Interim pump and treat remedial actions initiated in 1993 have recovered approximately 33,000 gallons of dense non-aqueous phase liquid (DNAPL) from the source area (Oolman et al., 1995). The Selected Remedy for the site included a requirement for installation of a source encircling containment wall (USEPA, 1996). Containment technologies are widely used in construction dewatering and hazardous waste applications. The application of containment wall technologies to the OU2 DNAPL site involved particular consideration of the physical constraints of the site, the location on a large landslide, and chemical compatibility with the contamination.

The source area and dissolved plume at OU2 are located on a hillside that is the site of a former landslide of several million cubic yards in size. Site characterization methods included conventional drilling and aquifer testing supplemented by in situ Cone Penetrometer Tests and Hydropunch™ water samples in the heterogeneous subsurface conditions. In the source area, the downward migration of the DNAPL was impeded by the Alpine Formation. The Alpine Formation is a low permeability deltaic deposit composed primarily of silty clay with numerous thin silt lenses and occasional thin silty sand lenses. Contaminant recovery is primarily from the large pools of DNAPL retained at the source area. Transport of the dissolved phase contaminants has continued down the

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steep terraced hillside to the alluvial aquifer in the Weber River Valley floor. The dissolved plume contaminants are found in the shallow, unconfined groundwater system.

These conditions were evaluated during design of a containment system for the DNAPL contaminated source area. Samples of the DNAPL obtained during the Remedial Investigation indicated the following compounds and range of percentages: trichloroethylene (TCE) (53% to 63%), 1,1,1,-trichloroethane (TCA) (5% to 12%), tetrachloroethylene (PCE) (3% to 5%), with freon TF, oil and grease, methylene chloride, and water making up the remainder. The high specific gravity of TCE (1.46 g/cm^3) and the other chlorinated organic compounds present in the DNAPL, cause it to sink through a water column. The DNAPL will continue downward unless its' progress is impeded by a reverse hydraulic gradient or low permeability barrier. TCE has a moderate aqueous solubility. Therefore, the DNAPL at the site can potentially be a source of dissolved groundwater contamination for many decades. A pump and treat system was constructed in 1992 as an Interim Remedial Action to extract and treat the highly contaminated groundwater and DNAPL associated with the Source Area. The system includes stainless steel extraction wells, phase-separation tanks and treatment by steam stripper. The pump and treat system has recovered approximately 33,000 gallons of DNAPL to date.

PHYSICAL SETTING

Hill Air Force Base (HAFB) is located approximately 25 miles north of Salt Lake City, Utah. HAFB is an active U.S. Air Force facility occupying approximately 6,700 acres. It is located on a terrace of the Weber delta, which is approximately 300 feet above the surrounding valley floors in Davis County, Utah.

OU2 is located along the northeastern boundary of the Base, as shown in Figure 1. The source area of OU2 includes two unlined trenches or pits where disposal of the waste solvents occurred, as shown in Figure 2. Figure 2 also illustrates the defined areas of the source (DNAPL and high dissolved contaminant concentration groundwater) and non-source (moderate to low dissolved contaminant concentration groundwater) areas at OU2. The distribution of TCE contamination is shown in Figure 3.

Figure 3 also shows the steep escarpment that drops approximately 140 feet in elevation between the Source Area and the toe of the plume. The escarpment forms the south wall of the Weber River Valley. Numerous seeps and springs occur on the hillside. Traversing the escarpment at approximately mid-height of the hillside is the Davis-Weber Canal. In 1993 the canal was lined with concrete across the contaminated area of OU2 to reduce infiltration due to canal leakage. Recent slope movement is evident in localized areas of the hillside. The movement is generally occurring at the lateral scarp areas where the slope has been oversteepened during canal excavation. These actively moving areas coupled with evidence of springs indicate a high potential for slope instability in some areas of the hillside complex. At the bottom of the hillside, generally defined by South Weber Drive, the valley floor extends at a slight slope toward the Weber River located approximately three-quarters of a mile north.

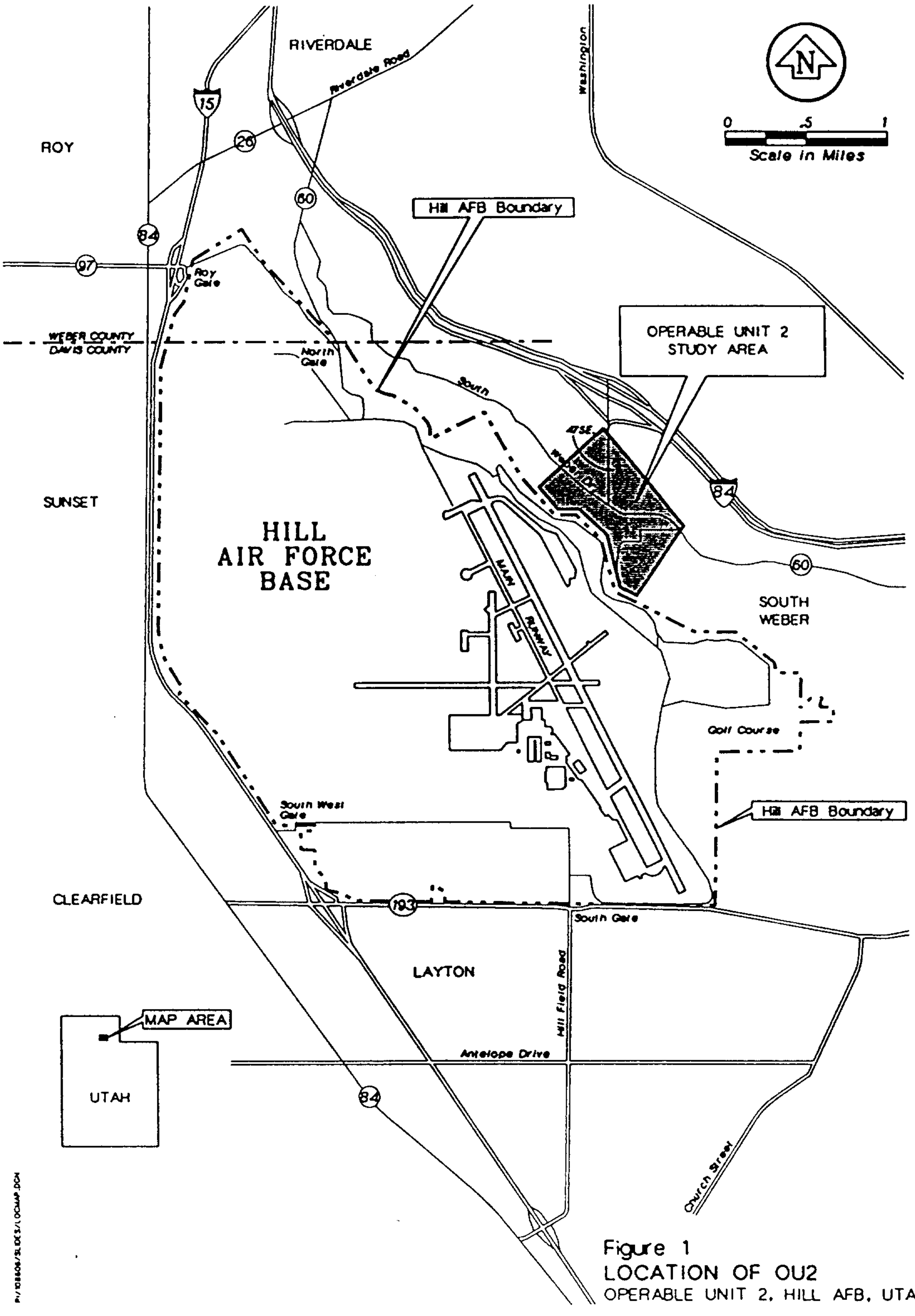

Figure 1
LOCATION OF OU2
OPERABLE UNIT 2, HILL AFB, UTAH

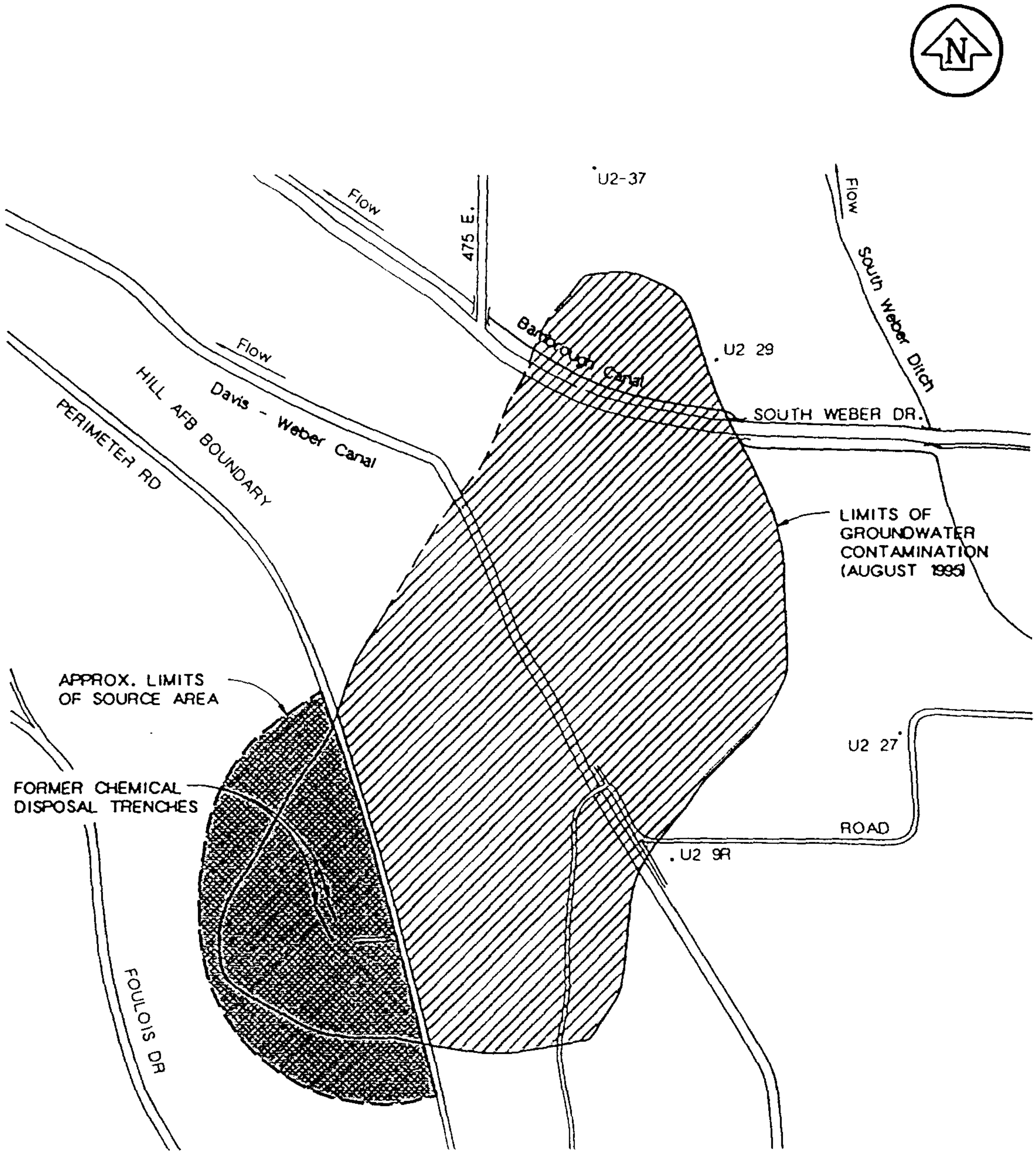

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Figure 2
DELINEATION OF SOURCE AREA AND NON-SOURCE AREA AT OU2
OPERABLE UNIT 2, Hill AFB, Utah

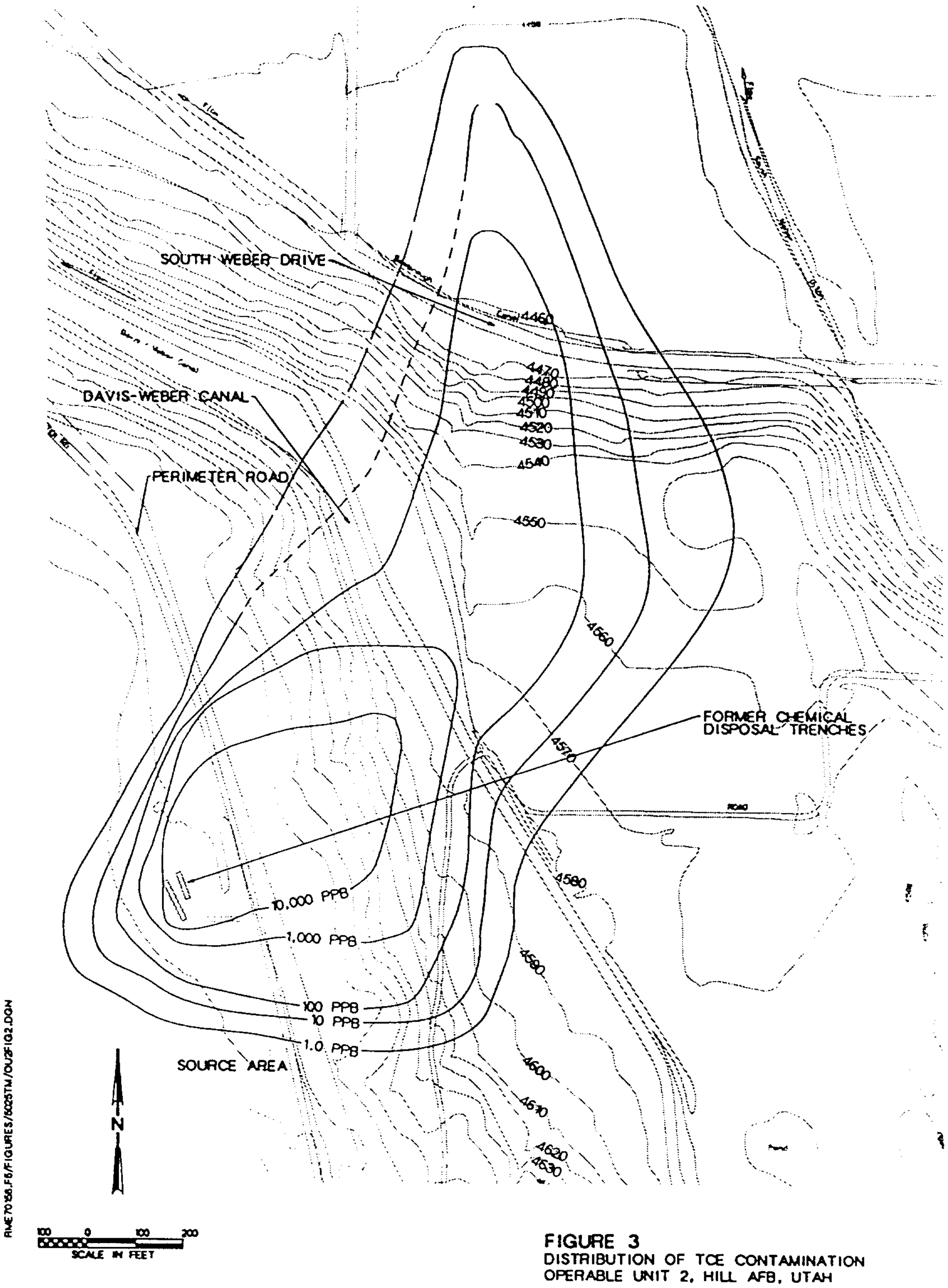

FIGURE 3
DISTRIBUTION OF TCE CONTAMINATION
OPERABLE UNIT 2, HILL AFB, UTAH

There is evidence of three shallow unconfined groundwater systems within the extent of the plume as shown in Figure 4. These consist of a shallow system extending from the source area to a north-south transverse ridge located near the bottom of the hill; a second shallow system located east of the transverse ridge; and a third shallow system contained in the Weber River alluvium of the valley bottom to the east of South Weber Drive.

The degree of hydrogeologic continuity between these systems is difficult to define because of the complex nature of the geology observed in the off-Base area. Description of the subsurface is further complicated because the steep escarpment is part of the Weber Delta Landslide Complex (Pashley and Wiggins, 1971).

The OU2 landslide is the most evident, and probably the largest, slope movement feature on the south wall of the valley. A conceptual geologic section is also shown in Figure 4. The length of the landslide from the crown near Foulois Drive to toe at South Weber Drive is approximately 3,000 feet. The vertical change in elevation is 240 feet from the head to the toe. The maximum width is estimated to be 2,000 feet. The slide mass is estimated to be in the range of 6 million cubic yards.

It appears both slump and earthflow types of mass movements occurred during the landslide. This interpretation is based on geomorphic features evident from site inspection and airphoto interpretation. Slump type features are more prevalent in the higher elevations of the slide mass as evidenced by rotated blocks forming a terrace-like surface. Earthflow features are more prevalent in the lower elevations as evidenced by relatively horizontal surfaces and a transverse ridge, or mudflow lobe, feature near the toe.

The Weber Delta primarily consists of two Pleistocene age sediments of the Lake Bonneville Group. The Provo Formation terrace deposit consisting primarily of sand and gravel which caps the delta deposits and underlies most of the Hill AFB facilities, and the Alpine Formation, a cyclically deposited deltaic formation consisting primarily of silty clay to clay with locally discontinuous sand and gravel lenses. Uplift along the Wasatch Front coupled with lowering of ancient Lake Bonneville, to the existing Great Salt Lake, caused down-cutting of the Weber River through these deltaic deposits. This down-cutting resulted in the formation of the Weber River Valley and the steep terrace slope that characterizes the eastern boundary of Hill AFB.

Subsurface investigations in the Source area indicate the thickness of the Provo Formation ranges from approximately 20 to 50 feet. At lower elevations on the hillside, the Alpine formation is exposed at the ground surface with exception of local colluvium cover. The thickness of the Alpine Formation deposits is estimated to be 300 feet or more. Subsequent to the main landslide movement, the surface of the landslide is expected to have been reworked by erosion, deposition of sediments (specifically in fractures and cavities resulting in the landslide surface), numerous smaller mass movements, and human agricultural and industrial activities.

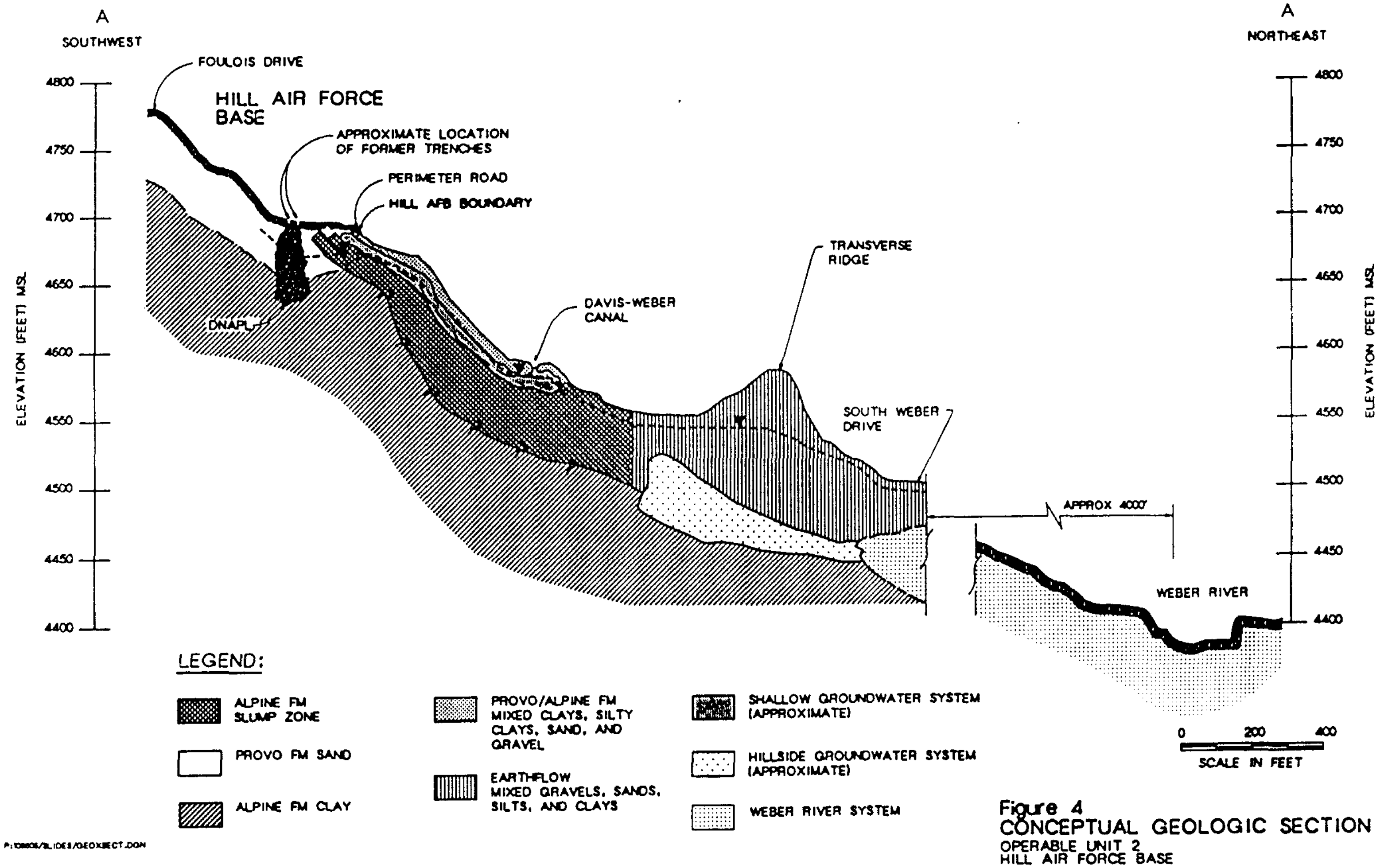

Figure 4
CONCEPTUAL GEOLOGIC SECTION
OPERABLE UNIT 2
HILL AIR FORCE BASE

REMEDIAL STRATEGY AT TCE DNAPL SITES

The Selected Remedy at this site includes containment. The objective of the containment is to reduce the short-term risk associated with the source. The long-term plan for the site is to monitor the development of promising contaminant mass reduction technologies with the purpose of implementing an appropriately capable technology when it is practicable.

Several technologies are available for mass reduction at DNAPL sites. However, it is generally accepted that no remedial technologies currently exist to restore DNAPL zones in aquifers to drinking water standards (NRC 1994, USEPA 1991, and USEPA 1993).

Freeze and McWhorter, 1997, present a qualitative framework for understanding the level of mass-removal efficiency required to achieve long-term risk reduction for DNAPL in low-permeability soils. The distribution of the contaminant mass between the soil media (fractures, matrix) and phase (aqueous, sorbed, or NAPL) greatly influences the efficiency of mass removal. It is expected the distribution of TCE mass in low-permeability soils will be primarily in the form of sorbed contamination on the soil phase and as NAPL in the soil fractures. This mass provides the source for continued long-term dissolved contamination in the water phase.

The ability to remove TCE sorbed on, and in fractures of, low-permeability soils is key to efficient mass-removal technologies. Mass-removal technologies must first achieve contact with the sorbed/fracture TCE to transfer the mass to the removal media. In addition, contact needs to occur over an extended period of time because transfer of TCE mass from these conditions occurs very slowly. There is also a cost issue in the additional expense of additives that accelerate the mass-removal process versus the very long time-frame (30 years or more) involved with less aggressive technologies.

Assuming a quantity of 30,000 gallons remains today, a mass reduction technology with overall removal efficiencies as high as 95 percent would leave a significant long-term source quantity (1,500 gallons) of DNAPL in the subsurface. The corresponding reduced aqueous concentration would likely be above 5,000 ug/l and would not result in significant changes in the expected long-term risk and site operational cost requirements.

CONTAINMENT SYSTEM DESIGN

Containment Wall Objectives

The purpose of the containment wall is to hinder horizontal migration of the highly contaminated groundwater and the source area DNAPL pools. The wall provides a continuous low permeability physical barrier around the source area by reworking and sealing permeable zones with the soil. The containment wall also forms a hydraulic barrier when groundwater extraction from within the contained area produces an inward gradient. An associated objective is the reduction of groundwater flow into the source area thereby requiring less groundwater to be extracted and treated.

Design Alternatives Evaluation

Several alternatives were considered during development of the containment wall design. The design alternative's evaluation included the following structures:

- sheet pile walls with grouted joints (Waterloo Barrier™ (cold rolled 7.5 mm thickness with internal sealable cavity), or hot rolled piles with external sealable cavity)
- structural soil-cement-bentonite wall using panel construction or in-place-mixed (IPM) method
- conventional soil-bentonite slurry wall
- IPM soil-bentonite slurry wall

The results of a sheet pile drivability study (Montgomery Watson, 1993) indicated a high probability that sheet piles could not be driven without damage to the target elevation. In addition, internally sealable sheet piles were not commercially available with sufficient wall thickness' to drive to the required depth at this site. An uncertainty with sheet piles is the integrity of the inter-sheet seal that can be damaged during installation. The damaged seal may not be correctable in all cases.

Construction of a structural soil-cement-bentonite wall, using conventional slurry wall methods, is subject to the constraints of that method. These constraints represent the need for a relatively large site with large radius corners in the alignment. Construction of a structural soil-cement-bentonite wall using panel methods would be appropriate for the site. This type of construction is expected to be more expensive than conventional slurry wall construction or IPM wall construction. Also, the addition of cement provides more structural strength to the backfill but results in an adverse increase in wall permeability. The potential benefit of increased structural strength was considered secondary to the requirement to provide the lowest practical permeability. A structural wall was also considered to allow future excavation and removal of the contamination. A stronger wall could be constructed with a smaller perimeter around the DNAPL area to support deep excavations. However, the excavation alternative was not carried beyond the Feasibility Study level due to considerations of cost, exposure to workers, and the potential for DNAPL "stringers" to exist outside the wall which would be impossible to identify and excavate.

A three-stage process is used for construction of a conventional soil-bentonite slurry wall. The process includes trench excavation by a large trackhoe or clamshell, temporary trench support by a bentonite water slurry, and backfill with a soil-bentonite mixture. Due to the fluid nature of the slurry mixture, it is not practical to construct a slurry wall in confined sites. The short lengths and short radius curves required to encircle the site does not enable construction to the required depths because of the shallow (approximately 10H:1V) slope formed by the backfill in the trench. Also, the slope along the alignment exceeds a 2 percent grade which would require significant earthwork to regrade the site or provide retaining berms. The method would also require excavation and handling of contaminated soil and groundwater. Management of large quantities of contaminated materials in a slurry backfill processing area would be difficult given the small size of the OU2 source area.

The IPM method allows soil-bentonite walls to be constructed in-place, leading to significant reductions in the requirements for excavation, out-of-trench mixing, and contaminated materials handling. Deep IPM wall construction involves a large crane with a bank of turning augers and mixing paddles suspended from the boom that drill the soil as well as mix the injected reagents with the cuttings. Continuity is produced by overlapping adjacent columns of mixed soil to form a continuous wall. The IPM method is suited for use in a confined area where the wall alignment has tight curves, and existing structures and facilities are in close proximity. The target depths required at the site are within the capability of available commercial IPM equipment.

Similar to conventional slurry wall construction, the IPM method results in a trench filled with low shear strength fluid that will flow along and out of the trench on sloping sites. Typically, a system of berms is constructed to contain the slurry fluids. The bentonite content of the injected slurry is generally limited to six percent bentonite by weight, because of the increased difficulty with pumping thicker slurries. A six percent bentonite slurry mixture translates to a maximum two percent bentonite by dry weight of soil in-place. The permeability of an IPM wall is generally slightly higher than, but competitive with, the conventional slurry wall in most soil conditions. This is because the consistency of the barrier mixture is controlled by the potentially variable native soil incorporated into the mixture. The native soil needs to be suitable for auger installation and for use as the barrier backfill.

The IPM method was selected for the design because of its' ability to produce a low-permeability wall having properties comparable to a conventional slurry wall, its' ability to achieve depths of 90 feet below ground surface, and its' ability to negotiate the corners and constraints of a small site with existing structures.

Containment Wall Alignment and Depth

The approximate containment wall alignment is shown relative to interpreted contamination contours in Figure 5. The wall alignment encircles approximately 2 acres of the Source Area and includes the area where TCE concentrations were greater than 100 ppb.

The wall was constructed to the maximum achievable depth of approximately 90 feet for IPM equipment generally available in the United States. It would be relatively easy to extend the auger shaft length of the IPM equipment and thereby achieve greater depths. However, the cost is expected to increase considerably below 90 feet due to expected slower drilling progress, and there is increased potential for misalignment of the individual strokes resulting in discontinuities in the wall.

Therefore, the target elevation for the bottom of the wall was established at elevation 4620 feet MSL, approximately 15 feet below the elevation of the deepest known TCE contamination at the site. At this depth, the containment wall is keyed a minimum of 35 feet into the low permeability Alpine clay soils. Also, the wall will be completed below the landslide slip surface which was estimated at approximately 55 feet below the existing ground surface in the Source Area.

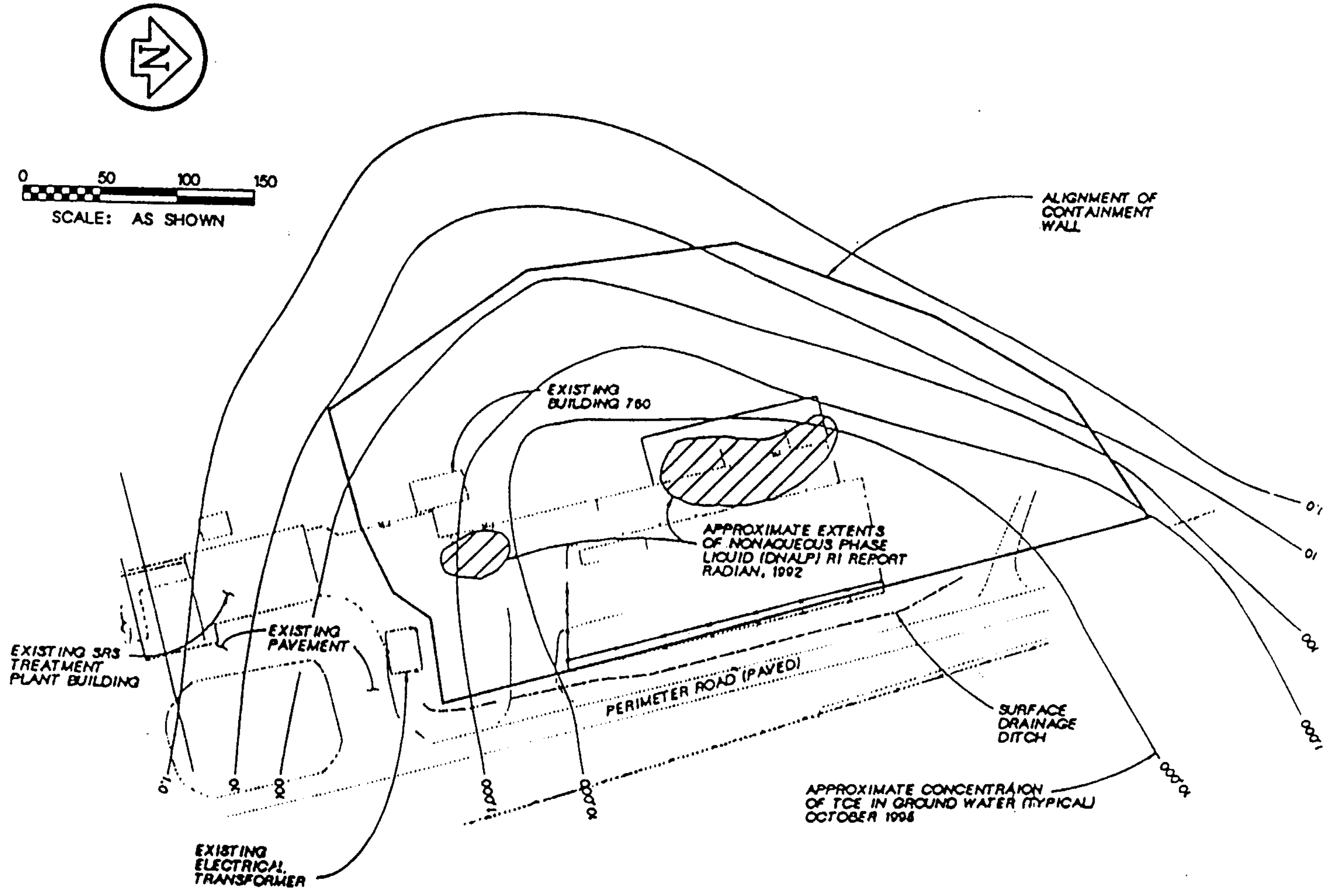

Figure 5
CONTAINMENT WALL ALIGNMENT
OPERABLE UNIT 2, HILL AFB, UTAH

Compatibility of Backfill with Site Contaminated Groundwater

Chemical compatibility bench-scale tests were performed to evaluate the effects of site contaminated groundwater on the geotechnical properties of various barrier wall mix design recipes. The tests were conducted using four commercially available high swelling sodium bentonite clays.

The bentonite was mixed with native clay samples and a composite native sand sample. The sand sample was included to represent worst-case conditions for the upper portion of the wall that is constructed through the sand deposits of the Provo Formation. During actual construction, a substantial fraction of the Alpine Formation clay will be lifted and mixed with the sand in the upper portion of the containment wall.

Compatibility testing was performed by J&L Testing Company, Inc. of Canonsburg, PA and included initial screening tests, mix design and test sample preparation, and long-term permeability compatibility tests. The testing program included initial compatibility screening, blow-out testing, and long-term permeability testing.

Initial Compatibility Screening: The ability of the clay to remain in suspension after a 24-hour time period was qualitatively demonstrated by mixing bentonite clay with contaminated groundwater and comparing the results with mixes using deionized water and site tap water. This test can provide a general indication of adverse result if flocculation is excessive. The four bentonite clays performed similarly during this phase of the test, and for reasons of economy, three of the bentonite clays were carried forward for the next phase of testing.

Blow-out Test: Blow-out or Pressure Testing was performed to evaluate the susceptibility of a bentonite slurry to be pushed into the adjacent native soil when subject to high hydraulic gradients. The bentonite slurry was tested against a filter of native sand soil to represent a worst–case condition. The blow-out test was performed in general conformance with the procedure developed by Xanthakos, 1979.

Long term permeability testing: The objective of the long-term permeability tests was to evaluate the effect of the contaminated groundwater on the permeability characteristics of the soil and slurry mixes after passing approximately 3 pore volumes of groundwater through the test samples. Two groups of samples were prepared, one consisting of native sand and bentonite additives and another consisting of native clay and bentonite additives. Long-term flexible wall permeability tests were performed using an initial permeant of site tap water followed by contaminated groundwater. The contaminated groundwater was saturated with dissolved TCE at a concentration over 100 ppm. The samples were prepared with a 2 percent concentration of bentonite by dry weight of soil basis. This represents the highest bentonite concentration practically achievable using the in-place mixed wall construction method. The low permeability of these samples required the gradient to be increased mid-way through the contaminated water permeant to speed up the test. The native clay sample tests were terminated after 200 days when three pore volumes had passed through the samples.

The testing results indicated the following:

- Blow-out or piping of the containment wall slurry material is not likely even under the highest potential hydraulic gradient expected during operation of the facility.
- The permeability of sand matrix soil mixed with 2 percent bentonite ranged from 6.5×10^{-7} cm/sec to 1.4×10^{-6} cm/sec when permeated with water.
- Sand matrix mixes showed an increase in permeability when permeated with three pore volumes of contaminated site groundwater. Permeability measurements, after passing three pore volumes, ranged from 6×10^{-7} cm/sec to 3×10^{-6} cm/sec. The increase in permeability ranged from 30 percent to 360 percent for the three bentonite soils tested.
- The permeability of clay matrix soil, mixed with 2 percent bentonite by dry weight, varied between 6×10^{-9} cm/sec and 8×10^{-9} cm/sec for the three mixes when permeated with water.
- The clay matrix mixes showed no increase in permeability when permeated with three pore volumes of contaminated groundwater flow. The final permeability ranged from 2.5×10^{-9} cm/sec to 6×10^{-9} cm/sec.
- The long-term permeability tests indicate the clay-bentonite samples performed well when subject to highly concentrated site groundwater. The sand-bentonite samples were significantly affected by the contaminated groundwater. This result was expected because the chlorinated solvents are able to collapse the double-layer structure of the bentonite clay. The sand-bentonite tests represented a worst-case condition that is not expected to be encountered under operating conditions. However, the sand-bentonite tests do point to the need to maintain an inward gradient through the containment wall to reduce the potential for contact with highly concentrated site groundwater.

IN-PLACE MIXED WALL CONSTRUCTION

The primary features of the containment wall are the key trench and the IPM wall. The key trench was constructed to contain the excess, potentially contaminated, soil-bentonite material lifted during the in-place-mixing process. Because the site will be frequently accessed by drilling rigs and other vehicles in the future, the upper portion of the key trench was designed to support such traffic. The size of the key trenches needed to allow space for the necessary surface restoration backfill in addition to the excess soil-bentonite materials.

Geo-Con Incorporated, of Denton, Texas, was the specialty subcontractor for the IPM wall construction. The approximately 1,500 foot long IPM wall construction was completed in 39 working days, for an average production rate of approximately 3,000 square feet per day as measured on the wall face. The IPM rig consisted of four overlapping mixing shafts, with bottom bentonite slurry discharge, capable of creating a wall with a minimum thickness of 24 inches. The mixing assembly was mounted on a Manitowoc 4100 Series II crane. The mixing augers and blades blend the injected bentonite-water slurry with the soil. The bentonite slurry was mixed in a high shear colloidal mixing plant and delivered to a holding tank by positive displacement pumps.

In order to achieve an in-place 2 percent bentonite by dry weight of native soil, the injected bentonite-water slurry would need to have a minimum 6 percent bentonite by weight. The injected slurry ranged from 7 percent to 9 percent bentonite. The corresponding estimated volume of bentonite slurry to achieve the minimum specified 2 percent bentonite ranged from approximately 92 to 73 gallons per foot of augured area for each primary stroke.

The IPM wall was constructed using a sequence of overlapping primary and secondary auger strokes such that no soil within the specified alignment and depth remained unmixed, as shown in Figure 6. A system of markers were placed at the ground surface to enable visual verification that the end augers of the secondary stroke penetrated the end auger holes from the primary strokes. The location of each stroke was surveyed and the coordinates recorded. If an auger stroke experienced lateral drift or vertical misalignment during penetration, and field measurements indicated that overlap was not achieved full depth, an additional stroke was added between the primary and secondary strokes to complete the mixing. Extra effort was put into mixing the lower portion of each stroke by raising and lowering the auger system a distance of approximately 20 feet off the bottom of the borehole while mixing.

ASSURING THE CONSTRUCTION QUALITY

A comprehensive quality assurance (QA) and quality control (QC) program was incorporated into the IPM wall construction. The QA/QC program included the following monitoring, measurements and testing:

- Preparation, mixing and sampling of the bentonite slurry prior to injection. The bentonite slurry was tested for viscosity using a Marsh Funnel, and for unit weight using a mud balance.
- The slurry injection rate was determined using volumetric quantities of injected bentonite slurry from digital flow-meter readings and penetration rate of the augers.
- Depth measurements provided verification that the augers were drilled to the specified depth profile
- Verticality measurements and auger overlap calculations were performed for each IPM stroke
- Samples of the constructed soil-bentonite wall were obtained for visual inspection of the mix quality. The samples were obtained at approximately 100 foot intervals along the wall alignment and from randomly selected depths. The samples were also subject to Methylene Blue and X-Ray Diffraction testing to obtain additional qualitative information on the percentage of bentonite in the soil-bentonite mix.

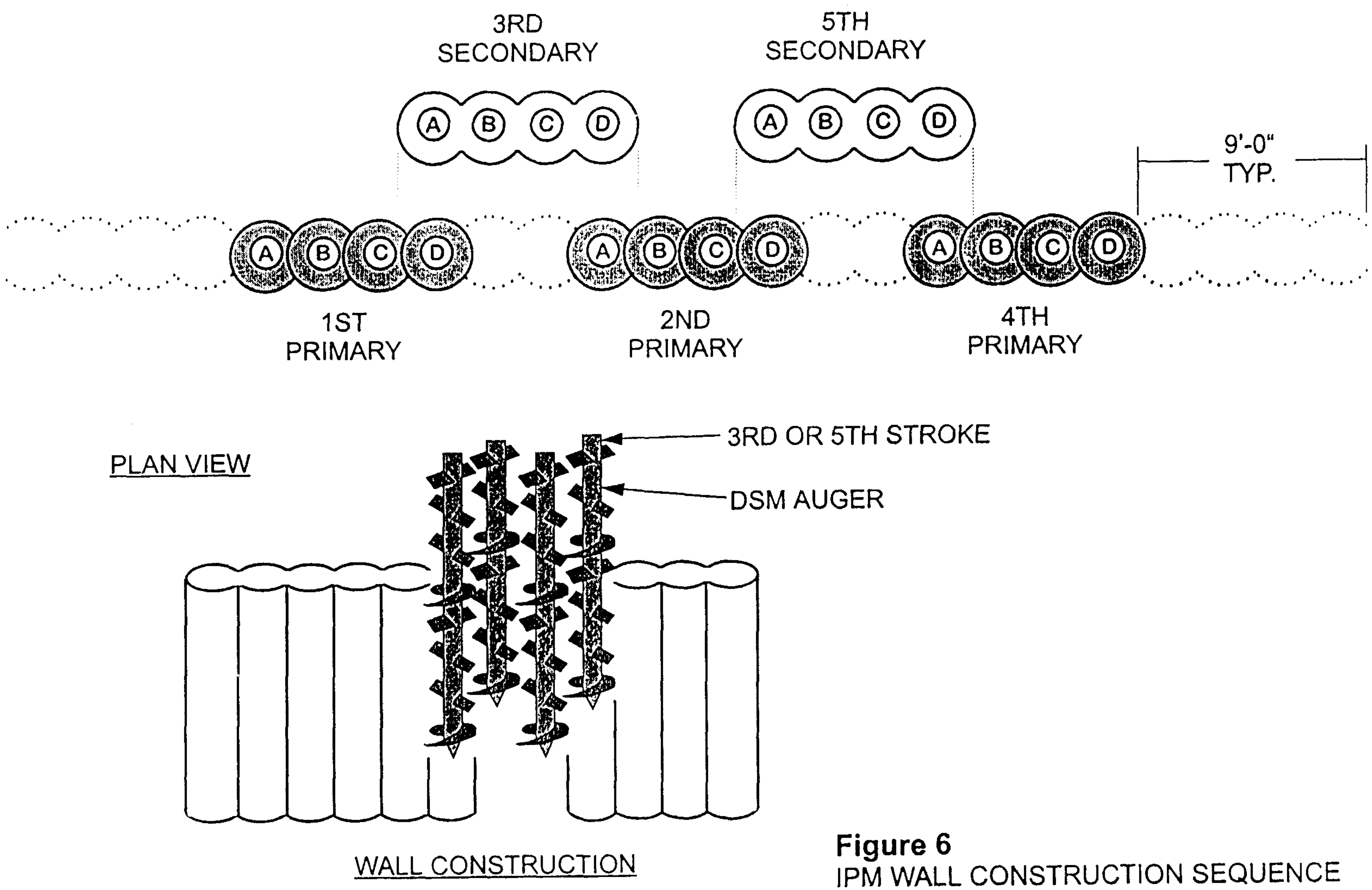

Figure 6
IPM WALL CONSTRUCTION SEQUENCE
OPERABLE UNIT 2, Hill AFB, Utah

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PERFORMANCE MONITORING

Long-term operation of the containment wall involves controlled groundwater removal from the interior of the wall to maintain an inward gradient to the source area. Twenty one piezometers, installed along the containment wall, will be used to verify that an inward gradient is maintained into the source area. Maintaining an inward gradient will promote hydraulic containment of contaminated groundwater within the containment wall. In the unlikely event a localized defect such as a permeable zone occurs in the containment wall, the containment system will not be compromised because the inward gradient will still provide hydraulic containment. A localized defect of the wall will merely increase the amount of water to be pumped and treated to maintain the inward gradient.

The containment wall system is operated in conjunction with an upgradient groundwater control system consisting of a gravel-filled trench to a depth of approximately 20 feet, collection sump and pump with level control system. The operation of the upgradient groundwater control system ensures the groundwater does not rise above a prescribed elevation to avoid potential instability of the steep slope to the north of the containment wall.

The containment wall will facilitate the implementation of DNAPL treatability studies or remediation using in situ soil and groundwater treatment methods. To date, planned treatability studies include a micellar surfactant flood, surfactant foam, and steam injection.

SUMMARY AND CONCLUSIONS

The process for selection and design of a containment system for a DNAPL source area has been presented. The application of currently available containment technologies to the site was evaluated with regard to the physical constraints of the site, the geologic setting modified by a historic large landslide, and the chemical compatibility of the wall materials with the contamination. The IPM method was selected for construction of the wall, leading to significant reductions in the requirements for excavation, out-of-trench mixing, and contaminated materials handling over conventional slurry wall construction methods. The IPM was found to be suited for use in a confined area where the wall alignment has tight curves, and existing structures are in close proximity. The installation of the IPM wall at OU2 was completed in December, 1996.

REFERENCES

Advanced Applied Technology Demonstration Facility, *Technology Practices Manual for Surfactant and Cosolvents*, prepared for the Department of Defense, February 1997.

CH2M HILL, *Draft Remedial Design Investigation Technical Memorandum for Operable Unit 2*. Hill Air Force Base, Ogden Air Logistics Center, March 1996.

CH2M HILL, *Draft Remedial Action Work Plan for Operable Unit 2, Schedule A and B Construction*. Hill Air Force Base, Ogden Air Logistics Center, March 1996.

Freeze, R.A., and McWhorter, D.B., *A Framework for Assessing Risk Reduction Due to DNAPL Mass Removal from Low Permeability Soils*. Journal of Ground Water, Vol. 35, No. 1, January-February 1997.

Montgomery Watson, *Sheet Pile Constructability Evaluation Report Operable Units 1, 2, and 4*, Hill Air Force Base, Ogden Air Logistics Center, October 1993

Oolman, T., Godard, S.T., Pope, G.A., Jin, M., and Kirchner, K., *DNAPL Flow Behavior in a Contaminated Aquifer: Evaluation of Field Data*, Journal of Groundwater Monitoring and Remediation, Vol. 15, No. 4, 1995.

Pashley, E.F., and Wiggins, R.A., *Landslides of the Northern Wasatch Front*, Utah Geologic Association, Publication No. 1, 1971.

Radian Corporation, *Final Remedial Investigation Report for Operable Unit 2, Site WP07, SS21*. Hill Air Force Base, Ogden Air Logistics Center, July 1992.

Radian Corporation, *Final Addendum to the Remedial Investigation Report for Operable Unit 2, Site WP07, SS21*. Hill Air Force Base, Ogden Air Logistics Center, August 1993.

Schroder, J.F., *Landslides of Utah*. Utah Geological and Mineralogical Survey and University of Utah. September 1971.

USEPA, 1996, *Record of Decision for Operable Unit 2, Hill Air Force Base, Ogden Air Logistics Center*, U.S. Environmental Protection Agency, Region VIII, September 1996

Utah Geological Association. *Environmental Geology Tour of the Wasatch Front (Brigham City-Nephi)*. Field Conference No. 1. September/October, 1971.

Xanthakos, P.P., *Slurry Walls*, McGraw Hill Book Company, 1979