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SGW-47062
Revision 0

Treatability Test Report for Field-Scale Apatite Jet Injection Demonstration for the 100-NR-2 Operable Unit

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company

P.O. Box 1600
Richland, Washington 99352

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Terms

bgs	below ground surface
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
DOE	U.S. Department of Energy
DOE-RL	U.S. Department of Energy-Richland Operations Office
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
K_{sp}	solubility product
LWDF	liquid waste disposal facility
OU	operable unit
PRB	permeable reactive barrier
ROD	record of decision
Sr-90	strontium-90
TPH	total petroleum hydrocarbon
Tri-Party Agreement	*Hanford Federal Facility Agreement and Consent Order*
TTP	treatability test plan

1 Introduction

This document presents the results for the field-scale jet injection demonstration conducted during fiscal year 2010 in the 100-NR-2 Operable Unit (OU) of 100-N at the Hanford Site (Figure 1-1) near Richland, Washington. Jet injections were conducted to evaluate potential strategies for emplacement of three different media: a phosphate solution, pre-formed apatite (fishbone), and the same phosphate solution with the addition of the pre-formed apatite. The demonstration was also used to determine the implementability of using jet injection technology to inject these media within the vadose zone and upper unconfined aquifer. Work was conducted under *Strontium-90 Treatability Test Plan for 100-NR-2 Groundwater Operable Unit* (DOE/RL-2005-96, Addendum 3).

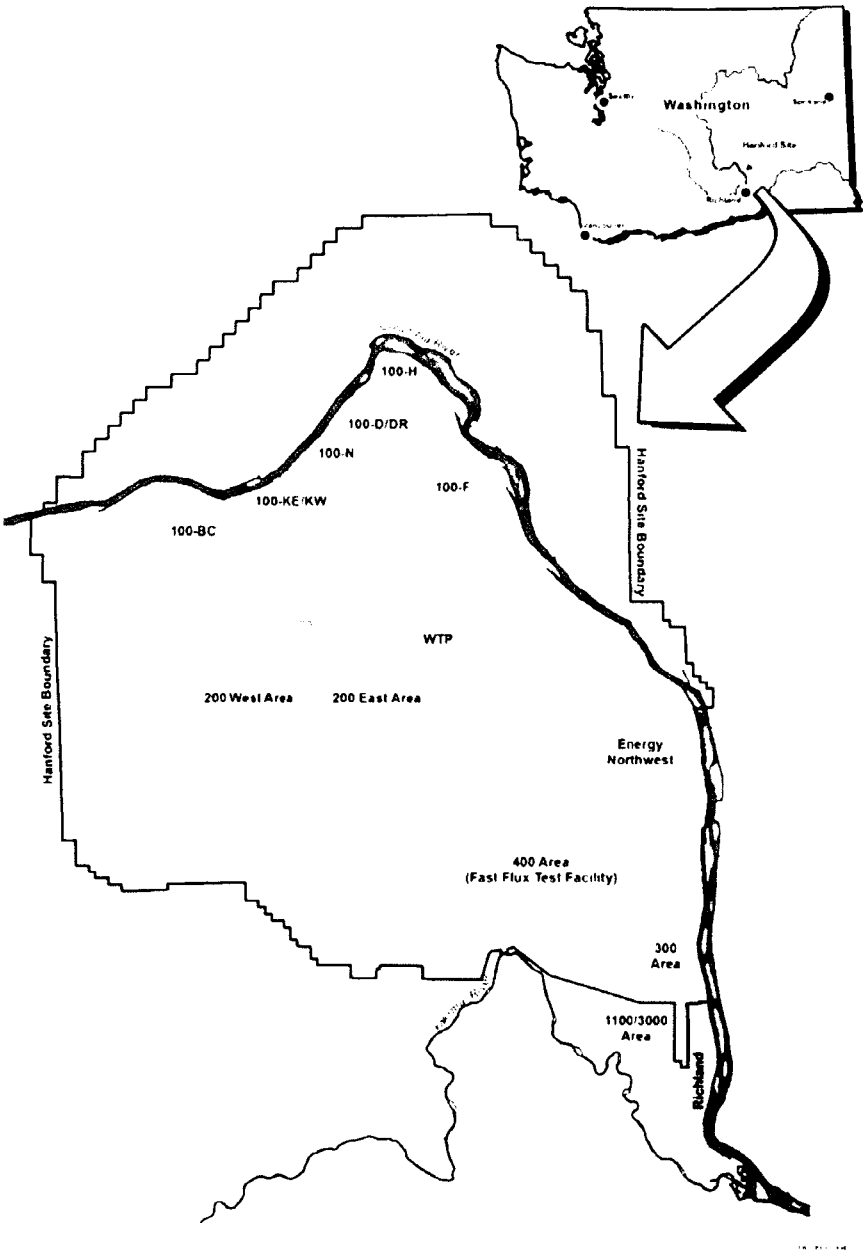


Figure 1-1. The Hanford Site and Washington State

1.1 Site Description

This section briefly discusses previous work activities and regulatory decisions associated with the 100-NR-2 Groundwater OU. General summaries of hydrogeology, site history, and contaminants of concern are presented.

1.1.1 Site Location

The Hanford Site is located in southeastern Washington State near Richland, Washington. The 100 Area is located along the Columbia River and includes nine U.S. Department of Energy (DOE) nuclear reactors previously used for plutonium production, one of which is the 100-N Reactor. The 100-NR-2 Groundwater OU was established to address groundwater issues associated with 100-N. The 100-NR-2 OU follows the 1989 listing of the Hanford Site on the Environmental Protection Agency's (EPA's) National Priorities List pursuant to the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERLCA). The 100-NR-2 OU is located in the northern part of the Hanford Site adjacent to the Columbia River, and is defined to include the groundwater beneath 100-N plus the adjacent groundwater, surface water, sediments, and aquatic biota impacted by operations in 100-N.

1.1.2 Site Hydrogeology

Stratigraphic units of significance in 100-N include the Ringold Formation and the Hanford formation (Figure 1-2). The unconfined aquifer at 100-N near the shoreline is composed of gravels and sands of the Ringold Formation and the Hanford formation. The Ringold Formation is composed of several lithologic facies. Of most interest at 100-N is the Ringold Unit E, which primarily forms the unconfined aquifer beneath the Hanford formation, and the Ringold Upper Mud Unit, which forms the base of the unconfined aquifer and is believed to be an aquitard below Unit E.

The uppermost Ringold stratum at 100-N is Unit E, consisting of variably cemented pebble to cobble gravel with a fine- to coarse-grained sand matrix. Sand and silt interbeds also may be present. Unit E primarily forms the unconfined aquifer in 100-N and is approximately 12 to 15 m (39 to 49 feet [ft]) thick. The base of the aquifer is situated at the contact between Ringold Unit E and the underlying, much less transmissive, silty strata referred to locally as the Ringold Upper Mud, approximately 60 m (197 ft) thick.

The uppermost stratigraphic unit in 100-N is the Hanford formation, which consists of uncemented and clast-supported pebble, cobble, and boulder gravel with minor sand and silt interbeds. The matrix in the gravel is composed mostly of coarse-grained sand, and an open-framework texture is common. For most of 100-N, the Hanford formation extends from ground surface to just above the water table, 5.8 to 23.5 m (19 to 77 ft) in thickness. However, channels of Hanford gravels extend below the water table. Overlying the Hanford formation in the river shore area is a layer of highly compacted roadbed backfill material ranging from 1.5 to 2.7 m (5 to 9 ft) thick.

The Hanford formation is more transmissive (3 to 10 times) than the underlying Ringold Unit E. However, due to geologic heterogeneity, the hydraulic conductivity in both units is highly variable. Typical values of 5 and 182 meters per day (m/d) (19 and 597 feet per day [ft/d]) have been used for modeling purposes for the Ringold Formation and Hanford formation, respectively (HydroGeoLogic, Inc., 2001). It should be noted that because the texture of the sediments between the upper stratigraphic units (Ringold Unit E, Hanford formation, and backfill) is so similar (i.e., sandy gravel), there is uncertainty, in some cases, associated with distinguishing between these units. Furthermore, the boundaries between these units are not always discrete, but instead often grade into one another as a result of the sediment reworking and mixing during deposition.

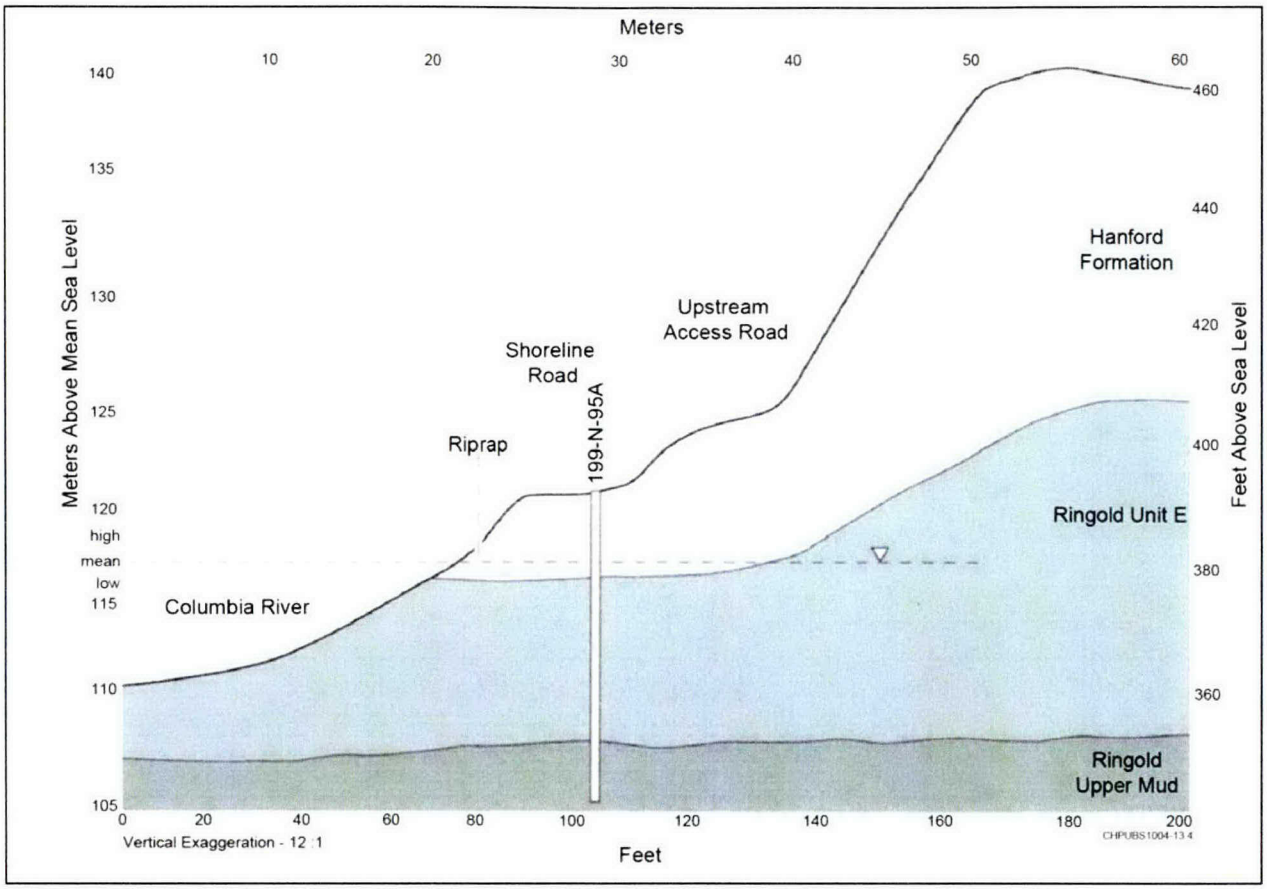


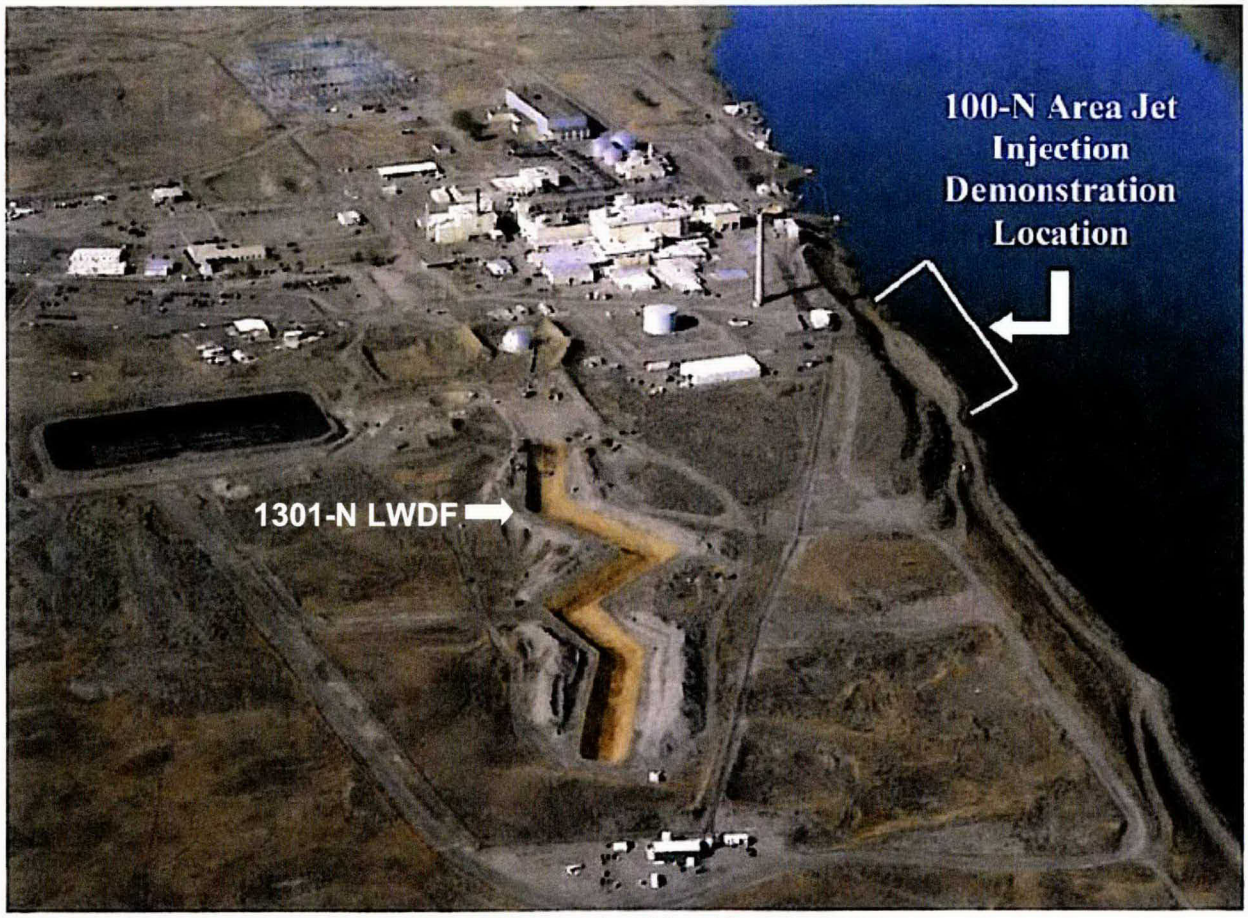
Figure 1-2. Site Geologic Model in Cross-Section

Groundwater flows primarily in a north-northwesterly direction most of the year and discharges to the Columbia River, although flow is reversed (river water flow into the aquifer) for short periods under high river stage. The groundwater gradient varies from 0.0005 to 0.003 m/m. Near the liquid waste disposal facilities, average groundwater velocities are estimated to be between 0.03 and 0.6 m/d (0.1 and 2 ft/d), where 0.3 m/d (1 ft/d) is generally considered as typical. However, groundwater flows near the river are significantly influenced by both diurnal (daily) and seasonal variability in Columbia River stage.

Fluctuations in river stage resulting from seasonal variations and daily operations of Priest Rapids Dam, located 29 km (18 mi) upstream of 100-N, have a significant impact on groundwater flow direction, hydraulic gradient, and groundwater levels near the river. The volume of water moving in and out of the unconfined aquifer on both a daily and seasonal basis is an order of magnitude greater than groundwater flowing as a result of the regional hydraulic gradient. During high river stage, river water moves into the bank and mixes with groundwater. The zone of mixing is restricted to within tens-of-meters of the shoreline. During a low river stage, this bank storage water drains back into the river and may be observed as springs along the riverbank. Springs, seeps, and subsurface discharge along the Columbia River bank are the primary pathway of 100-N groundwater discharge to the Columbia River. Additional details on the extent of seasonal and daily changes in river stage at the site from Priest Rapids Dam discharge is reported in *100-NR-2 Apatite Treatability Test: Low-Concentration Calcium-Citrate-Phosphate Solution Injection for In Situ Strontium-90 Immobilization* (PNNL-17429).

1.1.3 Site History and Previous Work Activities

Operation of the 100-N nuclear reactor required the disposal of bleed and feed cooling water from the reactor's primary cooling loop, the spent fuel storage basins, and other reactor-related sources. Two crib and trench liquid waste disposal facilities (LWDFs) were constructed to receive these waste streams, and disposal consisted of percolation into the underlying sediment. The first LWDF (1301-N/116-N-1) was constructed in 1963, about 244 m (800 ft) from the river (Figure 1-3). Liquid discharges to this facility primarily contained radioactive fission and activation products, including cobalt-60, cesium-137, strontium-90 (Sr-90), and tritium. Minor amounts of hazardous wastes such as sodium dichromate, phosphoric acid, lead, and cadmium were also part of the waste stream. When very high concentrations of Sr-90 were detected in the shoreline discharges, a second LWDF (1325-N/116-N-3) was constructed farther inland (1983) and disposal at the 1301-N LWDF was eventually terminated. Discharges to the 1325-N LWDF ceased in 1991.



Note: The 1301-N LWDF has been backfilled since this photo was taken. Adapted from PNNL-17429.

Figure 1-3. Test Site Location Aerial Photo in 2003

Remedial investigations to address groundwater contamination in 100-NR-2 OU were initially conducted in the early 1990s. In response to Action Memorandum: N-Springs Expedited Response Action Cleanup Plan (Ecology and EPA, 1994), an expedited response action to address Sr-90 groundwater contamination was implemented at N-Springs. The Action Memorandum required the installation and operation of a 189 L/min (50-gpm) pump-and-treat system and the construction of a grouted-hinge sheet pile wall at the river's edge by September 1995.

In March 1995, Washington Department of Ecology (Ecology) and EPA concurred with U.S. Department of Energy-Richland Operations Office (DOE-RL) that installing the sheet pile wall could not be achieved in the manner specified. Ecology and EPA subsequently directed DOE-RL to proceed with installing a pump-and-treat system as an expedited response action. The 100-NR-2 OU pump-and-treat system was completed by August 1995 and was in full operation by September 1995, meeting the *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement) Milestone M-16-12D (Ecology et al., 1989a). Based on recommendations in the *N Springs Expedited Response Action Performance Evaluation Report* (DOE/RL-95-110), the system was upgraded to operate at 227 L/min (60 gpm) beginning on December 17, 1996.

Subsequently, an Interim Action Record of Decision (ROD) was issued by EPA in 1999 (EPA/ROD/R10-99/112, *Interim Remedial Action Record of Decision for the 100-NR-1 and 100-NR-2 Operable Units of the Hanford 100-N Area*). The remedial action objectives listed in the Interim Action ROD require the protection of the Columbia River from adverse impacts from the 100-NR-2 Groundwater OU and the protection of the unconfined aquifer from both radioactive and nonradioactive contaminants.

The pump-and-treat system installed in 1995 at 100-N used four extraction wells, a treatment skid (using clinoptilolite), and two injection wells. The system operated from September 1995 through March 2006, removing approximately 1.8 Curies (Ci) of Sr-90 from the aquifer. The 0.2 Ci removed each year by the pump–and-treat system was estimated to be 10 times less than the amount removed by natural radioactive decay (DOE/RL-2004-21). However, the pump-and-treat system effectiveness was limited in producing a hydraulic barrier, removing Sr-90, and creating ambient conditions to test the proposed permeable reactive barrier (PRB). Therefore, DOE, Ecology, and EPA approved placing the system in standby mode in March 2006 (M-16-06-01, Change Request to Construct and Test a Permeable Reactive Barrier at 100-NR-2, approved by DOE, EPA, and Ecology).

As required by the Interim Action ROD, DOE conducted a comprehensive review of Sr-90 treatment technologies to complement the existing interim remedial actions. This review was commissioned under DOE's Innovative Treatment & Remediation Demonstration program and the results were presented in the Hanford 100-N Area Remediation Options Evaluation Summary Report (ITRD, 2001). Based on the evaluation presented in that document, the technical advisory group recommended that monitored natural attenuation, soil flushing, phytoremediation, stabilization by phosphate injection (apatite), impermeable barriers (sheet pile and cryogenic), and treatment barriers (clinoptilolite) be evaluated further for Sr-90 remediation. Subsequent evaluations and field trials led to the elimination of soil flushing and sheet pile barriers as viable technologies for the 100-NR-2 OU.

Sr-90 sequestration through injection of apatite forming chemicals is a promising technology that was carried forward for laboratory and field-testing. Apatite-forming chemicals have been injected into a series of wells that cover an approximately 91 m (300-ft) long section of the highest Sr-90 concentrations in 100-N (Figure 1-4). Injections of apatite-forming chemicals were performed in 2006, 2007, and 2008, using different permutations of calcium-citrate-phosphate solutions. These injections have created a PRB that appears to have significantly reduced the concentration of Sr-90 in groundwater within the footprint of the barrier.

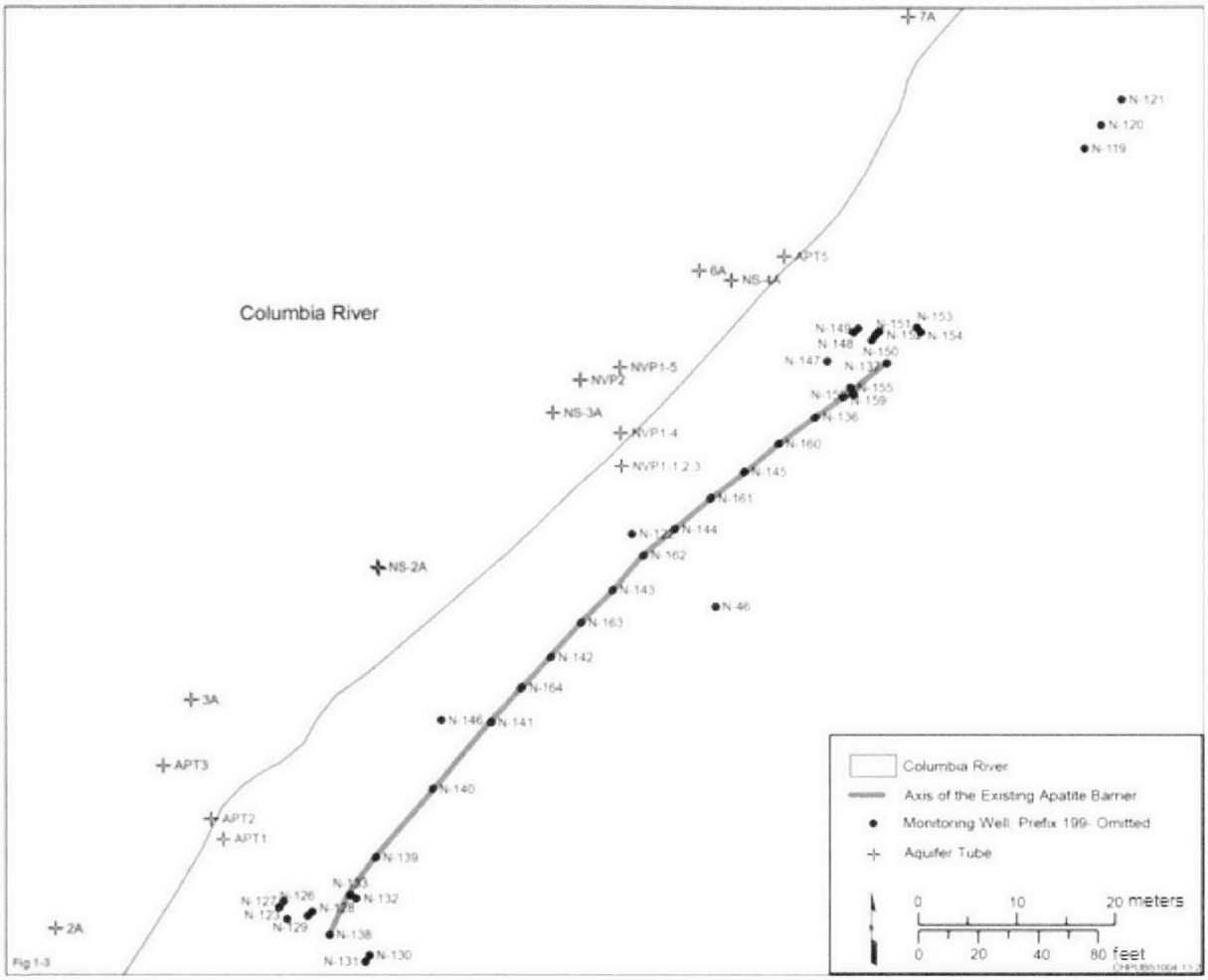


Figure 1-4. Location of Existing Apatite Permeable Reactive Barrier

1.1.4 Contaminants of Concern

Sr-90 is the primary contaminant of concern in the 100-NR-2 OU. The Sr-90 contaminated zone resulted from 30 years of wastewater discharge to the LWDFs and includes portions of the vadose zone that were water-saturated during discharge operations, and the underlying aquifer, which extends from below the LWDFs to the Columbia River (Figure 1-5). Other contaminants detected in groundwater include tritium, petroleum hydrocarbons, nitrate, sulfate, manganese, and iron.

Total petroleum hydrocarbon (TPH) concentrations are associated with a 302,832 L (80,000-gallon [gal]) diesel spill that occurred in 1966. A trench was excavated along the Columbia River bank to intercept the diesel oil before it could reach the river and the diesel was periodically burned off in 1966 and 1967. In 1994, the trench was backfilled with clean material.

1.2 Technology Description

This section describes the characteristics of apatite in general, the properties that make it amenable as a sequestering agent for Sr-90, and the different forms of apatite.

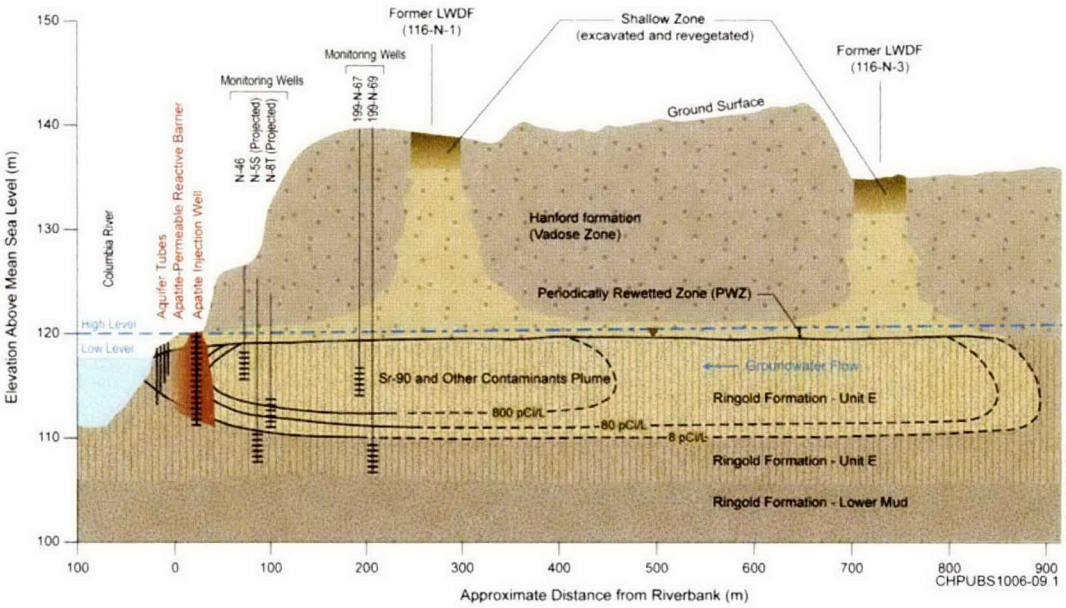


Figure 1-5. Conceptual Site Model for the 100-NR-1 and 100-NR-2 Operable Units

Apatite [Ca10(PO4)6(OH)2] is a natural calcium phosphate mineral occurring primarily in the Earth's crust as phosphate rock. It is also a primary component in the teeth and bones of animals. Apatite minerals sequester elements into their molecular structures via isomorphic substitution, whereby elements of similar physical and chemical characteristics replace calcium, phosphate, or hydroxide in the hexagonal crystal structure. Because of the extensive substitution into the general apatite structure (Figure 1-6), more than 350 apatite minerals have been identified (Moelo et al., 2000). Apatite minerals are very stable with very low solubility in pH neutral to alkaline water (Wright et al., 2004). The solubility product (K_{sp}) of hydroxyapatite is about 10^{-44}, while quartz crystal, which is considered the most stable mineral in the weathering environment, has a K_{sp} of 10^{-4} (GeoChem Software, Inc., 1994). Strontiapatite, Sr10(PO4)6(OH)2, which is formed by the complete substitution of calcium by strontium (or Sr-90), has a K_{sp} of about 10^{-51}, another 107 times less soluble than hydroxyapatite (Verbeeck et al., 1977). The substitution of strontium for calcium in the crystal structure is thermodynamically favorable, and will proceed, provided the two elements coexist.

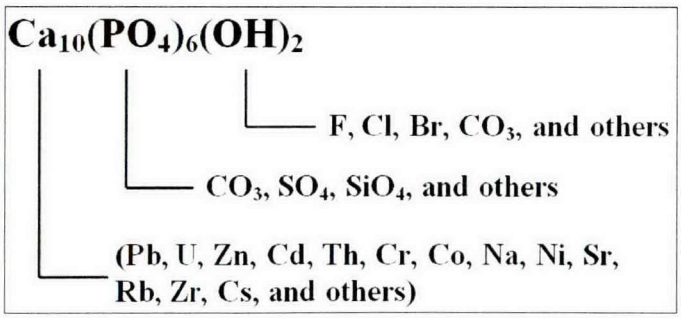


Figure 1-6. Cationic and Anionic Substitution in Apatite

Apatite formed from precursor aqueous solutions can remove soluble strontium and Sr-90 from groundwater both during and after its formation. Removal can occur via precipitation of strontium in solution with phosphate anions, adsorption to the apatite surface (adsorption of Sr-90 to apatite is approximately 55 times stronger than to Hanford sediment), and slow substitution into the apatite

structure (months-to-years time scale). Precipitation directly from solution, or homogeneous nucleation, generally occurs only at very high metal concentrations; that is, greater than 10 parts per million. However, apatite will act as a seed crystal for the precipitation of metal phosphates at much lower concentrations (Ma et al., 1993). The apatite itself serves as a small but sufficient source of phosphate to solution and, with low concentrations of cations such as strontium or calcium, heterogeneous nucleation occurs on the surface of the apatite seed crystal (Lower et al., 1998). Over time, the precipitated metals are sequestered into the apatite crystal matrix.

Although the rate of metal incorporation into the apatite crystal lattice can be relatively slow, the precipitation reaction is nearly instantaneous on the molecular scale. Initially, the precipitate formed is amorphous apatite; however, over time, it will transform into a more stable apatite crystal.

1.3 Previous Treatability Studies at the Site

Previous apatite sequestration treatability studies were conducted at the 100-NR-2 OU, including low-concentration and high-concentration calcium-citrate-phosphate solutions. Several methods were considered for apatite emplacement into the subsurface, which included pneumatic injections of solid apatite and vertical hydrofracture for apatite emplacement. Ultimately, aqueous injections of apatite precursors were carried forward because of the advantage of an increased treatment zone around the injection point and the prospect of treating a larger area of the near-shore aquifer.

The 2006 Treatability Test Plan (TTP) outlined field testing to be conducted in two separate phases: an initial field pilot test at two locations on either end of the barrier, followed by installation and treatment of a sufficient number of wells to create a 91 m (300-ft) PRB. The pilot tests were to be located at the east and west ends of the barrier because of the extensive monitoring networks at those locations. Monitoring results from the first pilot test injection showed an average increase in Sr-90 concentrations of 8.4 times the average baseline concentrations. Based on the results of the first pilot test, the injection solution was modified, with calcium and citrate concentrations two times lower. This resulted in an average peak in Sr-90 that was 3.8 times that of the average baseline concentration. The injection formulation was again revised for the barrier injection wells in 2007. This solution had calcium and citrate concentrations that were two times lower than the second pilot test formulation, as well as an approximately four times higher phosphate concentration. A more complete summary of the low-concentration injection can be found in the *100-NR-2 Apatite Treatability Test: Low-Concentration Calcium Citrate-Phosphate Solution Injection for In Situ Strontium-90 Immobilization* (PNNL-17429).

The primary objective of the high-concentration injection solution was to maximize the amount of apatite formation, providing long-term treatment while limiting the temporary increase in Sr-90 caused by the injection solution. The high-concentration injection solution had approximately four times higher phosphate concentration than the final low-concentration injection solution of 1 mM calcium chloride, 2.5 mM citrate, and 10 mM phosphate used for barrier emplacement in 2007. The final high-concentration solution formulation was determined in the laboratory prior to field implementation and documented in an injection-specific field test instruction. Results from the high-concentration injection are presented in *100-NR-2 Apatite Treatability Test FY09 Status: High-Concentration Calcium-Citrate-Phosphate Solution Injection for In Situ Strontium-90 Immobilization* (PNNL-SA-70033).

2 Treatability Study Approach

This section presents the approach used in the installation of the injection wells and the injection of the amendment solutions.

2.1 Treatability Study Objectives

The objectives of the jet injection pilot scale demonstration were twofold:

1. Evaluate the ability of jet injection technology to deliver different apatite material/apatite-forming chemical solutions into the vadose zone and upper unconfined aquifer within three distinct treatment zones along the 100-N shoreline.
2. Evaluate the ability of the jet injection technology to deliver apatite forming solutions to install a PRB in the vadose zone containing 3.4 mg apatite/g sediment (1.1 mg phosphate/g sediment).

2.2 Experimental Design and Procedures

Three separate test plots were selected for testing the amendments (Figure 2-1). Test plot locations were selected to maximize the potential for successful apatite formation and minimize disturbance to ongoing work in 100-N. The demonstration was conducted upstream (west) of the existing apatite PRB, while still within the moderate Sr-90 plume and downstream (east) of the TPH wells. Jet injections were conducted using three treatments:

- Phosphate-only solution
- Pre-formed apatite
- Combination of both pre-formed apatite and phosphate solution

The phosphate solution and pre-formed apatite were procured by the vendor and brought onsite, where the pre-formed apatite was mixed with potable water to create an injectable slurry. For the combined solution, the pre-formed apatite was mixed with the vendor-supplied phosphate solution to create an injectable slurry.

2.2.1 Phosphate Solution

A phosphate-only solution has been previously investigated in some laboratory experiments and in this field pilot study (jet injection). The injection of phosphate only is effective to a concentration of 25 to 35 mM, with the utilization of adsorbed calcium on sediment within the targeted treatment zone. Higher phosphate concentrations require additional calcium to precipitate. This can occur as the aqueous phosphate plume drifts downgradient from the targeted zone and into additional aquifer sediment. As such, one advantage of the phosphate solution is the potential for forming a larger PRB beyond the initially targeted treatment zone, due to the mobility of the phosphate solution through sediment as compared to pre-formed apatite. Another known advantage of the phosphate solution is that Sr-90 can be removed from groundwater both during and after the resulting apatite formation.

The phosphate solution injected during the jet injections consisted of a combination of phosphoric acid and sodium hydroxide in specific proportions for a final pH of 7.5. The phosphate solution produces a mixture consisting of 85 percent disodium hydrogenphosphate (Na_2HPO_4) and 15 percent sodium dihydrogenphosphate (NaH_2PO_4). The total aqueous concentration of phosphate did not exceed 100 mM.

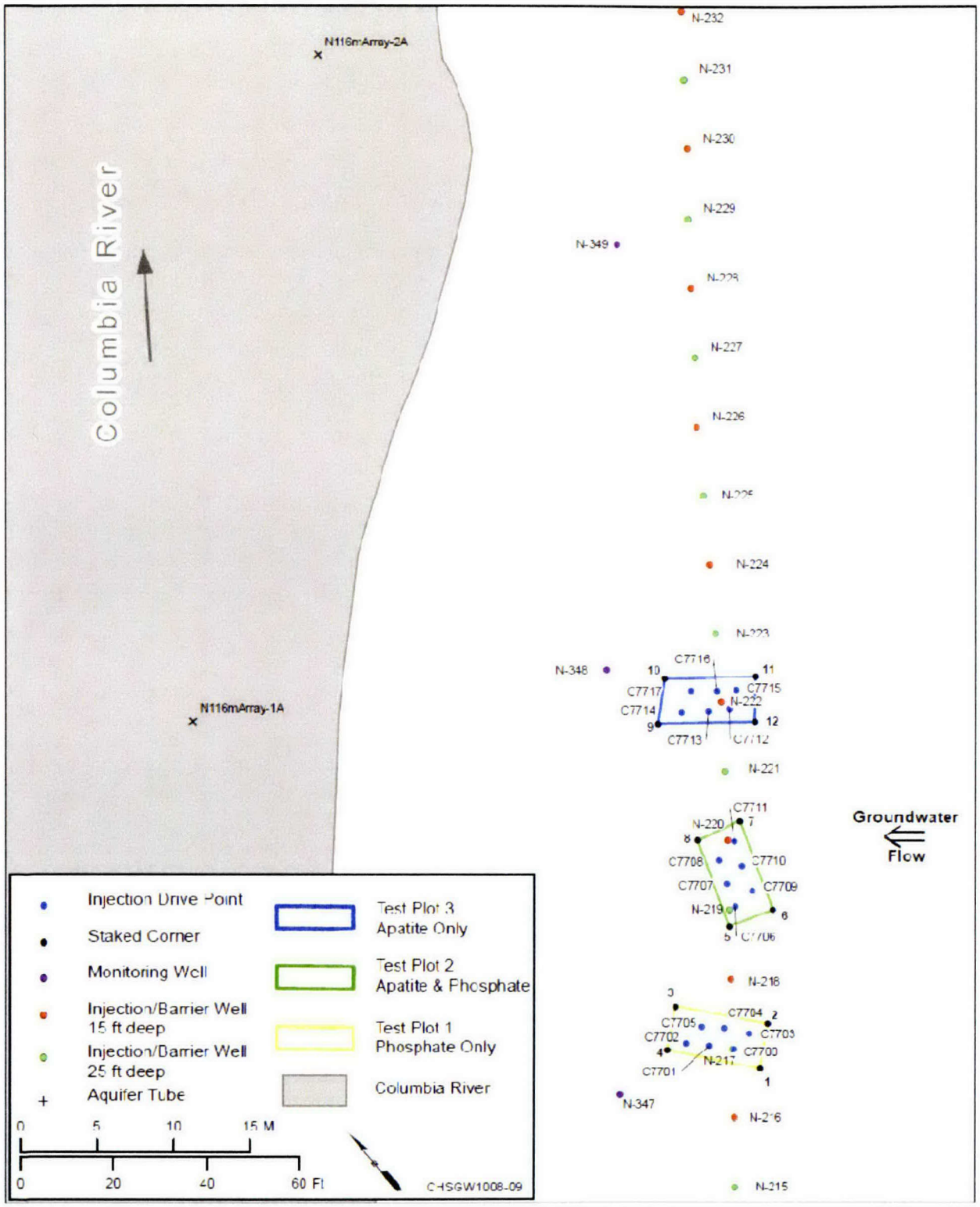


Figure 2-1. Locations of Jet Injection Test Plots

The preblended phosphate mixture of food-grade phosphoric acid and sodium hydroxide was delivered warm to the site due to weather in 18,927 L (5,000-gal) loads via tanker truck. The solution in the tanker trucks was heated by the exothermic reaction caused by chemical addition and/or by boilers at the vendor distribution center. The solution was offloaded into holding tanks, and piping was installed between the holding tanks and the jet injection pump.

2.2.2 Pre-formed Apatite

Raw apatite material composed of ground fishbone was used for the pre-formed apatite injections. One advantage of the pre-formed apatite is its reactive surface area, which allows it to immediately adsorb Sr-90 onto the apatite surface and, subsequently, incorporate it into the apatite structure. Another is that the pre-formed apatite eliminates the time delay for the initial formation of apatite and can be injected independent of river stage.

Prior to injection, the granular apatite was mixed with potable water to create an injectable slurry. The pre-formed apatite slurry was prepared using a mixture of 23.1 kg (51 lb) of powdered fishbone apatite material (Alaskan pollock from Bering Sea, mesh size, less than 2 microns) blended with 1,000 L (265 gal) of potable water trucked onsite by the same contractor that supplied the phosphate solution.

2.2.3 Phosphate with Addition of Pre-formed Apatite

The injection of phosphate solution with the additional injection of pre-formed fishbone apatite was done to determine the added benefit, if any, of injecting both forms of apatite in combination. The combination of these media should produce a higher overall apatite concentration. One unique advantage to this combination is the potential for the pre-formed apatite, when combined with the phosphate solution, to serve as the seed crystal (and catalyst) for subsequent phosphate precipitation and apatite formation from the phosphate solution.

Prior to injection, the granular apatite was mixed with the pre-blended phosphate solution described in Section 2.2.1 to create an injectable slurry. This slurry was prepared using a mixture of 23.1 kg (51 lb) of powdered fishbone apatite material blended with 1,000 L (265 gal) of phosphate solution.

2.2.4 Injections

In each of the three test plots, a containment trench (approximately 9 × 3 × 0.6 m [30 × 10 × 2 ft]) was constructed prior to jet injection (Figure 2-2). Excavated soil was used to create a berm around each trench to contain any drilling spoils and/or injection fluids that may have risen to the surface. Jet injection borings were spaced in an offset pattern as shown in Figure 2-3. All injection borings were drilled using a hydraulic drill rig equipped with jet grout injection capabilities. The borings were advanced from the bottom of the trench (~ 0.6 m [2 ft] below ground surface [bgs]) to 5.2 to 7.6 m (17 to 25 ft) bgs using a rotary external wash drilling method. The actual total depth of each boring varied depending on the geologic conditions encountered, as shown in Table 2-1. The phosphate injection solution was used as the external wash (drilling fluid) in the phosphate-only and combination test plots as the boreholes were advanced. The pre-formed apatite slurry was not used in the drilling fluid in the pre-formed apatite-only and combination test plots since the accumulation of the apatite solids in the containment trench would prevent subsequent infiltration of the liquid. Water was used as the drilling fluid for the pre-formed apatite-only test plot. In the case of the phosphate-only and combination test plots, this use of phosphate as the drilling fluid increased the amount of phosphate solution placed in the borehole.

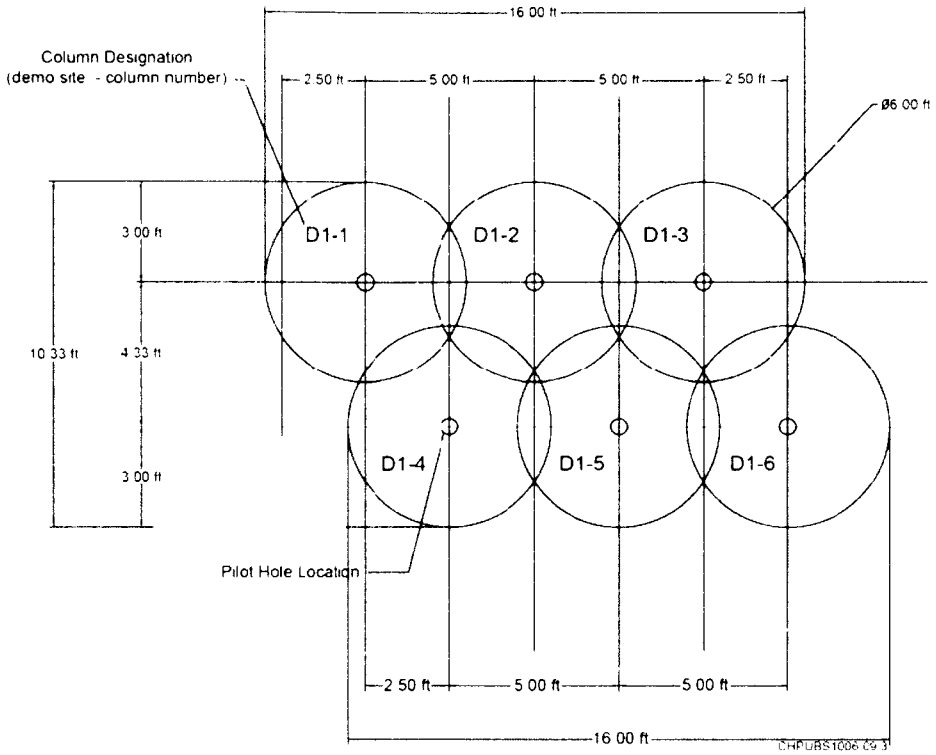
Jet injections were performed using a proprietary jet injection system capable of injecting the solutions at approximately 400 bars (5,800 pounds per square inch [psi]). This high-pressure injection mixes the sediment with the solutions to the expected minimal radial distance of 1 m (3 ft) from the injection nozzle (Figure 2-4).

2.2.5 Injection Well Decommissioning and Waste Management

Following injections, the 18 temporary injection wells were decommissioned according to the *Description of Work for NR-2 Jet Injection Treatability Test* (SGW-43882). Excavated soil from the containment trenches that was used as berm material was also used to backfill the trenches following injection well abandonment.

Wastes generated during the installation of 18 temporary injection wells included decontamination waste, personal protective equipment, and miscellaneous solid waste. No drill cuttings were produced as waste, as all of the cuttings were captured in the containment trenches (with most of it re-entering the boreholes after the drill/injection tools were removed). The remaining/residual drill cuttings were then covered with the backfill material (excavated soil). All wastes generated in the scope of this project were managed according to the *Interim Action Waste Management Plan for the 100-NR-2 Operable Unit* (DOE/RL-2000-41) and as outlined SGW-43882.

Figure 2-2. Photo of Trench at Jet Injection Test Plots



Source: Nicholson, 2010.

Figure 2-3. Jet Injection Layout

Table 2-1. Jet Injection Borehole Identifications, Depths, and Surveyed Locations

Boring Identification	Injection Boring Identification (from Drilling Log)	Final Drill Depth (m)	Easting (m)	Northing (m)
C7700	D11	5.30	571,238.500	149,820.268
C7701	D12	5.49	571,237.380	149,821.495
C7702	D13	5.41	571,236.346	149,822.619
C7703	D14	6.74	571,239.915	149,820.463
C7704	D15	5.61	571,238.928	149,821.754
C7705	D16	5.33	571,237.852	149,822.793
C7706	D21	5.30	571,244.665	149,827.486
C7707	D22	5.43	571,245.203	149,829.015
C7708	D23	5.58	571,245.806	149,830.502
C7709	D24	5.43	571,246.212	149,827.587
C7710	D25	5.34	571,246.716	149,829.284
C7711	D26	5.51	571,247.346	149,830.811
C7712	D31	6.15	571,252.730	149,837.770

Table 2-1. Jet Injection Borehole Identifications, Depths, and Surveyed Locations

Boring Identification	Injection Boring Identification (from Drilling Log)	Final Drill Depth (m)	Easting (m)	Northing (m)
C7713	D32	6.62	571,251.628	149,838.594
C7714	D33	5.92	571,250.235	149,839.638
C7715	D34	7.64	571,253.920	149,838.440
C7716	D35	6.72	571,252.933	149,839.245
C7717	D36	6.98	571,251.553	149,840.310

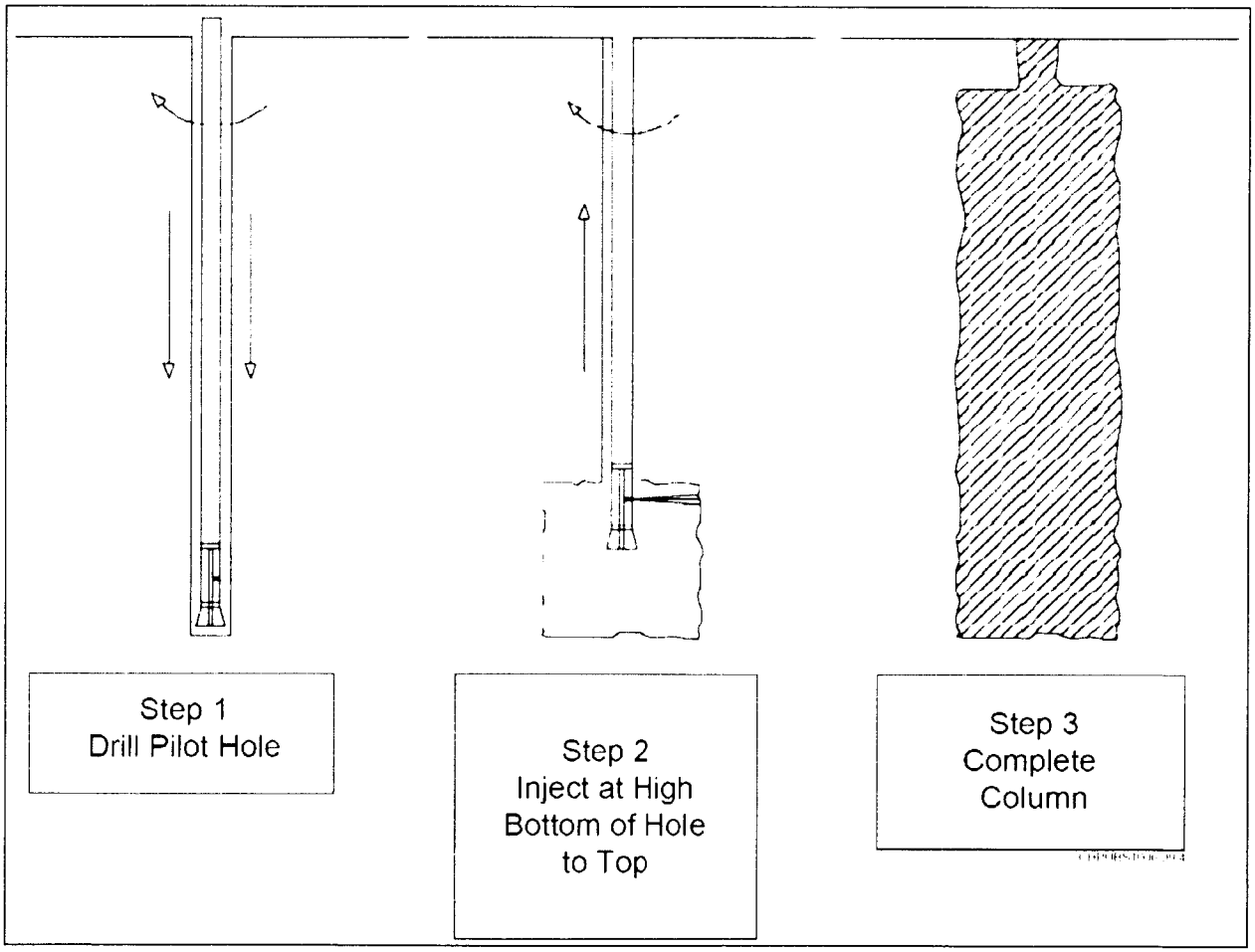


Figure 2-4. Jet Injection Process

2.3 Equipment and Materials

This section presents the equipment and materials used to inject the different solutions into the test plots.

2.3.1 Apatite Mixing Unit

A custom-fabricated mixer equipped with multiple aggressive blades was used to blend the apatite product with water or phosphate solution to form the apatite injection mixture (slurry). An auger conveyed the apatite material into the mixing unit. The super sack storage unit was equipped with load cells that accurately weighed and delivered the proper proportion of apatite product to the mixer for each batch. Potable water or phosphate solution was delivered to the mixer through a flow meter that delivered a consistent volume to each batch. A mission-type pump was used to recirculate and continuously agitate the apatite mixture.

2.3.2 Jet Injection Pump

A jet injection pump was used to deliver the injection solution to the drill rig and jet grout tooling via a 38 mm (1.5-in.) high-pressure hose. The apatite mixing unit and/or phosphate storage containers delivered the injection solutions to the injection pump via flexible 76 or 102 mm (3- or 4-in.) hoses.

2.3.3 Drill Rig

A crawler-mounted hydraulic drill rig equipped with jet grouting timers and data recorders was connected to the pump via the 38 mm (1.5-in.) hose.

2.3.4 Data Recording

A data recorder was used during the injections to record important parameters during drilling of each borehole. The parameters recorded were drill depth, drill duration, rod rotation, lifting rate, jet injection pressure, solution flow rate, and solution injection quantity. Recorder data for each borehole is presented in Appendix A.

2.4 Sampling and Analysis

Aquifer tube samples and sediment cores were collected to determine the concentration of apatite formed in the test plots and to quantify changes in Sr-90 concentrations relative to baseline conditions. Samples were collected in accordance with DOE/RL-2005-96, Addendum 3.

Aquifer Tube Arrays N116m-1A and N116m-2A, located downgradient from the jet injection test plots (Figure 2-1), were monitored for Sr-90 (gross beta), metals, anions, and field parameters both prior to and following the jet injections, with the exception that the Array N116m-2A sample was not collected prior to the jet injections because the tube was frozen. Samples were collected weekly for the first six weeks following completion of the three test plots. Additional samples were collected three months after injection. Aquifer tube samples were collected according to DOE/RL-2005-96, Addendum 3.

Sediment cores were collected from four boreholes (subsequently completed as wells) that were drilled as part of a separate 171-well drilling effort (*100-NR-2 Groundwater Operable Unit Sr-90 Plume Rivershore Sampling and Analysis Plan*, DOE/RL-2009-32) and that were located within the test plot footprints. The continuous cores were collected according to DOE/RL-2005-96, Addendum 3, to provide data about the effectiveness of jet injection technology for apatite PRB installation and apatite formation in both the vadose and saturated zone. The boreholes were drilled using roto-sonic methods. One core was taken from the phosphate-only and pre-formed fishbone apatite test plots. Two cores were taken from the combined phosphate and pre-formed fishbone test plot. The spatial relationship of these wells to the jet injection boreholes is shown on Figure 1-6.

Recovered well cores were approximately 7.6 m (25 ft) long. Samples from the cores were taken at approximately 0.6 m (2-ft) intervals at 15 locations along the length of the core. These samples were analyzed for phosphate, Sr-90, ion-exchangeable strontium and calcium, and grain size (used to infer

saturated hydraulic conductivity [Masch and Denny, 1966]). The concentration of phosphate in the core was used to determine the concentration of apatite formed in the subsurface.

2.5 Data Management

Data management procedures were conducted in accordance with the TTP, Addendum 3 (DOE/RL-2005-96, Addendum 3).

2.6 Deviations from the Work Plan

Various deviations from the TTP Addendum 3 (DOE/RL-2005-96, Addendum 3) were necessary during the jet injections for a variety of reasons. These deviations included the following:

- ACS puriss-grade (meeting the specifications of the American Chemical Society and at least 98.5 percent pure) anhydrous disodium and monosodium phosphate was not used for preparation of the phosphate injection solution. Instead, a mixture of food-grade phosphoric acid and sodium hydroxide was used. The food-grade solutions were more readily available and economical than the reagent-grade solutions.
- The TTP Addendum 3 did not specify a method of drilling. The actual drilling was done using a rotary wash method. The injection solutions were used as the drilling fluid as described in Section 2.2.4. This was not specified in the work plan.
- The work plan called for performing the jet injections beginning at 0.46 m (1.5 ft) bgs. However, because of the excavated trench depths, jet injections began at 0.61 m (2 ft) bgs.
- The injection wells were not all driven to 7.6 m (25 ft) prior to commencement of jetting. This was due to the difficulty of drilling through the Ringold E Formation. However, the main target of treatment was the upper vadose zone and the actual jetting depths covered this target zone (Table 2-1).
- The TTP Addendum 3 called for injecting phosphate solution, followed by pre-formed apatite material, into the combined test plot. In the field, these solutions were mixed together and injected simultaneously.
- The N116m-2A sample was not collected prior to the jet injections because the aquifer tube was frozen.
- The work plan called for investigating apatite crystal formation in the sediment core samples using scanning electron microscope identification to analyze at least one sample per borehole. This analysis was not performed on any of the collected sediment cores because the pre-formed and combination plots had solid apatite injected, so apatite identification was deemed unnecessary. The phosphate solution plot received the same phosphate solution that had been used previously in aqueous injections of apatite-forming materials (but at a higher concentration than previously used). Extensive scanning electron microscope analysis of a sediment core sample from these aqueous injections had already been performed, so it was deemed unnecessary to repeat the procedure for the jet-injected solution.
- The TTP Addendum 3 specified that aquifer tube monitoring would be conducted for only three months following the jet injections. An additional sampling event was conducted six months after the injections to provide additional monitoring information.

3 Results and Discussion

This section summarizes the results from the aquifer tube and sediment core sampling analyses.

The amount of injection solution used during drilling and jetting operations is summarized in Table 3-1. The variable lithology in the Ringold E Formation resulted in the use of more injection solution than anticipated in the cases where this solution was also used during drilling as the external wash (drilling fluid). Based on injection rates and boring size, it was calculated that each boring would require 37,597 L (9,932 gal) of solution for the injection phase and 7,734 L (2,043 gal) during the jetting phase. Table 3-1 presents actual versus planned jetting injection volumes.

Table 3-1. Injection Volumes

	Planned Total Injection Volume (L)	Actual Total Injected Volume (L)	Volume of Fluid Injected During Drilling (L)[a]	Volume of Fluid Injected During Jetting (L)	Percentage Injected During Drilling (%)	Percentage Injected During Jetting (%)
Phosphate	46,344	145,738	113,305	32,433	77.75	22.25
Apatite Only	46,344	39,932	0	39,932	0	100
Phosphate and Apatite[b]	46,344	72,301	37,729	34,572	52.18	47.82
		34,568	0	34,568	0	100

a. Fluid injected during drilling refers only to phosphate solution used in drilling. The water used as drilling fluid for the apatite-only plot is not included in the table.

b. Phosphate solution is shown in the top row and pre-formed apatite slurry is shown in the bottom row.

3.1 Sediment Core Analysis

A summary of the results from the sediment core collection and analysis are presented in the following section. The details of the core analyses can be found in *Hanford 100-N Area In Situ Apatite and Phosphate Emplacement by Groundwater and Jet Injection: Geochemical and Physical Core Analysis* (PNNL-19524). Sediment cores were collected two months after the jet injections were performed.

3.1.1 Phosphate

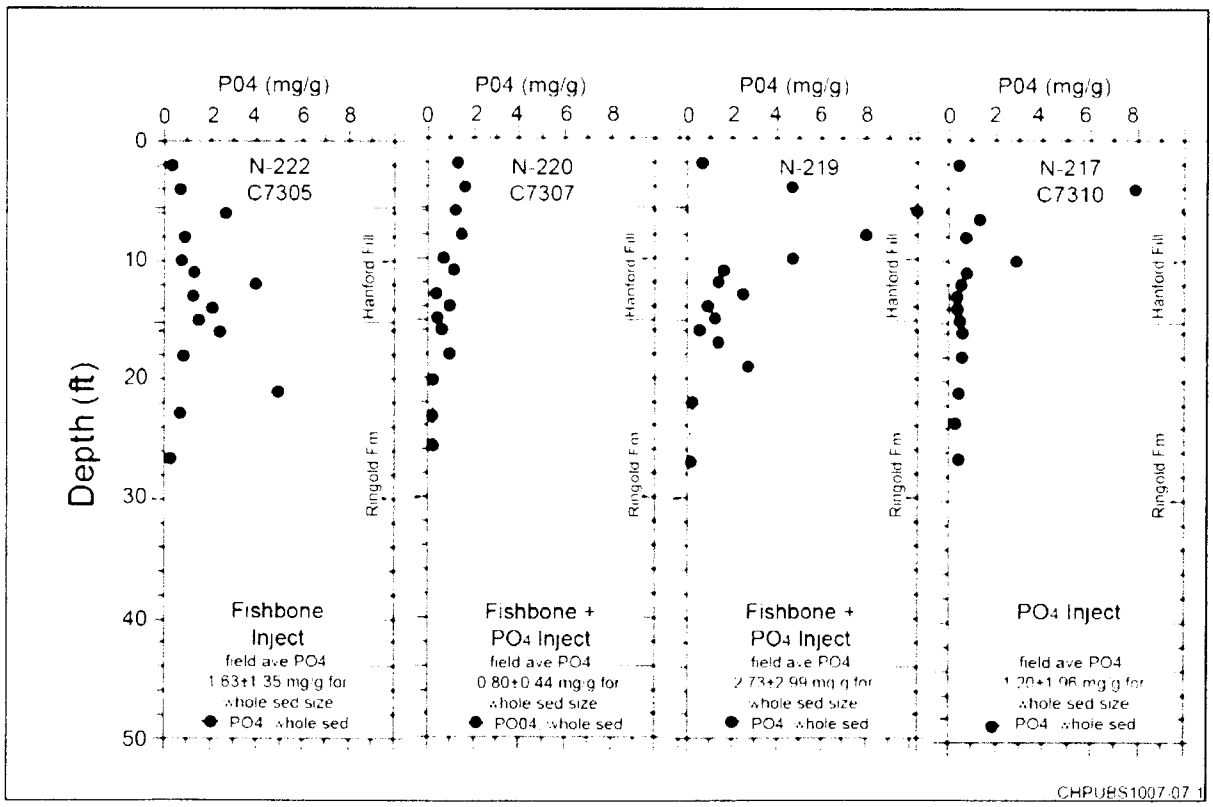
Collected sediment cores were sampled in 14 or 15 vertical locations and analyzed for phosphate concentrations to determine vertical distribution of phosphate in the cores and develop an average concentration of phosphate following injection. An average of these phosphate concentrations and corresponding apatite concentration is presented in Table 3-2.

The target concentration of 3.4 mg apatite/g sediment corresponds to a phosphate concentration of 1.1 mg phosphate/g of sediment. Sediment core C7307 (phosphate and pre-formed apatite) was the only sediment core that did not meet the target concentration. However, core C7308 (also phosphate and pre-formed apatite) had the highest phosphate concentration. The other core samples from the phosphate-only and pre-formed apatite-only injections both exceeded the target concentration. Based on phosphate mass only, there was little difference between the different materials used to inject phosphate into the subsurface.

Table 3-2. Phosphate Concentrations

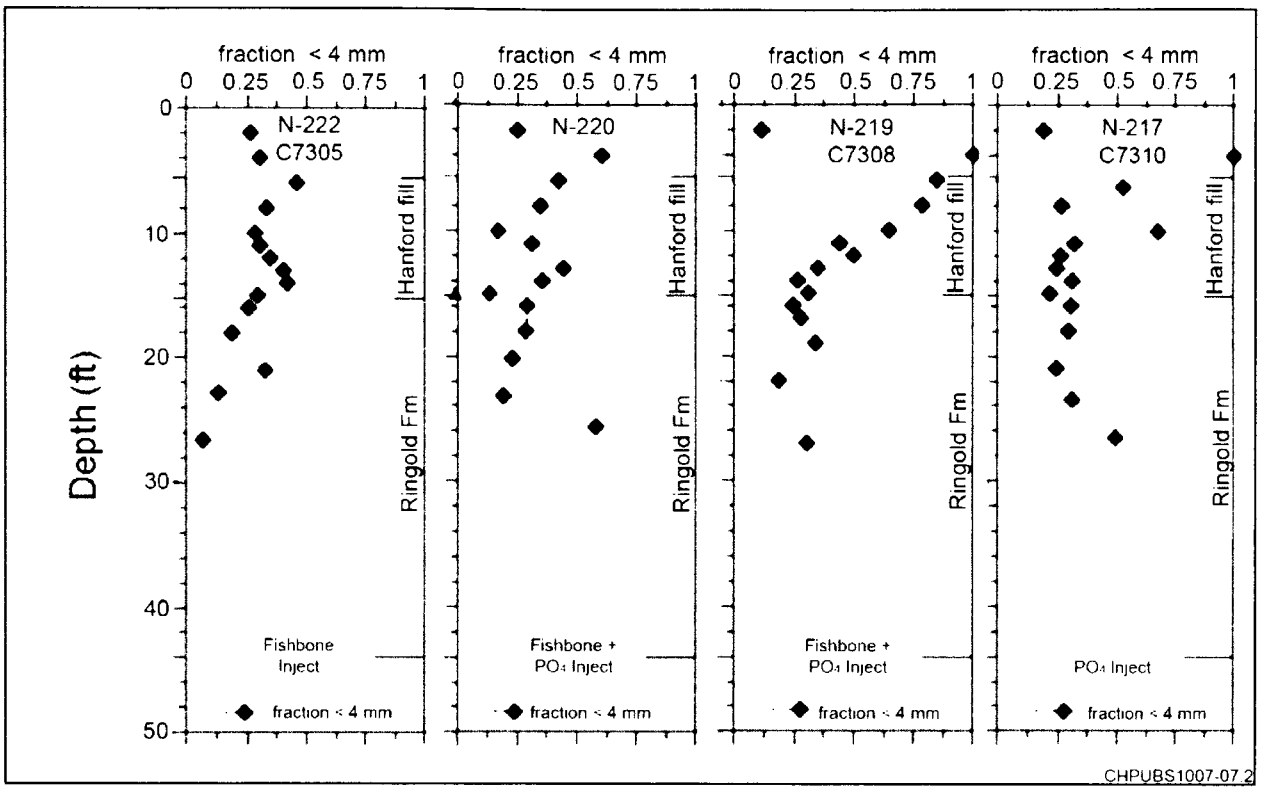
Sediment Core/Well ID/Jet Injection Material	Average Phosphate Concentration (mg/g)	Average Apatite Formed (mg/g) (Target—3.4 mg/g)
C7310/199-N-217/Phosphate only	1.20	3.7
C7308/199-N-219/Combined phosphate and pre-formed fishbone apatite	2.73	8.4
C7307/199-N-220/Combined phosphate and pre-formed fishbone apatite	0.80	2.5
C7305/199-N-222/Pre-formed fishbone apatite only	1.63	5.0

The vertical distribution of phosphate in each borehole is shown in Figure 3-1. The phosphate in Borehole C7307 (phosphate and pre-formed apatite) had an approximately even vertical distribution. The other three boreholes all showed greater vertical variability, with higher concentrations of phosphate in zones with finer-grained sediments and lower phosphate concentrations in the zones of coarser-grained sediments (Figure 3-2), indicating that finer-grained zones may have greater retention than coarser-grained zones. The finer-grained zones may also have been more significantly mixed, resulting in greater emplacement. The higher phosphate concentrations in the shallow sediment near the top of the injections may also be attributed to the phosphate injection solution that was captured in the trench during injections and was allowed to infiltrate into the sediment.



Source: Adapted from PNNL-19524 (Draft), 2010.

Figure 3-1. Phosphate Concentration with Depth in Boreholes



Source: Adapted from PNNL-19524 (Draft), 2010.

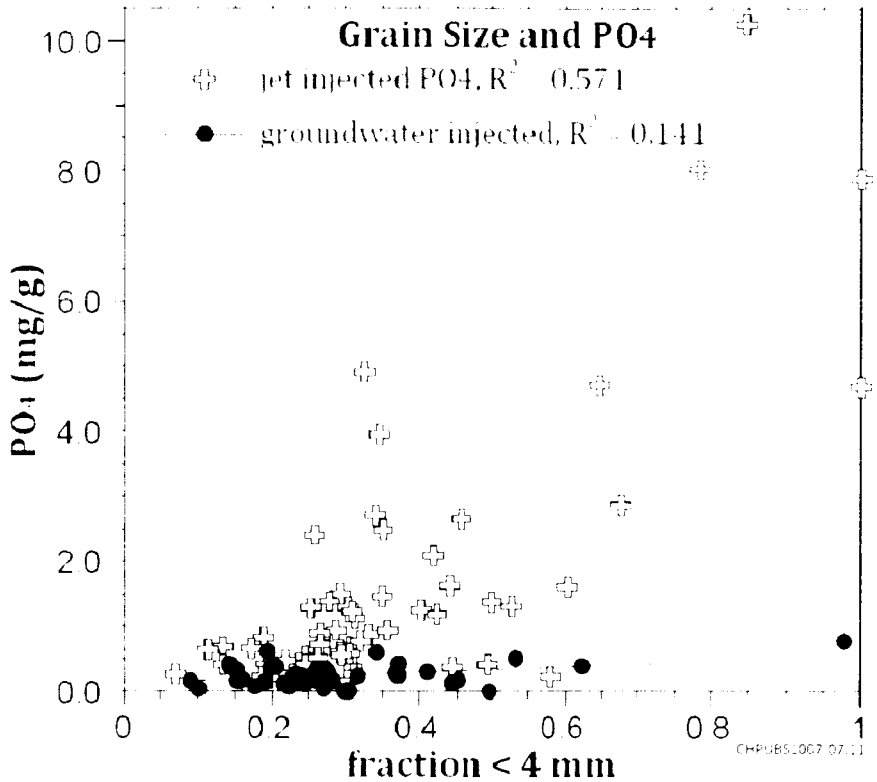
Figure 3-2. Vertical Distribution of Fine-Grained Sediments in Boreholes

The vertical distribution of phosphate resulting from these jet injections is greater than the spatial variability in phosphate concentration seen with previous aqueous injections. This may be an artifact of the injection into unsaturated sediment as compared to saturated sediment. The gravitational "draining" effect on the injection solution in unsaturated sediments may limit the exposure time for the apatite formation to take place at a particular depth. Conversely, this phenomena did not influence the apatite formation in past aqueous injections in the saturated sediment. This possible unsaturated-zone condition may have a greater effect on coarser, more transmissive sediments when compared to the finer, less transmissive sediments. The correlation between finer-grained sediments and phosphate concentrations for the jet injection cores was also greater than the correlation seen for the previous aqueous injections (Figure 3-3).

Sediment cores collected from the test plots where pre-formed apatite was injected showed visual evidence of microbial biomass in and on the cores. The increase in biomass is likely due to the large amount of organic matter in the fishbone. The uptake and long-term stability of Sr-90 in biomass is not well understood at this time.

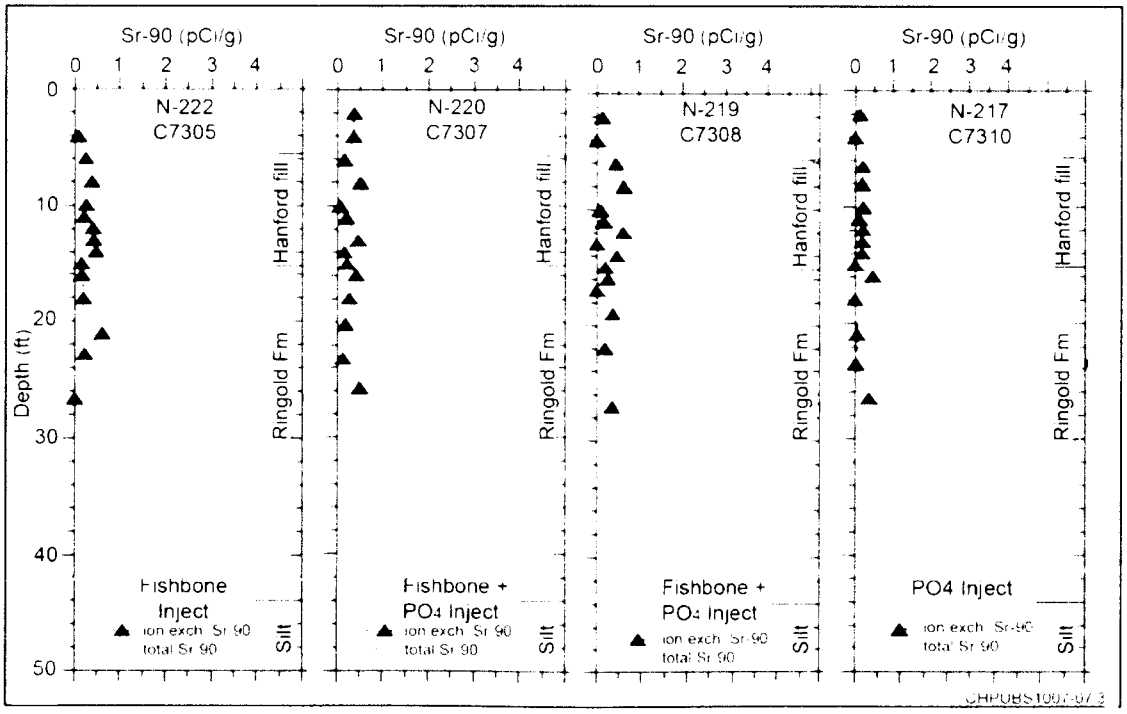
3.1.2 Sr-90

Sr-90 concentrations in all four boreholes are less than 5 pCi/g (Figure 3-4). This is significantly less than the maximum Sr-90 concentration of 90 pCi/g found in N-123, 70 m (230 ft) northeast of Borehole N-222. In all boreholes, the ion exchangeable Sr-90 is less than 20 percent of the total Sr-90. In comparison, untreated sediments average 90 percent ion exchangeable Sr-90, which seems to indicate that most of the Sr-90 in these jet injection test plots is bound in apatite.



Source: Adapted from PNNL-19524 (Draft), 2010.

Figure 3-3. Correlation Between Fine-Grain Size Fraction and Phosphate Concentration in Sediment Cores



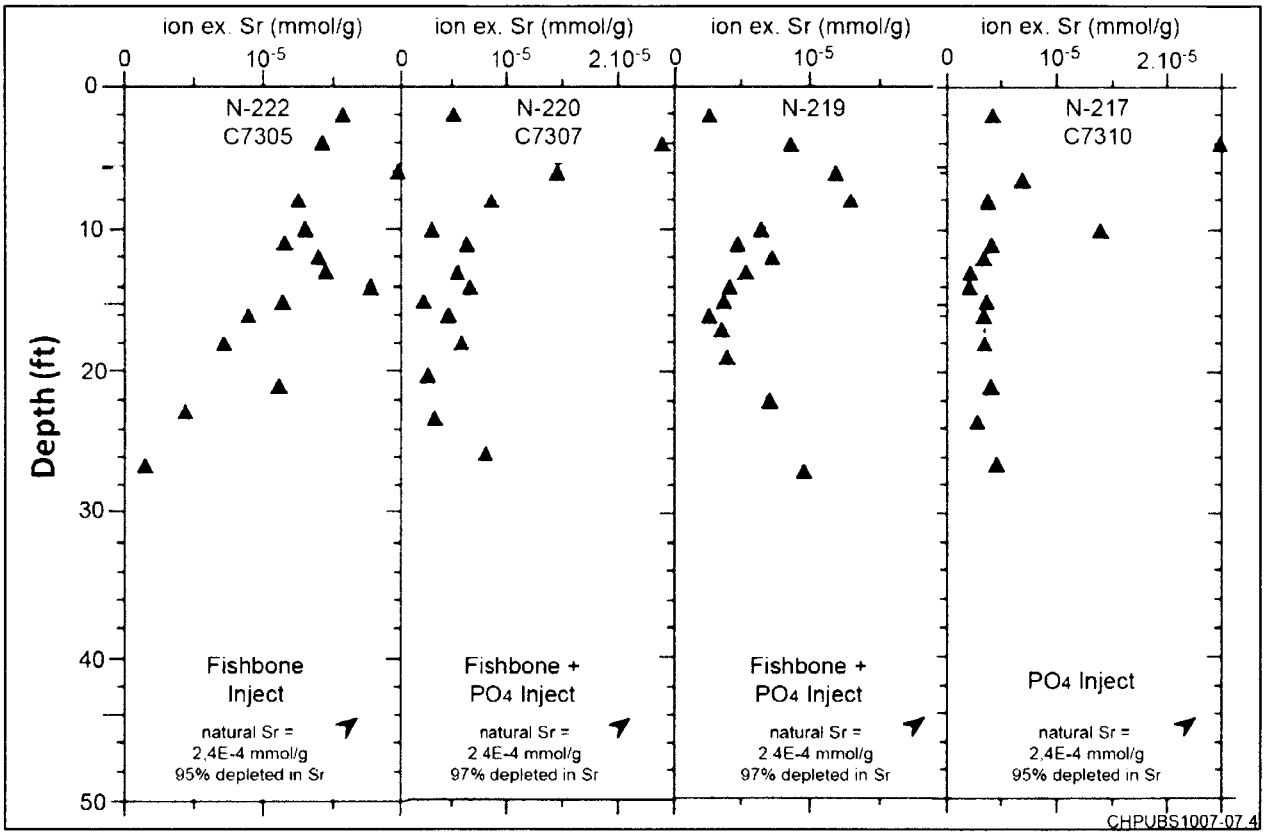
Source: Adapted from PNNL-19524 (Draft), 2010.

Figure 3-4. Sr-90 Concentration with Depth in Boreholes

The fraction of ion exchangeable Sr-90 varied with the three different injection formulations. The phosphate-only injection had the lowest fraction at 12 percent ion exchangeable Sr-90. The phosphate and fishbone injections averaged at 21 percent ion exchangeable Sr-90. Lastly, the fishbone-only injection had 20 percent ion exchangeable Sr-90. This is likely because there was greater Sr-90 incorporation into field-formed phosphate precipitates with the phosphate-only injection than the phosphate and fishbone or fishbone-only injections. However, over time, the areas that received jet injections of solid apatite are expected to incorporate additional Sr-90 mass into the apatite.

3.1.3 Ion Exchangeable Calcium and Strontium

The ion exchangeable calcium and strontium show vertical profiles similar to the Sr-90 data. Sediment zones with higher fractions of fine-grained material (and higher surface area) had higher concentrations of ion exchangeable strontium (Figure 3-5) and calcium (Figure 3-6).



Source: Adapted from PNNL-19524 (Draft), 2010.

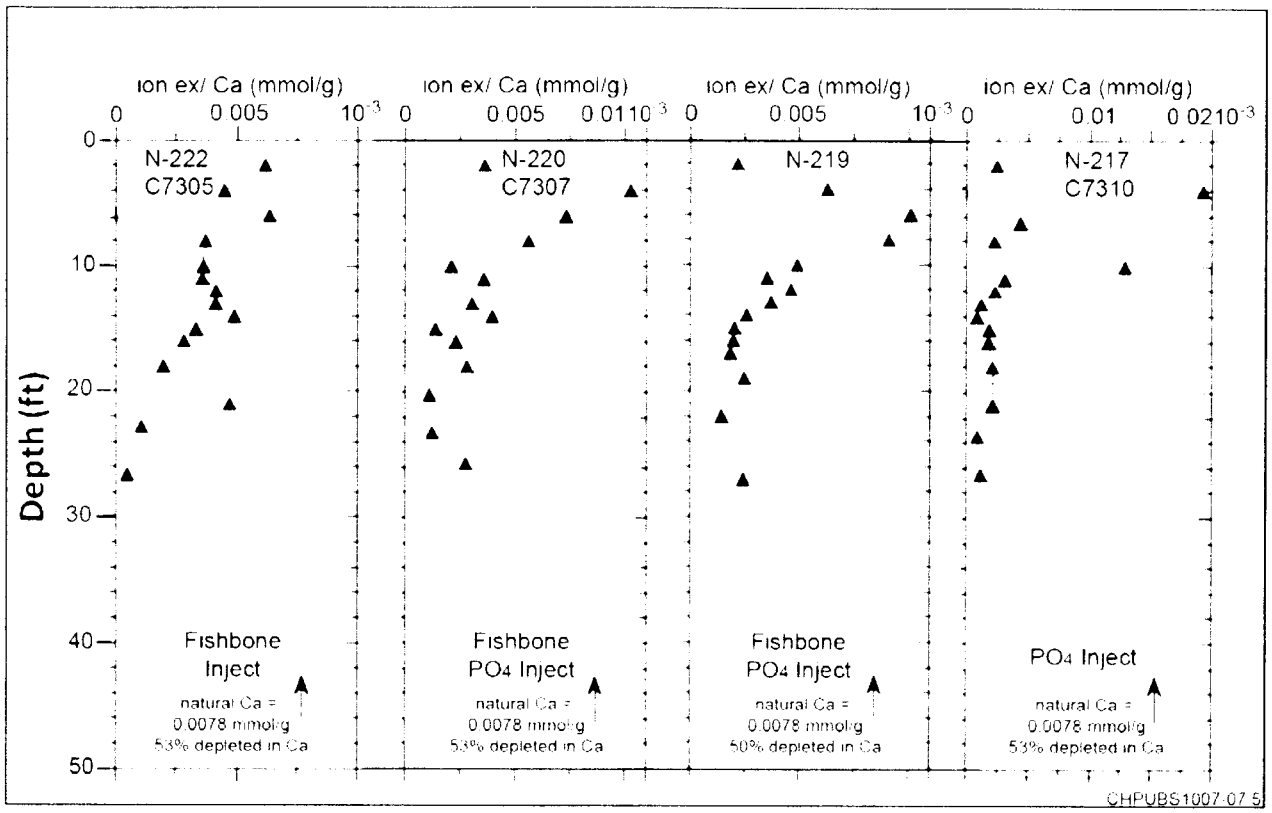
Figure 3-5. Ion Exchangeable Strontium Concentration with Depth in Boreholes

3.1.4 Sieve Analyses and Saturated Hydraulic Conductivity

Four to six segments of each borehole core were sieved to obtain an approximate grain size distribution and resulting saturated hydraulic conductivity with depth. The saturated hydraulic conductivity was calculated from the grain size distribution (Masch and Denny, 1966). As shown previously by the <4 mm fractions (Figure 3-2), Wells C7308 and C7310 had shallow zones of fine-grained sediments (Table 3-3) overlying coarser-grained zones at greater depths.

For these data, the Hanford formation had a slightly lower average hydraulic conductivity compared to the underlying Ringold Formation, which is contrary to what is typically observed in 100-N. This could

be an artifact of too few samples, or the specific test area having somewhat different properties, or the jet injections having altered the hydraulic conductivity.



Source: Adapted from PNNL-19524 (Draft), 2010.

Figure 3-6. Ion Exchangeable Calcium Concentration with Depth in Boreholes

Table 3-3. Carbon Concentrations

Injection Type	Borehole	Depth (ft)	Total Carbon (%)	Inorganic Carbon (%)	Organic Carbon (%)
Fishbone apatite	N-222	6.0	0.423 ± 0.065	0.040 ± 0.010	0.392 ± 0.059
		11.0	0.226 ± 0.002	0.022 ± 0.011	0.204 ± 0.002
		15.0	0.211 ± 0.046	0.032 ± 0.009	0.180 ± 0.039
Fishbone apatite and phosphate solution	N-220	8.0	0.283 ± 0.014	0.041 ± 0.005	0.242 ± 0.012
		16.0	0.093 ± 0.016	0.019 ± 0.004	0.074 ± 0.013
Fishbone apatite and phosphate solution	N-219	8.0	0.588 ± 0.066	0.056 ± 0.005	0.532 ± 0.059
		14.0	0.144 ± 0.024	0.018 ± 0.006	0.126 ± 0.021
Phosphate solution	N-217	4.0	0.246 ± 0.028	0.040 ± 0.004	0.206 ± 0.024
		10.0	0.216 ± 0.025	0.055 ± 0.031	0.161 ± 0.019
		16.0	0.018 ± 0.002	0.017 ± 0.005	0.001 ± 0.001

Source: Adapted from PNNL-19524 (Draft), 2010.

3.1.5 Organic Matter and Influence on Sr-90 Mobility

The fishbone apatite-injected cores (N-219, N-220, and N-222) contained 25 to 45 percent organic matter. Organic carbon measured in 10 sediment samples showed an increase as high as 0.2 percent (grams of organic carbon per gram of sediment) over natural organic carbon (Table 3-3).

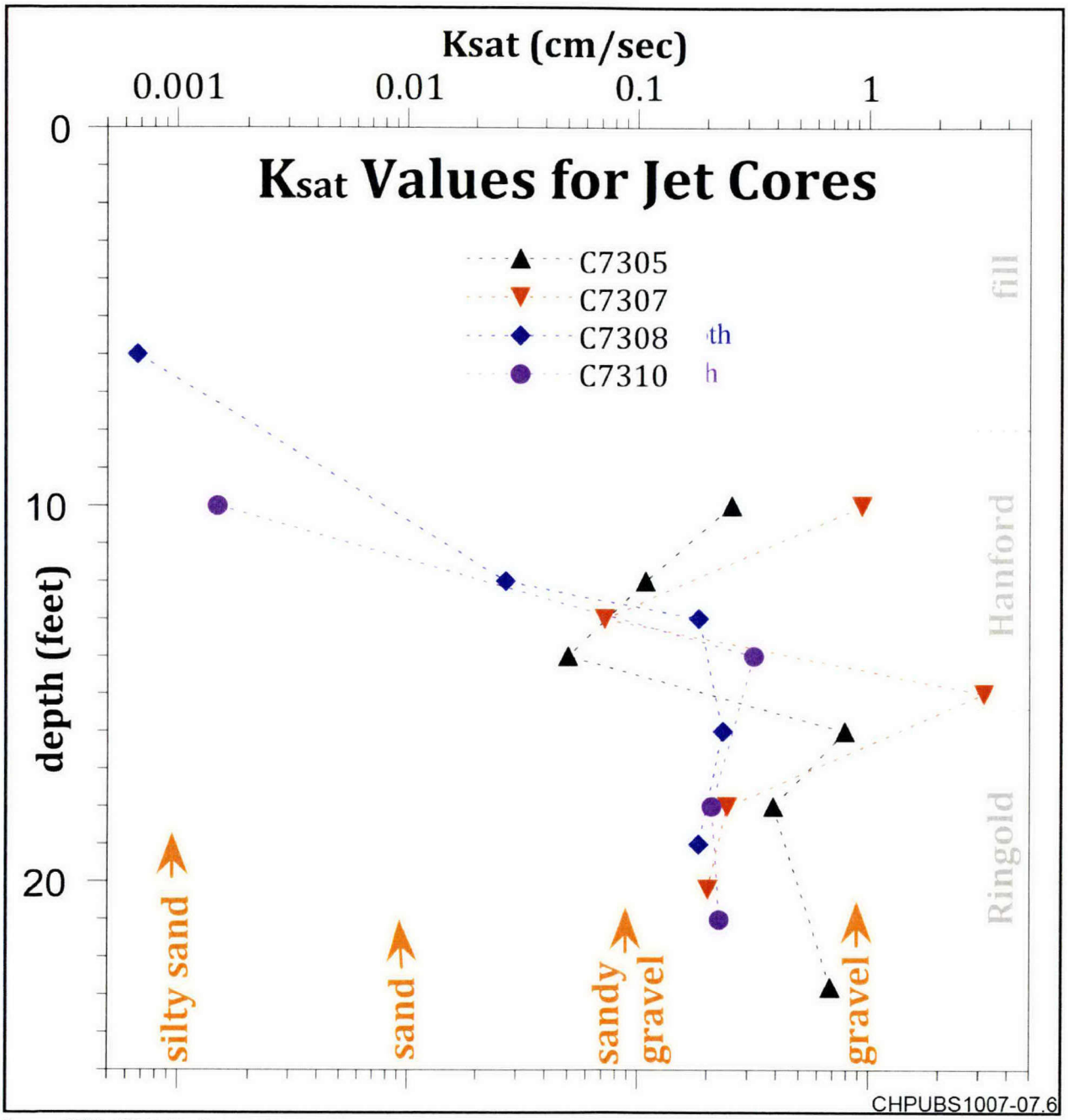
Because biomass will grow on this organic matter (and the supplied phosphate source), there is some uptake of Sr-90. Subsequent death of the biomass when the organic matter is depleted can lead to Sr-90 release. Experiments conducted to assess Sr-90 release upon biomass death showed an increase in ion exchangeable Sr-90. However, because the total Sr-90 in the samples used was low (<1 pCi/g), the release was insignificant. It is possible that the Sr-90 release would be more significant for fishbone apatite injected into areas of higher Sr-90. Hydraulic conductivity with depth of boreholes is calculated in Figure 3-7.

3.2 Aquifer Tube Monitoring

Aquifer tubes were monitored for adverse impacts on the underlying groundwater from vadose zone jet injections. This monitoring was not included as a core objective of the jet injection pilot scale test. However, the aquifer tubes were the only monitoring locations available near the test plots. The aquifer tube data was obtained from the Hanford Environmental Information System database. Aquifer Tube Arrays N116m-1A and N116m-2A (Figure 2-1) were sampled and analyzed for cation and anion concentrations for six weeks following jet injection. Additional sampling events occurred three and six months after injection. Pre-injection samples were collected from Array N116m-1A immediately prior to injection. However, pre-injection samples from Array N116m-2A were not able to be collected because the aquifer tube was frozen. Nonetheless, samples had been collected in both arrays periodically for more than three years prior to the jet injections as part of an aqueous injection-monitoring program. The results of these monitoring activities are presented in Tables 3-4 and 3-5.

Post-injection monitoring in Array N116m-1A showed a slight increase in concentrations of calcium and Sr-90, along with magnesium, sodium, barium, and strontium four weeks after injection (Figure 3-8), which decreased again by the following week. Samples collected three months after the injections showed that concentrations of these constituents were very similar to the baseline concentrations measured in September and December 2009, prior to injection. The Sr-90 concentration had decreased 14 percent relative to the September 2009 sampling event. The most recent samples, collected six months after the jet injections, were higher than those measured three months after the injections, but were still within the range of historical pre-injection concentrations for all the above constituents except Sr-90, iron, and manganese, which were slightly above the pre-injection concentration ranges.

Sulfate, nitrate, and chloride concentrations in Array N116m-1A were on an increasing trend after injection (Figure 3-9). Three months after injection, the concentration of all three of these species exceeded the baseline-sampling event in September 2009. Phosphate, nitrite, or fluoride were not detected in the aquifer tube over the six-month sampling span from September 2009 to June 2010. The detection limit for phosphate was 0.0045 mM (429 μg/L), which was much lower than the 100 mM concentration of the phosphate injection solution.



Source: PNNL-19524 (Draft), June 2010.

Figure 3-7. Calculated Saturated Hydraulic Conductivity with Depth in Boreholes

Table 3-4. Cation Concentrations in Aquifer Tubes

Date	Calcium (µg/L)	Magnesium (µg/L)	Manganese (µg/L)	Iron (µg/L)	Sodium (µg/L)	Potassium (µg/L)	Barium (µg/L)	Strontium (µg/L)	Strontium-90 (pCi/L)
N116m-1A									
3/8/2006	24,001	NA	NA	NA	2,938	NA	NA	NA	*45.3*
5/10/2006	22,122	NA	NA	NA	2,686	1,173	19.92	NA	*20.2*
6/6/2006	NA	NA	NA	NA	NA	NA	NA	NA	0.836
3/13/2007	NA	NA	NA	NA	NA	NA	NA	NA	8.5
8/9/2007	19,400	4,100	5.44	46.5 C	1,680	728	27.2	97.4	0.78
12/11/2007	NA	NA	NA	NA	NA	NA	NA	NA	*0.61*
3/25/2008	NA	NA	NA	NA	NA	NA	NA	NA	*1.26*
4/1/2009	20,000	5,140	4 U	34.4 B	2,320	836	27.6	110	0.31
9/17/2009	22,800	3,820	24.7	693	2,650	1,550	21.9	94	35
12/3/2009	17,600	2,130	10.8 B	221 C	2,420	1,320	14.3 B	78.7	29
12/11/2009	18,400	3,230	23.3	1,090	2,280	1,260	14.5 B	78.6	23
12/17/2009	17,700	3,040	32.4	741	2,160	1,100	13.9 B	72.5	28
12/21/2009	18,100	3,060	4.4 B	214	2,320	1,240	14.0 B	77.0	30
12/28/2009	34,000	6,160	4.4 B	18 U	7,320	1,430	17.8 B	150	92
1/6/2010	18,800	3,130	12.7 B	433	2,310	1,160	14.3 B	76.4	24
3/2/2010	25,600	4,250	12.2 B	500	2,890	1,340	19.1 B	109	30
6/7/2010	37,200	6,720	45.0	718	3,840	1,910	36	160	52
N116m-2A									
3/8/2006	**10,000**	NA	NA	NA	15,294	NA	NA	NA	*357*
5/10/2006	57,520	NA	NA	NA	4,607	1,418	13.82	NA	*92*
6/6/2006	NA	NA	NA	NA	NA	NA	NA	NA	80
9/25/2006	76,000	13,400	3 B	25 U	14,400	4,400	46.4 B	333	272

Table 3-4. Cation Concentrations in Aquifer Tubes

Date	Calcium (µg/L)	Magnesium (µg/L)	Manganese (µg/L)	Iron (µg/L)	Sodium (µg/L)	Potassium (µg/L)	Barium (µg/L)	Strontium (µg/L)	Strontium-90 (pCi/L)
3/12/2007	NA	NA	NA	NA	NA	NA	NA	NA	360
6/27/2007	NA	NA	NA	NA	NA	NA	NA	NA	200
8/9/2007	56,000	8,500	1.2	38.2	12,200	2,400	32	218	180
6/3/2008	25,500	4,120	156	19.1	3,640	1,410	14	111	*85*
10/29/2008	68,900	10,300	6.7	20 U	10,100	2,290	40.1	401	*215.5*
12/3/2008	51,800	8,660	4 U	25 U	9,400	2,250	27.7	327	*140*
12/11/2009	**22,600**	**4,980**	**4 U**	**18 U**	**3,410**	**960**	**25**	**109**	**12**
12/17/2009	34,500	6,250	4 U	18 U	7,040	1,440	16.7 B	145	100
12/21/2009	48,100	8,470	4 U	18 U	9,470	1,760	25.3	212	150
12/28/2009	18,200	3,130	22.8	283	2,320	1,200	14.6 B	77.4	28
1/6/2010	49,600	8,420	4 U	18 U	9,120	1,670	24.3	205	160
3/2/2010	87,400	14,800	4 U	20.5 B	12,400	2,160	45.5	374	250
6/7/2010	30,500	5,300	4 U	20.0 B	5,660	1,810	17.0 B	134	100

Notes:

Bold lines indicate date of jet injections.

Numbers in italics are Sr-90 estimates arrived at by taking half the gross beta value measured for that day's sample. This was done in cases where Sr-90 was not measured, but gross beta was; it is known that in most cases, Sr-90 concentrations are approximately half the measured gross beta value.

U = not detected at the specified reporting limit

B = analyte <RDL but ≥ the IDL/MDL (inorganic)

C = analyte found in associated blank

D = diluted

E = concentration is out of instrument calibration range

N = matrix spike or matrix spike duplicate was out of limits

NA = not analyzed

Table 3-5. Anion Concentrations in Aquifer Tubes

Date	Fluorine (µg/L)		Chlorine (µg/L)		Nitrite-N (µg/L)		Nitrate-N (µg/L)		Phosphate-P (µg/L)		Sulfate (µg/L)	
N116m-1A												
3/8/2006	60		1,210		NA		3,110		230		12,000	
5/10/2006	80		1,220		NA		880		170		9,250	
8/9/2007	36	B	889		32.8	U	235	B	123		8,730	
4/1/2009	46	UD	1,110	D	85.4	UD	637	BD	368	UD	10,100	
9/17/2009	60	U	1,130	D	118	U	2,590	D	429	U	10,200	D
12/3/2009	62.6	BD	1,070	D	118	U	1,873	D	429	U	10,200	D
12/11/2009	60	U	1,130	D	118	U	1,425	D	429	U	12,300	D
12/17/2009	60	U	1,140	D	118	U	1,899	D	429	U	11,800	D
12/21/2009	60	U	1,110	D	118	U	2,085	D	429	U	10,900	D
12/28/2009	60	U	1,160	D	118	U	2,085	D	429	U	11,500	D
1/6/2010	60	U	1,560	D	118	U	2,220	D	429	U	11,800	D
3/2/2010	60	U	1,660	D	118	U	4,000	D	429	U	13,200	D
6/7/2010	60	U	5,710	D	36	UD	2,590	D	429	UD	24,300	D
N116m-2A												
3/8/2006	60		30,200		NA		29,700		170		100,000	
5/10/2006	80		1,380		NA		720		160		11,200	
9/25/2006	110		20,800		13.1	U	26,100		190	BN	92,400	D
8/9/2007	53	B	12,500		32.8	U	12,200		123		59,000	
12/11/2007	20.7		10,100		65.7	UD	13,800		245	U	46,700	
3/25/2008	12	U	27,200		65.7	UD	33,500	D	245	U	100,000	
6/3/2008	21	U	1,250		32.8	U	159	U	175	B	7,870	
10/29/2008	200	UD	15,700		328	UD	26,500	D	1,840	UD	67,800	
12/3/2008	232	UD	10,800	D	420	UD	17,600	D	1,860	UD	52,400	D
6/17/2009	60	U	2,330	D	118	U	415	BD	429	U	11,500	D
12/11/2009	60	U	1,410	D	118	U	1,549	D	429	U	11,800	D
12/17/2009	60	U	3,270	D	118	U	6,730	D	429	U	23,800	D
12/21/2009	60	U	8,140	D	118	U	16,700	D	429	U	45,700	D
12/28/2009	60	U	4,060	D	118	U	7,610	D	429	U	25,600	D
1/6/2010	60	U	8,520	D	118	U	17,625	D	429	U	45,900	D
3/2/2010	60	U	19,400	D	118	U	36,700	D	429	U	89,300	D
6/7/2010	60	U	2,080	D	36	UD	249	D	140	UD	13,500	D

Table 3-5. Anion Concentrations in Aquifer Tubes

Date	Fluorine (µg/L)	Chlorine (µg/L)	Nitrite-N (µg/L)	Nitrate-N (µg/L)	Phosphate-P (µg/L)	Sulfate (µg/L)

Notes:

Bold lines indicate date of jet injections.

U = not detected at the specified reporting limit

B = analyte <RDL but ≥ the IDL/MDL (inorganic)

C = analyte found in associated blank

D = diluted

E = concentration is out of instrument calibration range

N = matrix spike or matrix spike duplicate was out of limits

NA = not analyzed

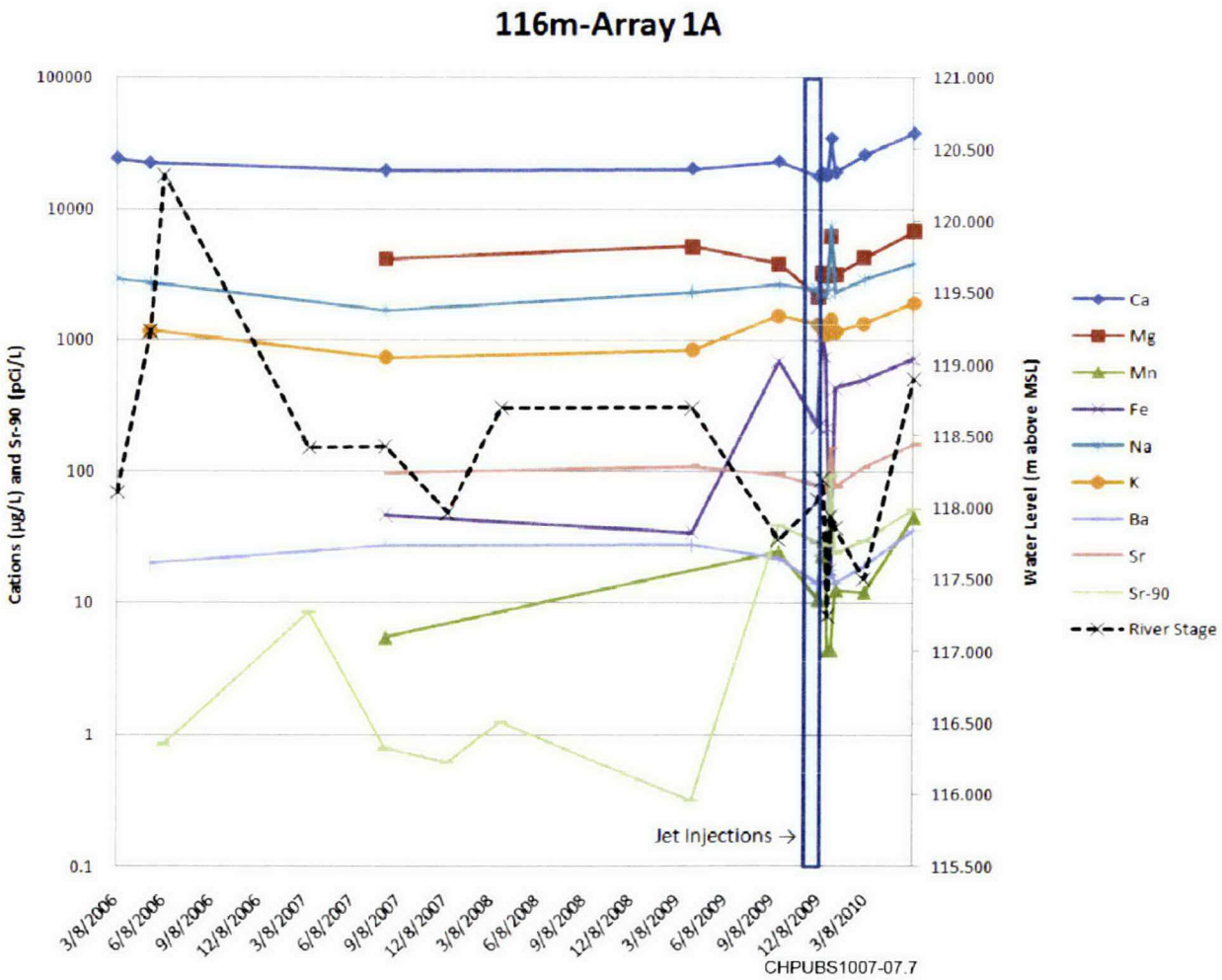


Figure 3-8. Cation Concentrations/Activities with River Stage in Aquifer Tube 116m Array 1A

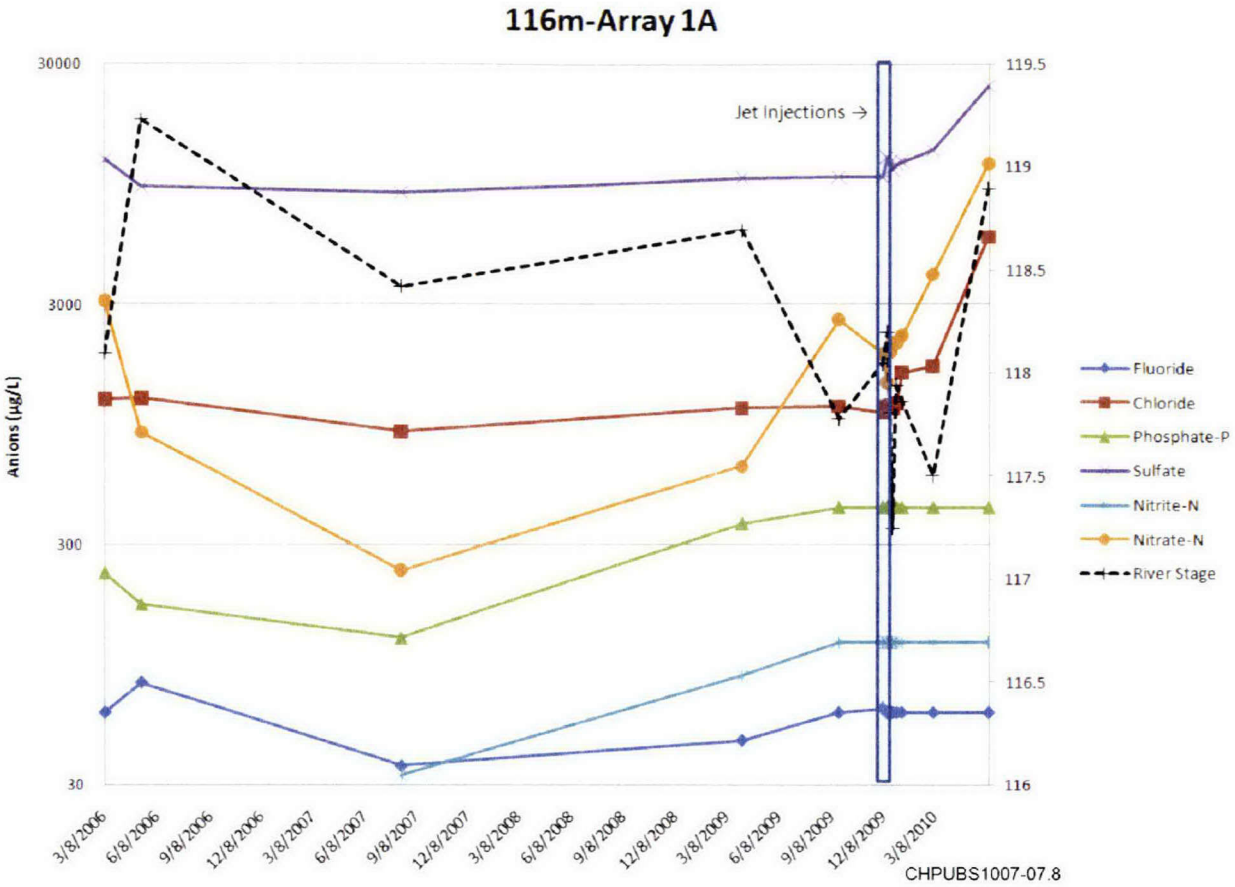


Figure 3-9. Anion Concentrations with River Stage in Aquifer Tube 116m Array 1A

In Array N116m-2A, post-injection sampling showed the concentrations of calcium and Sr-90, along with magnesium, sodium, potassium, strontium, and barium increasing for the three weeks immediately following injection, followed by a decrease in week four to nearly the initially measured concentrations (Figure 3-10). The concentrations then increased again. After three months, the concentrations of these constituents were all significantly higher than the concentrations measured one week after injections. However, these concentrations all decreased again by the six-month post-injection sampling event. During both of these longer-term post-injection sampling events, the concentrations of Sr-90, strontium, sodium, and potassium were within the range of historical pre-injection concentrations. The concentrations of calcium, magnesium, and barium measured three months after the jet injections were greater than the historical pre-injection concentrations. However, by the six-month post-injection sampling event, these concentrations had all decreased to within the range of historical concentrations. The manganese and iron concentrations both increased at four weeks post-injection, followed by a subsequent decrease in concentration to the original measurements at week one post-injection, which were within the range of historical pre-injection concentrations. The concentrations then remained constant through the six-month post-injection sampling event.

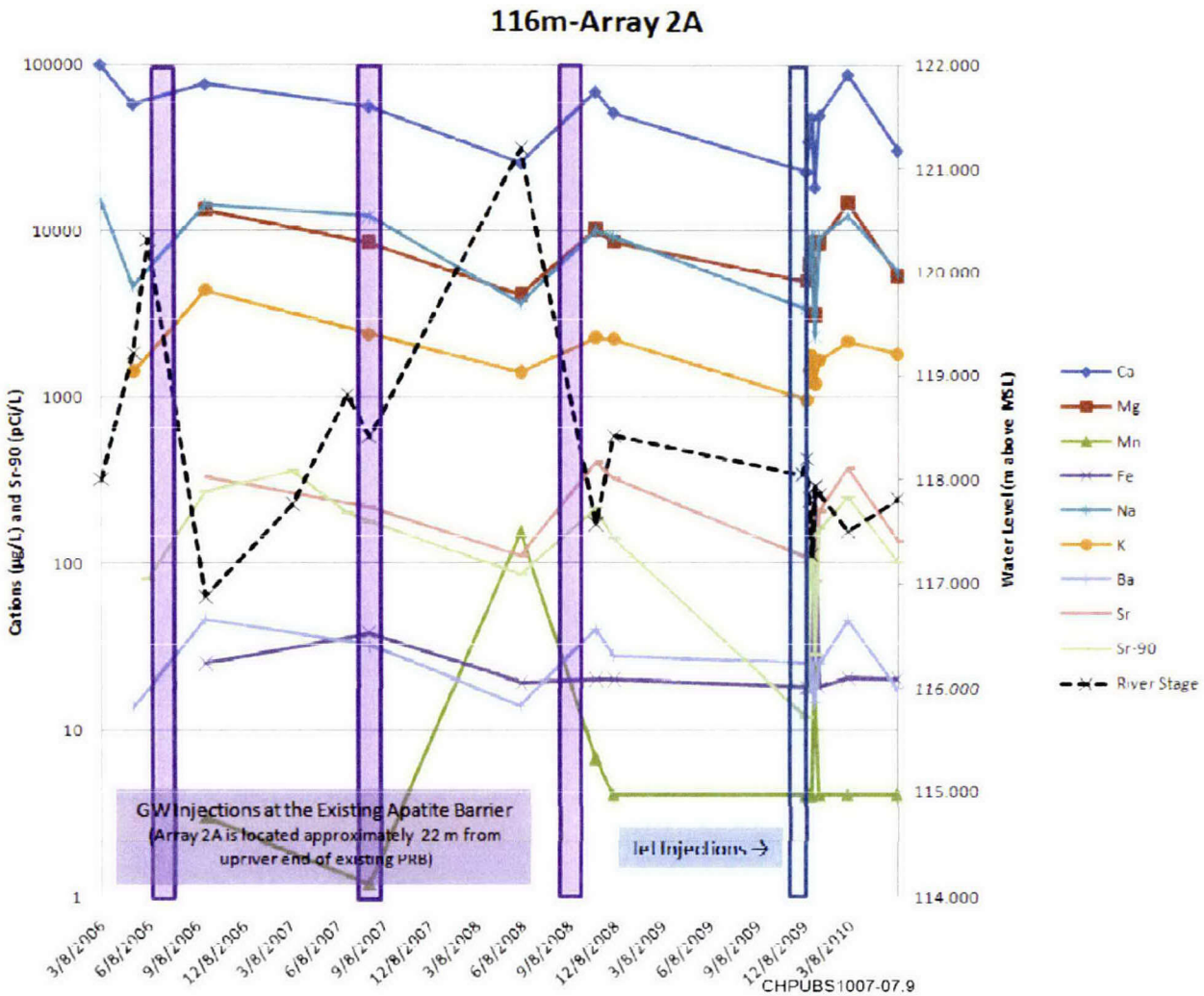


Figure 3-10. Cation Concentrations/Activities with River Stage in Aquifer Tube 116m Array 2A

Two weeks after injection, the concentrations of sulfate, nitrate, and chloride all increased (Figure 3-11). The concentrations of these constituents decreased slightly after four weeks, but then increased again, and all were significantly higher three months after injections than they were six months prior to the injections. These concentrations all decreased significantly by the six-month post-injection sampling event. The concentrations measured during both the three- and six-month post-injection sampling events were within the ranges of historical pre-injection concentrations. The initial anion concentration changes may be explained by small fluctuations in river stage, as the increases in concentration correspond to decreases in river stage and vice versa. Phosphate, nitrite, and fluoride were not detected in the aquifer tube array at any point during the six-month post-injection monitoring period.

The observed increases in cation and metal concentrations following injection are likely due to the ionic strength of the injection solutions causing increased desorption of the cations from the sediments, as was seen in the previous aqueous injection field tests.

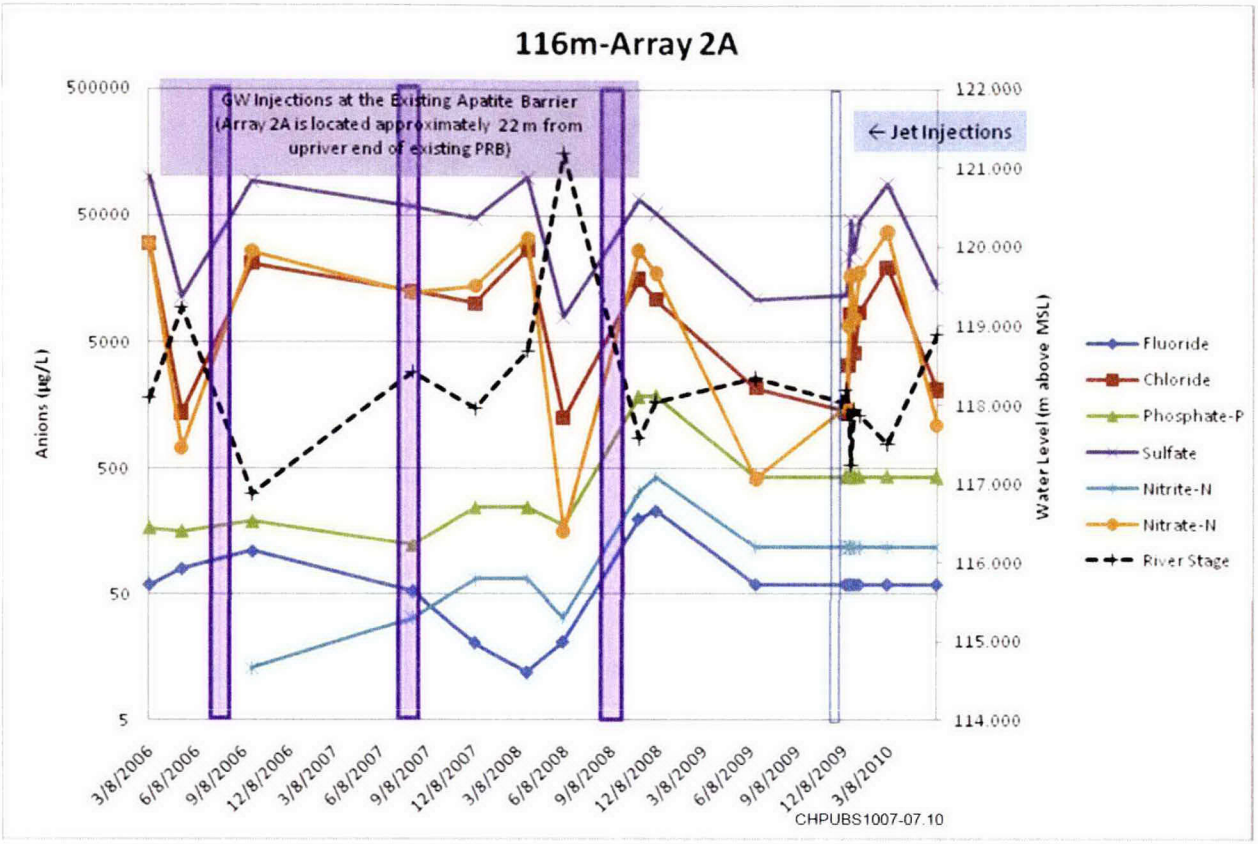


Figure 3-11. Anion Concentrations with River Stage in Aquifer Tube 116m Array 2A

3.3 Quality Assurance/Quality Control

Quality assurance/quality control samples and procedures were conducted in accordance with the TTP, Addendum 3 (DOE/RL-2005-96, Addendum 3). A quality assurance surveillance (QA-EQA-SURV-10-008) was performed during the jet injection activity. The surveillance examined the cleaning of down-hole equipment, driller qualification, drilling and injection method, borehole configuration, documentation for the injected chemicals, and daily reports. One finding was issued regarding the driller's lack of a Washington State driller's license.

4 Conclusions and Recommendations

Following are the objectives of the jet injection pilot scale demonstration:

- Evaluate the ability of different technologies to deliver material/chemical solutions into the vadose zone and upper unconfined aquifer within three distinct treatment zones along the 100-N shoreline
- Evaluate the ability of the methods to install a PRB in the vadose zone containing 3.4 mg apatite/g sediment (1.1 mg phosphate/g sediment)

4.1 Conclusions

Results from collected sediment cores indicate that jet injection is a viable method for emplacement of phosphate and pre-formed apatite in the vadose zone. These cores also show that jet injection is a viable method for installing a PRB in the vadose zone at a target concentration of 3.4 mg apatite per gram of sediment (1.1 mg phosphate/g sediment). In each of the test areas, apatite concentrations met or exceeded these values in all cases but one (Borehole C7307—phosphate and pre-formed fishbone apatite). Some vertical variability in phosphate concentrations was seen, with sediment cores showing higher phosphate concentrations in fine-grained material compared to coarse-grained sediment. Phosphate concentrations were also generally higher in the shallow sediments for the test areas that used phosphate than the area using only pre-formed apatite.

While jet injection of all three formulations led to emplacement of apatite in the vadose zone, injection of phosphate only resulted in a greater fraction of Sr-90 incorporated into phosphate precipitates at the time of core sampling. Over time, zones that received solid-phase apatite mass will also incorporate additional Sr-90 mass into the apatite. The potential effects of increased biomass in the sediments that received pre-formed apatite are still under investigation.

Aquifer tube data show an increase in Sr-90 of approximately 30 percent in Array N116m-1A four weeks after completion of jet injections but, by three months after injections, Sr-90 concentrations had decreased to below pre-injection concentrations. By six months after completion of the jet injections, Sr-90 had increased to slightly above pre-injection concentrations. Data from Array N116m-2A show that after three months, the concentrations remained higher than the concentrations measured one week after the jet injections, but all Sr-90 concentrations measured post-injection were within the range of historical pre-injection concentrations.

4.2 Recommendations

Jet injection is capable of delivering a specified amount of apatite into the vadose zone and upper unconfined aquifer. It is recommended that use of jet injection be further tested over a larger area in the 100-NR-2 OU to evaluate effectiveness of jet-injected materials for reducing Sr-90 flux to the Columbia River. Testing over a larger area would also allow collection of more sediment core samples to evaluate the technology's radial extent of emplacement. More samples would also allow refinement of technology to inject near existing features such as monitoring wells, which were not present in these smaller test plots. Additionally, it is recommended that the expanded area for demonstration-scale testing be the vadose zone above the existing saturated-zone PRB. This would be done to evaluate the ability of the saturated-zone PRB to deal with the slugs of elevated metal and Sr-90 concentrations resulting from jet injection-emplacement of vadose zone PRB. Furthermore, the pilot test treatment zones were previously untreated sediments. Therefore, performing additional injections in previously treated sediments above the existing saturated zone PRB will allow evaluation of the response differences between previously treated and untreated sediments.

Use of the aqueous phosphate solution proved successful and it is recommended for future use in all jet injections, at a minimum as the drilling solution. Injection of fishbone apatite appeared to effectively reduce Sr-90 concentrations and provide sufficient apatite emplacement into the vadose zone. However, because of the large amount of biomass observed, it is recommended that monitoring be performed to establish the potential of future Sr-90 release. Other forms of apatite such as calcined fishbone or cowbone should be evaluated as possible alternatives as these do not contain the organic fraction and, thus, have more apatite per unit mass. Cost and availability will need to be considered when establishing the particular type of pre-formed apatite to be used.

The aquifer tube data used in this pilot scale test for monitoring potential adverse impacts on the underlying groundwater from the jet injections is highly variable, related to seasonal and diurnal fluctuations in Columbia River stage. It is recommended that additional demonstration-scale jet injection testing be performed in an area of the river shore with an extensive monitoring well network to allow for collection of less variable monitoring data from the groundwater itself.

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Appendix A

Jet Injection Logs

NICHOLSON

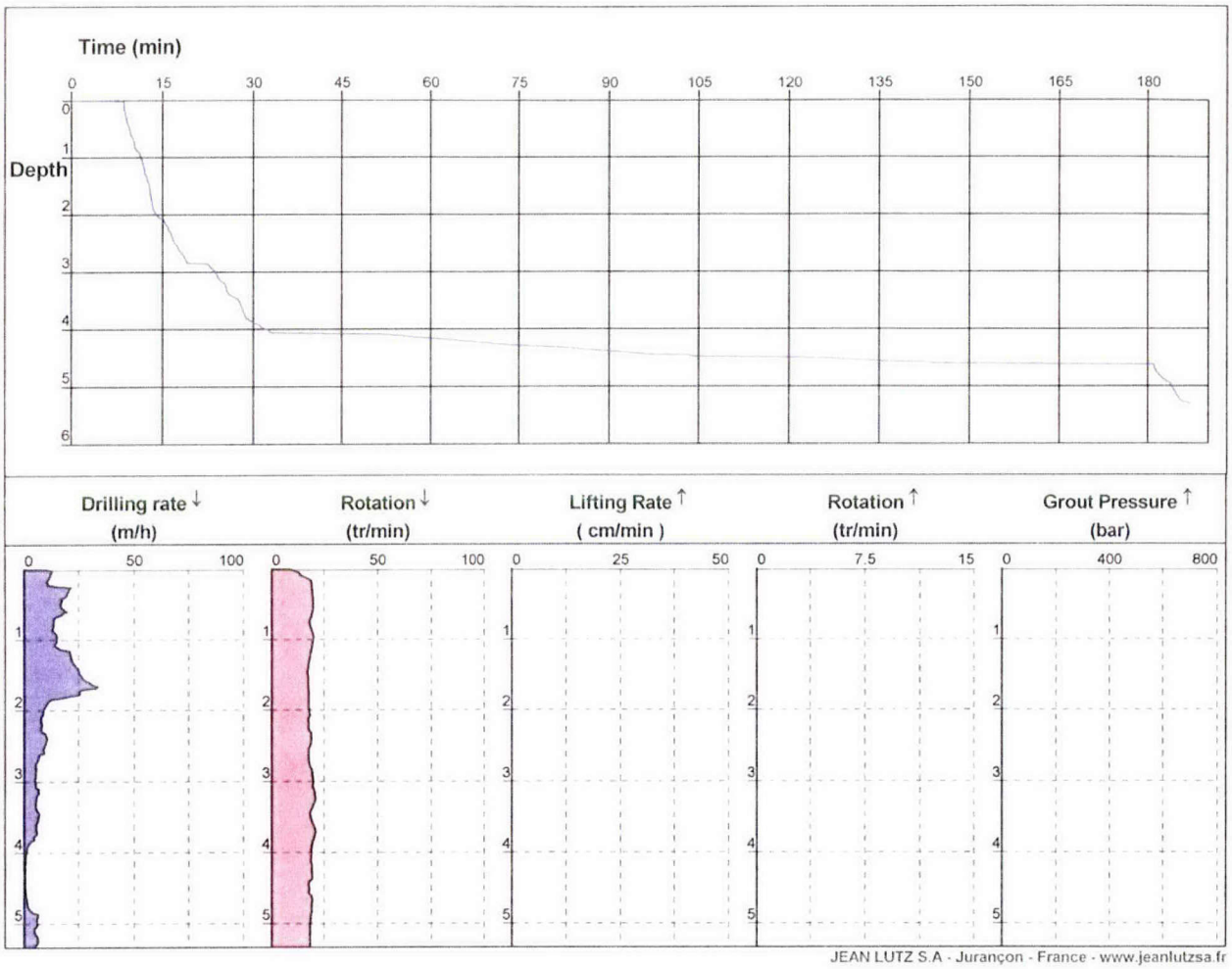
HANFORD DOE
JETGROUTING

(Contract 39790)

Date : **12/3/2009**	Drilling duration : **03:07:16**	Rig : **CM12 01**	Drill Depth : **0.00-5.32 m**
Begin : **14 h 27**	JET duration : **00:00:00**	Grout volume : **0.000 m3**	Jet Depth : **0.00-0.00 m**
End : **17 h 41**	Total duration : **03:07:16**	Volume by meter :	JET Length :

Column D14 (3)

EXJTC 5.50/LC2JTC834EN



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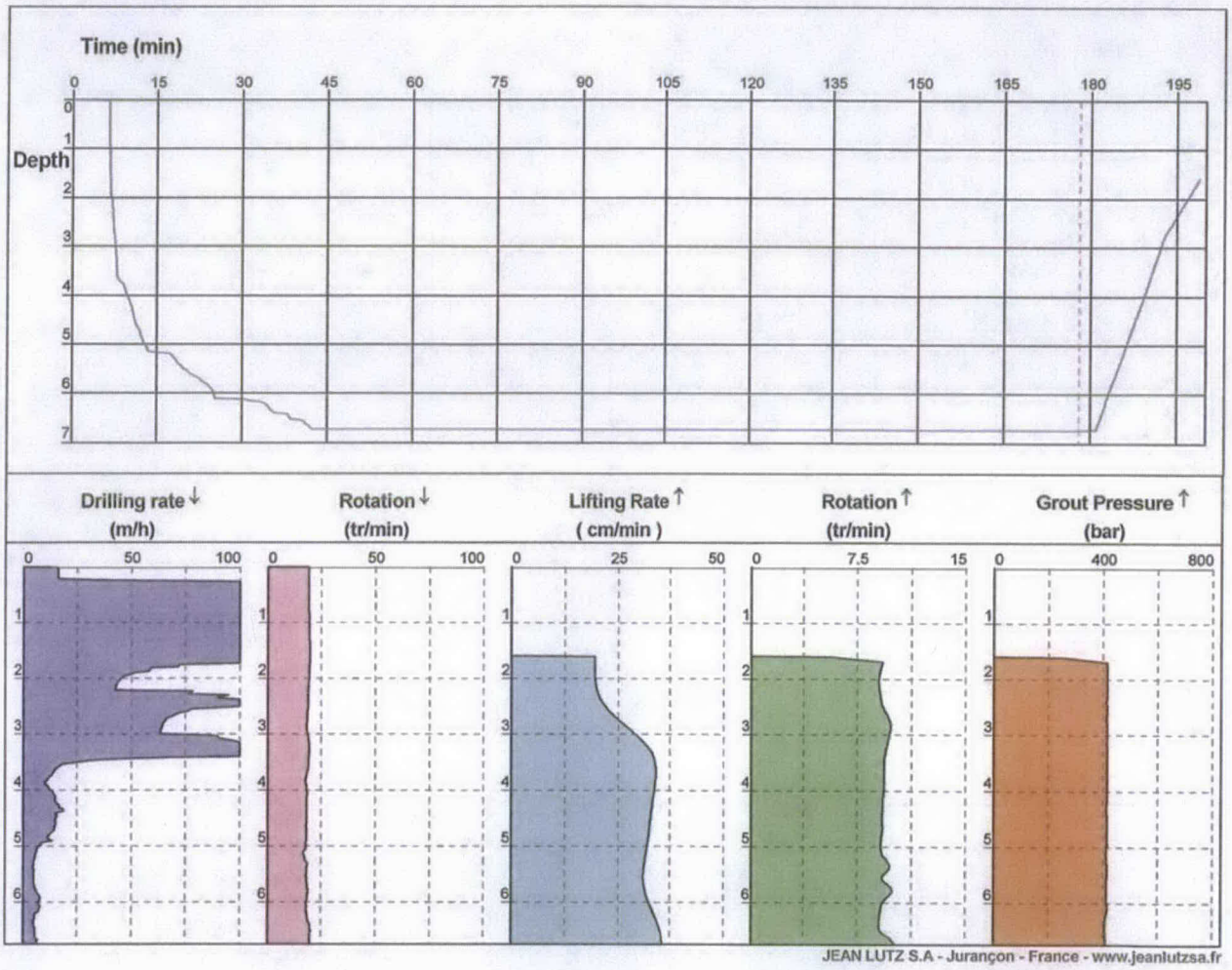
NICHOLSON

HANFORD DOE
JETGROUTING
(Contract 39790)

Date : **12/4/2009**	Drilling duration : **02:58:01**	Rig : **CM12 01**	Drill Depth : **0.00-6.74 m**
Begin : **10 h 04**	JET duration : **00:20:52**	Grout volume : **6.588 m3**	Jet Depth : **1.60-6.74 m**
End : **13 h 23**	Total duration : **03:18:53**	Volume by meter : **1282 l/m**	JET Length : **5.14 m**

Column D14A

EXJTC 5.50/LC2JTC834EN



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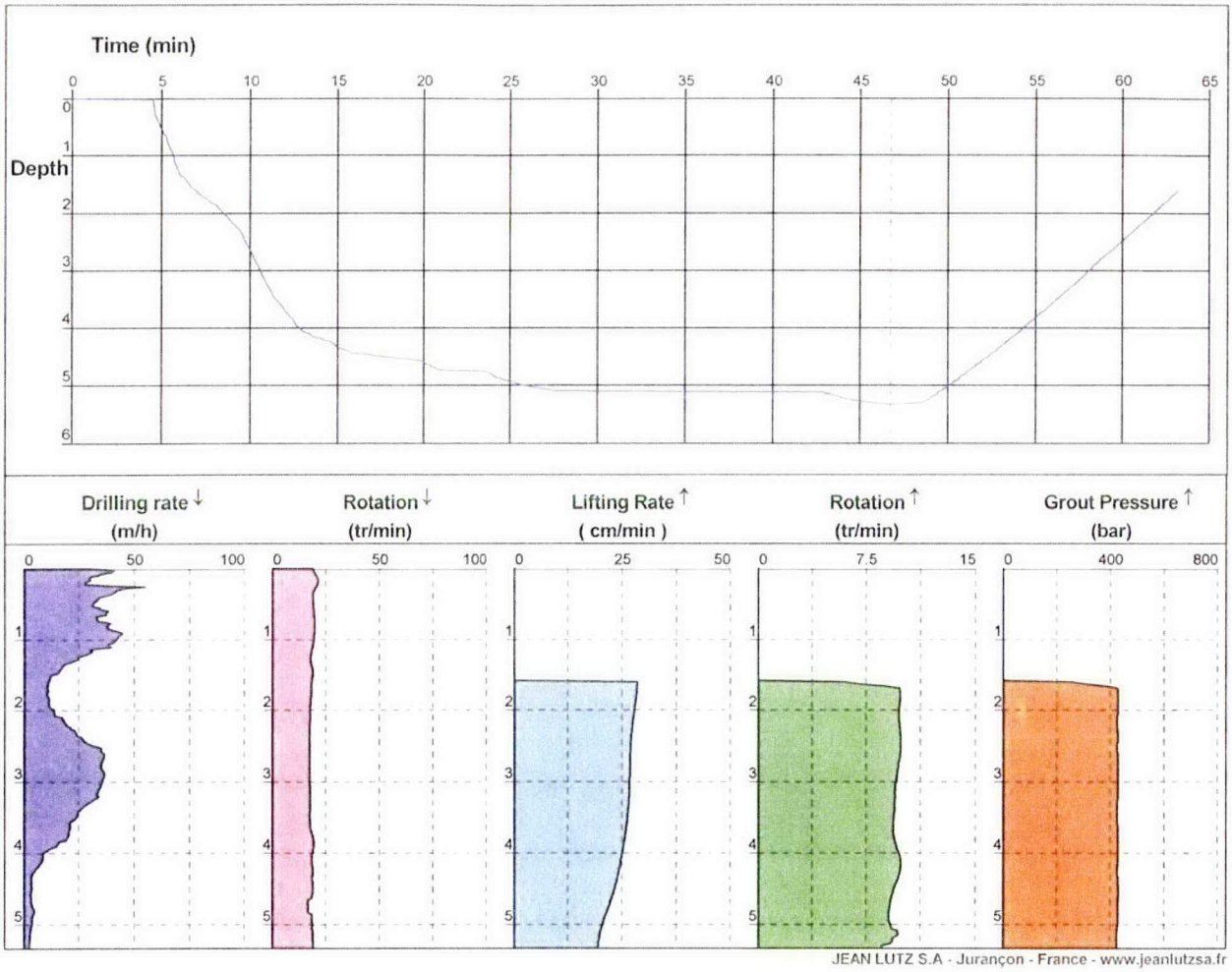
HANFORD DOE
JETGROUTING

(Contract 39790)

Date : **12/7/2009**	Drilling duration : **00:46:43**	Rig : **CM12 01**	Drill Depth : **0.00-5.32 m**
Begin : **10 h 33**	JET duration : **00:16:28**	Grout volume : **4.767 m3**	Jet Depth : **1.59-5.33 m**
End : **11 h 37**	Total duration : **01:03:11**	Volume by meter : **1275 l/m**	JET Length : **3.74 m**

Column D16

EXJTC 5.50/LC2JTC834EN



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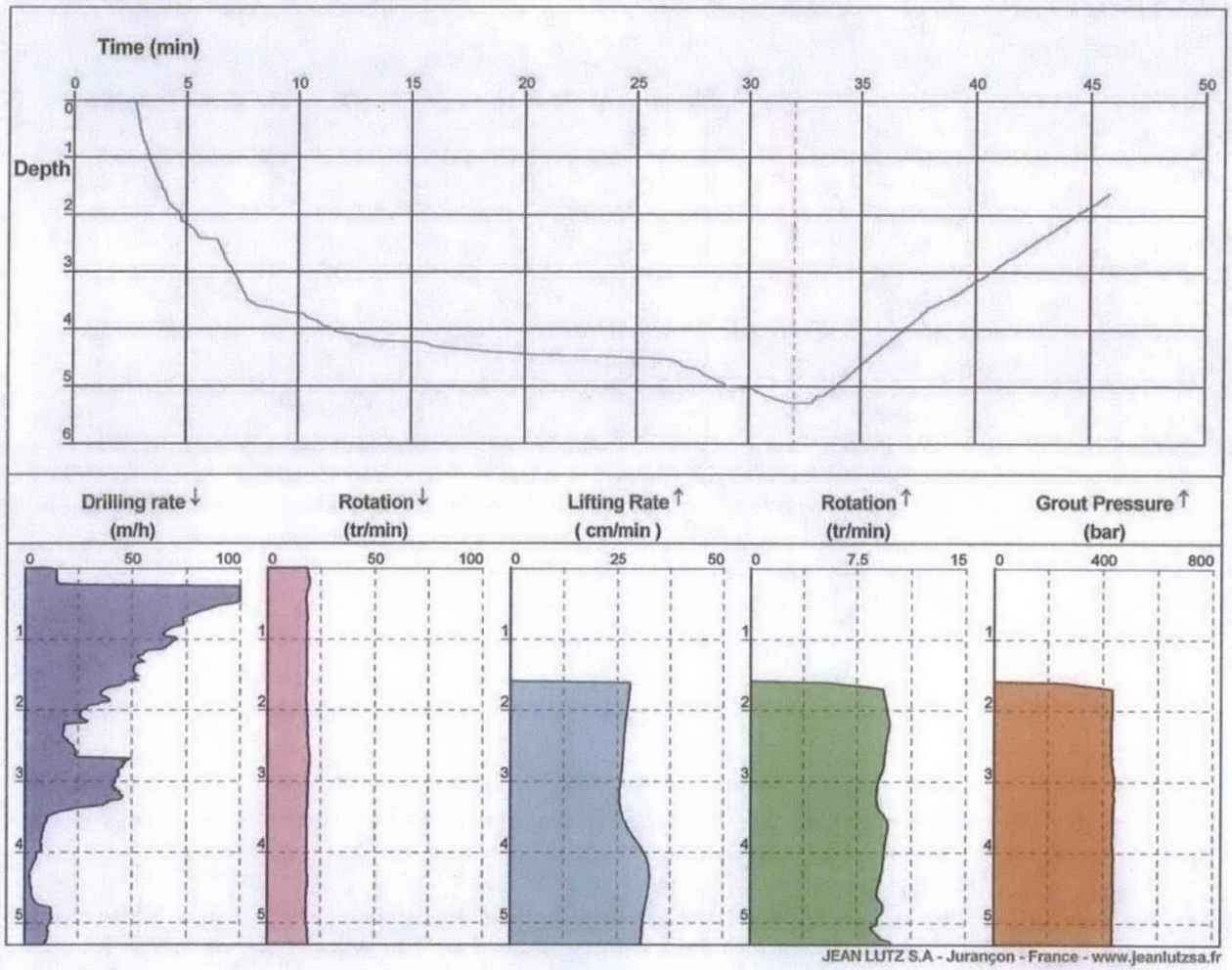
NICHOLSON

HANFORD DOE
JETGROUTING
(Contract 39790)

Date : **12/7/2009**	Drilling duration : **00:32:01**	Rig : **CM12 01**	Drill Depth : **0.00-5.30 m**
Begin : **12 h 33**	JET duration : **00:13:45**	Grout volume : **4.165 m3**	Jet Depth : **1.61-5.30 m**
End : **13 h 20**	Total duration : **00:45:46**	Volume by meter : **1129 l/m**	JET Length : **3.69 m**

Column D11

EXJTC 5.50/LC2JTC834EN



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NICHOLSON

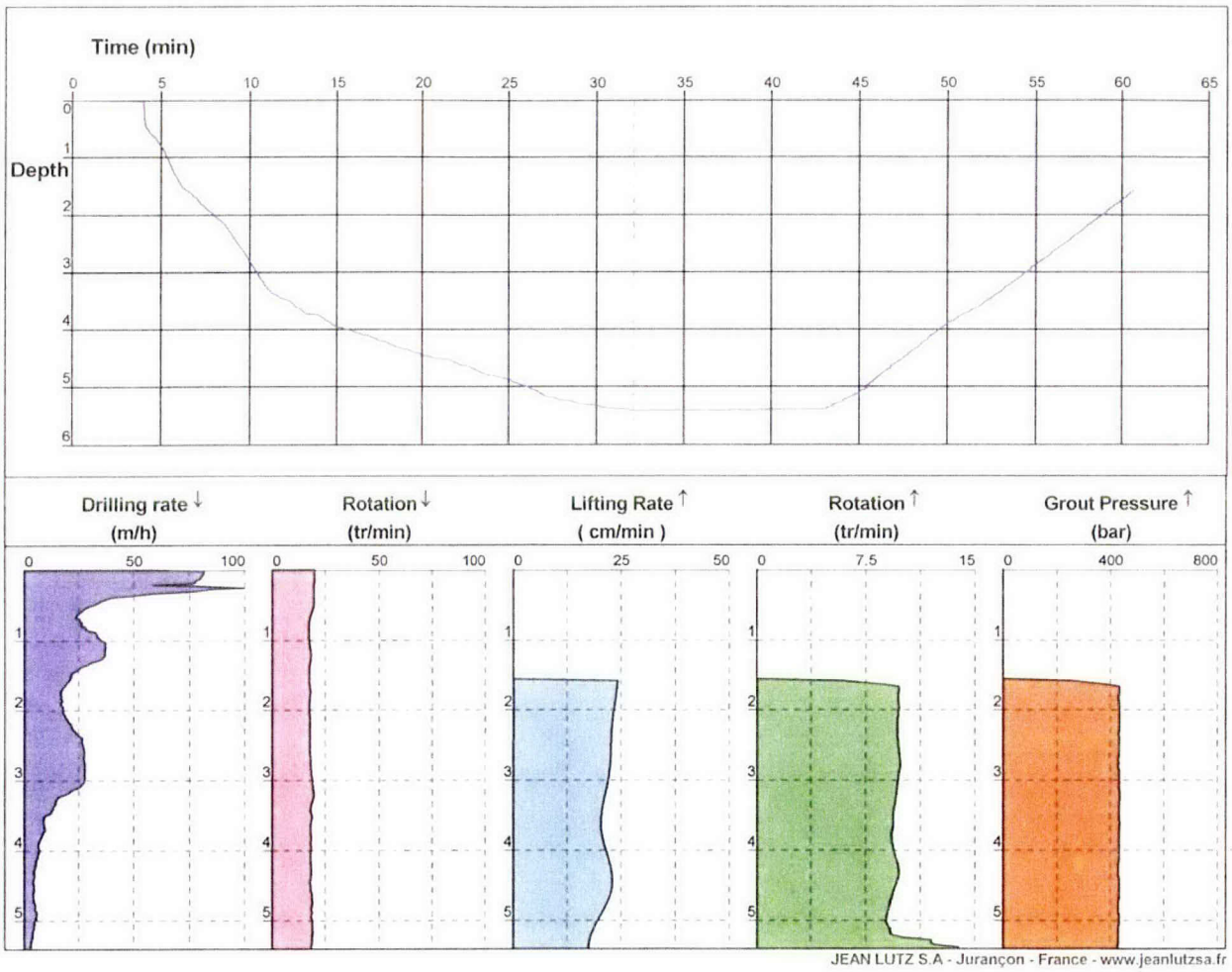
HANFORD DOE
JETGROUTING

(Contract 39790)

Date : **12/8/2009**	Drilling duration : **00:32:07**	Rig : **CM12 01**	Drill Depth : **0.00-5.40 m**
Begin : **11 h 53**	JET duration : **00:28:31**	Grout volume : **5.631 m3**	Jet Depth : **1.57-5.41 m**
End : **12 h 54**	Total duration : **01:00:38**	Volume by meter : **1466 l/m**	JET Length : **3.84 m**

Column D13

EXJTC 5.50/LC2JTC834EN



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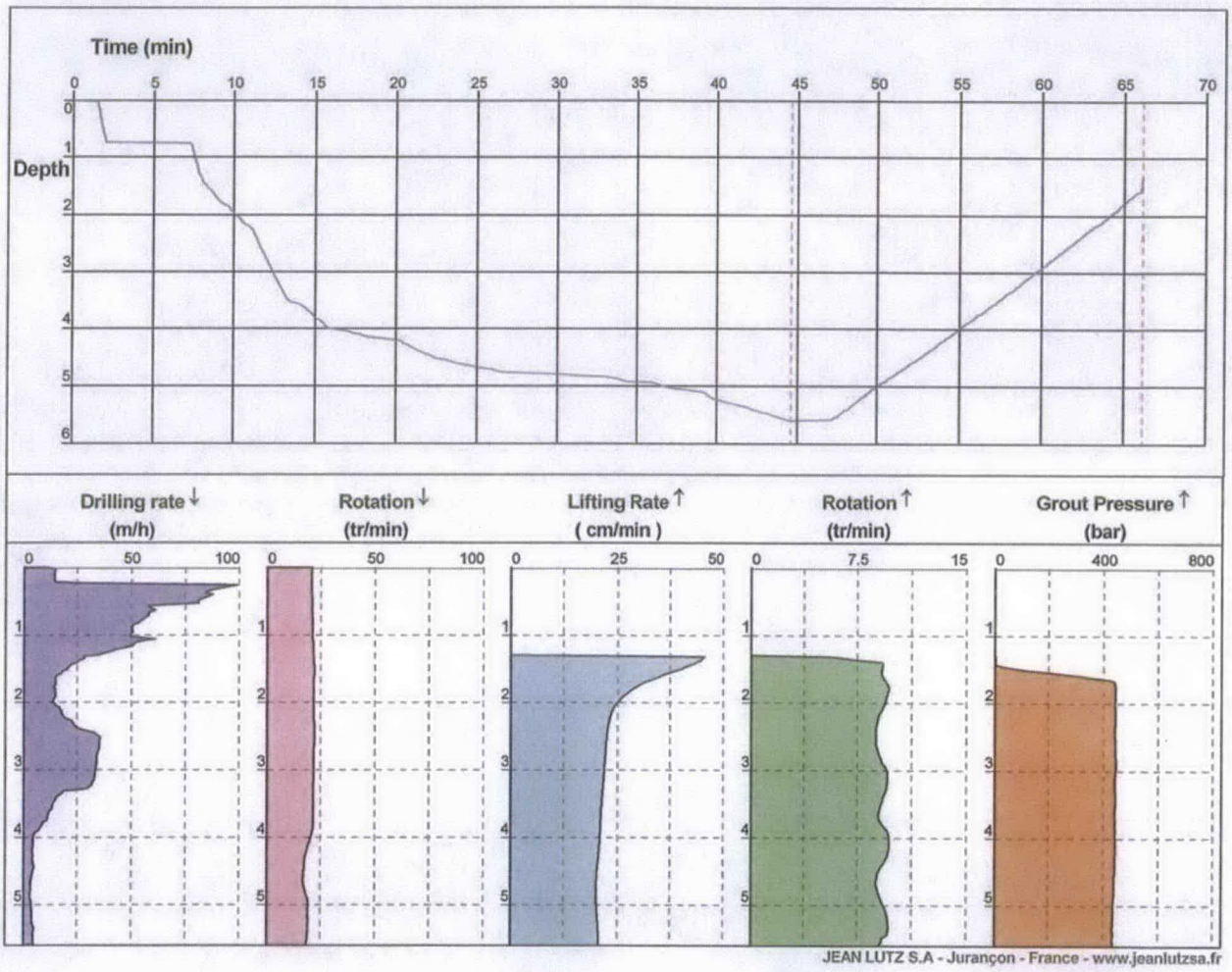
NICHOLSON

HANFORD DOE (Contract 39790)
JETGROUTING

Date : **12/9/2009**	Drilling duration : **00:44:35**	Rig : **CM12 01**	Drill Depth : **0.00-5.60 m**
Begin : **08 h 51**	JET duration : **00:21:31**	Grout volume : **6.115 m3**	Jet Depth : **1.31-5.61 m**
End : **09 h 57**	Total duration : **01:06:06**	Volume by meter : **1422 l/m**	JET Length : **4.30 m**

Column D15 EXJTC 5.50/LC2JTC834EN



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NICHOLSON

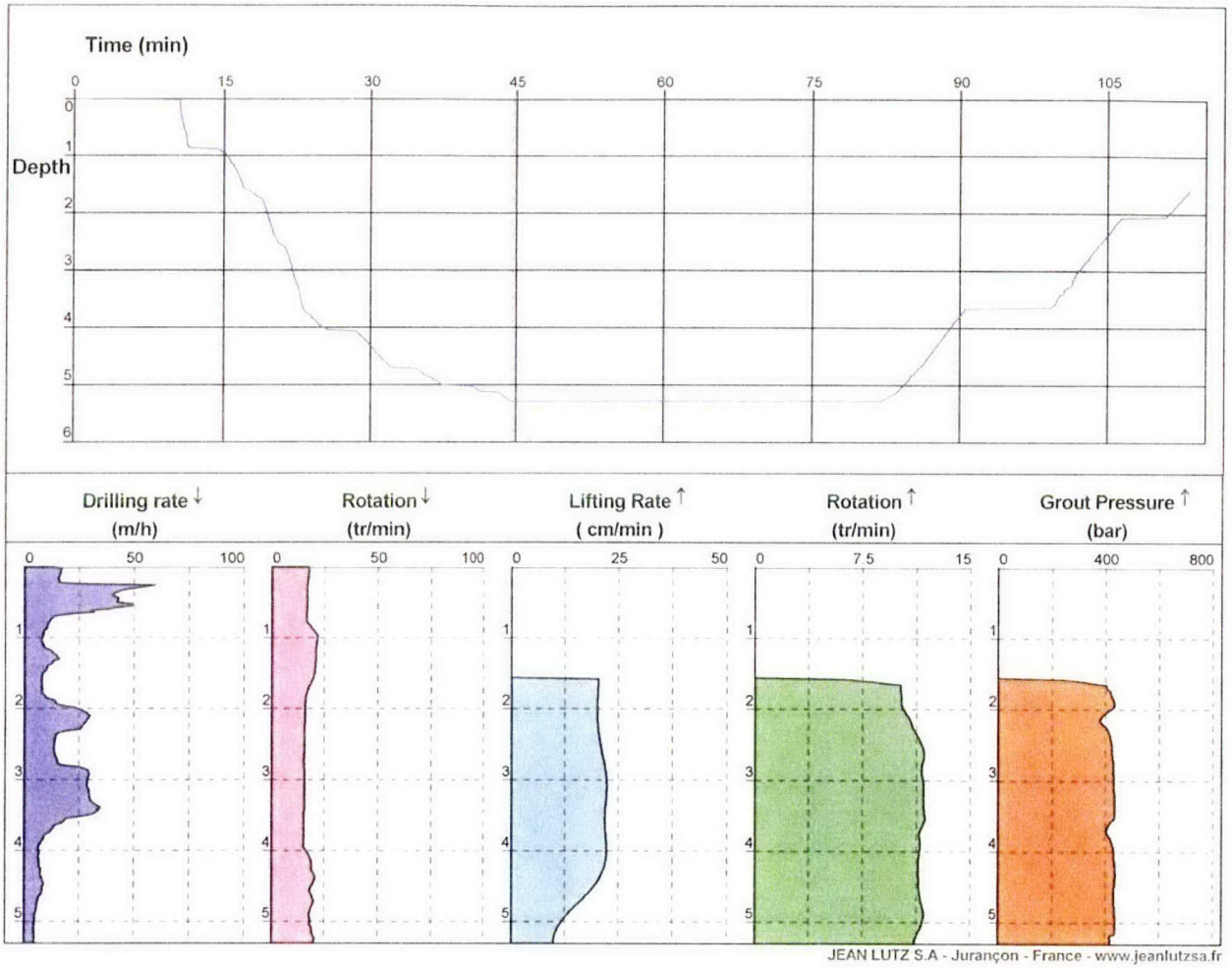
HANFORD DOE
JETGROUTING

(Contract 39790)

Date : **12/11/2009**	Drilling duration : **00:44:42**	Rig : **CM1201**	Drill Depth : **0.00-5.30 m**
Begin : **10 h 31**	JET duration : **01:08:38**	Grout volume : **6.237 m3**	Jet Depth : **1.57-5.30 m**
End : **12 h 25**	Total duration : **01:53:20**	Volume by meter : **1672 l/m**	JET Length : **3.73 m**

Column D21

EXJTC 5.50/LC2JTC834EN



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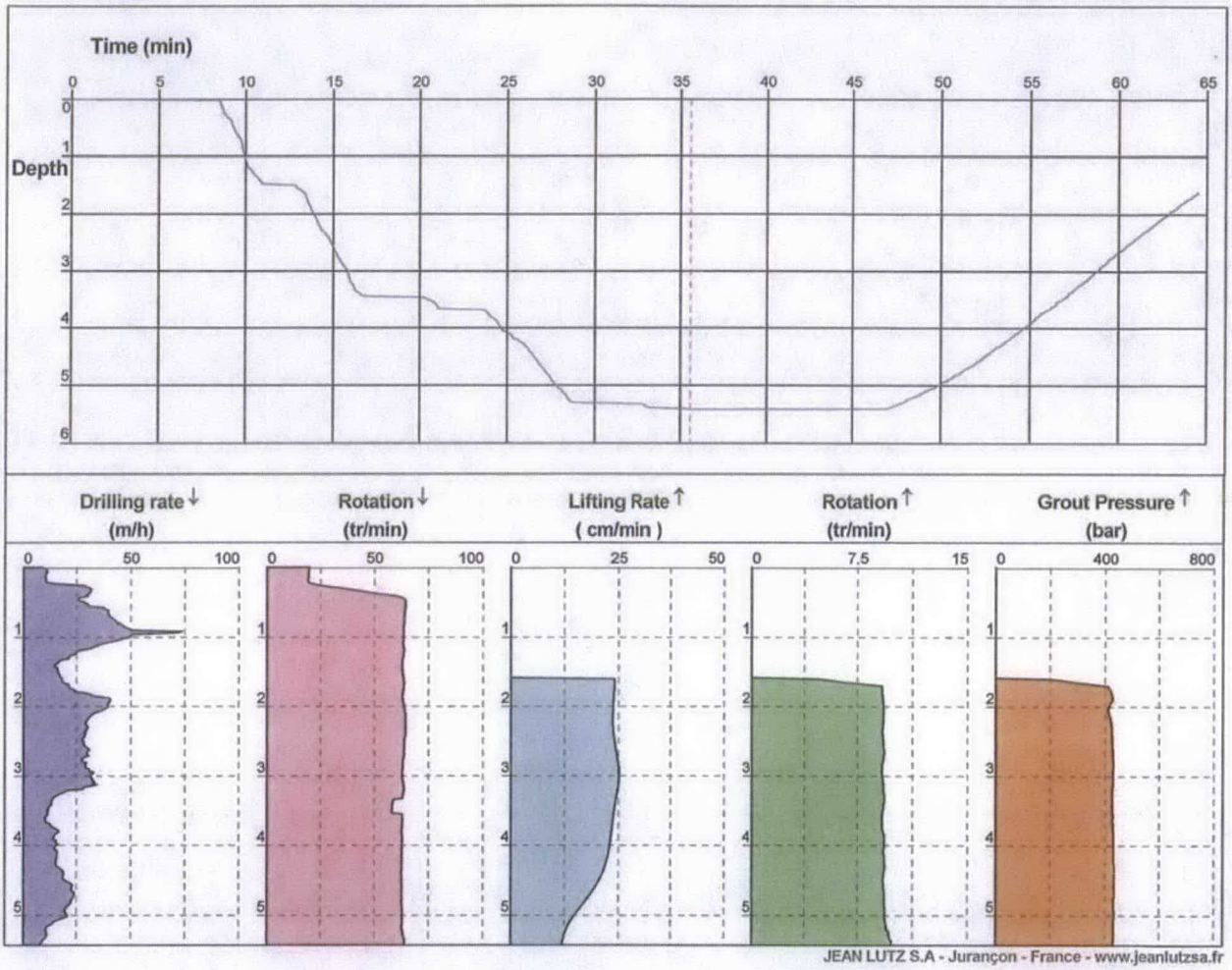
JETGROUTING

(Contract 39790)

Date : **12/14/2009**	Drilling duration : **00:35:35**	Rig : **CM12 01**	Drill Depth : **0.00-5.42 m**
Begin : **08 h 48**	JET duration : **00:28:54**	Grout volume : **5.899 m3**	Jet Depth : **1.60-5.43 m**
End : **09 h 53**	Total duration : **01:04:29**	Volume by meter : **1540 l/m**	JET Length : **3.83 m**

Column D22 (2)

EXJTC 5.50/LC2JTC834EN



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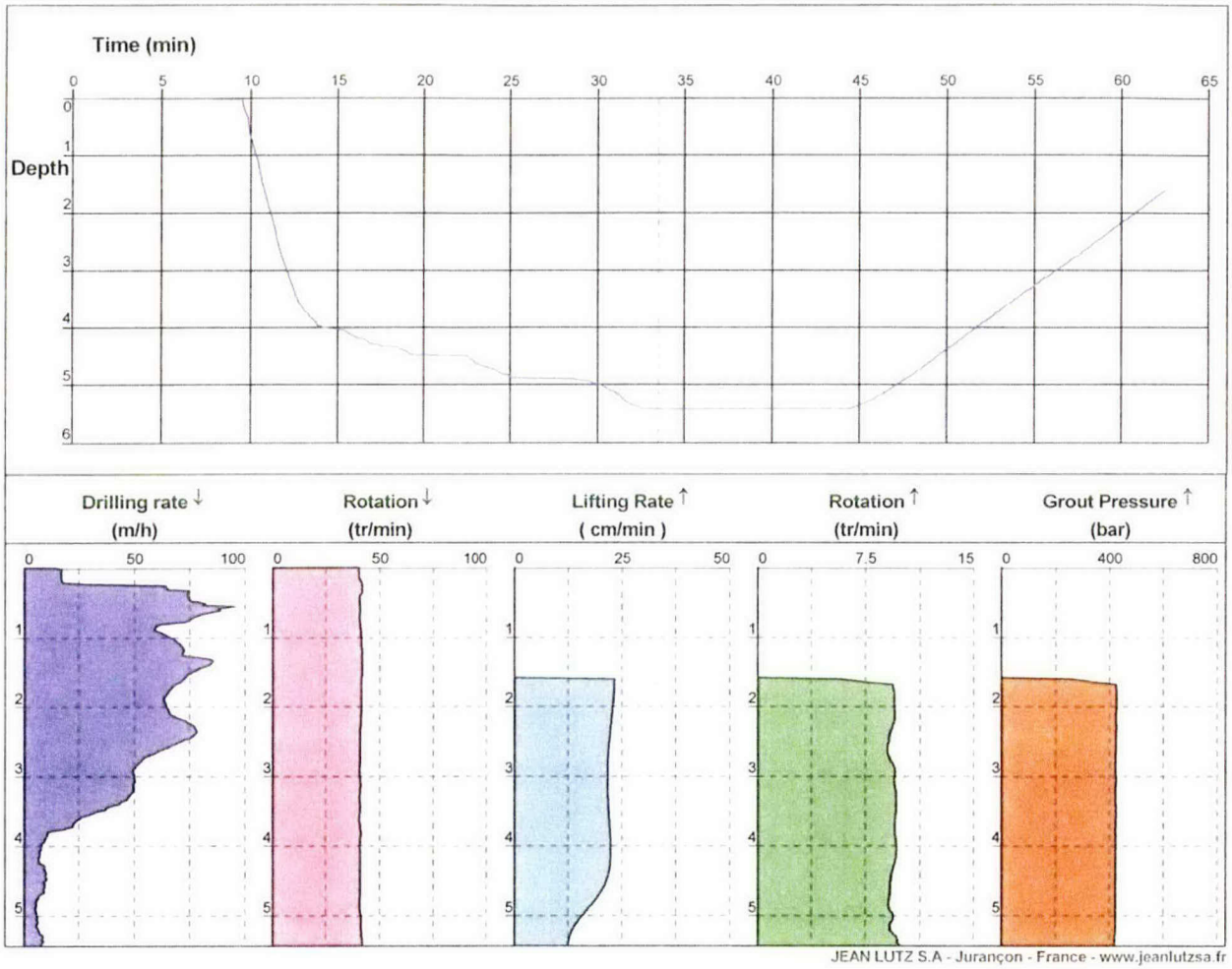
HANFORD DOE
JETGROUTING

(Contract 39790)

Date : **12/14/2009**	Drilling duration : **00:33:28**	Rig : **CM12 01**	Drill Depth : **0.00-5.42 m**
Begin : **11 h 27**	JET duration : **00:29:03**	Grout volume : **5.976 m3**	Jet Depth : **1.60-5.43 m**
End : **12 h 30**	Total duration : **01:02:31**	Volume by meter : **1560 l/m**	JET Length : **3.83 m**

Column D24 (2)

EXJTC 5.50/LC2JTC834EN



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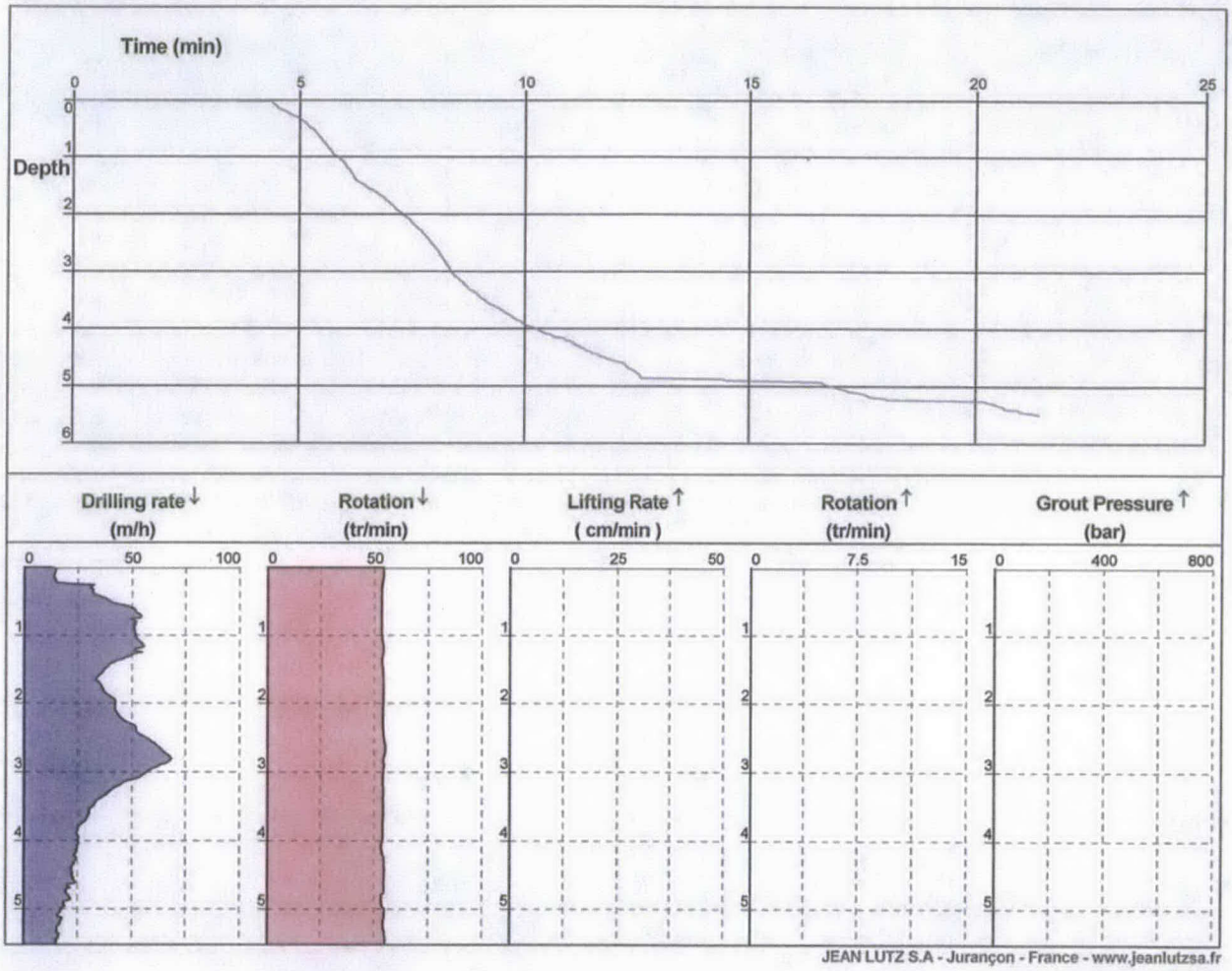
JETGROUTING

(Contract 39790)

Date : **12/14/2009**	Drilling duration : **00:21:23**	Rig : **CM12 01**	Drill Depth : **0.00-5.51 m**
Begin : **13 h 32**	JET duration : **00:00:00**	Grout volume : **0.000 m3**	Jet Depth : **0.00-0.00 m**
End : **15 h 18**	Total duration : **00:21:23**	Volume by meter :	JET Length :

Column D26 (2)

EXJTC 5.50/LC2JTC834EN



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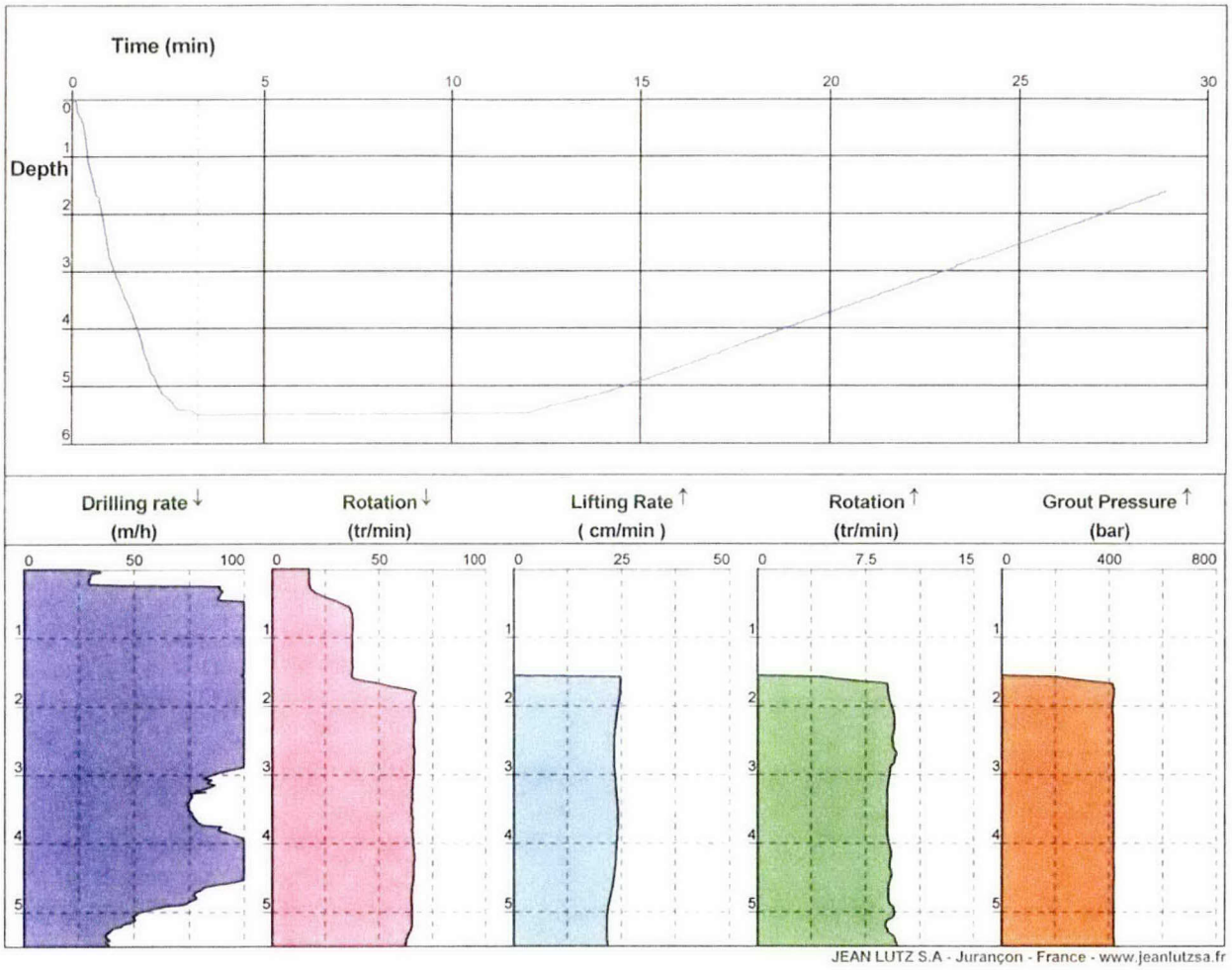
JETGROUTING

(Contract 39790)

Date	: **12/14/2009**	Drilling duration	: **00:03:15**	Rig	: **CM12 01**	Drill Depth	: **0.00-5.50 m**
Begin	: **15 h 18**	JET duration	: **00:25:37**	Grout volume	: **5.155 m3**	Jet Depth	: **1.58-5.51 m**
End	: **15 h 48**	Total duration	: **00:28:52**	Volume by meter	: **1312 l/m**	JET Length	: **3.93 m**

Column D26 (4)

EXJTC 5.50/LC2JTC834EN



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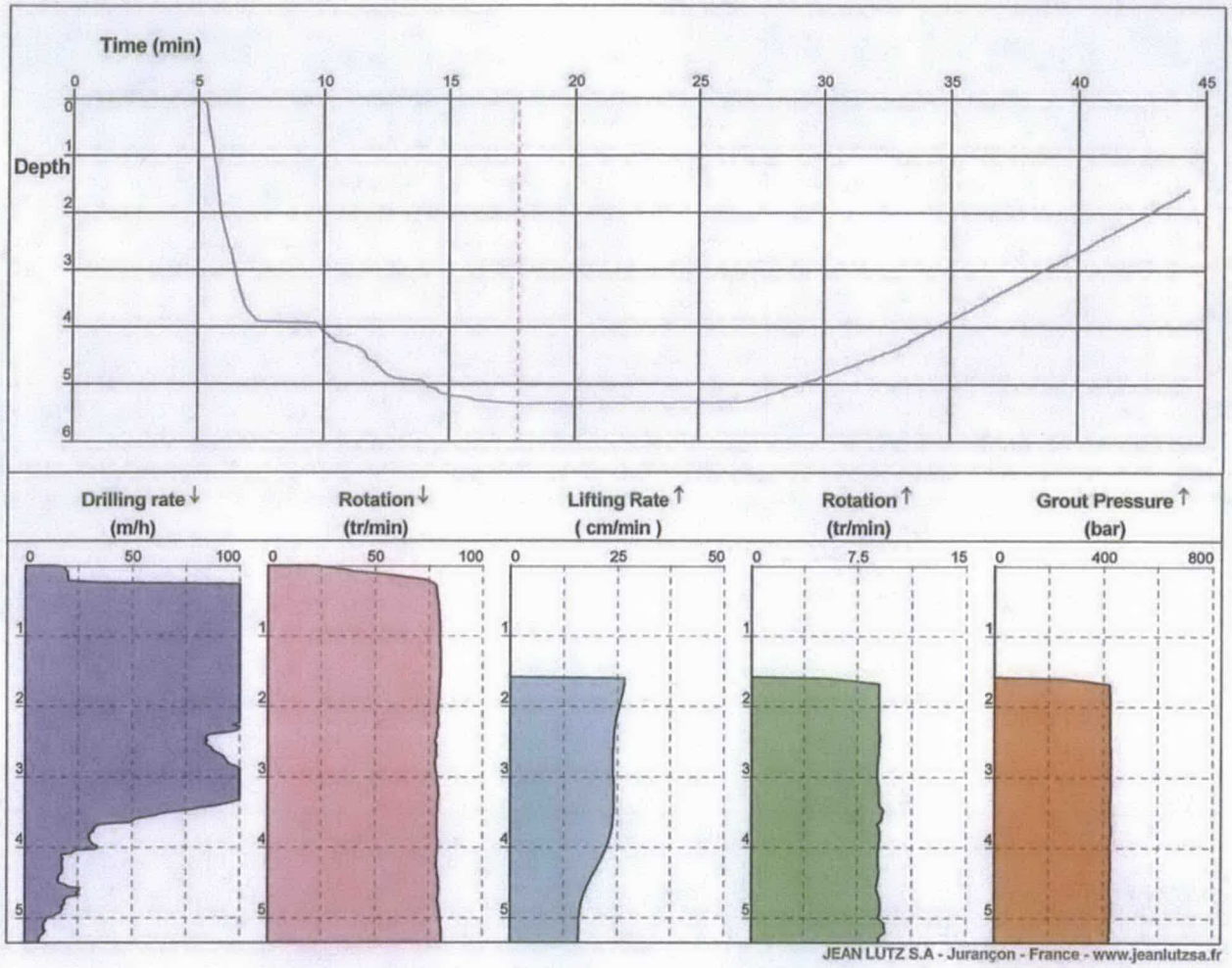
JETGROUTING

Date : **12/15/2009**	Drilling duration : **00:17:44**	Rig : **CM12 01**	Drill Depth : **0.00-5.34 m**
Begin : **10 h 49**	JET duration : **00:26:35**	Grout volume : **5.461 m3**	Jet Depth : **1.59-5.34 m**
End : **11 h 34**	Total duration : **00:44:19**	Volume by meter : **1456 l/m**	JET Length : **3.75 m**

Column D25 (2)

EXJTC 5.50/LC2JTC834EN



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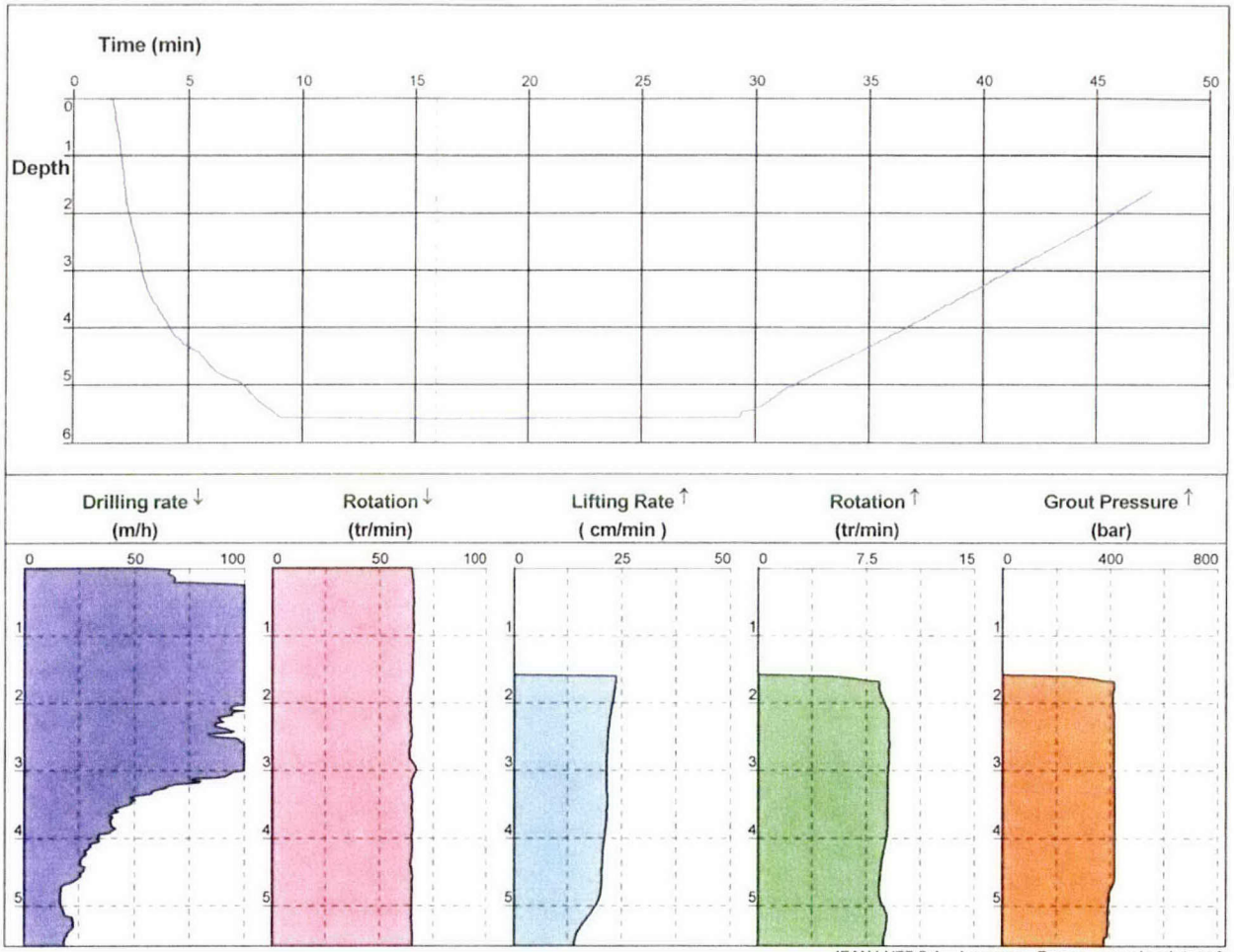
JETGROUTING

(Contract 39790)

Date : **12/15/2009**	Drilling duration : **00:15:53**	Rig : **CM12 01**	Drill Depth : **0.00-5.58 m**
Begin : **12 h 47**	JET duration : **00:31:34**	Grout volume : **5.736 m3**	Jet Depth : **1.60-5.58 m**
End : **13 h 35**	Total duration : **00:47:27**	Volume by meter : **1441 l/m**	JET Length : **3.98 m**

Column D23 (2)

EXJTC 5.50/LC2JTC834EN



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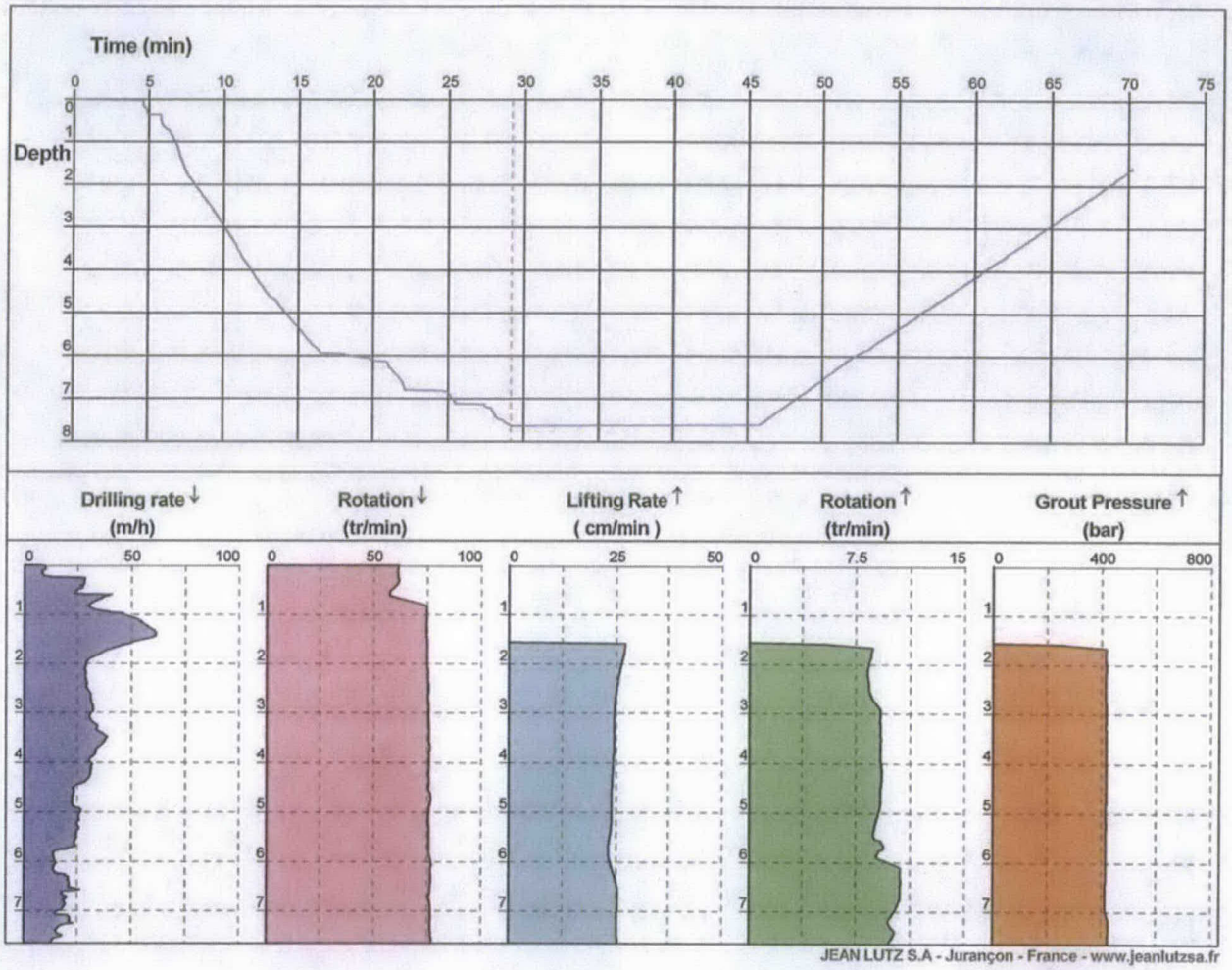
JETGROUTING
(Contract 39790)

Date : **12/16/2009**	Drilling duration : **00:29:12**	Rig : **CM12 01**	Drill Depth : **0.00-7.64 m**
Begin : **12 h 43**	JET duration : **00:41:03**	Grout volume : **7.647 m3**	Jet Depth : **1.57-7.64 m**
End : **13 h 54**	Total duration : **01:10:15**	Volume by meter : **1260 l/m**	JET Length : **6.07 m**

Column D34 (2)

EXJTC 5.50/LC2JTC834EN



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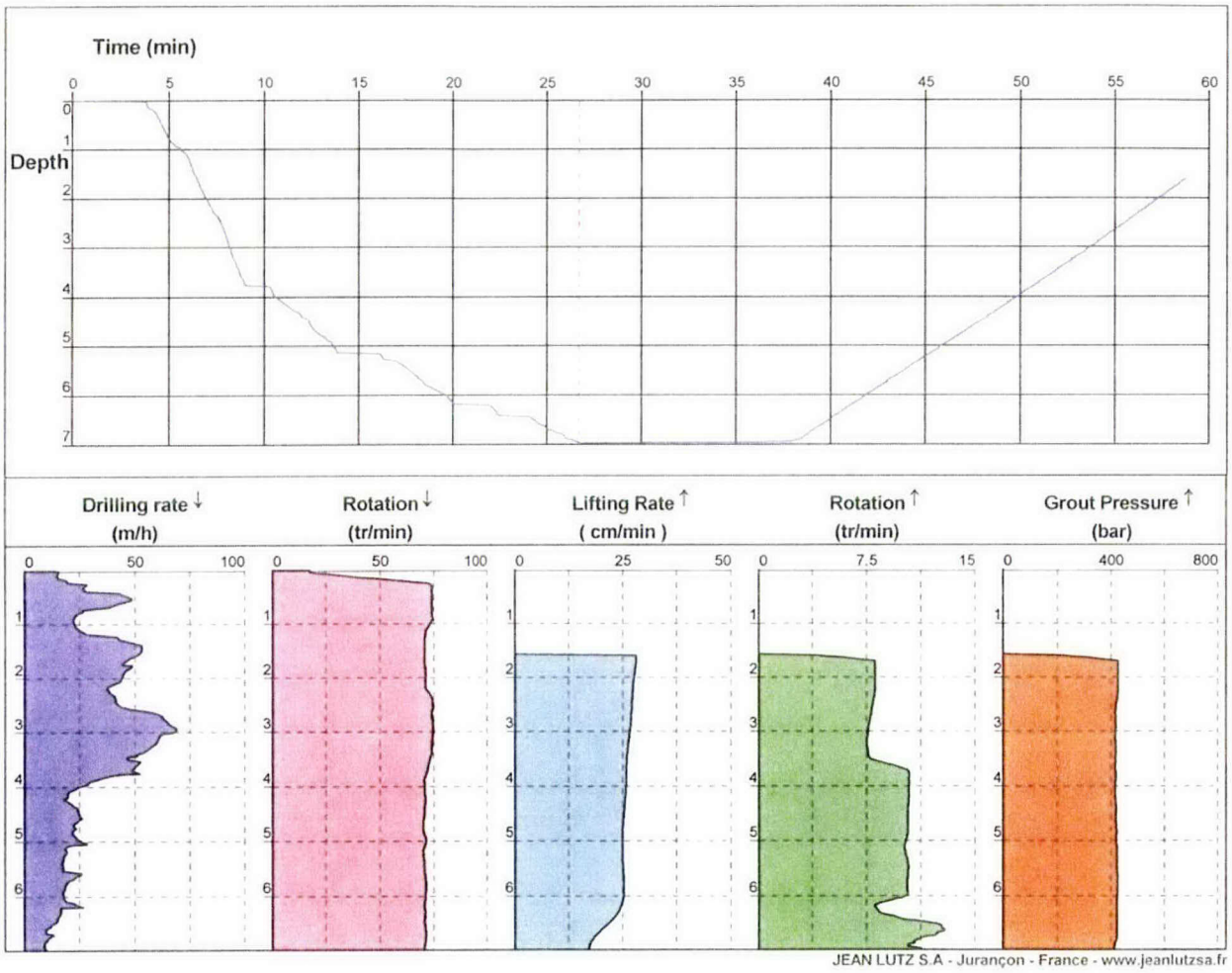
JETGROUTING

(Contract 39790)

Date : **12/16/2009**	Drilling duration : **00:26:42**	Rig : **CM12 01**	Drill Depth : **0.00-6.98 m**
Begin : **14 h 04**	JET duration : **00:32:03**	Grout volume : **6.729 m3**	Jet Depth : **1.58-6.98 m**
End : **15 h 03**	Total duration : **00:58:45**	Volume by meter : **1246 l/m**	JET Length : **5.40 m**

Column D36

EXJTC 5.50/LC2JTC834EN



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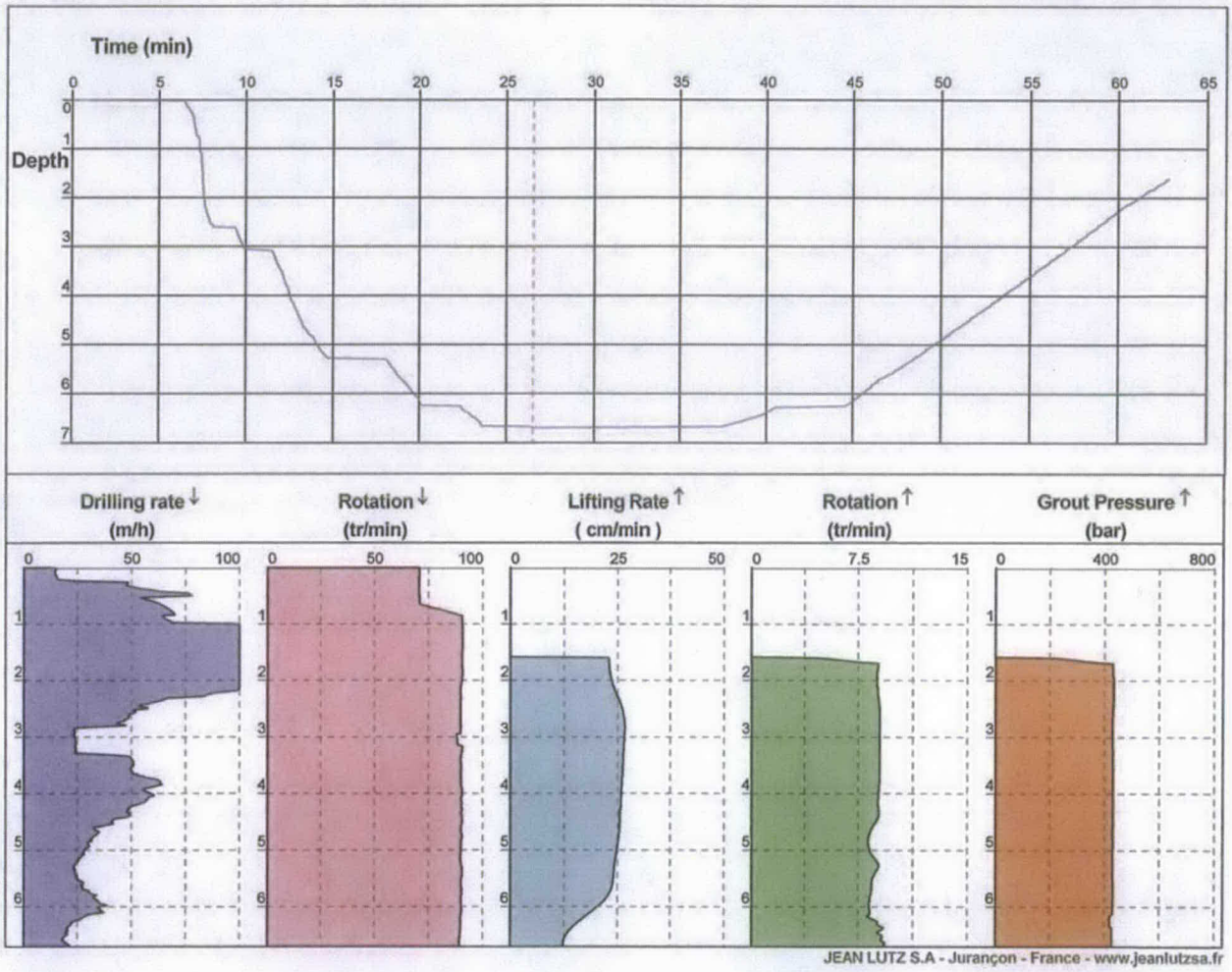
JETGROUTING

Date : **12/17/2009**	Drilling duration : **00:26:30**	Rig : **CM12 01**	Drill Depth : **0.00-6.70 m**
Begin : **07 h 51**	JET duration : **00:36:23**	Grout volume : **7.576 m3**	Jet Depth : **1.60-6.71 m**
End : **08 h 54**	Total duration : **01:02:53**	Volume by meter : **1483 l/m**	JET Length : **5.11 m**

Column D35 (2)

EXJTC 5.50/LC2JTC834EN



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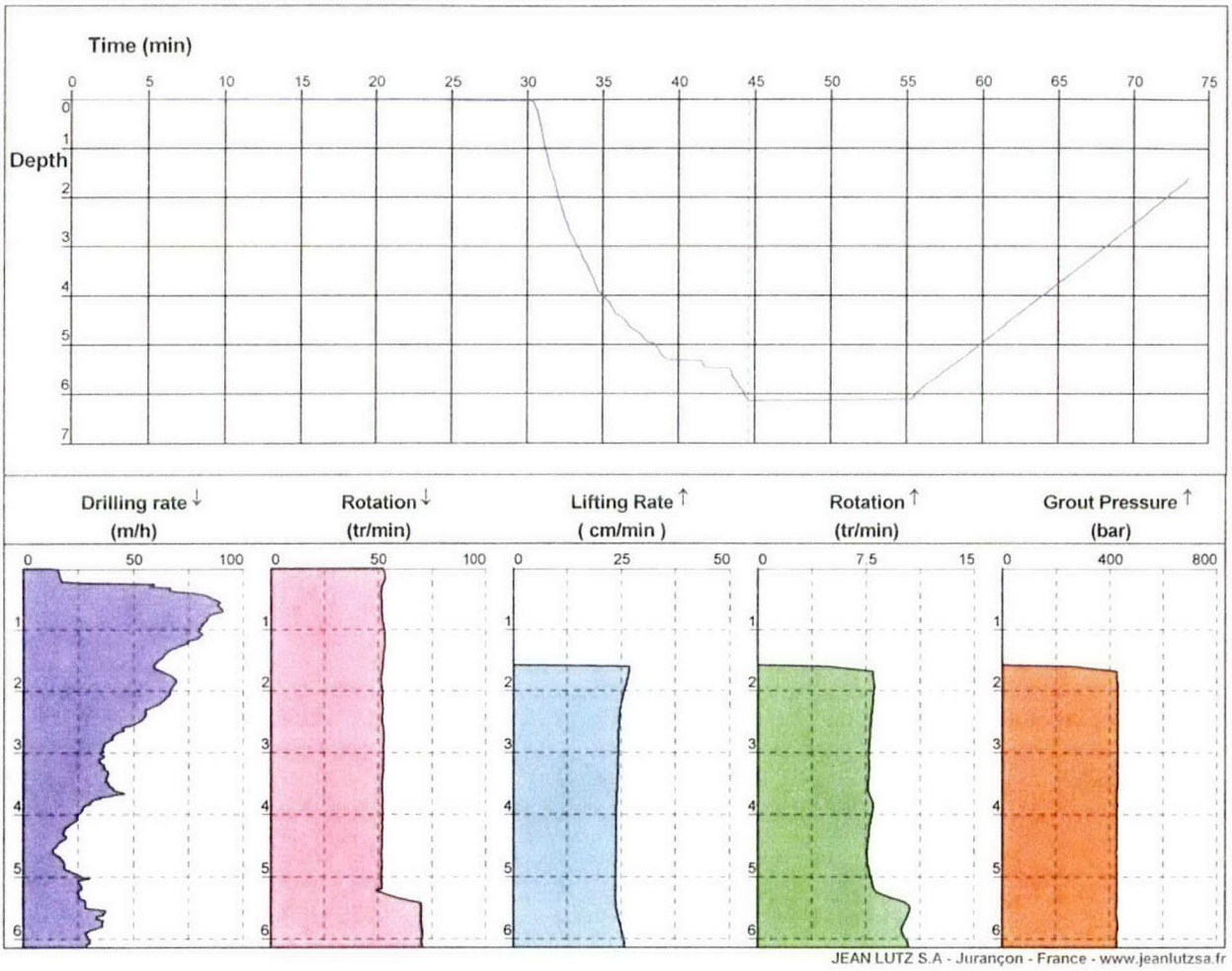
JETGROUTING

(Contract 39790)

Date : **12/17/2009**	Drilling duration : **00:44:36**	Rig : **CM12 01**	Drill Depth : **0.00-6.14 m**
Begin : **09 h 43**	JET duration : **00:29:07**	Grout volume : **5.959 m3**	Jet Depth : **1.59-6.15 m**
End : **10 h 57**	Total duration : **01:13:43**	Volume by meter : **1307 l/m**	JET Length : **4.56 m**

Column D31 (2)

EXJTC 5.50/LC2JTC834EN



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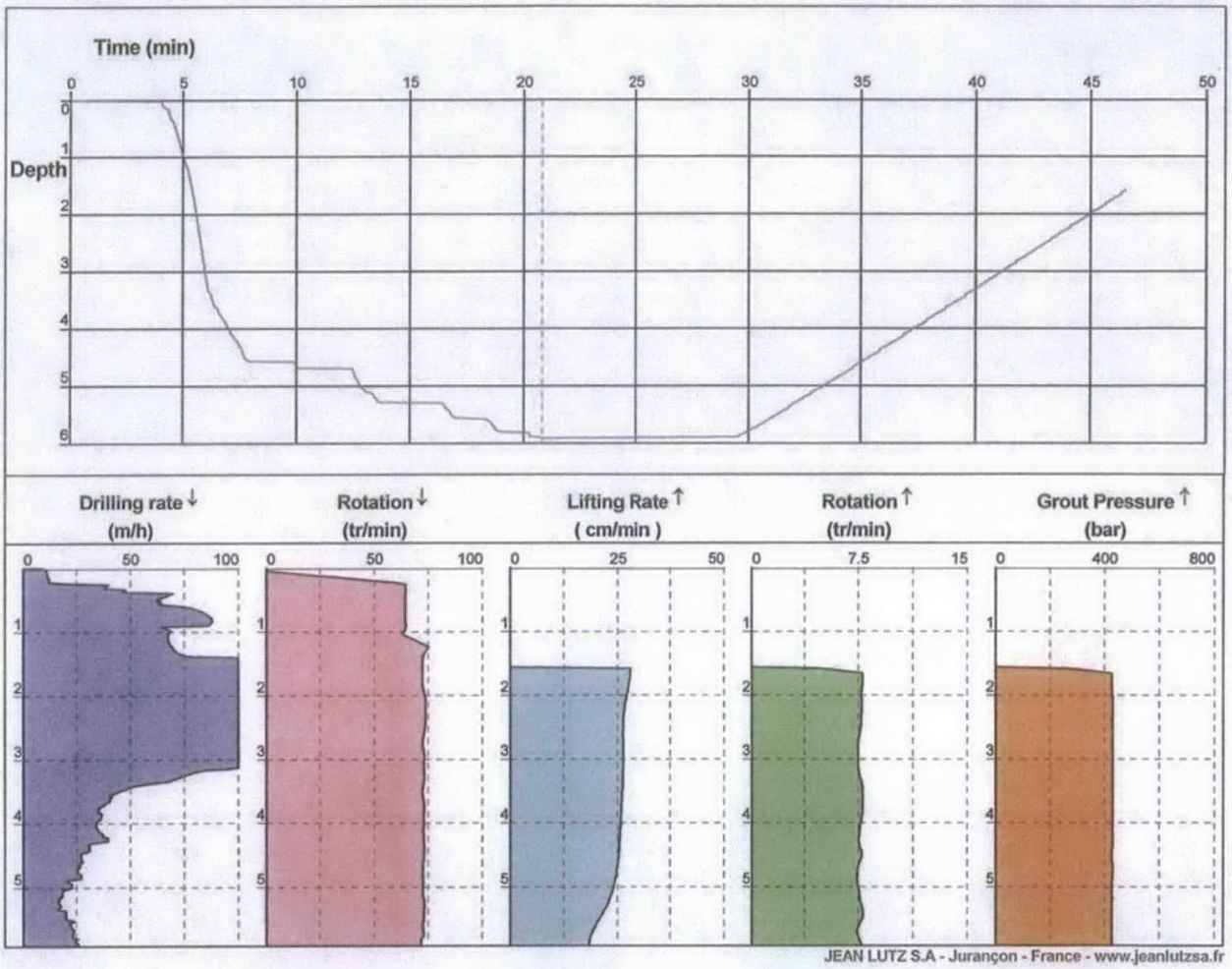
HANFORD DOE (Contract 39790)
JETGROUTING

Date : **12/17/2009**	Drilling duration : **00:20:49**	Rig : **CM12 01**	Drill Depth : **0.00-5.92 m**
Begin : **11 h 10**	JET duration : **00:25:40**	Grout volume : **5.598 m3**	Jet Depth : **1.57-5.92 m**
End : **11 h 57**	Total duration : **00:46:29**	Volume by meter : **1287 l/m**	JET Length : **4.35 m**

Column D33 (2)

EXJTC 5.50/LC2JTC834EN



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NICHOLSON

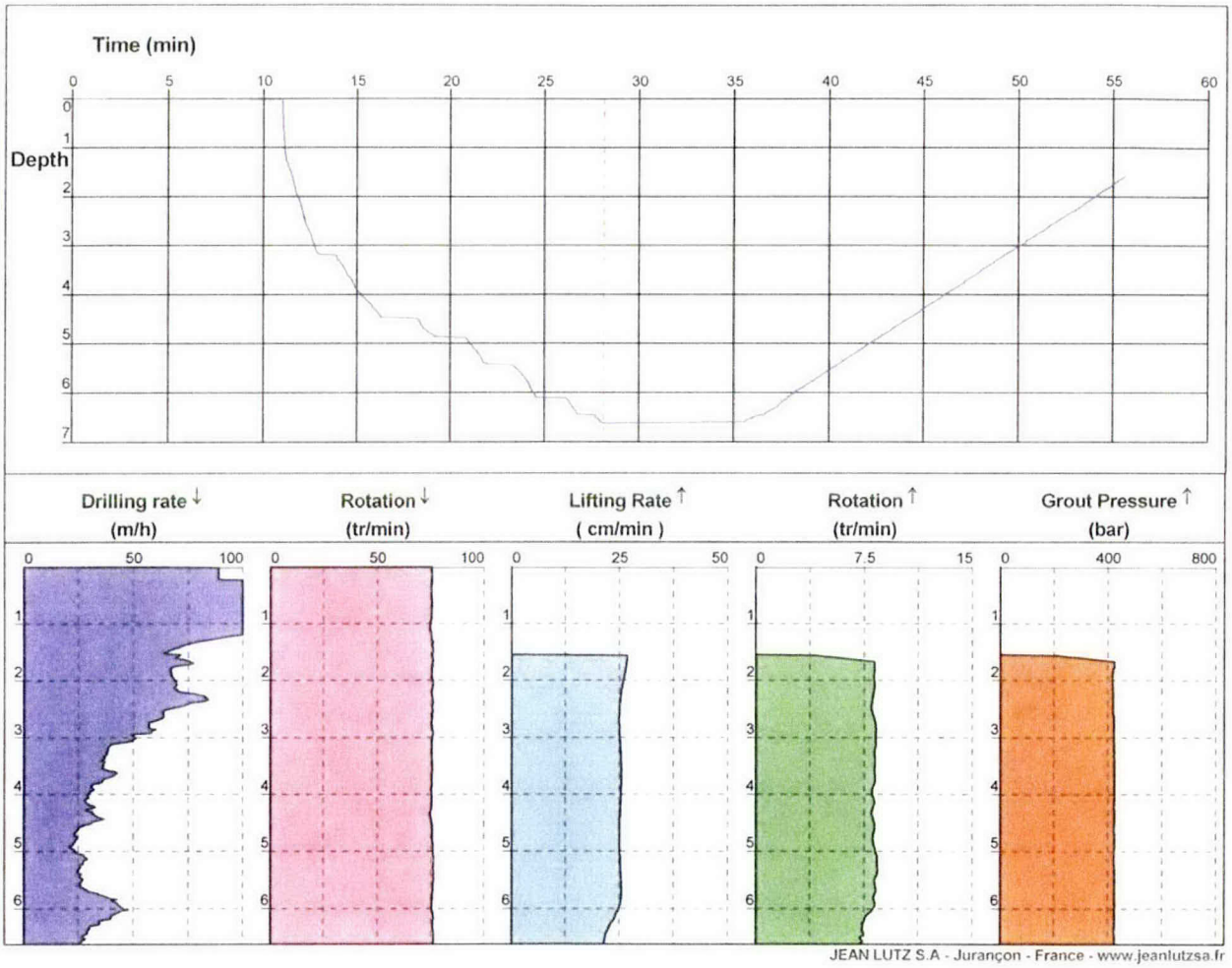
HANFORD DOE
JETGROUTING

(Contract 39790)

Date : **12/17/2009**	Drilling duration : **00:28:08**	Rig : **CM12 01**	Drill Depth : **0.00-6.62 m**
Begin : **12 h 16**	JET duration : **00:27:28**	Grout volume : **6.369 m3**	Jet Depth : **1.56-6.62 m**
End : **13 h 12**	Total duration : **00:55:36**	Volume by meter : **1259 l/m**	JET Length : **5.06 m**

Column D32 (2)

EXJTC 5.50/LC2JTC834EN



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Appendix B

Sediment Core Borehole Logs

BOREHOLE LOG

Page 1 of 1
Date: 2/10/10

Well ID: C7305	Well Name: 199-N-222	Location: 15' NE of 199-N-221	
Project: 100-NR-2 171 wells		Reference Measuring Point: Ground Surface	

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0-26' bgs - Sandy Gravel (SG) to Gravel 70-85% gravel, 15-30% Sand. Gvl is predominantly basalt in upper 10-15 ft. Consisting of Mp - Cp, R-SR. (3 cm avg) Sandy gravel to gravel Transition is unknown, likely around 16' bgs based on surrounding lithology. Successive cleanouts + split spoon sampling make descriptions difficult. Sand is predominantly QTZ rich, MS, SR. Upper 10-15 ft is darker (7.5YR 3/1 - Dark Gray) moist. than bottom 10 ft.	Sonic w/ split spoon
	S.S. I-001	60% recovery			
	2.5'				
	S.S. I-002	100%			
5'					
	SS I-003	80%			
	7.5'				
	S.S I-004	100%			
	9.8				
10'	10.3'				
	I-005 S.S.	100%			
	12.8'				
	S.S. I-006	100%			
15'	15.2'				
	I-007 S.S.	100%			TD = 17.4' (well placement)
	17.7'				TD = 27.1' (split spoon)
	18.1 S.S. I-008	100%			DTW = NA 2/10/10 TH
20'	20.6'				
	S.S. I-009	100%			
	22.8				
	S.S I-010	~~100%~~ TAS 40%			
25'	24.8				
	S.S. I-011	100%			
	27.1				
30'					

Reported By: Troy Stevens		Reviewed By: L.D. Walker	
Title: Geologist		Title: Geologist	
Signature:	Date: 2/10/10	Signature:	Date: 4/1/10

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 1

Date: 2/9/10

Well ID: C7307	Well Name: 199-N-220	Location:	15' NE of 199-N-219
Project: 100-NR-2 171 wells		Reference Measuring Point:	Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0	S.S I-001	60% recovery		0-26' bgs - Sandy Gravel (SG) transition to Gravel (G). 70-85% gvl, 30-15% Sand. Gvl: Predominantly more basalt in upper 10-15', R-SR, Mp-Cp (3cm avg). Boulders + large cobbles @ ~15' bgs. Transition from Sandy gravel to gravel unknown due to Split spoon sampling + re-work of borehole with successive cleanouts. Sand is predominantly QTZ rich with basalt content 30-40%. Medium Sand, SR. Upper 10-15' of borehole is predominantly darker (7.5YR 3/1-Dark Gray), moist + somewhat muddy.	Sonic w/ split spoon + core barrel
2.5'	SS I-002	100%			Borehole is located in jet injection test plot, Descriptions of cuttings when available due to split spoon.
5'	S.S I-003	60%			
7.5'	S.S. I-004	80%			
10'	S.S. I-005	60%			
12.5'	SS I-006	100%			
15'	SS I-007	90%			
17.5'	SS I-008	100%			Split Spoon I-008 from 17.5'-19.0'
20'	I-009				
21.2'	I-010	100%			Split Spoon I-009 from 18.7-21.2'
23.7'	S.S. I-011				TD w/ split spoon = 26.2
25'	26.2				TD for well = 16.3'
					DTW NA 2/9/10
30'					

Reported By: Troy Stevens		Reviewed By: L.D. Walker	
Title: Geologist		Title: Geologist	
Signature:	Date: 2/9/10	Signature:	Date: 4/1/10

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 1
Date: 2/8/10

Well ID: C7308	Well Name: 199-N-219	Location: 15' NE of 199-N-218	
Project: 100-NR-2 171 wells		Reference Measuring Point: Ground Surface	

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0-16' bgs- Sandy Gravel (SG) 70% gvl, 30% Sand. Gvl: Pred. basalt, SR-SA, Mp Sand: mix of QTZ + basalt, pred. QTZ.	Sonic w/ split spoon & core barrel.
	S.S. I-001	I-001 60%			
	2.5'				
	S.S. I-002	I-002 80%			
5'	5.0'				
	S.S. I-003	I-003 60%			
	7.5'				
	S.S. I-004	I-004 90%			
10'	10.0'				
	S.S. I-005	I-005 100%			
	12.5'				
	S.S. I-006	100%			
15'	15.0'			cw 2/10/10 27.5' 16-~~20~~ bgs- Gravel (G) 85% gvl, 15% Sand Gvl: Mix of basalt, SR-SA, Mp. Fragmented, Slightly muddy.	
	S.S. I-007	100%			
	17.5'				
	SS I-008	100%			
20'	20.0'				
	S.S. I-009	95%			
	22.1'				
	S.S. I-010	60%			
25'	24.6'	I-011 40%			TD=27.5' DTW = 19.23' bgs 2/9/10 TH
30'					

Reported By: Troy Stevens		Reviewed By: L.D. Walker	
Title: Geologist		Title: Geologist	
Signature: [signature]	Date: 2/8/10	Signature: [signature]	Date: 3/10/10

A-6003-642 (03/03)

LW 3/8/10

C7310

BOREHOLE LOG

217 LW 3/8/10

Page 1 of 1

Date: ~~2/5/10~~ 2/5/10 LW 3/10/10

Well ID: ~~C7310~~	Well Name: 199-N-~~207~~	Location: 15' NE of 199-N-~~206~~	
Project: 100-NR-2 171 wells		Reference Measuring Point: Ground Surface	

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0	S.S. I-001	20% recovery		0-16' bgs- Sandy Gravel (SG) 80% gvl, 20% Sand. Gvl: Predominantly basalt, R-SR, Cp (2cm avg). Sand: Predominantly Qtz, SR, MS-VCS.	Sonic w/ core barrel + Split spoon.
	2.5'				0-3' is reworked back-fill of jet injection pit.
	S.S. I-002	100%			
5'	5'				
	S.S. I-003	40%			
	7.5'				
	S.S. I-004	100%			
10'	10'				
	S.S. I-005	100%			
	12.5' 12' S.S. I-006	100%			
15'	14.5'			LW 3/10/10 26.7'	
	S.S. I-007	100%		16-~~27~~ bgs- Gravel (G) 85% gvl, 15% Sand Gvl: Non-basalt, SR, Cp-Vcp. Sand ↑ in basalt, pred. Qtz. SR, MS-CS.	
	17.0'				
	S.S. I-008	100%			
20'	19.5'				
	S.S. I-009	100%			
	22.0'				
	S.S. I-010	100%			
25'	24.5				
	S.S. I-011	100%			TD= 26.7' DTW = 19.22' bgs 2/8/10 TAS
	27.0'				
30'					

Reported By: Troy Stevens		Reviewed By: C.D. Walker	
Title: Geologist		Title: Geologist	
Signature:	Date: 2/5/10	Signature:	Date: 3/10/10

A-6003-642 (03/03)

Appendix C

Survey Data

SURVEY DATA REPORT				Request No. 102-178
Project No.	Title: NR-2 Jet Injection Boreholes C7700 -C7717 & Test Plot Locations			File No. 1NT14R26
Job No. PRC /CACN: 300108-CA10	Prepared By L.A. Henke	Date 1/13/10	Reviewer	Page 1 of 1

DESCRIPTION OF WORK	DISTRIBUTION	SDR	PLOT	DWG
1. Obtain coordinates and ground elevation of staked location of proposed boreholes C7700 thru C7717 and located corners of 10ft by 20ft area around each cluster as directed by field contact.	Survey File	OR		
	N.A. Bowles	1		
	A.C. Macke	1		
	B.P. Esparza	1		
Horizontal Coordinate System: WCS83S/91 (Meters)	D.J. Alexander	1		
Vertical Datum: NAVD88 (Meters)	C.S. Wright	1		
Equipment Used: Trimble GPS 5800 RTK				

SURVEY RESULTS AND COMMENTS

Borehole ID	Northing	Easting	Ground Elev.	Description
C7700	149820.27	571238.50	123.11	STAKE
C7701	149821.50	571237.38	123.07	STAKE
C7702	149822.62	571236.35	123.16	STAKE
C7703	149820.46	571239.92	123.16	STAKE
C7704	149821.75	571238.93	123.10	STAKE
C7705	149822.79	571237.85	123.11	STAKE
C7706	149827.49	571244.67	123.17	STAKE
C7707	149829.02	571245.20	123.15	STAKE
C7708	149830.50	571245.81	123.17	STAKE
C7709	149827.59	571246.21	123.17	STAKE
C7710	149829.28	571246.72	123.15	STAKE
C7711	149830.81	571247.35	123.19	STAKE
C7712	149837.77	571252.73	123.18	STAKE
C7713	149838.59	571251.63	123.05	STAKE
C7714	149839.64	571250.24	123.09	STAKE
C7715	149838.44	571253.92	123.21	STAKE
C7716	149839.25	571252.93	123.04	STAKE
C7717	149840.31	571251.55	123.06	STAKE
COR 1	149818.20	571239.00	123.13	SOUTH GRID
COR 2	149820.19	571241.30	123.20	SOUTH GRID
COR 3	149824.93	571237.41	123.18	SOUTH GRID
COR 4	149823.07	571235.12	123.18	SOUTH GRID
COR 5	149826.74	571243.51	123.19	CENTER GRID
COR 6	149825.73	571246.41	123.27	CENTER GRID
COR 7	149831.64	571248.51	123.26	CENTER GRID
COR 8	149832.40	571245.56	123.19	CENTER GRID
COR 9	149840.01	571248.54	123.15	NORTH GRID
COR 10	149842.02	571250.78	123.20	NORTH GRID
COR 11	149838.32	571255.47	123.26	NORTH GRID
COR 12	149836.01	571253.47	123.44	NORTH GRID

NOTE: This Survey was performed under the supervision of a Licensed Professional Land Surveyor registered in the State of Washington.

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Distribution

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