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11-AMCP-0085

FEB 17 2011

Ms. J. A. Hedges, Program Manager
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Dear Ms. Hedges:

JET INJECTION DESIGN OPTIMIZATION STUDY FOR 100-NR-2 GROUNDWATER OPERABLE UNIT, DOE/RL-2010-68, REVISION 0

This letter transmits the approved Jet Injection Design Optimization Study for 100-NR-2 Groundwater Operable Unit, DOE/RL-2010-68, Revision 0. The document was signed by the U.S. Department of Energy Richland Operations Office and the State of Washington Department of Ecology on January 4, 2011. This document presents a design optimization study for evaluating and further refining the use of jet injection to place apatite precursors at specific depths for establishing a vadose zone treatment in the 100-NR-2 Operable Unit.

If you have any questions, please contact me, or your staff may contact Briant Charboneau, of my staff, on (509) 373-6137.

Sincerely,

Richard A. Holten, Acting Assistant Manager
for the Central Plateau

AMCP:KMT

Attachment

cc: See Page 2

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DOE/RL-2010-68
Revision 0

Jet Injection Design Optimization Study for 100-NR-2 Groundwater Operable Unit

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

U.S. DEPARTMENT OF ENERGY

Richland Operations Office

P.O. Box 550
Richland, Washington 99352

Approved for Public Release;
Further Dissemination Unlimited

DOE/RL-2010-68
Revision 0

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

U.S. DEPARTMENT OF ENERGY

Richland Operations Office

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Approval Page

Title *Jet Injection Design Optimization Study for 100-NR-2 Groundwater Operable Unit*

Concurrence B.L. Charboneau

U.S. Department of Energy, Richland Operations Office

Signature Date 1-4-11

N.M. Menard

Washington State Department of Ecology

Signature Date 1-4-11

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Terms

ALARA	as low as reasonably achievable
amsl	above mean sea level
ARAR	applicable or relevant and appropriate requirement
bgs	below ground surface
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
DOE	U.S. Department of Energy
DOE-RL	DOE Richland Operations Office, also known as RL
DOS	design optimization study
DQA	data quality analysis
DQO	data quality objective
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERA	ecological risk assessment
HEIS	Hanford Environmental Information System
ITRD	Innovative Treatment and Remediation Demonstration
LWDFs	liquid waste disposal facilities
MNA	monitored natural attenuation
NEPA	*National Environmental Policy Act*
OU	operable unit
PNNL	Pacific Northwest National Laboratory
PP	proposed plan
PRB	permeable reactive barrier
QA	quality assurance
QC	quality control
RAO	remedial action objective
RI/FS	Remedial Investigation/Feasibility Study
ROD	record of decision
RUM	Ringold Formation upper mud

SAP	sampling and analysis plan
TAG	Technical Advisory Group
TD	total depth
Tri-Party Agreement	*Hanford Federal Facility Agreement and Consent Order*
TTP	Treatability Test Plan
UMM	Unit Managers Meeting

1 Introduction

This document presents a design optimization study (DOS) for evaluating and further refining the use of jet injection to place apatite precursors at specific depths for establishing a vadose zone treatment in the 100-NR-2 Operable Unit (OU). The 100-NR-2 OU is a groundwater OU and part of the 100-N area. Figure 1 shows the location of the 100-N area within the Hanford Site and the location of the Hanford Site within Washington State. The vadose zone treatment is designed to immobilize subsurface strontium-90 (Sr-90) in the vadose zone and minimize migration to groundwater and ultimately the Columbia River. This DOS describes the field trials developed to evaluate the jet injection method for the delivery and emplacement of pre-formed apatite and/or apatite-forming chemicals in the vadose zone. If successful, this study will result in the vertical extension of the existing apatite permeable reactive barrier (PRB) into the unsaturated vadose zone along the existing 91 m (300 ft) length and show beneficial results. Figure 2 shows the details of the existing saturated zone barrier, including the locations of monitoring wells and aquifer tubes used to monitor performance of the existing barrier.

This work is being performed under the *Interim Remedial Action Record of Decision for the 100-NR-1 and 100-NR-2 Operable Units* (EPA/ROD/R10-99/112) to fulfill the interim remedial action objective (RAO) of evaluating treatment technologies. This new DOS will further evaluate the PRB technology for use in the vadose zone, building on work completed under the original Treatability Test Plan (TTP), the *Strontium-90 Treatability Test Plan for 100-NR-2 Groundwater Operable Unit* (DOE/RL-2005-96), and the *Design Optimization Study for Apatite Permeable Reactive Barrier Extension for the 100-NR-2 Operable Unit* (DOE/RL-2010-29). The scope presented in this DOS was not included in the 2006 TTP.

1.1 Basis for the Design Optimization Study

Contamination of the 100-NR-2 OU with Sr-90 is a result of historical disposal of cooling water from the 100-N nuclear reactor. Efforts to reduce the flux of Sr-90 to the Columbia River from past practice liquid waste disposal sites have been underway since the early 1990s at 100-N. Termination of all liquid discharges to the ground by 1993 was a major step toward meeting this goal. However, Sr-90 adsorbed on aquifer and vadose zone sediments downgradient of the liquid waste disposal sites and extending to the near-shore riverbed remains a continuing source to groundwater and the Columbia River.

The Interim Remedial Action Record of Decision (ROD) for the 100-NR-1 and 100-NR-2 OUs, (EPA/ROD/R10-99/112) recognized the limitations of pump-and-treat technology for Sr-90 remediation by requiring that alternative treatment technologies be evaluated. The need for alternative technologies was affirmed in the first *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) five-year review (EPA, 2001, *US DOE Hanford Site First Five Year Review Report*). The review re-emphasized the need to pursue alternative remedial action technologies aggressively for the removal, mass reduction, and/or attenuation of Sr-90 from the 100-NR-2 aquifer sediments and to further reduce the net flux of Sr-90 to the river. Additionally, the *Hanford Site Groundwater Monitoring for Fiscal Year 2006* (PNNL-16346) recognized from the onset that groundwater pump-and-treat was unlikely to be an effective long-term treatment method because of the tendency of Sr-90 to remain primarily sorbed to the sediments. Subsequent monitoring of Sr-90 in the 100-N area has substantiated this determination.

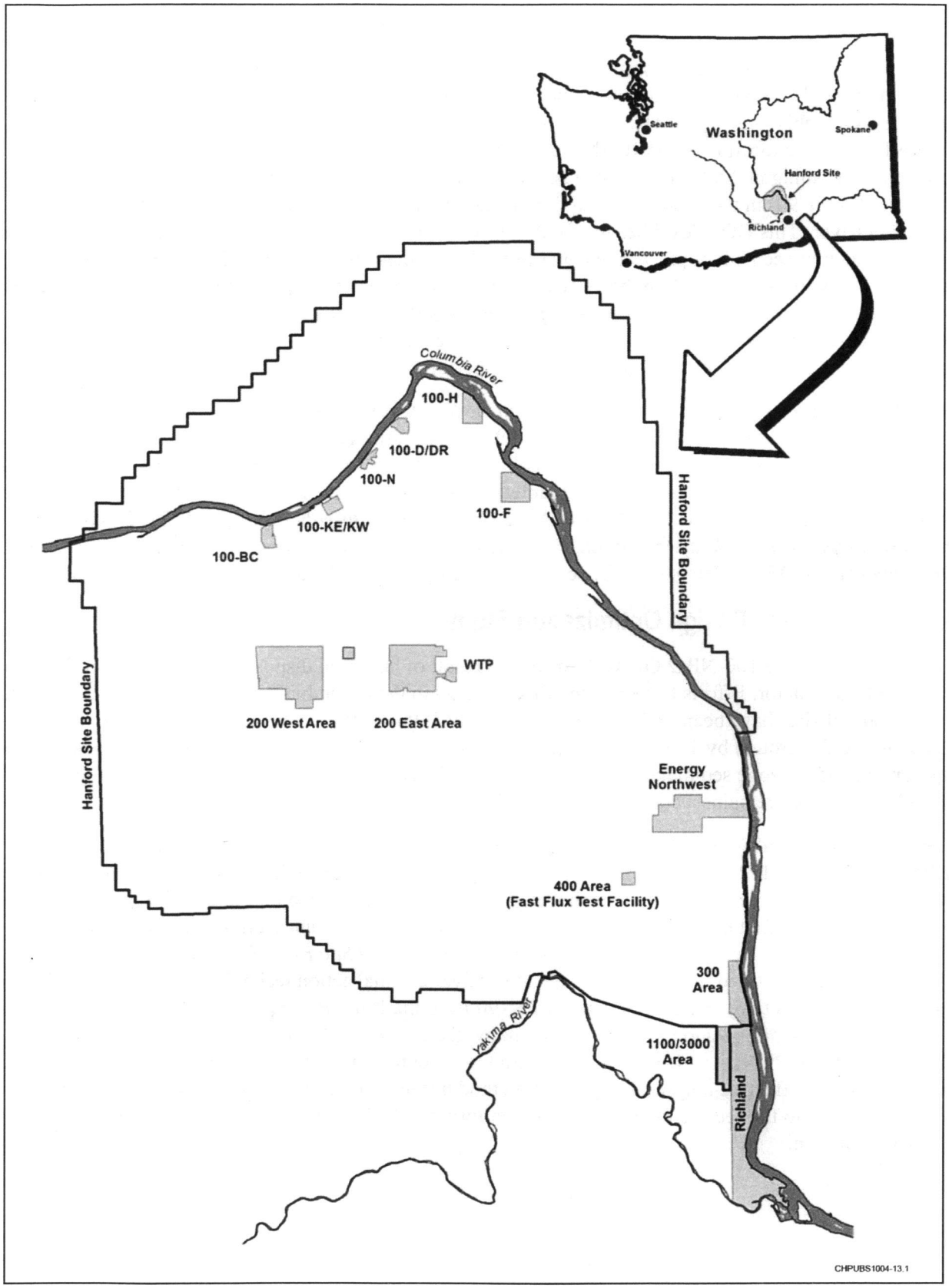


Figure 1. The Hanford Site and Washington State

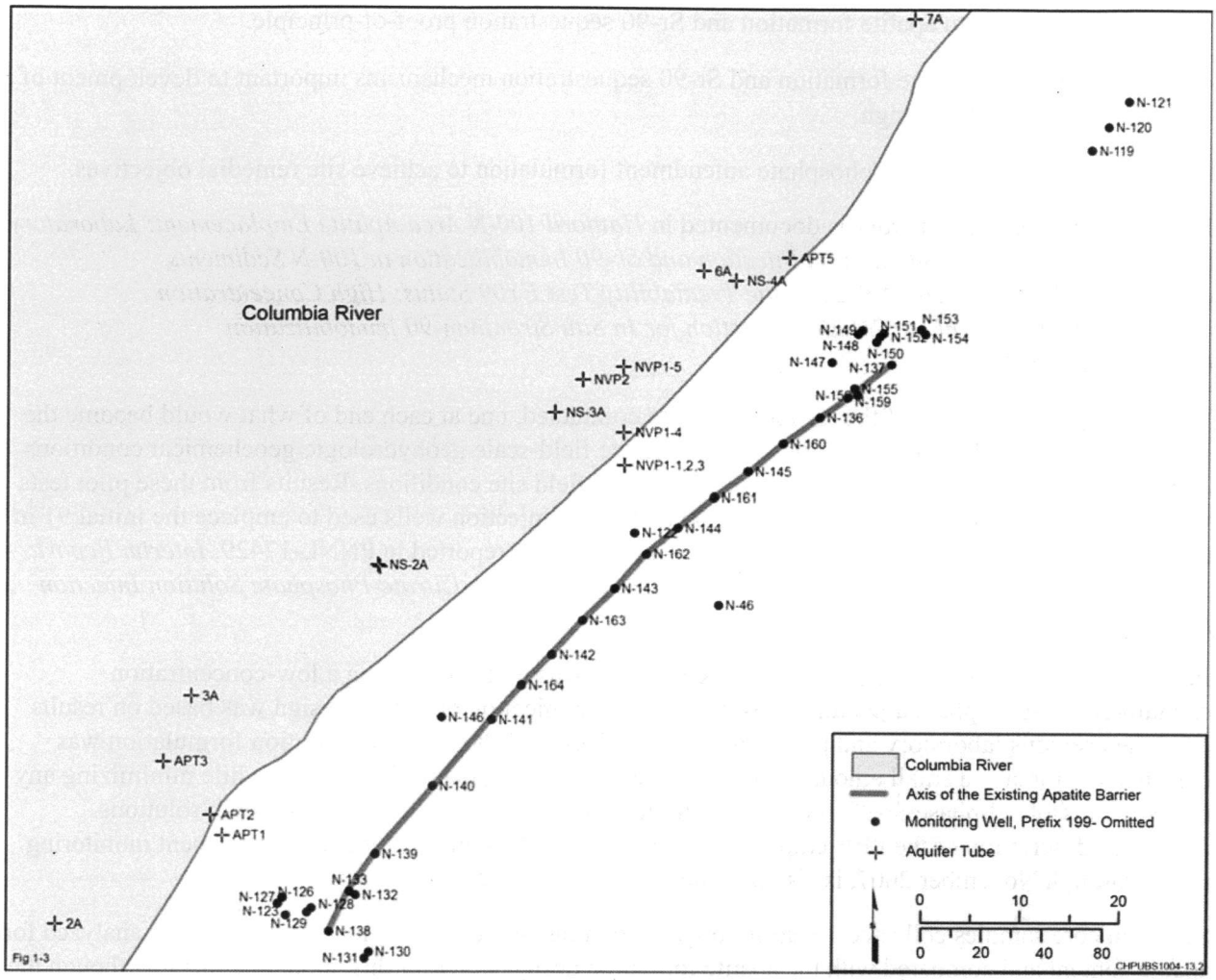


Figure 2. Location of Existing Apatite Permeable Reactive Barrier

Following an evaluation of potential Sr-90 treatment technologies and their applicability for the 100-NR-2 hydrogeologic conditions, the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the Washington State Department of Ecology (Ecology) agreed that the long-term strategy for groundwater remediation at 100-N should include strontium sequestration using apatite as the primary treatment technology (DOE/RL-2006-20, *The Second CERCLA Five-Year Review Report for the Hanford Site*). Apatite is a calcium phosphate mineral, which can sequester elements into its molecular structure via isomorphic substitution, as discussed further in Section 3.1. This agreement was based on results from an evaluation of remedial alternatives that identified the apatite PRB technology as the best approach for reducing Sr-90 flux to the Columbia River at a reasonable cost. As a result, aqueous injection (i.e., the introduction of apatite-forming chemicals into the subsurface through standard injection wells) was selected as the preferred technology for treatability testing. The generalized approach for developing an in situ remedial technology for the sequestration of Sr-90 in the saturated zone through the formation of calcium-phosphate mineral phases (i.e., apatite) was initially documented in the Sr-90 TTP for 100-NR-2 conducted in 2006 through 2008 (DOE/RL-2005-96).

1.2 Work Completed in Support of 2006 Treatability Test Plan

Laboratory-scale studies in support of DOE/RL-2005-96 were performed to:

- Demonstrate in situ apatite formation and Sr-90 sequestration proof-of-principle.
- Characterize the apatite formation and Sr-90 sequestration mechanisms important to development of a pilot field-scale test design.
- Optimize calcium-citrate-phosphate amendment formulation to achieve site remedial objectives.

Bench-scale development work is documented in *Hanford 100-N Area Apatite Emplacement: Laboratory Results of Ca-Citrate-PO4 Solution Injection and Sr-90 Immobilization in 100-N Sediments* (PNNL-16891), and 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).

Two pilot-scale field tests of the technology were conducted, one at each end of what would become the initial 91 m (300 ft) long PRB section, to characterize field-scale geohydrologic/geochemical conditions and assess the upscaling of laboratory results to actual field site conditions. Results from these pilot tests were used to refine the injection design for the remaining injection wells used to emplace the initial 91 m (300 ft) PRB section (Figure 1-2). These testing activities are reported in PNNL-17429, *Interim Report: 100-NR-2 Apatite Treatability Test: Low-Concentration Calcium-Citrate-Phosphate Solution Injection for In Situ Strontium-90 Immobilization.*

Initial treatment of the 91 m (300 ft) long PRB section was performed using a low-concentration calcium-citrate-phosphate amendment formulation. The injection operation design was based on results from the previous laboratory and pilot field-scale test results. The low-concentration formulation was designed to emplace a small amount of treatment capacity (i.e., apatite formation), while minimizing any release of dissolved-phase Sr-90 associated with injection of relatively high ionic strength solutions. A detailed description of the PRB emplacement operations, including performance assessment monitoring results through November 2007, is also provided in PNNL-17429.

Sediment core samples collected 1 year following the initial low-concentration treatments were analyzed for apatite content and compared with the apatite formation design target for this initial treatment. Although the apatite contents were small, they were sufficient to demonstrate that phosphate mineral phases had been formed. The overlap zone between adjacent wells received an average treatment of 110 percent of the targeted apatite content within the Hanford formation and 30 percent treatment within the Ringold Formation (PNNL-18303).

Preliminary results of the high-concentration injections were reported in an interim report (PNNL-SA-70033). In addition to amendment arrival responses observed in available Ringold Formation monitoring wells, the Ringold apatite content data support the decision to install Ringold-only injection wells that were utilized during subsequent high-concentration treatments. A preliminary evaluation based on sediment core samples was collected in November 2009, over a year after the high-concentration injections presented in *Hanford 100N Area In Situ Apatite and Phosphate Emplacement by Groundwater and Jet Injection: Geochemical and Physical Core Analysis* (PNNL, 2010 [PNNL-19524]). The results indicate that the phosphate precipitation was relatively uniform up to 4.8 m (15.7 ft) from the injection well. The sediment cores indicated an average treatment of 100 percent of the targeted apatite content within the Hanford formation and 50 percent treatment within the Ringold Formation.

A field-scale jet injection demonstration of phosphate, pre-formed apatite, and phosphate combined with pre-formed apatite was conducted in 2009. The injections were conducted on the upstream (west) end of the existing apatite PRB and maximum Sr-90 plume concentrations, but still within the Sr-90 plume area (greater than 80 pCi/L). The solutions were emplaced into the vadose zone and upper unconfined aquifer

using jet injection technology. Testing was done to evaluate the technology's ability to deliver material/chemicals into the vadose zone and evaluate the ability of jet injection to emplace a specified quantity of apatite. Preliminary results indicate that jet injection is a viable technology for emplacement of phosphate and pre-formed apatite in the vadose zone, with injected chemicals meeting the injection target goal within 1.2 m (4 ft) of the injection point. The results of the jet injection demonstration will be documented in a final test report scheduled for completion in fiscal year 2010. Preliminary results from jet injection demonstration are summarized in Section 5.1.

Based on the information and experience gained from performance of the work discussed previously (PNNL-19524, SGW-47062), enhancements have been identified to improve on the delivery and emplacement of pre-formed apatite and/or apatite-forming chemicals within the vadose zone to produce an effective PRB. This DOS has been prepared to aid in the deployment and evaluation of these enhancements to demonstrate the effectiveness of the jet injection method. This technology, if successful, could be implemented as a full remedial action under an amended Interim ROD or the ROD for the site. Implementation of this technology, if it proves successful, would meet the *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement) Milestone M-016-110-T03 (Ecology et al., 1989a). This Milestone requires reducing the Sr-90 concentration in the groundwater plume to achieve a concentration less than 8 pCi/L in the hyporheic zone and river water column by 2016.

2 Project Description

This DOS provides a detailed discussion of the installation of an apatite PRB in the vadose zone through jet injections. The jet injections would be placed over the existing PRB in the saturated zone and result in an overall minimum length of 91 m (300 ft) in the area shown in Figure 3.

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

Figure 3. Test Site Location Aerial Photo in 2003

A significant amount of Sr-90 (40 to 70 percent) is held in sediments along the Columbia River shoreline at 100-NR-2, which is in the periodically rewetted zone. The periodically rewetted zone is controlled by the seasonal and diurnal variability in the Columbia River stage (PNNL-16891) and is either saturated or unsaturated depending on the river stage. It is also likely that there is a higher concentration of Sr-90 in low-conductivity zones in this rewetted zone, due to less water flushing.

2.1 Background

The Hanford Site is located in southeastern Washington State near Richland, Washington. The 100 Area is located along the Columbia River and includes nine DOE nuclear reactors previously used for plutonium production, one of which is the 100-N Reactor. An overview of the Hanford Site is shown in Figure 1.

Operation of the 100-N nuclear reactor required the disposal of water from the reactor's primary bleed and feed cooling loop, the spent fuel storage basins, and other reactor-related sources. The bleed and feed system had water fed into it or bled out of it as necessary to maintain a constant pressure in the cooling loop. As water was bled out of the system, it was discharged to two crib and trench liquid waste disposal facilities (LWDFs). These LWDFs were constructed to receive these waste streams, and disposal consisted of percolation into the soil. Figure 4 shows the locations of these LWDFs in relation to the rest of 100-N and the Columbia River shoreline. The first LWDF (1301-N/116-N-1) was constructed in 1963, about 244 m (800 ft) from the river. Liquid discharges to this facility primarily contained radioactive fission and activation products, including Co-60, Cs-137, 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 Sr-90 was detected at the shoreline, a second LWDF (1325-N/116-N-3) was constructed farther inland in 1983. This led to termination of disposal at the first LWDF. Finally, discharges to the 1325-N LWDF ceased in 1991. All liquid discharges to the ground stopped in 1993.

The *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan, Addendum 5: 100-N Decision Unit* (DOE/RL-2008-46-ADD5, Draft A) presents a more complete history of the groundwater contamination at 100-N. In summary, because of wastewater disposal practices, soils beneath the LWDFs were contaminated from the surface sediments to the unconfined aquifer. A portion of the contaminants migrated to the Columbia River via groundwater. To address contamination in 100-N, it was divided into a source and a groundwater OU. The 100-NR-1 OU contains all the source waste sites located within the main industrial area around the 100-N Reactor and the Hanford Generating Plant, and includes the surface sediments and subsurface sediments associated with the LWDFs. Remedial activities are ongoing to address the contamination in this OU. The 100-NR-2 OU consists of sediment below historical high-groundwater levels and contaminated groundwater beneath the 100-NR-1 OU.

2.2 Site Hydrogeology

Stratigraphic units of significance in 100-N include the Ringold Formation and the Hanford formation. Figure 5 shows that the unconfined aquifer at 100-N near the shoreline is composed of gravels and sands of the Ringold Formation and Hanford formation. The Ringold Formation is composed of several lithologic facies including Ringold unit E, which primarily forms the unconfined aquifer beneath the Hanford formation, and the RUM, which forms the base of the unconfined aquifer and is believed to be an aquitard for unit E.

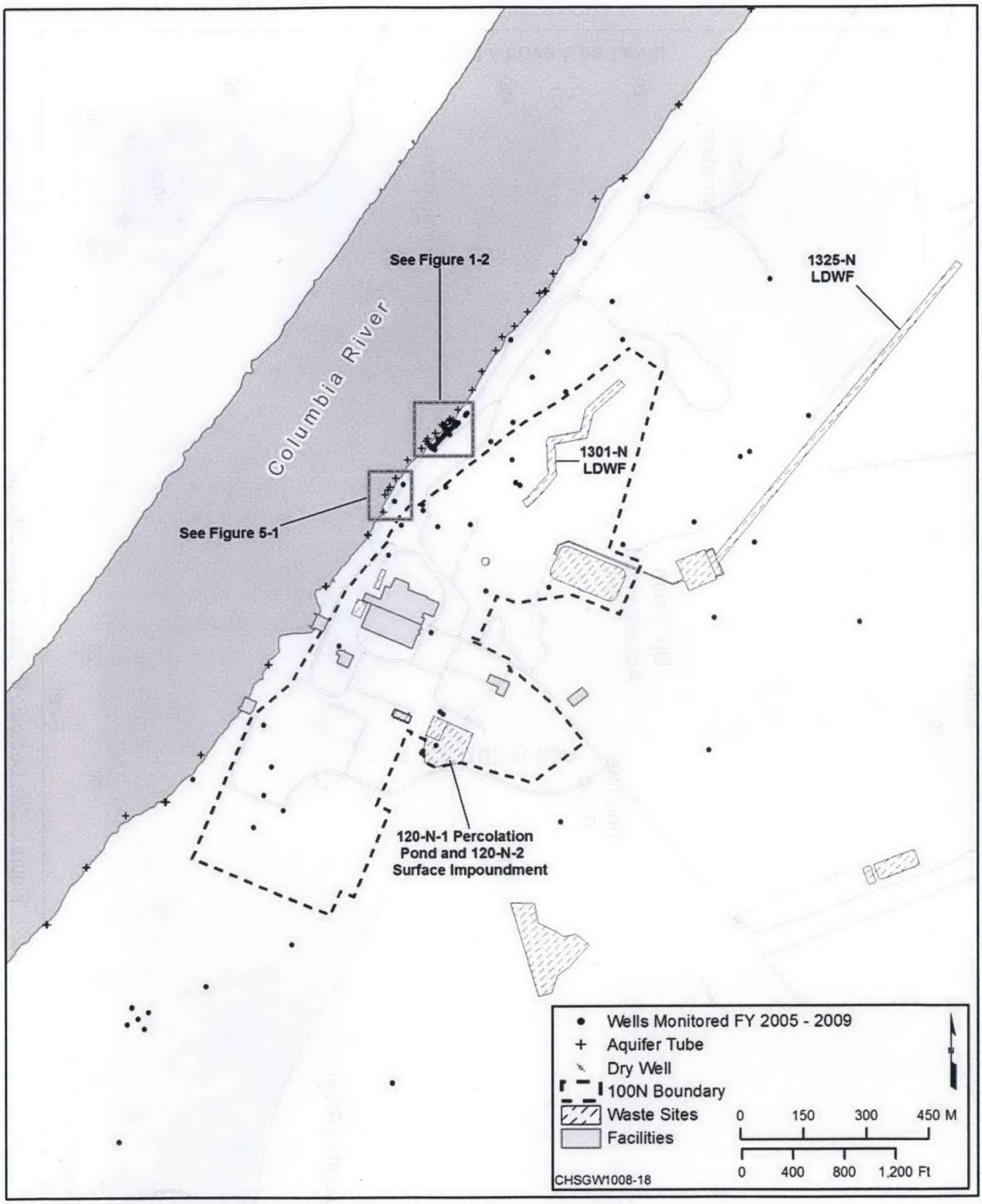


Figure 4. 100-N Area Groundwater Monitoring Wells

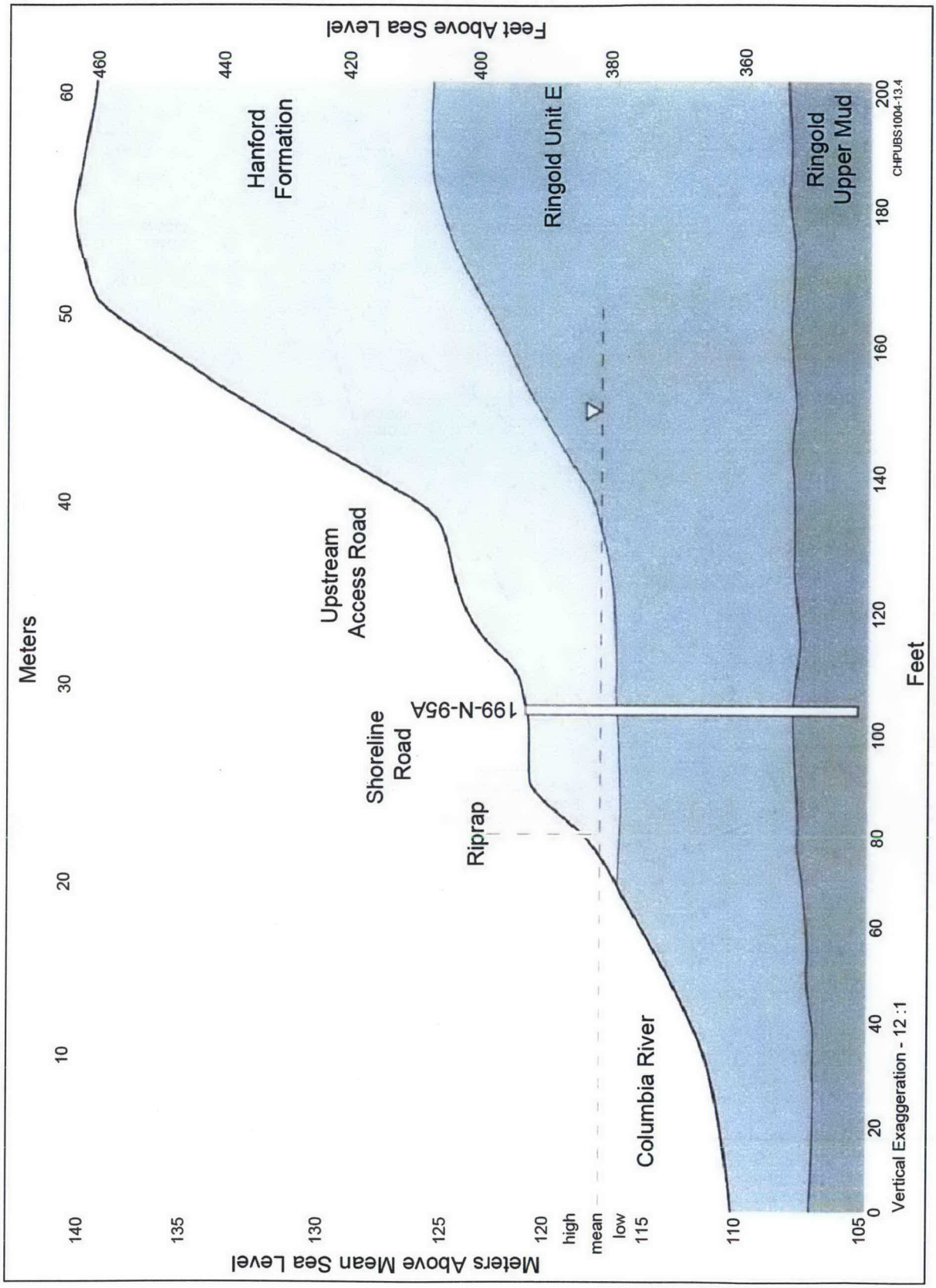


Figure 5. Site Geologic Model in Cross Section

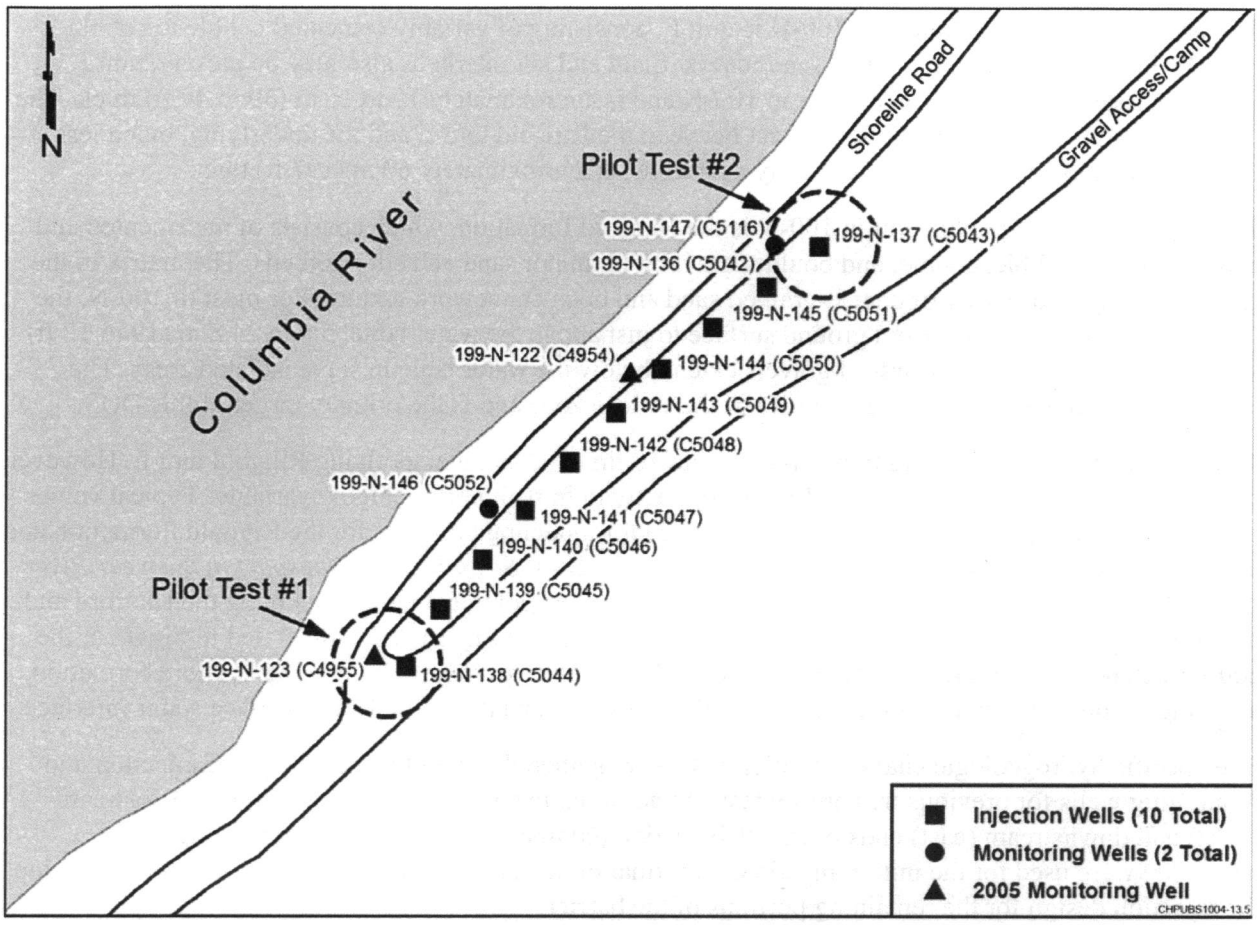
The uppermost Ringold stratum at 100-N is unit E, consisting of variably cemented pebble to cobble gravel with a fine- to coarse-grained sand matrix. Sand and silt interbeds also may be present. unit E primarily forms the unconfined aquifer in 100-N and is approximately 12 to 15 m (39 to 49 ft) thick. The base of the aquifer is situated at the contact between the Ringold unit E and the underlying, much less transmissive, silty strata referred to locally as the RUM, 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 open-framework texture. For most of 100-N, the Hanford formation extends from ground surface to just above the water table, 5.8 to 24.5 m (19 to 77 ft) in thickness. However, the Hanford gravels extend below the water table in some isolated areas. The Hanford formation comprises the majority of the vadose zone and is the primary target of this DOS.

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 15 and 182 m/d (19 and 597 ft/d) have been used for modeling purposes for the Ringold Formation and Hanford formation, respectively (HydroGeoLogic, Inc., 2001, *Strontium-90 Transport in the Near River Environment at the 100-N Area*). A cross section of the site geological model including the Hanford and upper Ringold units in the near river environment is depicted in Figure 5. As illustrated in Figure 5, the aquifer extends to the Columbia River channel and the high river stage rises into the Hanford formation, allowing groundwater in the aquifer to mix with river water and the groundwater/surface water interface.

Site-specific hydrogeologic characterization data were gathered during the installation of injection and monitoring wells for previous treatability tests. In addition, two pilot test sites located at the upstream (west) and downstream (east) ends of the PRB section (equipped with extensive monitoring well networks) were used for the initial injections. Information learned from these efforts was used to develop the injection design for the remaining portions of the barrier.

Figure 6 shows the locations of these pilot test sites in relation to the existing barrier. Comparison of test results from these two locations indicate that permeability contrast between the Hanford formation and Ringold Formation is significantly less over the upstream one-third of the barrier. The estimated hydraulic conductivity for the Hanford formation and Ringold Formation over the upstream portion of the barrier is 12 and 10 m/day (39 and 32 ft/day), respectively (PNNL-17429). By contrast, hydraulic conductivity for the Hanford formation and Ringold Formation over the downstream portion of the barrier was estimated at 29 and 9 m/day (95 and 29 ft/day), respectively. It should be noted that these hydraulic conductivity estimates for the Hanford formation are significantly lower than had previously been used in 100-N modeling studies (HydroGeoLogic, Inc., 2001). The decrease in estimated conductivity was the result of new site-specific characterization data including revised topography, geology, and material properties that were available for the Hanford formation.



Source: Adapted from PNNL-17429

Figure 6. Existing Apatite Permeable Reactive Barrier Treatment Area and Pilot Test Sites

Geologic characterization data collected during well installation were used to develop a detailed geologic cross section along the 100-N shoreline. Figure 7 shows the vertical Sr-90 profiles along this cross section. Figure 8 shows the vertical Sr-90 profiles through the existing PRB. 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, distinguishing between these units. Furthermore, the boundaries between these units are not always discrete, but instead often grade into one another because of the sediment reworking and mixing during deposition. Although the actual formation contact depths remain somewhat uncertain, the geologic cross sections depicted in Figures 7 and 8 represent the working model for the site.

Groundwater flows primarily in a north-northwesterly direction most of the year and discharges to the Columbia River, as shown in Figure 9. During periods of high river stage, river water flows primarily to the southeast into the aquifer, causing the water table to rise throughout 100-N. Near the LWDF 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 the diurnal (daily) and seasonal variability in the Columbia River stage.

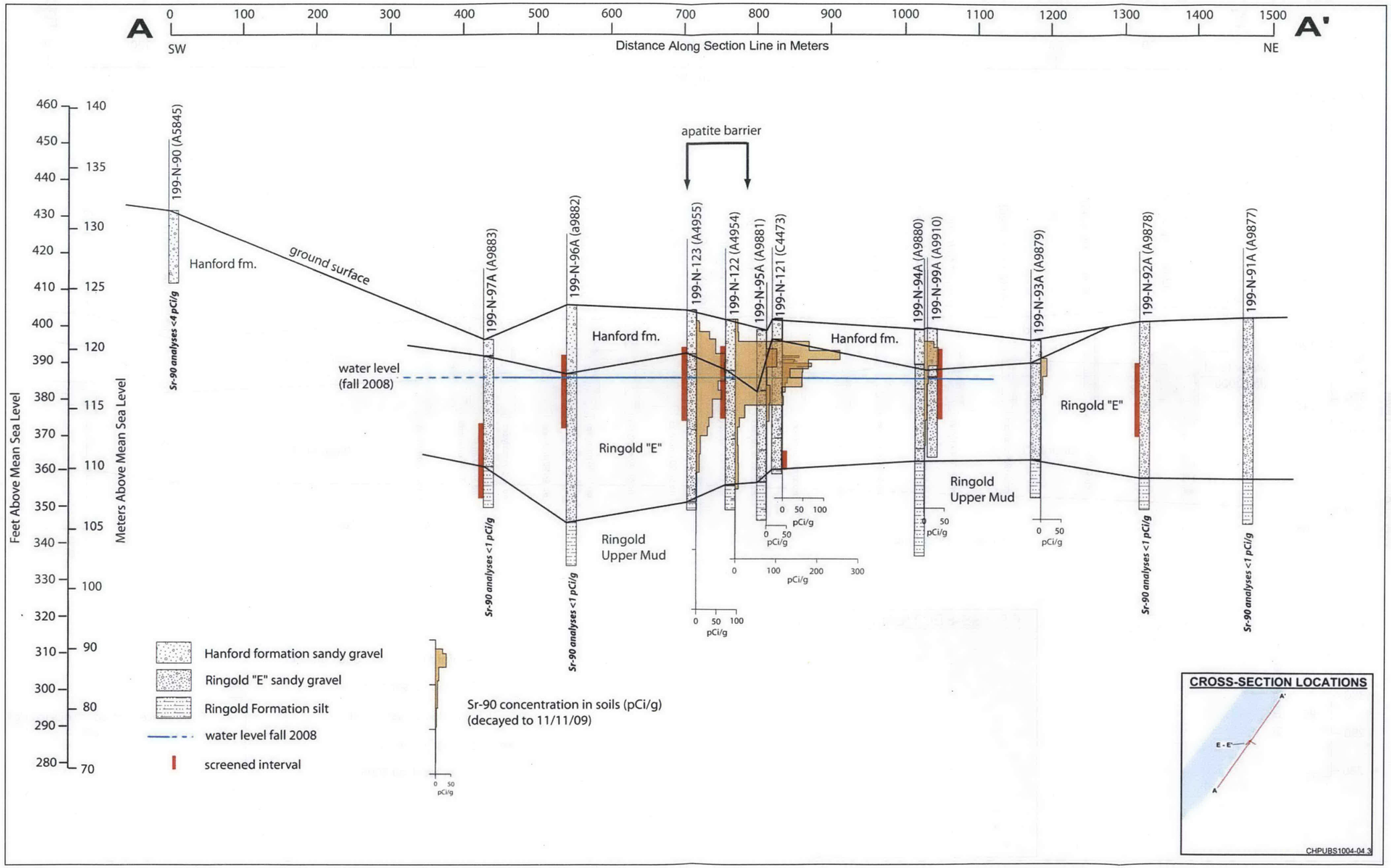


Figure 7. Geologic Cross Section with Vertical Strontium-90 Profiles

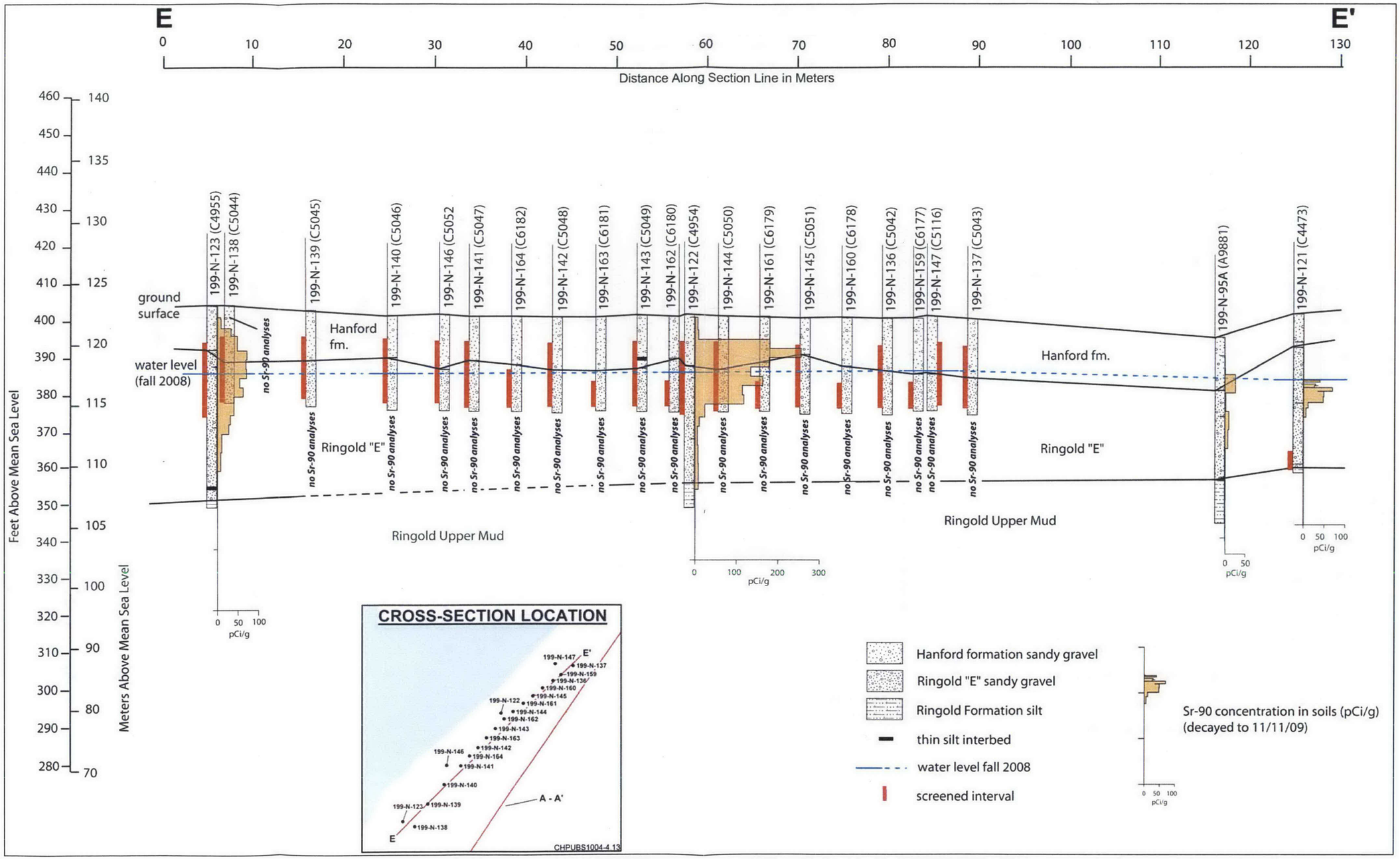


Figure 8. Geologic Cross Section through Existing Permeable Reactive Barrier with Vertical Strontium-90 Profiles

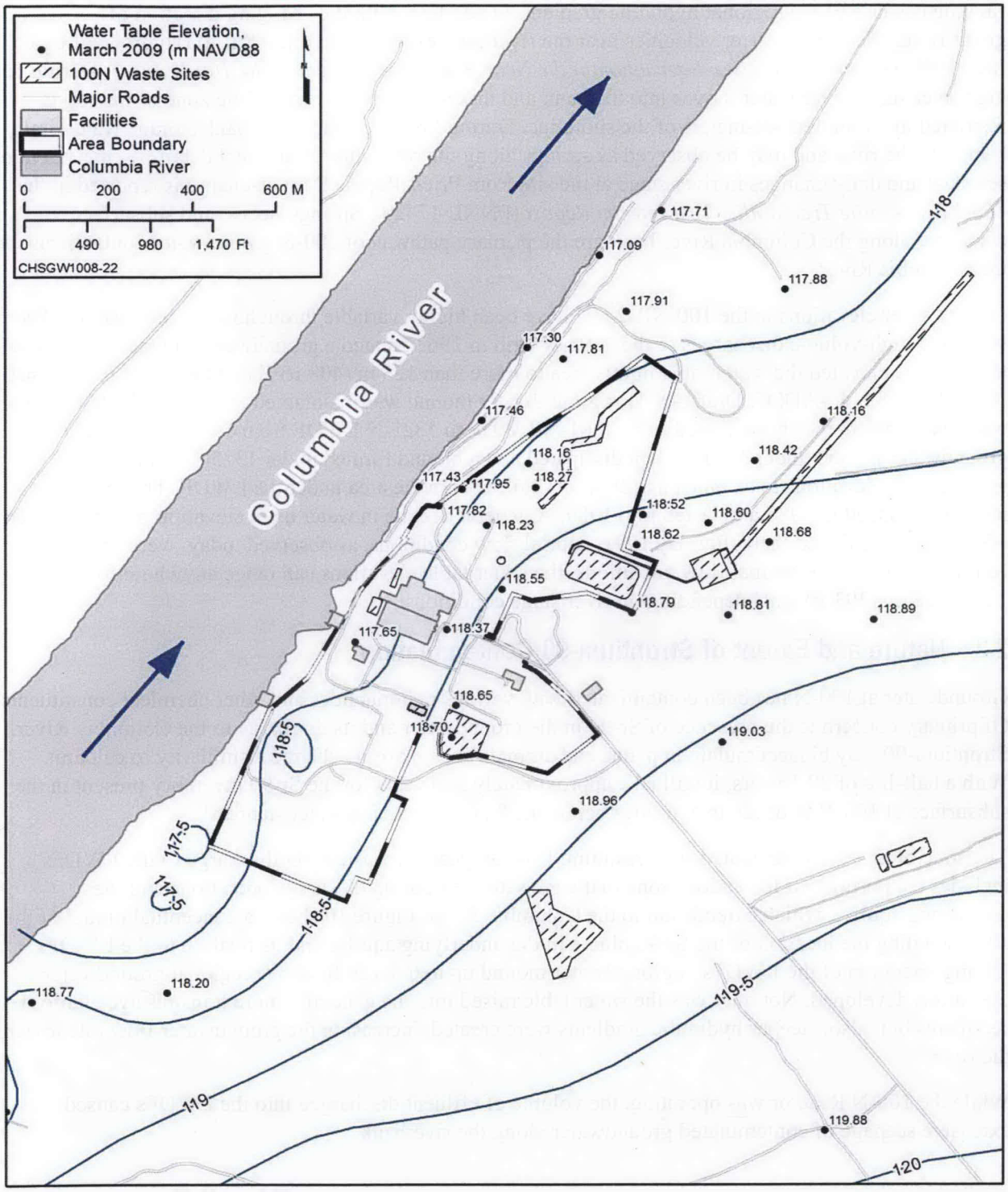


Figure 9. Groundwater Contour Map (March 2009)

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 a seasonal basis is an order of magnitude greater than groundwater

flowing because of the regional hydraulic gradient. In addition, with the changing direction of groundwater flow, pore water velocities near the river may exceed 10 m/d (32.8 ft/d) (HydroGeoLogic, Inc., 1999, *Groundwater-River Interaction in the Near River Environment at the 100-N Area*). During the 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 low river stage, this bank storage water drains back into the river and may be observed as springs along the riverbank. Additional details on the extent of seasonal and daily changes in river stage at the site from Priest Rapids Dam discharge is reported in the *100-NR-2 Apatite Treatability Test Interim Report* (PNNL-17429). Springs, seeps, and subsurface discharge along the Columbia River bank are the primary pathway of 100-N groundwater contaminants to the Columbia River.

Groundwater elevations in the 100-NR-2 OU have been highly variable throughout the site history. The startup of high-volume discharges to the 1301-N Crib in 1963 created a groundwater mound underneath the crib that elevated the water table in this area to more than 123 m (408 ft) above mean sea level (amsl) (DOE/RL-2008-46-ADD5, Draft A). This groundwater mound was maintained into the mid–1980s when wastewater discharges transitioned from 1301-N LWDF to 1325-N LWDF from 1983 to 1985. The groundwater mound under 1301-N then dissipated and a mound formed under 1325-N, which raised groundwater elevations to as much as 126 m (412 ft) amsl in the area under the LWDF. This mound was most pronounced in 1985 and lasted into 1989. A general decline in water table elevation began at the end of 1985 and continued thereafter. By 1991, natural flow conditions, as observed today, were essentially restored. Under these normal flow conditions, the water table elevations can range anywhere from 116 to 120 m (381 to 393 ft) amsl depending on river stage conditions.

2.3 Nature and Extent of Strontium-90 Contamination

Groundwater at 100-N has been contaminated with various radionuclides and other chemical constituents. Of primary concern is the presence of Sr-90 in the groundwater and its discharge to the Columbia River. Strontium-90 may bioaccumulate in plants and animals because of its chemical similarity to calcium. With a half-life of 29.1 years, it will take approximately 300 years for the Sr-90 inventory present in the subsurface at 100-N to decay to activities below the 8 pCi/L drinking water standard.

The zone of Sr-90-contaminated soils resulting from 30 years of wastewater discharge to the LWDFs includes the portions of the vadose zone that were saturated during discharge operations and the underlying aquifer, which extends out to the Columbia River. Figure 10 shows a conceptual model of the site, including the location of the Sr-90 plume in the underlying aquifer and its relation to the LWDFs. During operation of the LWDFs, a groundwater mound up to 6 m (20 ft) above regional groundwater elevations developed. Not only was the water table raised into the generally more transmissive Hanford sediments but, also, steeper hydraulic gradients were created, increasing the groundwater flow rate toward the river.

While the 100-N Reactor was operating, the volume of effluent discharged into the LWDFs caused extensive seepage of contaminated groundwater along the riverbank.

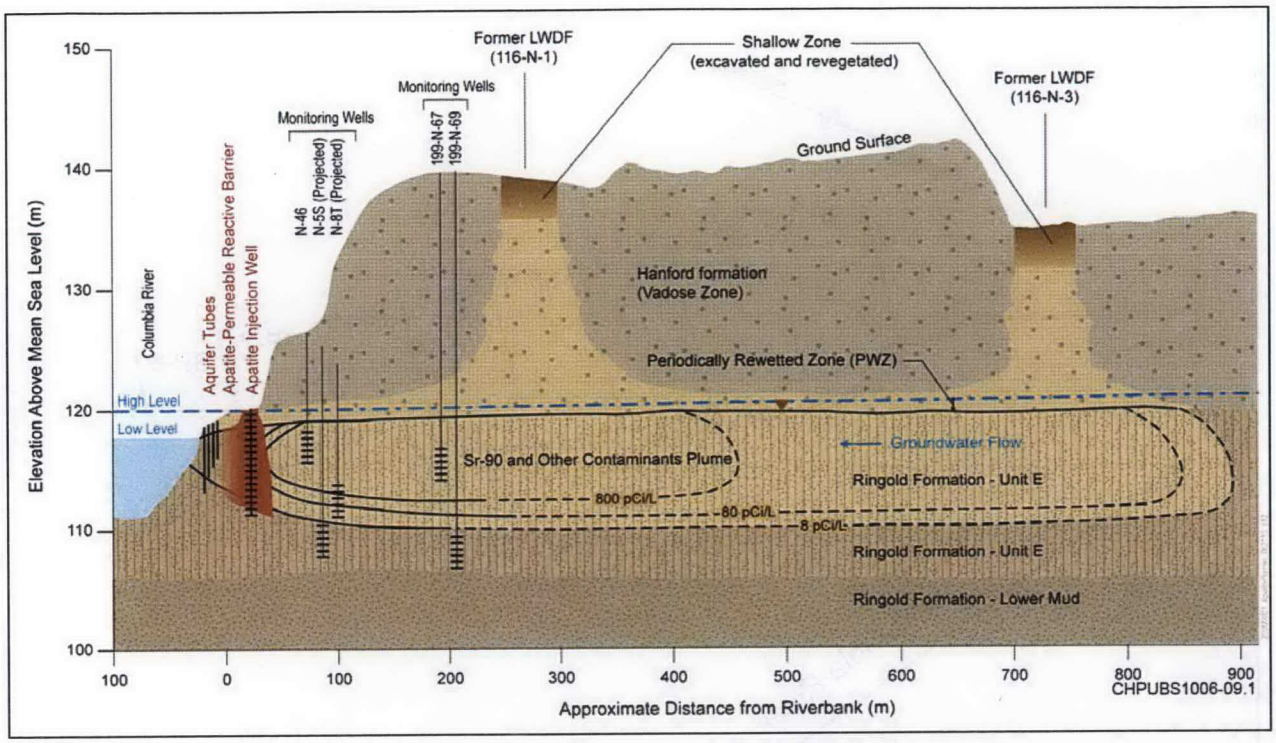
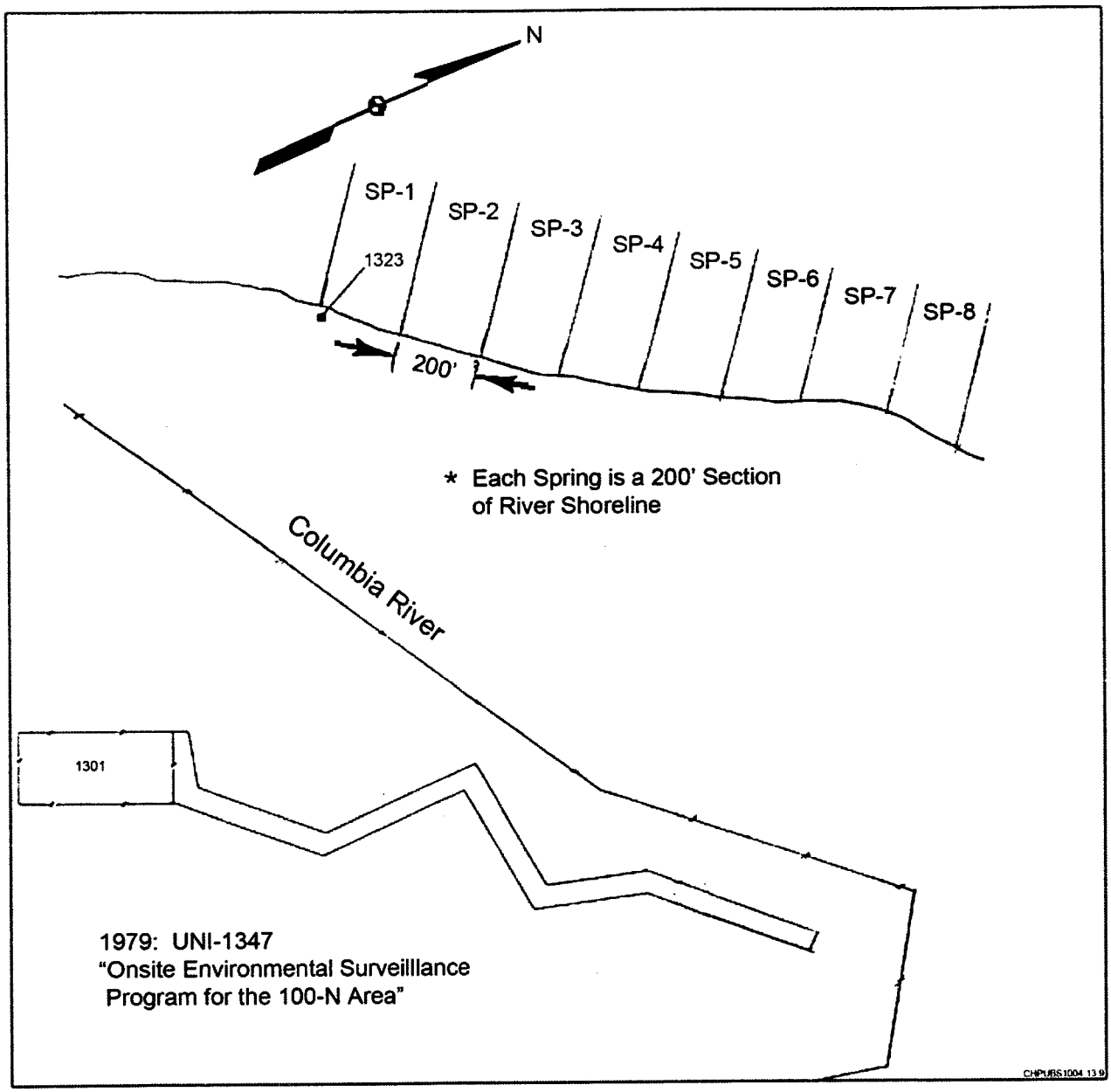


Figure 10. Conceptual Site Model for 100-NR-1/NR-2 Operable Units

Figure 11 shows the area of the riverbank that experienced seepage related to LWDF use, in relation to the location of LWDF 1301-N. Since that time, the number of springs and seeps has decreased in proportion to the decrease in artificial recharge caused by the wastewater disposal. The seepage contained high levels of radionuclides, which posed a risk to humans and aquatic biota. To mitigate the risk of radiological exposure, large basalt boulders were placed along the shoreline as riprap in 1984. Steel casings, referred to as "seep wells," were installed with the riprap to provide sampling access to the seepage. Figure 12 shows the location of these seep wells and the nearby seepage spots in relation to both LWDFs. The seep wells have been sampled annually in the past to satisfy near-field environmental monitoring requirements.

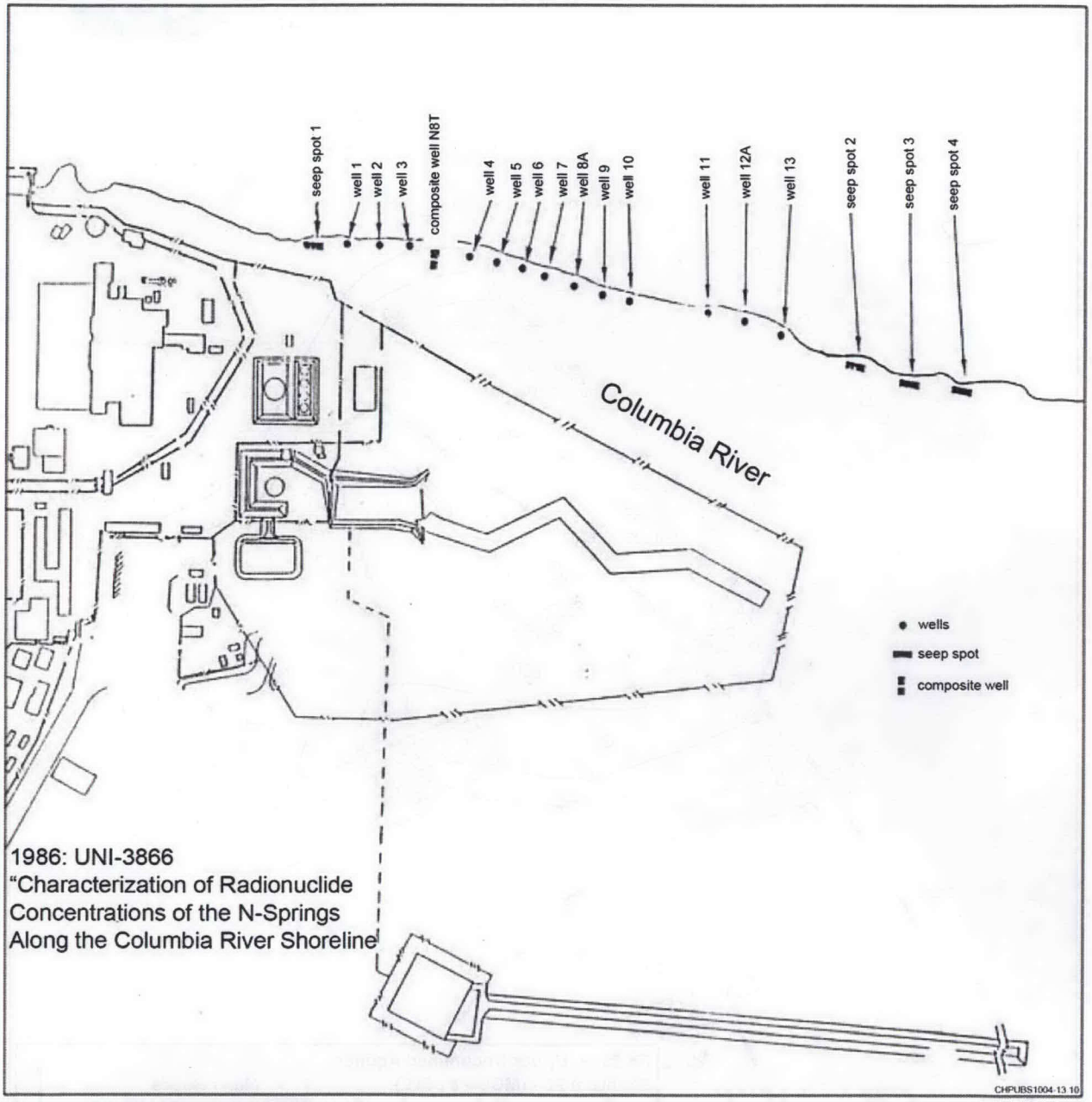
N-Springs data from 1985 to 1991 showed significantly higher concentrations of Sr-90 in seep wells NS-2, NS-3, and NS-4 (shown as Wells 2, 3, and 4 in Figure 12) compared to the adjacent springs upstream and downstream (BHI-00185, *Technical Reevaluation of the N-Springs Barrier Wall*). Well NS-3 and the neighboring monitoring wells (199-N-46 and 199-N-8T) have currently and historically shown the highest Sr-90 concentrations along the shoreline, with concentrations as high as 15,000 pCi/L observed at 199-N-46 in 2001 (TAG, 2001). Recent clam data collected for the ecological risk assessment (ERA) show that the highest concentrations of Sr-90 in clams were observed along approximately 91 m (300 ft) of riverbank that encompasses NS-1, NS-2, NS-3, and NS-4. The previous N-Springs data, recent aquifer tube data, groundwater data, and clam data (DOE/RL-2006-26, Rev. 0) all indicate that treating the 91 m (300 ft) of shoreline near 199-N-46 will address the highest concentration portion, if not the majority, of the near-shore Sr-90 contamination. The length of shoreline targeted by the existing PRB is between approximately NS-1 (Well 1) and NS-4 (Well 4).



Source: Adapted from UNI-1347, 1979, prior to seep well installation.

Figure 11. Areas of Riverbank Springs at 100-N During Operations

In 1995, the Sr-90 groundwater plume extended approximately 400 m (1,300 ft) along the river's length between the 1,000 pCi/L contours, and approximately 800 m (2,600 ft) between the 8 pCi/L (the drinking water standard) contours (HydroGeoLogic, Inc., 1999). An area of "preferential flow" was identified in BHI-00185 that encompasses 199-N-94, 199-N-95, and 199-N-46. The 199-N prefix for monitoring wells refers to a grid location (199) and reactor area (N). Because of an erosional feature in Ringold unit E, the Hanford formation dips below the water table at this location, forming a more transmissive flow path between the disposal crib and the Columbia River.



Source: Adapted from UNI-3866, 1986.

Figure 12. Locations of Seep Wells and Seepage Spots along the 100-N Shoreline

Wastewater appears to have concentrated along this route, resulting in higher concentrations in this area than would be predicted based on regional groundwater flow direction. Figure 13 shows the groundwater plume isoconcentration contours from 2009.

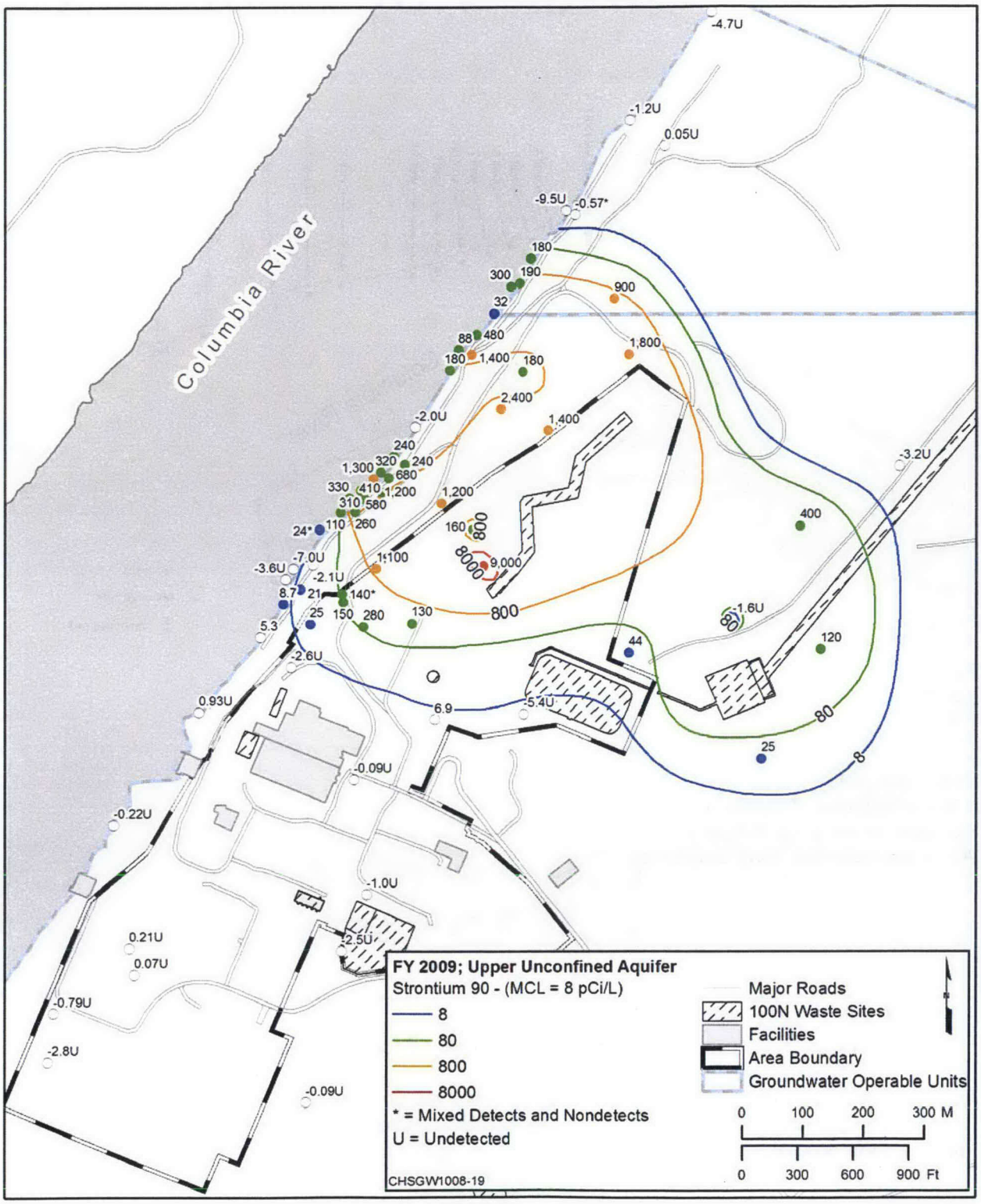


Figure 13. Strontium-90 in 100-N, 2009 Upper Part of Unconfined Aquifer, 2009

A 2003 pump-and-treat operations report indicated that the majority of the total Sr-90 inventory of 1,500 Ci remaining in the unsaturated and saturated zones in 100-N is present in the vadose zone above the aquifer (DOE/RL-2004-2, *Calendar Year 2003 Annual Summary Report for the 100-HR-3, 100-KR-4,*

and 100-NR-2 Operable Unit OU Pump & Treat Operations). An estimated 72 Ci of Sr-90 are contained in the saturated zone soils, approximately 0.8 Ci is in the groundwater, and 1,427 Ci are in the vadose zone. Data from soil borings collected along the riverbank indicate that Sr-90 concentrations in the soil reach a maximum concentration near the mean water table elevation and then decrease with depth (BHI-00185). This vertical contaminant distribution is also reflected in depth-discrete groundwater concentration data. Because Sr-90 has a much greater affinity for sediment than water (high distribution coefficient), its rate of transport in groundwater to the river is considerably slower than the actual groundwater flow rate. The relative velocity of Sr-90 to groundwater is approximately 1:100. Under current conditions, approximately 0.14 to 0.19 Ci are released to the Columbia River from 100-N annually (TAG, 2001).

The Sr-90 concentrations in groundwater along the Columbia River at 100-N show significant temporal variability based on measurements from aquifer tubes and compliance monitoring wells installed prior to the apatite treatability test. Additionally, as discussed previously, there is a general spatial trend in Sr-90 concentrations in the aquifer along the river. The highest concentrations exist over the central downstream portion of the 91 m (300 ft) long apatite PRB section and concentrations decrease from this high in both the upstream and downstream directions.

2.4 Remediation History

The following text discusses the remediation history studies to date.

2.4.1 National Priorities List/Corrective Measures Study

The 100-N area of the Hanford Site was placed on the National Priorities List in 1989 (40 CFR 300), the same year the Tri-Party Agreement was signed by DOE, EPA, and Ecology. In addition, the procedural framework and schedule for the remedial response actions at the Hanford Site was established (Ecology et al., 1989a). In 1994, the *Limited Field Investigation Report for the 100-NR-2 Operable Unit: Hanford Site, Richland, Washington* (DOE/RL-93-81) was published and, based on the data presented, a qualitative risk assessment was conducted. The qualitative risk assessment indicated that groundwater contaminants in the 100-NR-2 OU exceeded human health risk levels, prompting an expedited response action to address Sr-90 in groundwater. In 1995, a pump-and-treat system was installed as an interim measure to control the movement of Sr-90 to the Columbia River.

A corrective measures study, *Corrective Measures Study for the 100-NR-1 and 100-NR-2 Operable Units* (DOE/RL-95-111), conducted to support the selection of remedial alternatives to address contamination at the 100-NR-1 and 100-NR-2 OUs, determined that sufficient information was not available to decide a final groundwater remedy. Four alternatives were proposed for consideration as interim remedies (No Action, Institutional Controls, Hydraulic Controls, and Pump-and-Treat). Pump-and-treat was retained as the selected interim remedy because it was expected to provide a hydraulic barrier, while removing Sr-90 from extracted groundwater, and did not preclude any additional remedies.

The results from the corrective measures study and the Tri-Parties' preference for interim remedial action were summarized in the *Proposed Plan for Final Remedial Actions at the 100-NR-1 Source Sites Operable Unit and Interim Remedial Action at the 100-NR-2 Groundwater Operable Unit* (DOE/RL-96-102, Rev. 0). In September 1999, the Interim Action ROD for the 100-NR-2 OU (EPA/ROD/R10-99/112) was signed by DOE, Ecology, and EPA.

2.4.2 Expedited Response Action

In response to a regulatory Action Memorandum (Butler and Smith, 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, Ecology and EPA concurred with the DOE Richland Operations Office, also known as RL (DOE-RL) that installing the sheet pile wall could not be achieved in the manner specified due to the presence of numerous cobbles that caused the sheet pile to fold back upon itself during installation. EPA and Ecology 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 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.

2.4.3 Interim Action Record of Decision

The RAO specific to groundwater and surface water protection for the 100-NR-2 OU described in the Interim Action ROD included:

- Protect the Columbia River from adverse impacts from the 100-NR-2 groundwater so that designated beneficial uses of the Columbia River are maintained. Protect associated potential human and ecological receptors using the river from exposure to radioactive and nonradioactive contaminants present in the unconfined aquifer. Protection will be achieved by limiting exposure pathways, reducing, or removing contaminant sources, controlling groundwater movement, or reducing concentrations of contaminants in the unconfined aquifer.
- Protect the unconfined aquifer by implementing remedial actions that reduce concentrations of radioactive and nonradioactive contaminants present in the unconfined aquifer.
- Obtain information to evaluate technologies for Sr-90 removal and evaluate ecological receptor impacts from contaminated groundwater (by October 2004).
- Prevent destruction of sensitive wildlife habitat. Minimize the disruption of cultural resources and wildlife habitat in general and prevent adverse impacts to cultural resources and threatened or endangered species.

The following actions were taken to fulfill the requirements of the Interim Action ROD:

- The pump-and-treat system was operated continuously from 1995 to 2006, when it was placed in standby by Tri-Party Agreement change request M-16-06-01 approved by DOE, EPA, and Ecology (Ecology et al., 1989a). Groundwater monitoring has been conducted as approved by Ecology, and annual reports summarizing the monitoring data have been submitted each year since the beginning of operations in 1995.
- Under the Innovative Treatment and Remediation Demonstration (ITRD) Program, the Technical Advisory Group for 100-N completed a remedial options evaluation that included stabilization by phosphate injection (TAG, 2001) in November 2001.
- The *Strontium-90 at the Hanford Site and its Ecological Implications* (PNNL-13127) report was submitted to DOE in May 2000. This report presented an assessment of the potential for ecological impacts to salmon embryos.

- An ERA was conducted in accordance with an approved sampling and analysis plan (DOE/RL-2006-26, Rev. 0). A comment draft report was submitted to Ecology on October 31, 2005. The final draft was issued in 2009 (DOE/RL-2006-26, Rev. 1, Reissue).
- Fluor Hanford Inc./CH2M HILL submitted a letter report, *Evaluation of Strontium-90 Treatment Technologies for the 100-NR-2 Groundwater Operable Unit* (FH-0403540), to DOE in October 2004. This letter report and related public workshop comments (December 2004) and the ITRD Report contribute to the technology evaluation requirement specified in the Interim Action ROD.
- To field test a promising test treatment technology, a TTP was submitted to DOE in March 2006 (DOE/RL-2005-96). This TTP initiated implementation of an apatite PRB covering 91 m (300 ft) of the highest concentrations along the shoreline. In addition to the TTP, three separate addendums to the TTP have been submitted, each outlining additional testing to evaluate apatite emplacement methods or treatment areas. The first describes injection of a high-concentration aqueous solution to follow the initial low-concentration injection. Second is a plan for infiltration of aqueous solution into the vadose zone along the 100-N shoreline. The third investigates jet injection of various solutions.

2.4.4 Pump-and-Treat Performance

The pump-and-treat system at 100-N was installed in 1995. It 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 Ci of the total inventory 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). Although the pump-and-treat system may have met the objective of reducing the flow of groundwater (and non-adsorbing co-contaminants) in the Sr-90 plume area to the river, it did not meet the objective of reducing Sr-90 concentrations in aquifer pore fluid at the shoreline or in the stream bank storage zone. Based on the pump-and-treat system's limited effectiveness in removing Sr-90 from within these zones and the need for ambient conditions to test the PRB, the Tri-Parties agreed to place the system in a standby mode in March 2006 (M-16-06-01).

2.5 Evaluation of Strontium-90 Treatment Technologies

The following discussion describes the evaluation of the Sr-90 treatment technologies.

2.5.1 Innovative Treatment and Remediation Demonstration Report

As required by the Interim Action ROD, a comprehensive review of Sr-90 treatment technologies to complement the existing interim remedial actions was conducted by DOE. This review was commissioned under DOE's ITRD program and culminated with the *Hanford 100-N Area Remediation Options Evaluation Summary Report* (TAG, 2001). Based on the evaluation presented in this document, the Technical Advisory Group recommended that monitored natural attenuation (MNA), soil flushing, phytoremediation, stabilization by phosphate injection, 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.

2.5.2 Letter Report, 2004

The 2004 Letter Report evaluated the most promising treatment alternatives and proposed a path forward for selecting and testing alternatives (FH-0403540). Alternatives evaluated included PRBs, impermeable barriers, MNA, and phytoremediation. At that time, the final designed length of the barrier wall was assumed about 600 m (2,000 ft).

Four PRB technologies were considered: vertical hydrofracture, aqueous injection, air injection, and trenching. These technologies, with the exception of aqueous injection, emplace some form of mineral apatite into the subsurface to sequester Sr-90. In aqueous injection, apatite precursors are introduced as dissolved chemicals into the aquifer via injection wells, and apatite precipitates in a treatment zone surrounding the point of injection. Impermeable barriers reduce Sr-90 entering the river by increasing the groundwater flow path to allow time for the Sr-90 to decay. Barrier alternatives included a slurry wall installed via trenching and a bentonite grout curtain installed via hydrofracture. MNA allows for the natural decrease of Sr-90 concentrations over time, and phytoremediation uses plants to extract Sr-90 from the root zone on the riverbank.

One of the outcomes of the technology screening presented in the Letter Report was the decision that barrier walls constructed via trenching are not feasible along the shoreline. The letter report also reiterated the conclusion from the ITRD that MNA may be appropriate for portions of the plume far from the river, but will not limit current discharges of Sr-90 to the river (TAG, 2001). Phytoremediation was retained for consideration in conjunction with a barrier, but is not regarded as a stand-alone solution for the near-shore area.

The remaining technologies (aqueous injection PRB, air injection PRB, hydrofracture PRB, and hydrofracture grout curtain) were evaluated based on effectiveness, implementability, reduction of near-shore contamination, public acceptance, risk, and cost. Overall, these technologies compared closely; a single approach was not clearly identified. However, because aqueous injection has the potential to treat the sediments at the shoreline, the Letter Report recommended that it be the first technology to test in the field.

2.5.3 Treatability Test Plan, 2006

Following the presentation of the Letter Report (FH-040350), a TTP was written to address the path forward for field-testing of Sr-90 sequestration using apatite. Several methods were evaluated for emplacement, which include 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 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 located at the upstream and downstream ends of the barrier (Figure 6). The objectives of the pilot test phase were as follows:

- Determine if apatite will precipitate in the target zone.
- Determine if the apatite results in decreasing Sr-90 concentration in groundwater.
- Given a fixed spacing of 9 m (30 ft), determine the optimal injection volume per well for installation of a 91 m (300 ft) barrier wall.

The pilot testing and PRB emplacement were conducted in 2006 and 2007. The low-concentration injections were designed to stabilize the Sr-90 in the subsurface before a high-concentration injection. The low-concentration solution injected consisted primarily of calcium chloride, trisodium citrate, and sodium phosphate. Analyzing the results from the two pilot tests led to modifying the injection solution concentration, injection volumes, and operational parameters. The first pilot test was conducted in spring 2006 during high-river stage conditions. A second pilot test was conducted during low-river stage conditions. The associated location of the pilot test on the upstream or downstream end of the barrier,

well construction, and river stage during the injection were important parameters in determining the depth interval treated and the treatment efficiency.

Temporary increases in groundwater Sr-90 concentrations were expected because of the low-concentration injection. The observed increases were a result of injecting a solution of higher ionic strength than groundwater into the aquifer and increasing calcium concentrations, which causes some desorption of Sr-90 (and Sr^{2+}, Ca^{2+}, Mg^{2+}) from the sediment, as the majority of the Sr-90 mass is absorbed by ion exchange on sediment minerals. 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 2.5 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 lower calcium and citrate concentrations and an approximately four times increase in phosphate. A more complete summary of the low-concentration injection can be found in PNNL-17429.

The objectives of the original TTP were not fully met during the initial low-concentration injections. Injection of a high-concentration solution, which is addressed in Addendum 1 of that TTP, was required to meet the first two objectives of the TTP. The third objective of determining injection volumes for a fixed 9.1 m (30 ft) injection well spacing was met based on amendment arrival responses observed in neighboring wells.

2.5.3.1 Treatability Test Plan Addendum 1

Treatability Test Plan Addendum for 100-NR-2 Groundwater Operable Unit (DOE/RL-2005-96-ADD1), issued in April 2008, described the plan for conducting high-concentration injections of apatite-forming chemicals at the 100-N treatability test site. The pilot test sites used for the initial low-concentration injections were also used for the high-concentration apatite injection to assess the side effects of the process prior to continuing with the remaining barrier well injections.

The primary objective of the high-concentration injection 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 (PNNL-SA-70033). The phosphate concentration in the high-concentration injection solution (40 mM) was four times that of the low-concentration injection solution (10 mM) used for barrier emplacement in 2006 and 2007. The final high-concentration solution was determined in the laboratory prior to field implementation and documented in an injection-specific field test instruction.

Following the high-concentration injection, all of the objectives from the TTP (Section 2.5.3) were met. Apatite formation was confirmed in the target zone through collection of soil cores one year after the initial low-concentration injection. Reductions in Sr-90 concentrations in groundwater have been indicated by monitoring results following the low-concentration and high-concentration treatments. A treatment target of 90 percent reduction was observed at all four compliance monitoring wells (PNNL-SA-70033).

Injection well spacing of 9.1 m (30 ft) provides for overlap between adjacent injection wells of sufficient extent to form a continuous PRB. Injection volume requirements for this injection well spacing have been determined based on amendment arrival responses observed during the low-concentration calcium-citrate-phosphate injections (PNNL-17429) and the high-concentration injection (PNNL-SA-70033). In addition to the specified injection volumes, it was determined that, due to the difference in hydraulic conductivity in the Ringold Formation and Hanford formation, installation of injection wells targeting only the lower portion of the contaminated zone (Ringold Formation) was

needed to provide effective amendment coverage over the downstream section of the PRB. It was also determined that, in addition to the requirement that Hanford formation treatments be performed during the highest Columbia River-stage conditions (to treat the full saturated thickness), Ringold Formation-only injection wells should be treated during low Columbia River-stage conditions to achieve an acceptable radial extent of treatment.

2.5.3.2 Treatability Test Plan Addendum 2

Treatability Test Plan Addendum 2, issued January 2009, describes preliminary field-scale infiltration experiments near the apatite PRB. These tests do not build upon the jet injection technology but are included here for background information. The purpose of this test plan was to address strategies for infiltration of aqueous solution from near-ground surface into the vadose zone and the type of monitoring equipment that could be used to monitor the infiltration front. The use of infiltration reagents will help to treat the significant amount of Sr-90 mass that is in the sediments along the shoreline at 100-NR-2 in the vadose zone. Field testing of the wells installed in 2009 was completed in September 2010. Results of this study have not yet been published.

Previous evaluations (PNNL-18303) describe the potential for infiltrating water through the roadbed fill material. These studies have indicated that compaction of these materials may severely limit infiltration rates. In this test plan, the upper 1 m (3 ft) of roadbed would be excavated to increase infiltration. Laboratory experiments were conducted to determine whether the unsaturated Hanford formation is conducive to formation of apatite through surface application of reagents. Results indicate that infiltration rate, concentration of the calcium-citrate-phosphate solution, and addition of water after solution infiltration all affected apatite precipitation in the vadose zone. Rapid infiltration of calcium-citrate-phosphate solution resulted in apatite precipitation at greater depths, while decreasing the infiltration rate resulted in greater lateral spreading of the apatite precipitate. Infiltrating water into the vadose zone after the apatite precursor solution resulted in both improved depth of infiltration and lateral spreading of apatite precipitate. Increasing the injection concentration resulted in greater depths of apatite precipitation by decreasing the effects of phosphate adsorption onto sediment. These tests also showed that to precipitate adequate amounts of apatite, repeated cycles of infiltration with time between to allow for water drainage was necessary. The most effective method for emplacing apatite in low hydraulic conductivity soils involved repeated cycles of rapid infiltration of calcium-citrate-phosphate solution, followed by slow infiltration of water.

These laboratory tests showed that it is difficult to accurately emplace apatite in the vadose zone because of the infiltration rate control required. The jet injection method can emplace the apatite and be used to sequester Sr-90 in the subsurface. However, the most effective method found to date for emplacing apatite in high hydraulic conductivity regions was air/surfactant injection. During this injection method, the calcium-citrate-phosphate was present in foam.

2.5.3.3 Treatability Test Plan Addendum 3

Treatability Test Plan Addendum 3, issued in September 2009, described the plan for conducting a preliminary field-scale demonstration upstream of the current apatite PRB treatability test site. The demonstration was conducted to evaluate potential strategies for jet injection of three different media: a phosphate-only solution, pre-formed apatite, and the same phosphate solution with pre-formed apatite. The field-scale demonstration was conducted upstream of the existing apatite PRB.

The objective of the jet injection pilot-scale demonstration was twofold: (1) to evaluate the ability of the technology to deliver the different material/chemical solutions into the vadose zone and upper unconfined aquifer within three distinct treatment zones in the 100-N shoreline; and (2) to evaluate the ability of the

methods to install a PRB in the vadose zone containing a specific amount of apatite (4 mg apatite/g sediment).

Both objectives of Addendum 3 to the TTP were met. Jet injection technology was successfully used to emplace three different media in the vadose zone and upper unconfined aquifer. Collection and analysis of post-injection sediment cores enabled evaluation of apatite emplacement within the vertical sediment column. Apatite emplacement at concentrations equal to or greater than 4 mg apatite/g sediment was observed in the sediment cores in all three test plots (SGW-47062, Rev. 0).

2.5.4 Proposed Plan, 2010

Proposed Plan for Amendment of 100-NR-1/NR-2 Interim Action Record of Decision (DOE/RL-2009-54) has been drafted to propose an amendment to the Interim Action ROD for both OUs (EPA/ROD/R10-99/112). This proposed plan (PP) specifically addresses the use of aqueous apatite injection as a remedial alternative for treatment of the soil and groundwater in 100-N. The PP was based on agreement by DOE and Ecology (DOE/RL-2006-20), that the long-term strategy for groundwater Sr-90 remediation at 100-N should include apatite sequestration as the primary treatment technology to be tested (Tri-Party Agreement Milestone M-016-14B, Ecology et al., 1989a).

The proposed plan considered no action and four other alternatives, and evaluated them against the nine CERCLA criteria. The proposed alternatives included: (1) MNA with institutional controls, (2) resume pump-and-treat operations, (3) impermeable barrier, and (4) an apatite PRB. Based on existing information and the evaluation presented in the draft PP, Alternative 4 (apatite PRB) is identified as the proposed preferred alternative for Sr-90 interim remedial action at the 100-NR-1/NR-2 OU. If this PP is approved, the apatite PRB alternative may be implemented through an amendment to the Interim Action ROD for the 100-NR-2 OU.

2.5.5 Design Optimization Plan, 2010

A design optimization plan for the 100-NR-2 OU was drafted to outline the process for expanding the existing saturated zone PRB from 91 m (300 ft) to a total length of 274 m (900 ft) through aqueous injection of high-concentration calcium-citrate-phosphate solution. The objectives of the design optimization plan are to:

- Further refine application of the high-concentration calcium-citrate-phosphate solution over a larger scale
- Test the effectiveness of high-concentration calcium-citrate-phosphate injection in previously untested sediment to compare with areas that received sequential injections of low- then high-concentration calcium-citrate-phosphate injections
- Test the new well design installed under *100-NR-2 Groundwater Operable Unit Sr-90 Plume Rivershore Sampling and Analysis Plan* (DOE/RL-2009-32) to evaluate the adequacy of injection solution delivery to the target zone
- Test and optimize operation of the new injection system to verify that the system can deliver the designed injection solution flow volume at multiple well locations
- Evaluate if the new well design and injection system can complete chemical injections at various river stages, thereby eliminating the need for injections during specific river levels
- Evaluate that PRB can achieve up to 90 percent reduction in Sr-90 flux to the river

- Further test the impact the high-concentration calcium-citrate-phosphate solution has on the release of Sr-90 and other metals from previously untreated sediments to groundwater

Implementation of the optimization plan is planned for fall 2010.

3 Treatment Technology Description

This section describes the characteristics of apatite in general and the properties that make it amenable as a sequestering agent for Sr-90. It also provides a description of the different forms of apatite, the different injection solutions, and the mass of apatite needed in 100-N.

3.1 General Characteristics of Apatite

Apatite characteristics are described in PNNL-17429 as:

> *Apatite [$Ca_{10}(PO_4)_6(OH)_2$] is a natural calcium phosphate mineral that occurs 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, where elements of similar physical and chemical characteristics replace calcium, phosphate, or hydroxide in the hexagonal crystal structure (Hughes et al. 1989; Spence and Shi 2005). Because of the extensive substitution into the general apatite structure, more than 350 apatite minerals have been identified (Moelo et al., 2000). Apatite minerals are stable with very low solubility in pH neutral to alkaline water (Tofe, 1998; Wright, 1990; 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). A low value of K_{sp} indicates that the solid material has a low solubility. Strontiapatite, $Sr_{10}(PO_4)_6(OH)_2$, which is formed by the complete substitution of calcium by strontium (or Sr-90), has a K_{sp} of about 10^{-51}, another 10^7 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 14 shows cationic and anionic substitutions that commonly occur in the apatite structure.

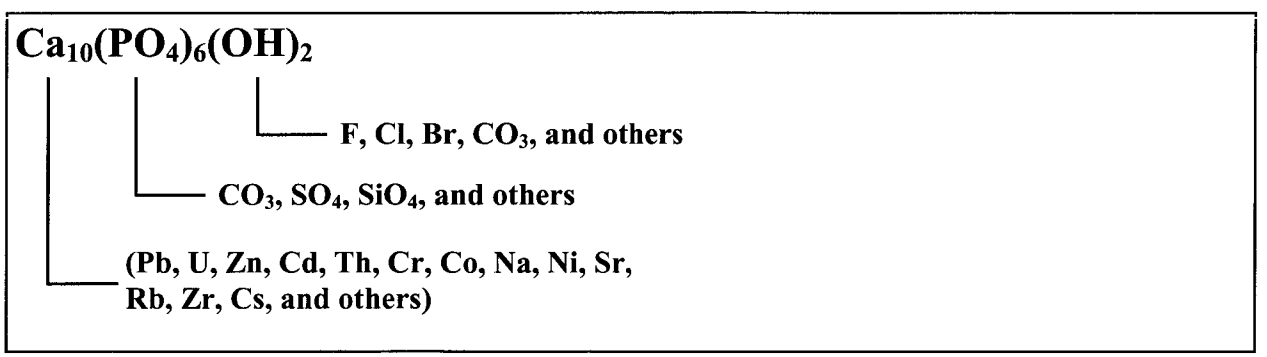


Figure 14. Cationic and Anionic Substitution in Apatite

Apatite 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 (time scale of days), adsorption to the apatite surface (adsorption of Sr-90 to apatite is about 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 ppm. 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.

Stable strontium and other competing cations in groundwater, especially the divalent transition metals (e.g., cadmium, zinc, iron, lead, manganese, etc.), can also be incorporated in the apatite structure. The average concentrations of stable strontium and competing cations present in groundwater will dictate the mass of apatite needed for long-term sequestration. Recent experiments measuring strontium incorporation in apatite from a solution containing only calcium and strontium, as compared to a solution containing calcium and strontium in groundwater (containing all transition metals), found no difference in the strontium uptake mass (PNNL-16891). The effect of competing cation concentrations is to reduce the in situ apatite longevity for a given mass loading. To achieve a desired longevity (e.g., a 300-year period during which most of the Sr-90 will have decayed), loading must be increased to account for the competing cation effect.

3.2 Apatite Placement in the Subsurface

Because pre-formed apatite exists as solid particles, it is difficult to displace laterally from an injection point in the subsurface to any significant distance. The surrounding soil tends to filter and block the particles from propagating outward. High-energy emplacement techniques exist to essentially force the particles outward by displacing the surrounding media (e.g., hydrofracturing and jet injection). These high-energy techniques can also be used for injection of apatite precursors to form apatite through in situ precipitation of aqueous reactants and to inject solid form apatite as a slurry. Jet injection relies on high pressure to mix the injection solution with the sediment around the injection point to the desired radius.

Three different formulations for aqueous injection in the saturated zone have been considered at the 100-NR-2 OU. These were high-concentration, low-concentration, and phosphate only. Jet injection pilot testing in the vadose zone has been performed using phosphate, pre-formed apatite, and phosphate combined with pre-formed apatite. The selected approach to be evaluated in this DOS for injection in the vadose zone is phosphate solution with pre-formed apatite. This approach was selected to emplace the maximum amount of apatite in the vadose zone for sequestration of Sr-90.

The specific steps of the jet injection of a phosphate and pre-formed apatite solution and the resulting processes that lead to sequestration and attenuation of Sr-90 are as follows:

- Injection of phosphate solution during drilling phase
- Injection of pre-formed apatite with the phosphate solution as a carrier fluid
- Precipitation of additional apatite from the phosphate solution, potentially using the pre-formed apatite as a seed crystal to initiate precipitation
- Adsorption of Sr-90 by the apatite surface (new Sr-90 migrating into the treated zone from upgradient sources resulting from fluctuations in river stage)
- Apatite recrystallization with Sr-90 substitution for calcium (permanent)

- Radioactive decay of sequestered Sr-90 to Y-90 to Zr-90 in apatite

Emplacement of pre-formed apatite in the vadose zone through jet injection has some significant advantages over other apatite emplacement technologies for application at the Hanford 100-N area. The major advantage is that pre-formed apatite can immediately begin incorporating Sr-90 into the apatite structure. Unlike aqueous injection, jet injection does not require the installation of wells to complete injections. Also during drilling of pilot holes for the jet injection, a solution containing phosphate can be used during drilling to suspend the pre-formed apatite in a slurry. Although each emplacement methodology has advantages and disadvantages, jet injection technology was selected because it is believed to provide the most economic emplacement methodology in the near-shore vadose zone sediments.

3.3 Mass of Apatite Needed for Hanford 100-N Area

Two factors control the amount of apatite needed to sequester Sr-90 in the Hanford 100-N area. First, from a mass balance standpoint, a specific amount of apatite is needed that will remove sufficient total inventories of strontium and Sr-90 from groundwater over the next 300 years. Based on an initial maximum Sr-90 concentration of 8,000 pCi/L in 2009 (Figure 13), and a half-life of 29.1 years, it will take 10 half-lives of decay before the river is fully protected.

Figure 15 shows the Sr-90 decay from this initial concentration of 8,000 pCi/L. The apatite mass calculation depends on the crystal substitution of strontium for calcium in apatite. If 10 percent substitution is assumed, then 1.7 mg of apatite per gram of sediment is sufficient to sequester strontium and Sr-90 from the estimated pore volumes of water that will flow through an apatite-laden zone. This calculation assumes an average groundwater flow rate of 0.3 m/day (1 ft/day) and a 10 m (32 ft) apatite PRB thickness (PNNL-18303). The 1.7 mg apatite/g sediment would occupy 13.6 percent of the pore space, so some degree of permeability decrease would be expected.

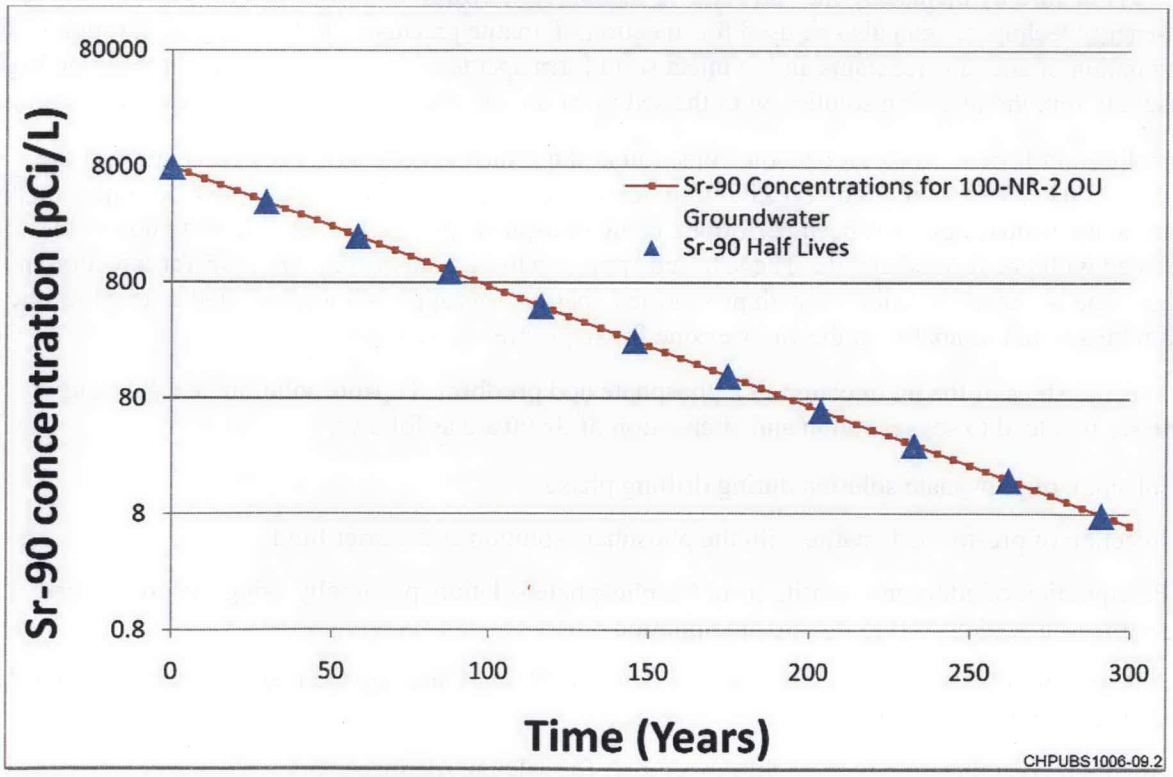


Figure 15. Sr-90 Decay at 100-NR-2

The second factor that controls the amount of apatite needed to sequester Sr-90 is the rate of incorporation. This PRB concept, which relies on emplacement of apatite in the aquifer, is viable only if the natural groundwater flux rate of strontium and Sr-90 (1.36×10^{-6} mmol strontium/day/cm^2) is slower than the removal rate of strontium and Sr-90 by apatite. If the groundwater flow rate is too high, even highly sorbing Sr and Sr-90 could advect through the apatite-laden zone more quickly than it is removed. This issue can be circumvented by adding more apatite than needed based on the mass balance calculation. Experiments indicate that at an apatite content of 1.7 mg apatite/g of sediment, Sr-90 would be incorporated into apatite more rapidly than the average groundwater flow rate and most high-flow events. The target apatite content of 1.7 mg apatite/g of sediment corresponds to a pore volume amendment concentration, on a molar basis, of 90 mM of phosphate precipitated in sediment with no retardation.

3.4 Phosphate Injection Formula

The dynamics of injecting an aqueous solution of high ionic strength into a Sr-90-contaminated aquifer near the Columbia River involves consideration of multiple objectives. First, sufficient mass of phosphate is needed to be emplaced in the aquifer to sequester Sr-90 for 300 years, as defined by both mass balance (incorporation of Sr-90 into apatite) and Sr-90 flux rate considerations. Second, any solution injected into the aquifer that is of higher ionic strength than groundwater will cause some desorption of Sr-90 (and Sr^{2+}, Ca^{2+}, Mg^{2+}) from the sediment, as 99 percent of the Sr-90 mass is absorbed by ion exchange on sediment minerals (PNNL-17429). The ion exchange process is further complicated not only by the ionic strength of the injecting solution, but also by the concentration of the monovalent and divalent ions in the solution, as well as the total volume injected.

A solution containing only phosphate has been investigated in some laboratory experiments and in a jet injection pilot study. The injection of phosphate was found to be effective to a concentration of 25 to 35 mM, with the utilization of adsorbed calcium on sediment. Higher phosphate concentrations would require additional calcium to precipitate and form apatite. However, the additional calcium can be encountered as the aqueous phosphate plume drifts downgradient into additional aquifer sediment, possibly resulting in increased apatite formation between the injection point and the shoreline.

Similar to the jet injection pilot study, the phosphate solution will consist of a combination of phosphoric acid and sodium hydroxide in specific proportions for a final pH of 7.5. The phosphate solution will be prepared such that a resulting mixture of 85 percent disodium hydrogenphosphate (Na_2HPO_4) and 15 percent sodium dihydrogenphosphate (NaH_2PO_4) is produced. The total aqueous concentration of phosphate will be approximately 40 mM. This phosphate solution will also be used in drilling of the jet injection pilot holes.

Results from the jet injection pilot testing showed that use of a 100 mM phosphate formula resulted in an average apatite content of 3.7 mg apatite/g of sediment. At this concentration, phosphate from the pilot jet injections was not observed in the aquifer tube samples following the injections, which indicates that the phosphate was precipitating in the near-shore sediment before discharging to the river. However, the relatively higher ionic strength of the 100 mM phosphate solution compared to the high-concentration calcium-citrate-phosphate formulation (at 40 mM phosphate) used for the saturated zone aqueous injections, may potentially result in increased initial Sr-90 mobilization. This mobilized Sr-90 may be intercepted by the existing apatite barrier in the saturated zone, but its ability to do so is currently unknown. Therefore, by reducing the concentration of phosphate from 100 to 40 mM, the potential for Sr-90 mobilization will be reduced. The total amount of apatite formed in the subsurface should be the same if the injection volume is increased proportionally.

3.5 Pre-Formed Apatite

The pre-formed apatite utilized in the jet injection pilot test consisted of fishbone apatite (Apatite II®). Because this product consists of dried and powdered fishbone, it contains up to 50 percent organic material. The organic material present in the raw fishbone does not contribute to the permanent sequestration of Sr-90. It can also serve as a readily available carbon source for microbial growth, resulting in foul odors and prolific microbial growth. Because of these concerns, calcined apatite products (including fishbone and cowbone) are being considered for use in this DOS. Because the calcined products are thermally treated at high temperatures, the organics are removed prior to injection, leaving a product containing a higher percentage of apatite per unit mass. A cost/benefit analysis is currently being conducted, and the selected form of apatite will be specified in the jet injection test instructions.

4 Test Objectives

This DOS is intended to fulfill the interim RAO of evaluating treatment technologies and to evaluate the PRB technology. It builds on work completed under the original TTP (DOE/RL-2005-96) in order to demonstrate the effectiveness of this technology prior to incorporation in an amended Interim ROD or ROD. Approval and successful implementation of this DOS will result in the vertical extension of the existing apatite PRB in the vadose zone over the existing 91 m (300 ft) length, extending treatment over the entire vertical profile of Sr-90 contamination where the bulk of the Sr-90 contamination resides. The PRB is designed to prevent subsurface Sr-90 migration into the Columbia River. This DOS describes the methods developed for the delivery and emplacement of apatite minerals in the vadose zone of the near-shore area in the 100-NR 2 OU. Implementation will be accomplished through jet injections of a phosphate solution and possibly pre-formed solid apatite. The study will further refine implementation of jet injection of phosphoric materials in the vadose zone over a larger scale considering existing features (road, wells, etc.) in the targeted area.

The objectives of this optimization study are as follows:

- Achieve at least 3.4 mg apatite per gram of sediment emplacement in the vadose zone as a result of the jet injections.
  - This will be demonstrated through sediment core sampling as described in Section 7.5 of this DOS.
- Evaluate if apatite emplacement in the vadose zone can achieve reduction of Sr-90 release to the river during high water events.
  - The effectiveness will be demonstrated through long-term monitoring of wells and aquifer tubes as explained in Sections 7.3 and 7.4 of this DOS and comparison to historical monitoring data.
- Evaluate the ability of combined saturated zone and vadose zone PRB to achieve up to 90 percent reduction in Sr-90 flux to the river.
  - This will be demonstrated through groundwater and aquifer tube sampling as described in Sections 7.3 and 7.4 of this DOS.
- Further study the impact the phosphate jet injections in the vadose zone have on the release of Sr-90 and other metals from previously untreated sediments to groundwater and the river.

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- This will be demonstrated through groundwater and aquifer tube sampling as described in Sections 7.3 and 7.4 of this DOS.

The ability of this optimization study to meet these objectives will be established based on continued monitoring of groundwater and aquifer tubes and comparison to pre- and post-emplacement conditions in addition to sediment core samples collected as described in Chapter 7. Since all vadose zone jet injections will take place directly above the existing saturated zone PRB, post-injection monitoring will be reflective of the combined vadose and saturated zone PRB. Elevated metals and Sr-90 concentrations resulting from jet injections in the vadose zone may be mitigated as the injected water subsequently flows through the existing PRB in the saturated zone. A minimum of three sediment core samples will be collected at least three months, but no more than one year, after the jet injections to determine the nature and extent of apatite-forming phosphate and pre-formed apatite in the vadose and saturated zones within the PRB.

5 Experimental Design

This section provides an overview of the results of pilot-scale jet injection testing and a general description of the field-test design and methods to be used in emplacing apatite in the vadose zone via jet injections resulting from the pilot-scale test.

5.1 Jet Injection Pilot-Scale Test

As discussed in Sections 1.1 and 2.5.3.3, a pilot scale jet injection test was performed in 2009 using three separate apatite or apatite-precursor amendments. One test plot was injected with phosphate solution, the second with pre-formed fishbone, and the third with both pre-formed fishbone apatite and phosphate solution (Figure 16).

5.1.1 Injection Materials

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 was prepared such that a resulting mixture of 85 percent disodium hydrogenphosphate (Na_2HPO_4) and 15 percent sodium dihydrogenphosphate (NaH_2PO_4) was produced. The total aqueous concentration of phosphate did not exceed 100 mM.

Raw apatite material composed of powdered fishbone was used for the pre-formed apatite injections. 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 ground fishbone apatite material blended with 1,000 L (265 gal) of potable water trucked onsite by the same contractor that supplied the phosphate solution.

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.

5.1.2 Injections

In each of the three test plots, a containment trench was constructed prior to jet injection. Excavated soil was used to create a berm around each trench to contain any drilling spoils or injection fluids that may have risen to the surface. 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 to 5.2 to 7.6 m (17 to 25 ft) bgs using a rotary external wash drilling method.

The phosphate injection solution was used as the external wash in the phosphate-only and combination test plots as the boreholes were advanced. The pre-formed apatite slurry was not used in the external wash 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. In the case of the phosphate-only and combination test plots, this 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 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.

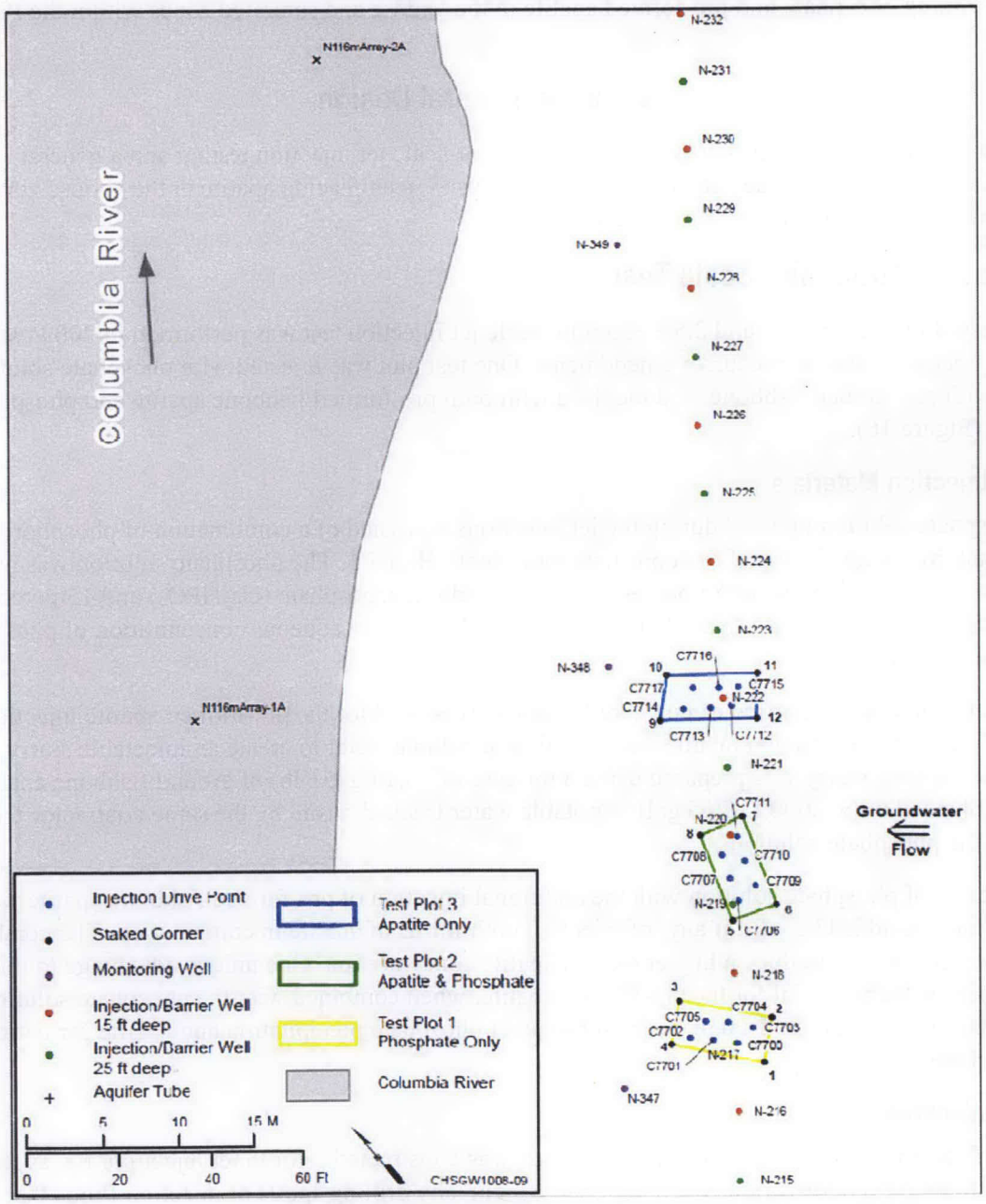


Figure 16. 2009 Jet Injection Pilot Test Plots

Aquifer tube samples and sediment cores were collected after the jet injection to monitor injection performance. Aquifer tube samples were also collected prior to the injections to establish baseline conditions.

5.1.3 Results

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 per gram of sediment). In each of the test areas, apatite concentrations met or exceeded these values in all cases but one. Some vertical variability in phosphate concentrations was observed, 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.

As shown in Figure 16, two aquifer tubes (N116m-1A and -2A) are located downgradient and cross-gradient of the jet injection test plots. Of these two aquifer tubes, N116m-1A is the most reflective of downgradient conditions. The aquifer tube data do show an increase in Sr-90 of approximately 30 percent in N116m-1A four weeks after completion of jet injections. However, 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 N116m-2A show that after three months, the concentrations remained higher than the concentrations measured one week after injections. However, the concentration of Sr-90 observed after three months at N116m-2A was within the range observed since 2006.

Full results of the Jet Injection Demonstration are documented in SGW-47062, Rev. 0.

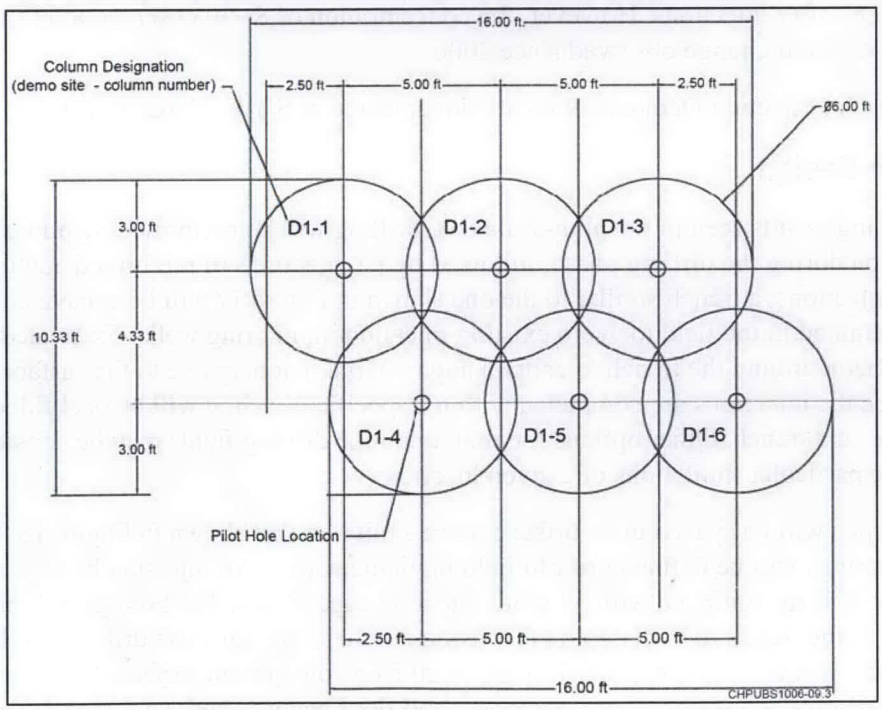
5.2 Injection Design

Based on promising results seen in the pilot-scale test, drilling will be performed by introducing phosphate solution during the drilling phase, followed by jet injections of preformed apatite. Prior to drilling and jet injections, a trench similar to the one shown in Figure 17 will be excavated. The trench size will be determined in the field to avoid existing injection/monitoring wells. Excavated soil will be used to create a berm around the trench to contain any material that may rise to the surface during drilling or injection. Once the injections are completed within a specific trench, it will be backfilled before moving on to the next trench. Other options for containing the drilling fluids may be considered depending on the particular limitations of a given location.

Jet-injection borings will be spaced in an offset pattern similar to that shown in Figure 18. Specific layout of jet injection borings will be defined prior to field implementation. All injection borings will be drilled using a hydraulic drill rig equipped with jet grout injection capabilities. The borings will be advanced from the bottom of the trench to total depth (TD) using a rotary external wash drilling method. The target TD for each boring will extend to 4.6 to 6.1 m (15 to 20 ft) below ground surface; however, the actual TD of each boring will vary depending on the geologic conditions encountered. Different drilling methods, such as water hammer, may be implemented as necessary.

The phosphate injection solution will be introduced as the boreholes are advanced. This will increase the amount of solution placed in the borehole and provide additional treatment further from the injection point. An advantage of using jet injection to deliver materials is that the emplacement can be conducted independent of river stage, although water table elevation should be considered during the development of the injection plan.

Figure 17. Photo of Trench at Jet Injection Pilot Test Plots

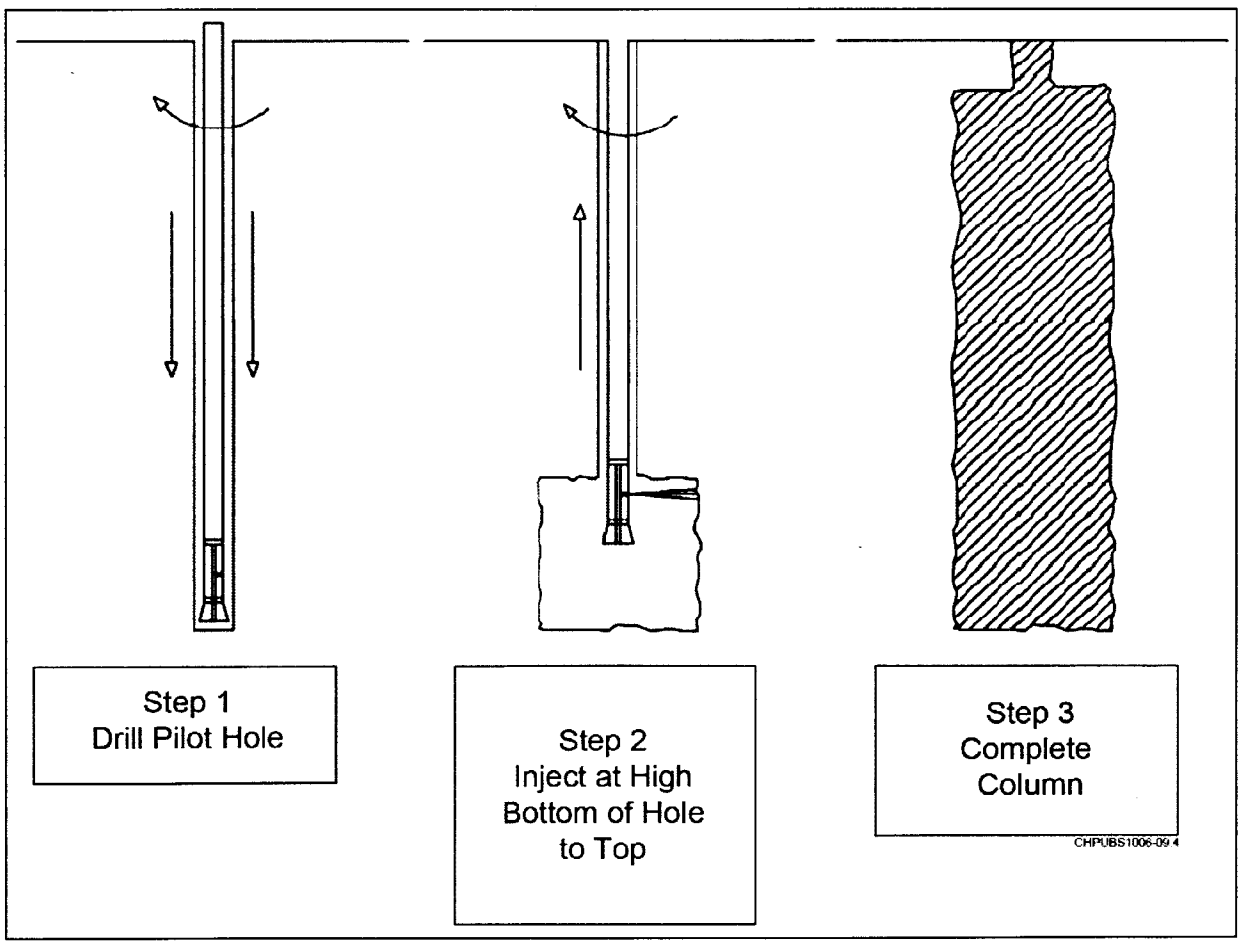


Source: Adapted from Nicholson, 2010.

Figure 18. Typical Jet Injection Layout

Jet injections will be performed using a jet injection system capable of injecting the solutions at pressures up to 400 bars (5,800 psi). This high-pressure injection will mix the soil with the injection solution to a minimum radial distance of 1 m (3 ft) from the injection nozzle (Figure 19).

The exact locations, number of injections, and the amount of phosphate and pre-formed apatite will be stated in the jet injection field instructions. However, approximately 180 injections will be needed and approximately 1,390,320 L (367,300 gallons) of phosphate solution and apatite will be used. However, the exact amount of material injected will depend on the conditions encountered in the field by the jet injection subcontractor and the capacity of the formation to receive the material. Based on observations during the emplacement of the existing saturated zone PRB, the estimated hydraulic conductivity for the Hanford formation over the upstream portion of the barrier is approximately 12 m/day (39 ft/day). The estimated hydraulic conductivity for the Hanford formation over the downstream portion of the barrier is approximately 29 m/day (95 ft/day). However, it should be noted that these estimates should be used as a rough guideline only, as significant variability in hydraulic conductivity is likely to be observed across the 91 m (300 ft) area of injections.



Source: From Nicholson, 2010.

Figure 19. Typical Jet Injection Process

5.2.1 Quality Assurance/Quality Control

Quality Assurance surveillance will be conducted during the jet injection design optimization effort, similar to that conducted during the previous jet injection activity. The surveillance will examine the

cleaning of down-hole equipment, driller qualification, drilling and injection method, borehole configuration, documentation for the injected chemicals, and daily reports.

6 Equipment and Materials

This section describes of the site utilities, monitoring equipment, analytical equipment, injection equipment, and the integration of these components into the operational systems required to conduct the vadose zone apatite PRB injection at the 100-NR-2 OU. Access to the emplacement construction zone will be provided along the existing ramp and gravel access road near the Columbia River. Construction activities will be limited by the width of the bench, which in some areas is only 5 m (15 ft). It is assumed that no modification will be needed to permit truck and equipment access to the construction area. Injection equipment will be built to support the jet injections for emplacement of the vadose zone PRB above the existing saturated zone barrier.

6.1 Site Utilities

Site utility requirements for this apatite injection include a generator and water supply. A substantial amount of water is needed to make up the injection solutions. Columbia River water will be used to dilute the phosphate solution and mix the pre-formed apatite slurry. A diesel generator will be used to operate the site facilities and the injection/monitoring equipment. The generator will also power ancillary equipment.

6.2 Injection Equipment

Jet injection nozzles capable of injecting the solution at an injection pressure of approximately 400 bars (5,800 psi) will be used. Pre-blended phosphate mixture of food grade phosphoric acid and sodium hydroxide can be delivered to the site in 18,927 m (5,000 gal) loads via tanker truck. The solution will be offloaded into holding tanks, with piping installed between the holding tanks and the jet injection pump.

A custom fabricated mixer equipped with multiple aggressive blades will be used to blend the apatite product with water to form the apatite injection mixture. An auger will convey the apatite material into the mixing unit. The super sack storage unit will be equipped with load cells that can accurately weigh and deliver the proper proportion of apatite product to the mixer for each batch. Columbia River water will be delivered to the mixer through a flow meter that can deliver a consistent volume to each batch. A mission type pump will be used to re-circulate and continuously agitate the apatite mixture.

A jet injection pump will be used to deliver the injection solution to the drill rig and jet grout tooling via a 1.5 in. diameter high-pressure hose. The apatite mixing unit and/or phosphate storage containers will deliver the injection solutions to the injection pump via flexible 3 or 4 in. hoses.

Appropriate QA/QC protocols will be followed with respect to injection equipment and system to insure that the design objectives are being met.

6.3 Materials

The jet injections will use pre-formed apatite and phosphate solution. The injectable slurry of pre-formed apatite will be created onsite by mixing the selected solid apatite material with Columbia River water. Both the specific type of solid apatite material and the mixing ratio will be specified in the test instructions. The phosphate solution will be delivered premixed to the site. Required quantities of these materials will be addressed in the test instructions, but the exact required amounts of materials will be based on the geologic conditions encountered in the field and collaboration with the jet injection subcontractor.

Actual materials used during the implementation of this project will be accounted for and reported in the test report. Appropriate QA/QC protocols will be followed with respect to injection materials to ensure that the design objectives are being met.

7 Sampling and Analysis

Sampling and analysis requirements for the jet injections include chemical make-up sampling, injection flow rate and volume monitoring, groundwater and aquifer tube sampling, and sediment core sampling. Field test instructions will be prepared prior to the injections, which will include sampling requirements along with a detailed set of operational parameters and procedures. Sampling will occur in a number of monitoring wells and aquifer tubes along the 100-N shoreline before, during, and after treatment. The wells and aquifer tubes that will be sampled will be chosen according to the proximity (nearest to and downgradient) from the treatment area (see Figures 1-2 and 2-4). Specifics on where sediment cores will be collected, if determined necessary, and which wells and aquifer tubes will be sampled and the sample frequency will be provided in activity-specific field test instructions. Groundwater and sediment core samples will be collected in accordance with the *Strontium-90 Treatability Test Plan for 100-NR-2 Groundwater Operable Unit,* DOE/RL-2005-96, and this DOS.

7.1 Sampling Frequency

Prior to injection, baseline sampling will be conducted from nearby multipurpose wells, nearby monitoring wells, and aquifer tubes. Where appropriate, data from other sampling events will be used. These samples will serve as the basis to compare the performance of the barrier. Sampling frequency will be initially increased immediately following injection to monitor any increase in Sr-90 flux toward the river. Sample frequency will decline over time as shown in Table 1. Specific sample location frequency and duration will be documented in the field test instructions. Sufficient samples from monitoring wells and aquifer tubes will be collected to ensure that the ephemeral impacts of the apatite emplacement are monitored. Approximately 70 samples from wells and aquifer tubes are expected to be collected.

Table 1. Sampling Locations and Frequencies

Sample Purpose	Sampling Locations	Approximate Sampling Frequency	Analytes
Pre-Injection Monitoring	Nearby monitoring wells/multipurpose wells/aquifer tubes	1 time immediately prior to injection	Cations, anions, Sr-90, gross beta, field parameters
Performance Monitoring	Nearby monitoring wells/multipurpose wells/aquifer tubes	Every other day for 1st week, 1 time per week for the next month, and then monthly for the next 6 months	Cations, anions, Sr-90, gross beta, field parameters

7.2 Injection Flow Rate and Volume

Flow rates during drilling and jet injection will be monitored during injections and any flow adjustments made as necessary. As discussed in Section 5.2, the flow rates will be determined by conditions encountered by the jet injection subcontractor and the capacity of the formation to accept the material. This capacity is expected to vary over the length of the barrier based on observed differences in hydraulic conductivity of the Hanford formation between the upstream and downstream ends of the barrier.

A data recorder will be used during the injections to record important parameters during drilling of each borehole. The parameters that will be recorded are drill depth, drill duration, rod rotation, lifting rate, jet injection pressure, solution flow rate, and solution injection quantity. All field activities will be overseen by qualified staff as described in Chapter 15.

7.3 Groundwater Sampling and Analysis

Groundwater samples will be collected using either a peristaltic pump or a 12-V electric submersible pump. Field parameters will be measured for each sample using portable field instruments. Specific conductance, oxidation-reduction potential, temperature, dissolved oxygen, and pH will all be measured in the field. Aqueous samples for offsite analyses of other parameters will be collected. Table 2 lists the analytic sampling requirements for the parameters, container volume, and preservation methods for offsite analyses. Table 3 lists parameters, analytic methods, and detection limits for aqueous analytes. Wells will be purged adequately according to standard practices and procedures to ensure that the sample collected represents the aquifer conditions.

7.4 Aquifer Tube Sampling

Aquifer tube sampling frequency will be specified in the field test instructions. Previous work for the low-concentration calcium-citrate-phosphate aqueous injections (PNNL-17429) have shown that if elevated Sr-90 and other metal concentrations occur, the aquifer stabilizes within a few weeks following injections. Because injections will be performed in the unsaturated zone, any potential increase in Sr-90 concentrations would be expected following high water conditions, which typically occur in May through June. Gross beta analysis will initially be used for estimating Sr-90 concentrations to provide a quicker turnaround on analytical results. If the sampling personnel observe floating product during sampling activities, the samples will also be analyzed for total petroleum hydrocarbon. Aquifer tube samples will be collected in accordance with the *Sampling and Analysis Plan for Aquifer Sampling Tubes* (DOE/RL-2000-59) and this DOS. Aquifer tubes will be purged adequately according to standard practices and procedures to ensure that the sample collected represents the aquifer conditions.

7.5 Core Sampling and Analysis

A minimum of three continuous core boreholes will be drilled through the vadose zone from within the PRB. Core samples will be collected for analysis at approximately 0.8 m (2.5 ft) intervals. Core samples will be collected at least three months, but not more than one year, after the jet injections at locations within the PRB and in alignment with existing downgradient monitoring wells to determine the nature and extent of the apatite-forming phosphate and pre-formed apatite emplacement. The cores will be collected from the ground surface to the top of the RUM. A determination of the amount of strontium and Sr-90 incorporated in the apatite matrix, adsorbed to apatite material by ion exchange, and sorbed to sediments may be completed later. Collection of continuous sediment cores will follow the procedures outlined in *100-NR-2 Apatite Treatability Test Plan Implementation* (DOE/RL-2005-96-ADD3) and this DOS.

Table 2. Sampling Requirements (Primary Analytes Shaded)

Parameter	Media/Matrix	Volume/Container	Preservation	Hold Time
Major Cations/Metals: Aluminum, Arsenic, Barium, Calcium, Cobalt, Chromium, Iron, Potassium, Magnesium, Manganese, Nickel, Zinc, Phosphorous, Strontium, Sodium, Antimony	Water	250 mL poly bottle	Unfiltered and filtered (0.45 μm)*, HNO_3 to pH <2	60 days
Hexavalent Chromium	Water	500 mL amber glass	Filtered (0.45 μm)*, Cool 4 °C	24 hours
Anions: Chloride, Sulfate, Phosphate, Nitrate, Nitrite	Water	120 mL poly bottle	Unfiltered and Filtered (0.45 μm)*, Cool 4 °C	45 days
Strontium-90	Water	1 L poly bottle	Filtered (0.45 μm)*, HNO_3 to pH <2	60 days
Gross Beta	Water	500 mL poly bottle	Filtered (0.45 μm)*, HNO_3 to pH <2	60 days
Apatite	Sediment	1 L/liner	Cool	N/A
Phosphate	Sediment	1 L/liner	Cool	N/A
Strontium-90	Sediment	1 L/liner	Cool	N/A
pH	Water	Field Measurement	N/A	N/A
Specific Conductance	Water	Field Measurement	N/A	N/A
Dissolved Oxygen	Water	Field Measurement	N/A	N/A
Oxidation Reduction Potential	Water	Field Measurement	N/A	N/A
Temperature	Water	Field Measurement	N/A	N/A

* Samples will be filtered (0.45 μm) for increased sample quality and to aid in the laboratory's ability to analyze the samples.

Table 3. Analytical Performance Requirements

Chemical Abstract Service Number	Analyte	Matrix	Analytical Method	Required Detection Limit	Accuracy Requirement (% Recovery)[a]	Precision Requirement (Relative Percent Difference)[a]
			Radiological Constituents			
Rad-Sr	Strontium-90	Water	Strontium 89/90 – Total Rad-Sr	2 pCi/L	80-120%	≤20%
12587-47-2	Gross Beta	Water	Gross beta	4 pCi/L	80-120%	≤20%
			Nonradiological Constituents			
7440-90-5	Aluminum	Water	ICP Metals – 6010	50 µg/L	80-120%	≤20%
7440-36-0	Antimony	Water	ICP Metals – 6010	60 µg/L	80-120%	≤20%
7440-38-2	Arsenic	Water	ICP Metals – 6010	100 µg/L	80-120%	≤20%
7440-39-3	Barium	Water	ICP Metals – 6010	20 µg/L	80-120%	≤20%
7440-43-9	Cadmium	Water	ICP Metals – 6010	5 µg/L	80-120%	≤20%
7440-70-2	Calcium	Water	ICP Metals – 6010	1,000 µg/L	80-120%	≤20%
7440-47-3	Chromium	Water	ICP Metals – 6010	10 µg/L	80-120%	≤20%
18540-29-9	Chromium (hexavalent)	Water	EPA 7196 (Cr (VI))	10 µg/L	80-120%	≤20%
7440-48-4	Cobalt	Water	ICP Metals – 6010	20 µg/L	80-120%	≤20%
7440-50-8	Copper	Water	ICP Metals – 6010	10 µg/L	80-120%	≤20%
7439-89-6	Iron	Water	ICP Metals – 6010	50 µg/L	80-120%	≤20%
7439-92-1	Lead	Water	ICP Metals – 6010	50 µg/L	80-120%	≤20%
7439-95-4	Magnesium	Water	ICP Metals – 6010	750 µg/L	80-120%	≤20%
7439-96-5	Manganese	Water	ICP Metals – 6010	5 µg/L	80-120%	≤20%

Table 3. Analytical Performance Requirements

Chemical Abstract Service Number	Analyte	Matrix	Analytical Method	Required Detection Limit	Accuracy Requirement (% Recovery)[a]	Precision Requirement (Relative Percent Difference)[a]
7439-98-7	Molybdenum	Water	ICP Metals – 6010	20 µg/L	80-120%	≤20%
7440-02-0	Nickel	Water	ICP Metals – 6010	40 µg/L	80-120%	≤20%
7440-09-7	Potassium	Water	ICP Metals – 6010	4,000 µg/L	80-120%	≤20%
7440-22-4	Silver	Water	ICP Metals – 6010	10 µg/L	80-120%	≤20%
7440-23-5	Sodium	Water	ICP Metals – 6010	500 µg/L	80-120%	≤20%
7440-24-6	Strontium	Water	ICP Metals – 6010	10 µg/L	80-120%	≤20%
7440-62-2	Vanadium	Water	ICP Metals – 6010	25 µg/L	80-120%	≤20%
7440-66-6	Zinc	Water	ICP Metals – 6010	10 µg/L	80-120%	≤20%
16887-00-6	Chloride	Water	Anions by IC – 300.0	200 µg/L	80-120%	≤20%
16984-48-8	Fluoride	Water	Anions by IC – 300.0	500 µg/L	80-120%	≤20%
NO2-N	Nitrogen in nitrate	Water	Anions by IC – 300.0	75 µg/L	80-120%	≤20%
NO3-N	Nitrogen in nitrite	Water	Anions by IC – 300.0	75 µg/L	80-120%	≤20%
PO4-P	Phosphorus in phosphate	Water	Anions by IC – 300.0	500 µg/L	80-120%	≤20%
14808-79-8	Sulfate	Water	Anions by IC – 300.0	100 µg/L	80-120%	≤20%
Field Measurements						
pH-150.1	pH	Water	150.1-pH-Field	0.1 pH unit	b	b
Temp-170.1	Temperature (°C)	Water	170.1-Temperature-Field	0.1 °C	b	b
Cond-120.1	Specific conductance (µS/cm)	Water	120.1-Conductivity-Field	0.1 µS/cm	b	b

Table 3. Analytical Performance Requirements

Chemical Abstract Service Number	Analyte	Matrix	Analytical Method	Required Detection Limit	Accuracy Requirement (% Recovery)[a]	Precision Requirement (Relative Percent Difference)[a]
Oxygen-360.1	Dissolved oxygen (mg/L)	Water	360.1-Oxygen-Field	0.1 mg/L	b	b
REDOX_FLD	Oxidation–Reduction Potential (mV)	Water	Redox-Probe-Field	±1 mV	b	b
PNNL Apatite Formation Testing						
14265-44-2 Rad-Sr	Phosphate, Sr-90	Sediment	Acid dissolution of sediment and phosphate measurement	N/A	c	c
N/A	Apatite	Sediment	Fluorescence of substituted apatites	N/A	c	c

a. Accuracy criteria for associated batch matrix spike percent recoveries. Evaluation based on statistical control of laboratory control samples is also performed. Precision criteria for batch laboratory replicate matrix spike analyses or replicate sample analyses.

b. This method has no quantitative requirements beyond adherence to the field measurement methodology.

c. PNNL laboratory procedures and QA plan will apply to all analyses performed by PNNL.

IC = ion chromatography
ICP = inductively coupled plasma
N/A = Not Applicable
PNNL = Pacific Northwest National Laboratory
QA = quality assurance

8 Data Management

The Sample Management and Reporting Organization, in coordination with the Project Manager, is responsible for ensuring analytical data are appropriately reviewed, managed, and stored in accordance with the applicable programmatic requirements governing data management procedures. All data will be entered into the Hanford Environmental Information System (HEIS) database. Electronic data access, when appropriate, will be via a database. (e.g., HEIS or a project-specific database). Where electronic data are not available, hard copies will be provided in accordance with Section 9.6 of the *Hanford Federal Facility Agreement and Consent Order Action Plan* (Ecology et al., 1989b).

8.1 Sample Collection and Analysis

Planning for sample collection and analysis will be in accordance with the programmatic requirements governing fixed laboratory sample collection activities, as discussed in the sample team's procedures. In the event specific procedures do not exist for a particular work evolution, or it is determined additional guidance to complete certain tasks is needed, a work package will be developed to control the activities, as appropriate. Examples of the sample team's requirements include activities associated with the following:

- Contaminant of concern/sample analysis requests
- Project and sample identification for sampling services
- Control of certificates of analysis
- Logbooks
- Checklists
- Sample packaging and shipping

Approved work control packages and procedures will be used to document field activities, including radiological measurements. All field activities will be recorded in the field logbook. Examples of the types of documentation for field radiological data include the following:

- Instructions regarding the minimum requirements for documenting radiological controls information as per 10 CFR 835, "Occupational Radiation Protection."
- Instructions for managing the identification, creation, review, approval, storage, transfer, and retrieval of primary contractor radiological records.
- The minimum standards and practices necessary for preparing, performing, and retaining radiological related records.
- The instruction of personnel on the development and implementation of sample plans.
- The requirements associated with preparing and transporting regulated material.
- Daily reports of radiological surveys and measurements collected during conduct of field investigation activities. Data will be cross-referenced between laboratory analytical data and radiation measurements to facilitate interpretation of the investigation results.
- Daily reports of radiological surveys and measurements collected during the field investigation activities. Data will be cross-referenced between laboratory analytical data and radiation measurements to facilitate interpreting the investigation results.

8.2 Resolution of Errors

Laboratory errors are reported to the Sample Management and Reporting Organization on a routine basis. For reported laboratory errors, the sample issue resolution process will be initiated in accordance with contractor procedures. This process is used to document analytical errors and to establish their resolution with the Project Manager.

9 Data Analysis and Interpretation

This chapter discusses the data analysis and interpretations used for determining whether the data meet the project objectives.

9.1 Data Validation and Usability

The following sections address the QA activities that occur after the data collection phase of the project is completed. Implementation of these elements determines whether data conform to the specified criteria, thus satisfying project objectives.

9.1.1 Data Review, Verification, and Validation

The criteria for verification may include:

- Review for completeness (all samples were analyzed as requested)
- Use of the correct analytical method/procedure
- Review for transcription errors
- Correct application of dilution factors
- Appropriate reporting of dry weight versus wet weight
- The correct application of conversion factors
- Laboratory personnel may perform data verification

Data validation will be performed to ensure that the data quality goals established during the planning phase have been achieved. Data validation will be in accordance with internal procedures. The criteria for data validation are based on a graded approach. The primary contractor has defined five levels of validation, A through E. Level A is the lowest level and is the same as verification. Level E is a 100 percent review of data (e.g., calibration data; calculations of representative samples from the dataset). Validation will be performed to contractor Level C, which is a review of the QC data. Level C validation specifically requires verification of deliverables and requested versus reported analyses and qualification of the results based on analytical holding times, method blank results, matrix spike/matrix spike duplicate, surrogate recoveries, duplicates, and analytical method blanks. Level C validation will be performed on at least 5 percent of the data by matrix and analyte group. Analyte group refers to categories, such as radionuclides, volatile and semivolatile chemicals, metals, and anions.

Relative to analytical data in sample media, physical data and/or field screening results are of lesser importance in making inferences of risk. Data validation will not be performed for physical property data and/or field screening results.

9.1.2 Verification and Validation Methods

Validation activities will be based on EPA functional guidelines, *US EPA Contract Laboratory Program National Functional Guidelines for Organic Data Review* (EPA540/R-99/008). Data validation may be

performed by the analytical laboratory, Sample Management and Reporting, and/or by a party independent of both the data collector and the data user.

Data qualifiers assigned during data validation will be compatible with HEIS.

When outliers or questionable results are identified, additional data validation will be performed. The additional validation will be performed for up to 5 percent of the statistical outliers and/or questionable data. The additional validation will begin with Level C and may increase to Levels D and E, as needed to ensure that data are usable. Level C validation is a review of the QC data, while Levels D and E include review of calibration data and calculations of representative samples from the dataset. Data validation will be documented in data validation reports. One example of questionable data is the instance when positive detections are greater than the practical quantitation limit or reporting limit in soil/aquifer sediment from a site that should not have exhibited contamination. Similarly, results below background would not be expected and could trigger a validation inquiry.

9.1.3 Reconciliation with User Requirements

The data quality assessment (DQA) process compares completed field sampling activities to those proposed in corresponding sampling documents and provides an evaluation of the resulting data. The purpose of the data evaluation is to determine whether quantitative data are of the correct type and of adequate quality and quantity to meet the project data quality objectives (DQOs). The Project Manager is responsible for determining whether a DQA is necessary and ensuring that it is performed, if required. The results of the DQA will be used in interpreting the data and determining if the objectives of this activity have been met.

The DQA (if performed) will be conducted in accordance with EPA's DQA process, *Data Quality Assessment: A Reviewer's Guide*, EPA QA/G-9R (EPA/240/B-06/002), and *Data Quality Assessment: Statistical Methods for Practitioners*, EPA QA/G-9S (EPA/240/B-06/003).

9.1.4 Corrective Actions

The responses to data quality defects identified through the DQA process will vary and may be data-specific or measurement-specific. Table 4 identifies some pre-identified corrective actions.

9.2 Data Interpretation

Data interpretation will be performed to assess the performance of the jet injection. The primary interpretation of the data will be to assess the effectiveness of the use of phosphate and pre-formed apatite in reduction of the Sr-90 and metals flux to the Columbia River relative to baseline concentrations. The secondary interpretation will be measuring apatite formation through collection of core samples.

Table 4. Data Quality Indicators

Data Quality Indicator	Definition	Example Determination Methodologies	Project-Specific Information*	Corrective Actions Examples
Precision	The measure of agreement among repeated measurements of the same property under identical, or substantially similar, conditions; calculated either as the range or as the standard deviation. May also be expressed as a percentage of the mean of the measurements, such as relative range, relative percent difference, or relative standard deviation (coefficient of variation).	Use the same analytical instrument to make repeated analyses on the same sample. Use the same method to make repeated measurements of the same sample within a single laboratory or have two or more laboratories analyze identical samples with the same method. Split a sample in the field and submit both samples for sample handling, preservation and storage, and analytical measurements. Collect, process, and analyze collocated samples for information on sample acquisition, handling, shipping, storage, preparation, and analytical processes and measurements.	Field precision: At randomly selected locations, duplicate samples will be collected 1 per 20 samples per media. Laboratory precision: Analysis of laboratory duplicate or matrix spike duplicate results.	If duplicate data do not meet objective: • Evaluate apparent cause (e.g., sample heterogeneity). • Request re-analysis or re-measurement. • Qualify the data before use.
Accuracy	A measure of the overall agreement of a measurement to a known value; includes a combination of random error (precision) and systematic error (bias) components of both sampling and analytical operations.	Analyze a reference material or re-analyze a sample to which a material of known concentration or amount of pollutant has been added (a spiked sample); usually expressed either as percent recovery or as percent bias.	Laboratory accuracy determination based on matrix spikes and matrix spike duplicate results.	If recovery does not meet objective: • Qualify the data before use. • Request re-analysis or re-measurement.

Table 4. Data Quality Indicators

Data Quality Indicator	Definition	Example Determination Methodologies	Project-Specific Information*	Corrective Actions Examples
Representativeness	A qualitative term that expresses the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition (ANSI/ASQC E4-1994).	Evaluate whether measurements are made and physical samples collected in such a manner that the resulting data appropriately reflect the environment or condition being measured or studied.	Samples will be collected as described in the sampling design. Judgmental sampling ensures areas most likely to be contaminated, based on current information, will be evaluated.	If results are not representative of the system sampled: • Identify the reason result is not representative. • Reject the data or, if data are otherwise usable, qualify the data for limited use and define the portion of the system the data represent. • Redefine sampling and measurement requirements and protocols. • Resample and reanalyze.
Comparability	A qualitative term that expresses the measure of confidence that one data set can be compared to another and can be combined for the decision(s) to be made.	Compare sample collection and handling methods, sample preparation and analytical procedures, holding times, stability issues, and QA protocols.	Sampling personnel will use the same sampling protocols. Samples will be submitted to the same laboratories when possible (based on laboratory contracts) for analysis by the same methods, thus data results will be comparable.	If data are not comparable to other data sets: • Identify appropriate changes to data collection and/or analysis methods. • Identify quantifiable bias, if applicable. • Qualify the data as appropriate. • Resample and/or reanalyze, if needed. • Revise sampling/analysis protocols to ensure future comparability.

Table 4. Data Quality Indicators

Data Quality Indicator	Definition	Example Determination Methodologies	Project-Specific Information*	Corrective Actions Examples
Completeness	A measure of the amount of valid data needed to be obtained from a measurement system.	Compare the number of valid measurements completed (samples collected or samples analyzed) with those established by the project's quality criteria (DQOs or performance/acceptance criteria).	The percent complete will be determined during data validation.	If data set does not meet completeness objective: • Identify appropriate changes to data collection and/or analysis methods. • Identify quantifiable bias, if applicable. • Qualify the data as appropriate. • Resample and/or reanalyze, if needed. • Revise sampling/analysis protocols to ensure future comparability.
Sensitivity	The capability of a method or instrument to discriminate between measurement responses representing different levels of the variable of interest.	Determine the minimum concentration or attribute that can be measured by a method (method detection limit), by an instrument (instrument detection limit), or by a laboratory (quantitation limit). The practical quantitation limit is the lowest level that can be routinely quantified and reported by a laboratory.	Ensure that sensitivity, as measured by detection limits, is appropriate for the action levels.	If sensitivity does not meet objective: • Request reanalysis or re-measurement. • Qualify/reject the data before use.

Source:

ANSI/ASQC E4-1994, *Specifications and Guidelines for Quality Systems for Environmental Data Collection and Environmental Technology Programs.*

* Field sampling requirements are noted. Laboratories will follow contract requirements for use and interpretation of laboratory control samples. Precision, accuracy, and sensitivity requirements are satisfied by following method procedures because analyses are being performed to support treatability test design (not for regulatory decision-making).

Table 4. Data Quality Indicators

Data Quality Indicator	Definition	Example Determination Methodologies	Project-Specific Information*	Corrective Actions Examples
ANSI	= American National Standards Institute	QAPP = quality assurance project plan		
ASQC	= American Society for Quality Control	QC = quality control		
DQO	= data quality objective	SOP = standard operating procedure		
PNNL	= Pacific Northwest National Laboratory	TTP = treatability test plan		
QA	= quality assurance			

10 Health and Safety

All field operations will be performed in accordance with CH2M HILL Plateau Remediation Company health and safety requirements, outlined in the latest revision of the Soil and Groundwater health and safety plan. Radiological contamination is probable during performance of the injection boring drilling and sampling activities. The sampling processes and associated activities will take into consideration exposure reduction and contamination control techniques (e.g., as low as reasonably achievable [ALARA] and Integrated Safety Management System) that will minimize chemical exposure to the sampling team. Health and safety personnel will use data collected during the activities addressed in this DOS as input to determine exposure levels to workers, and to conduct health and safety assessments during all field activities, in accordance with the health and safety plan.

11 Waste Management

All regulated waste generated from this DOS, including sampling activities, will be managed in accordance with the *Interim Action Waste Management Plan for the 100-NR-2 Waste Operable Unit* (DOE/RL-2000-41). Disposition of purgewater and miscellaneous solid waste will be conducted in accordance with DOE/RL-2000-41.

Unused samples and associated laboratory waste for the analysis will be dispositioned in accordance with the laboratory contract and agreements for return to the project site. Pursuant to 40 CFR 300.440, "Procedures for Planning and Implementing Off-Site Response Actions," DOE Project Manager approval is required before returning unused samples or waste from offsite laboratories (as applicable).

12 Reports

Following completion of the design optimization test, a final report will be prepared summarizing the results of the study. Interim reports may be produced during the implementation of the test as determined by the project team. Updates will be provided at the Unit Managers Meeting (UMM) and the annual groundwater monitoring report as the data become available.

13 Environmental and Regulatory Compliance

Laws and regulations pertaining to the response actions are identified through the applicable or relevant and appropriate requirements (ARAR) identification process. The ARARs identification process is based on CERCLA guidance (EPA/540/G-89/004, *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA*; EPA/540/G-89/009, *CERCLA Compliance with Other Laws Manual—Part II, Clean Air Act and Other Environmental Statutes and State Requirements*). Section 121 of CERCLA requires that any ARAR criterion or limitation under any federal environmental law, or any more stringent state requirement pursuant to a state environmental statute, be met (or a waiver justified) for any hazardous substance, pollutant, or contaminant that will remain onsite after completion of remedial action.

This DOS is conducted under the *Interim Remedial Action Record of Decision for the 100-NR-1 and 100-NR-2 Operable Units* (EPA/ROD/R10-99/112, 1999). The ARARs are discussed in the ROD for interim remedial action. The selected interim remedial actions for the 100-NR-2 OU that will be conducted under this DOS are protective of human health and the environment, comply with ARARs, and are cost effective.

Under DOE Order 451.1B, *National Environmental Policy Act Compliance Program*, Section 5.a.(13), DOE will "...incorporate *National Environmental Policy Act* (NEPA) values, such as analysis of cumulative, offsite, ecological, and socioeconomic impacts, to the extent practicable, in DOE documents prepared under the *Comprehensive Environmental Response, Compensation, and Liability Act*." These NEPA values include, but are not limited to, cumulative, ecological, cultural, historical, and socioeconomic impacts, and irreversible and irretrievable commitments of resources. This optimization study occurs in a previously disturbed area at 100-N, and does not have the potential to impact NEPA values. A general discussion of NEPA values anticipated to be addressed for the 100 Area can be found in the *100 Area Integrated RI/FS Work Plan* (DOE/RL-2008-46 Rev. 0). The complete analysis will be provided in the future feasibility study.

Well locations will be provided to Ecology following completion of injections and each borehole will be decommissioned according to AC-173-160 or to an Ecology-approved variance to WAC 173-160.

14 Schedule

A project field schedule will be developed and provided separately, outside of this DOS. This working schedule may be modified as necessary. Updates to the schedule will be provided on a regular basis in the UMM.

15 Management and Staffing

CH2M HILL Plateau Remediation Company is responsible for planning and managing all project activities, ensuring that the project has defined goals, the project team understands the goals and approaches used, and the planned outputs are appropriately documented. Project management roles and responsibilities discussed in this section apply to the major activities covered under the DOS. The project lead maintains a list of individuals or organizations as points of contact for each functional element in Figure 20. For each functional primary contractor role, a corresponding oversight role exists within DOE.

As shown in the figure, the following sections describe the project organization for the injection boring installation, apatite injection, health and safety, and the sampling and characterization tasks.

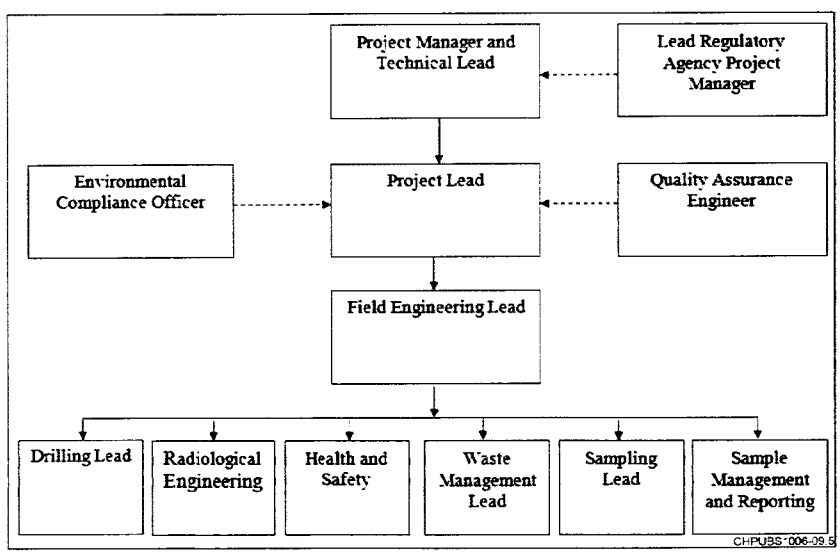


Figure 20. Jet Injection Design Optimization Study Organization

Lead Regulatory Agency Project Manager. The Lead Regulatory Agency (Ecology) has assigned Project Managers responsible for overseeing the cleanup projects and activities. Ecology has approval authority as the lead regulatory agency for the work being performed under this DOS. Ecology will work with DOE to resolve concerns regarding the work as described in this DOS in accordance with the Tri-Party Agreement (Ecology et al., 1989a).

Tri-Party Agreement Project Manager and DOE-RL Technical Lead. The Tri-Party Agreement Project Manager is responsible for authorizing Remedial Investigation/Feasibility Study (RI/FS) activities for the 100 Area OUs. The Tri-Party Agreement Project Manager also is responsible for obtaining lead regulatory agency approval of the DOS that authorizes the activities under the Tri-Party Agreement (Ecology et al., 1989a). The DOE-RL technical lead is responsible for overseeing the contractor in performing the work scope, working with the contractor and the regulatory agencies to identify and work through issues, and providing technical input to the Tri-Party Agreement Project Manager.

Project Lead. The project lead is responsible for managing field activities, subcontracted tasks, and ensuring the project file is properly maintained. The project lead ensures that the test plan design requirements are converted into field instructions (e.g., work packages) providing specific direction for field activities. The project lead works closely with the field engineer lead, QA, health and safety, the drilling lead, and the sampling lead to integrate these and other lead disciplines in planning and implementing the work scope. The project lead maintains a list of individuals or organizations filling each of the functional elements of the project organization (Figure 20). In addition, the project lead is responsible for version control to ensure that personnel are working to the most current job requirements. The project lead also coordinates with DOE-RL and the task leads on test plan implementation and sampling activities. The project lead supports DOE-RL in coordinating sampling activities with the regulators.

Environmental Compliance Officer. The environmental compliance officer provides technical guidance, direction, and acceptance of project and subcontracted environmental work and develops appropriate mitigation measures with a goal of minimizing adverse environmental impacts. The environmental compliance officer also reviews plans, procedures, and technical documents to ensure that environmental requirements have been addressed. Moreover, the environmental compliance officer identifies environmental issues affecting operations, develops cost-effective solutions, and responds to environmental and regulatory issues or concerns raised by DOE-RL and/or the regulatory agencies. The environmental compliance officer also may oversee project implementation for compliance with applicable internal and external environmental requirements.

Quality Assurance Engineer. The QA point of contact is matrixed to the project lead and is responsible for QA issues on the project. Responsibilities include, as appropriate, overseeing implementation of the project QA requirements; reviewing project documents, including data needs summary reports, field sampling plan, and the quality assurance project plan; and participating in QA assessments of sample collection and analysis activities. The QA point of contact must be independent of the unit generating the data.

Field Engineering Lead. The field engineering lead provides technical guidance and direction of project and subcontracted work. The field engineering lead also reviews plans, procedures, and technical documents to ensure technical requirements have been addressed. The field engineering lead also identifies potential issues affecting operations, develops cost-effective solutions, and oversees implementation of subcontractor tasks such as injection boring installation and apatite injection.

Drilling Lead. The drilling lead has overall responsibility for planning, coordinating, and executing drilling activities. Specific responsibilities include coordinating with the geological and drilling contractors. The drilling lead also communicates with the field engineering lead to identify field constraints or emergent

conditions affecting sampling design or execution, and directs the procurement and installation of materials and equipment needed to support fieldwork.

Waste Management Lead (Waste Coordinator). The waste management lead communicates policies and procedures and ensures project compliance for storage, transportation, disposal, and waste tracking in a safe and cost-effective manner. In addition, waste management is responsible for identifying waste management sampling and characterization requirements to ensure regulatory compliance, interpreting the characterization data to generate waste designations and profiles, and preparing and maintaining other documents that confirm compliance with waste acceptance criteria.

Sampling Lead. The sampling lead has overall responsibility for planning, coordinating, and executing sampling activities. Specific responsibilities include converting the sampling design requirements into field task instructions providing specific direction for field activities, as well as directing training, mock-ups, and practice sessions with field personnel to ensure the sampling design is understood and can be performed as specified. The sampling lead also communicates with the field engineering lead to identify field constraints or emergent conditions affecting sampling design or execution, directs the procurement and installation of materials and equipment needed to support fieldwork, and prepares data packages. The shipping lead reports to the sampling lead for shipment authorization. No sample material will be transported on or off the Hanford Site without permission from an authorized shipper or designee.

Radiological Engineering. The radiological engineering lead is responsible for the radiological/health physics support within the project. Specific responsibilities include conducting ALARA reviews, exposure, release modeling, and radiological controls optimization for work planning. In addition, the radiological engineering lead identifies radiological hazards and implements appropriate controls to maintain worker exposures ALARA (e.g., requiring personal protective equipment). The radiological engineering lead also interfaces with the project health and safety contact, and plans and directs radiological control technician support for activities.

Sample Management and Reporting. Sample Management and Reporting coordinates laboratory analytical work, ensuring the laboratories conform to Hanford Site internal laboratory QA requirements or their equivalent, as approved by DOE, EPA, and Ecology. Sample Management and Reporting receives analytical data from the laboratories, performs data entry into HEIS, and arranges for data validation. Sample Management and Reporting is responsible for informing the field engineering lead of any issues reported by the analytical laboratory. Sample Management and Reporting develops and oversees the implementation of the letter of instruction to the analytical laboratories, oversees data validation, and works with the project lead to prepare a characterization report on the sampling and analysis results.

The Sample Management and Reporting organization is also responsible for performing the data needs process, or equivalent. Additional related responsibilities include developing the sampling and analysis plan (SAP), including documenting the data needs and the sampling design, preparing associated presentations, resolving technical issues, and preparing revisions to the SAP. Samples collected in the field and released to the River Corridor Closure Contractor for shipping and analysis, as well as the resulting data, will be managed in accordance with applicable procedures and work plans.

Laboratories. The laboratories analyze samples in accordance with established procedures, provide necessary sample reports, and explain results in support of data validation. The laboratories must meet site-specific QA requirements and must have an approved QA plan in place.

Health and Safety. Health and safety is responsible for coordinating industrial safety and health support for the project through health and safety plans, job hazard analyses, and other pertinent safety documents required by federal regulation or by internal primary contractor work requirements. In addition, health and

safety assists project personnel in complying with applicable health and safety standards and requirements. Health and safety coordinates with radiological engineering to determine personal protective clothing requirements.

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