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Evaluation and Screening of Remedial Technologies for Uranium at the 300-FF-5 Operable Unit, Hanford Site, Washington

M. J. Nimmons

August 2007

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

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Summary

Pacific Northwest National Laboratory (PNNL) is presently conducting a re-evaluation of remedies addressing persistent dissolved uranium concentrations in the upper aquifer under the 300 Area of the Hanford Site in southeastern Washington State. This work is being conducted as a Phase III feasibility study for the 300-FF-5 Operable Unit on behalf of the U.S. Department of Energy. As part of the feasibility study process, a comprehensive inventory of candidate remedial technologies was conducted by PNNL. This report documents the identification and screening of candidate technologies. The screening evaluation was conducted in accordance with guidance and processes specified by U.S. Environmental Protection Agency regulations (EPA 1989[1]) associated with implementation of the *Comprehensive Environmental Response, Compensation, and Liability Act* process.

Recent Hanford Site investigations and historical monitoring indicate the persistent uranium in 300 Area groundwater originates from sediments above the groundwater, as well as in the aquifer. Consequently, the technology evaluation included technologies applicable to each of three zones as described in the site conceptual model. The original focus of the prior Phase I and Phase II feasibility studies (DOE-RL 1994[2]) on physical technologies of hydraulic containment and removal was expanded in this study to include chemical, biological, and physical processes.

Fifty-three technologies or management techniques for groundwater were initially identified. Thirteen of the 53 technologies were additions to the 40 identified in the original feasibility study (DOE-RL 1994). The additions are new in-situ technologies that were not known earlier. Evaluation of these technologies on the basis of criteria from the 1994 feasibility study (DOE-RL 1994), including adjustments for 2006 conditions and with a focus on groundwater technologies, narrowed the original 53 technologies to 29 candidate technologies for groundwater. With the consolidation of 3 institutional control actions into 1 action, 27 actions and technologies were reduced to 13 using criteria of effectiveness and implementability. The 13 remaining technologies were reduced to 2 active technologies and 2 passive management strategies using the relative cost criteria.

The resulting active technologies for groundwater are as follows:

- In-situ polyphosphate treatment
- In-situ calcium citrate and sodium phosphate treatment.

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[1] EPA. 1989. *The Feasibility Study: Development And Screening of Remedial Action Alternatives*. Directive 9355.3-01FS3, U.S. Environmental Protection Agency, Washington, D.C.

[2] U.S. Department of Energy, Richland Operations Office (DOE-RL). 1994. *Phase I and II Feasibility Study Report for the 300-FF-5 Operable Unit*. DOE/RL-93-22, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

The resulting passive management strategies for groundwater are as follows:

- Institutional Controls (land-use restrictions, access controls)
- Monitored Natural Attenuation.

Because the 1994 feasibility study (DOE-RL 1994) did not address the smear zone (Zone 3) where fluctuating water elevations produce a wetted layer of sediment, a new list of six prospective technologies was initially identified. These six technologies were reduced to two technologies using criteria of effectiveness and implementability. The two active technologies remained after applying relative cost criteria.

The resulting active technologies for the smear zone (Zone 3) are as follows:

- Selective excavation to the water table
- Stabilization by application of polyphosphate.

The 1994 feasibility study also did not address the lower vadose zone but assumed that remedies deployed in the 300-FF-1 Operable Unit upper vadose zone would protect groundwater. A new list of 10 candidate technologies was identified. Using criteria of effectiveness and implementability, the 10 were reduced to 4 technologies. Three active technologies remained after applying relative cost criteria.

The resulting active technologies for the vadose zone are as follows:

- More extensive excavation of sediment to the water table
- Vadose flushing with polyphosphate immobilizing agent
- Vadose flushing with calcium citrate and sodium phosphate.

Remedial strategies will be developed by combining selected technologies into multiple alternatives based on the results of this technology screening. The alternatives will likely incorporate different assemblages, sequencing, and application areas/zones of technologies. A detailed analysis of the remedial alternatives selected in the initial screen will be conducted using nine evaluation criteria mandated by statutory directives and regulatory guidance to form the forthcoming Phase III feasibility study.

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1.0 Introduction

An ongoing program of site characterization, technology development, and technology evaluation is being conducted at the Hanford Site, according to the *Work Plan for Phase III Feasibility Study 300-FF-5 Operable Unit* (DOE-RL 2005). As part of the feasibility study effort described in the work plan, a screening evaluation of candidate remediation technologies was conducted. This document presents the screening process used to select remediation technologies that will be assembled into alternatives for remediation of persistent uranium concentrations in groundwater beneath the 300 Area.

The contaminants of concern in the groundwater addressed by the interim actions were uranium, trichloroethene, and 1,2-dichloroethene. Of these three contaminants of concern, uranium was and remains the most pervasive. The earlier feasibility studies (DOE-RL 1994 and 1995) anticipated that natural attenuation processes, particularly naturally occurring groundwater flushing and dispersion, would reduce uranium within the groundwater to cleanup levels by 2004. Because observed uranium concentrations have persisted above the targeted cleanup level, a renewed effort to develop and implement groundwater cleanup was initiated in 2004.

The purpose of the Phase III feasibility study is to supplement and update earlier evaluation of remedial actions conducted within the *Phase 1 and Phase II Feasibility Study Report for the 300-FF-5 Operable Unit* (DOE-RL 1994) and the *Remedial Investigation/Feasibility Study Report for the 300-FF-5 Operable Unit* (DOE-RL 1995). Because of the persistence of uranium in the groundwater at the 300 Area, a new initiative to design and implement a remedy for the uranium started in 2005. The planning for this remedy is being conducted under the auspices of a *Phase III Feasibility Study for the 300-FF-5 Operable Unit.* The work plan for the Phase III feasibility study (DOE-RL 2005) describes the process the U.S. Department of Energy (DOE) will follow to develop and implement the remedy.

The conduct of the Phase III feasibility study will be based on several elements:

- Recent characterization findings of the limited field investigation and other ongoing site-related work
- Prescribed regulatory framework
- Prior remedial technology study conducted in the preceding feasibility study
- New remediation technology developments that are progressing.

The re-evaluation of the uranium remedial strategy is being conducted using the process specified by U.S. Environmental Protection (EPA) regulations (EPA 1989) associated with implementation of the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) process.

The results of the technology screening that supports the Phase III feasibility study are presented in the following sections.

- Section 2.0 provides a summary of relevant background information.
- Section 3.0 provides an overview of the conceptual model.
- Section 4.0 presents the regulatory framework context.

- Section 5.0 presents the identification and inventory of potential remediation technologies for remediation of uranium in three stratigraphic regimes.
- Section 6.0 presents the evaluation and screening of remedial technologies.
- Section 7.0 summarizes the screening process for remedial technologies for uranium.

2.0 Background

The 300-FF-5 Operable Unit comprises groundwater and sediments, specifically the upper-unconfined aquifer beneath the 300 Area, adjacent to and west of the Columbia River immediately north of the city of Richland. The 300-FF-5 Operable Unit also includes groundwater beneath the 618-10 and 618-11 burial grounds, north of the 300 Area. However, the focus of the Phase III feasibility study (DOE-RL 2005) is on dissolved uranium in the groundwater beneath the 300 Area.

The 300 Area was developed in the 1940s with manufacturing and industrial facilities necessary to fabricate uranium fuel for plutonium production reactors. The area also supported laboratory facilities designed and operated to test materials related to plutonium production processes. The manufacturing and laboratory operations that produced waste began in 1944 and ended in the 1980s.

Liquid and solid waste was discharged to the ground from two large ponds, trenches, and landfills and from various vessel and plumbing releases. The chemical characteristics and quantities of discharged waste are complex and poorly documented. A major portion of the waste originated from fuel rod fabrication and included basic aluminate solutions and acidic copper/uranyl nitrate solutions.

The water table continuously fluctuates near the Columbia River with changing river stage. Nominally, depth to groundwater in the 300-FF-5 Operable Unit ranges between 8 and 17 m (26 and 56 ft) below ground surface depending on the surface topography The 300-FF-5 Operable Unit aquifer is unconfined and flows through gravels and sands deposited by glacial floods. The vadose zone consists of similar sediments.

A large, persistent plume of dissolved uranium formed in the uppermost unconfined aquifer beneath the 300 Area. In the early 1990s, an attempt to implement a remedy was documented in two DOE Richland Operations Office (DOE-RL) feasibility studies (DOE-RL 1994 and 1995).

The earlier feasibility study documents a technology screening (Table 4-1 in DOE-RL 1994) and remedial alternative identification. The following technologies and process options were retained for further consideration at that time. These technologies focused only on uranium in groundwater:

- Institutional controls and monitoring
- Containment
  - Slurry walls
  - Grout walls by injection
  - Grout walls by deep soil mixing
  - Hydraulic containment by pumping

- Removal
  - Groundwater extraction
    - Wells
    - Interceptor trenches
  - Aquifer soil dredging/excavation
    - Excavation and dewatering
    - Mechanical dredging
- Disposal
  - Treated groundwater
    - Surface water discharge
    - Subsurface discharge
  - Sludge and soils disposal onsite
- Ex-situ treatment of groundwater
  - Gravity separation
  - Filtration
  - Ion exchange
  - Reverse osmosis
  - Precipitation
- In-situ treatment
  - In-situ flushing.

These technologies were further evaluated and assembled into 16 remediation alternatives that were screened in the feasibility study to produce a list of 6 alternatives that were evaluated.

The six alternatives considered in the 1994 feasibility study (DOE-RL 1994) were as follows:

1. No action
2. Institutional controls
3. Selective hydraulic containment
4. Selective hydraulic containment with in-situ flushing
5. Extensive hydraulic containment
6. Extensive hydraulic containment with selective in-situ flushing

In 1995, interim actions were selected for the groundwater of the 300-FF-5 Operable Unit because upgradient contamination (e.g., tritium) was migrating into that area, remedial actions for such contamination had not been fully identified, and uncharacterized waste sites in the vadose zone above the groundwater required further study. The selected interim remedies for the groundwater in the 300 Area adopted by the 300-FF-5 Operable Unit record of decision (EPA 1996) were 1) "Institutional Controls to prevent human exposure to groundwater" and 2) "Groundwater monitoring to verify modeled predictions of contamination attenuation and to evaluate the need for active remedial measures."

A recently conducted limited field investigation yielded a better understanding of the occurrence and geochemistry of uranium and hydrogeology of the 300 Area than was available when the 1996 record of decision was published. Better geochemical knowledge of uranium on site sediments, as well as better hydrogeologic understanding of the aquifer and groundwater movement, have significantly improved the conceptual model of the uranium source and its role in the persistent dissolved uranium plume. These findings contribute to the more realistic and effective development of a remediation strategy in accordance with the 2005 Phase III feasibility study work plan (DOE-RL 2005).

3.0 Preliminary Simplified Conceptual Model

A simplified conceptual site model is presented in this report to support identification of the characteristics of the contaminant distribution to be treated so that appropriate technologies are considered based upon site conditions. A more complete presentation of the conceptual site model will be documented in a separate report and will be referenced in the final feasibility study report that is being prepared.

Figure 1 presents a simplified schematic of the multiple zones influencing uranium concentrations in groundwater at the 300-FF-5 Operable Unit.

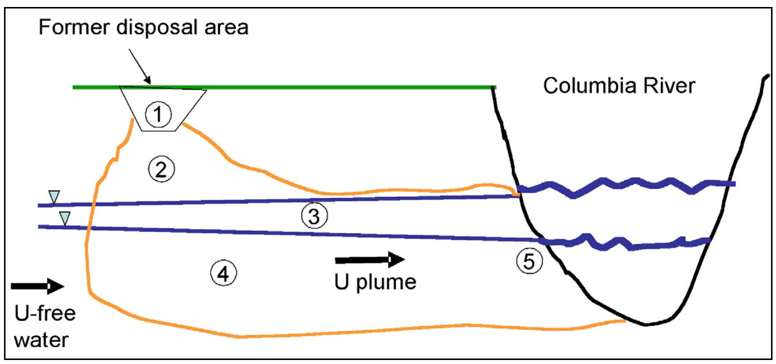

Figure 1. Simplified Conceptual Site Model

A brief description of the simplified conceptual model includes five different zones as shown on Figure 1.

- **Zone 1** represents the original waste disposal unit. It could be a former process pond, a process trench, or other waste discharge source. The waste discharge unit(s) and adjacent soil have or will be removed as part of source remedial actions. While initially a conduit for supplying uranium to the subsurface, no future impacts on the groundwater will occur. Backfill and surface cover materials will influence the degree that natural precipitation or water from human activities (e.g., irrigation) will infiltrate.

- **Zone 2** is the vadose zone between the deepest part of the source excavation and the highest excursion of the water table. Relatively high concentrations of uranium are likely to have migrated through this zone during operations. Limited sampling from test pits within and beneath excavated waste sites indicates that some amount of uranium remains sorbed to sediment in this zone.

- **Zone 3** is the zone between the maximum and minimum elevation of the water table. This zone is referred to as the "smear zone." During periods of unusually high water-table elevations (because of high-river stage conditions), uranium-contaminated groundwater moves into the lower vadose zone. When the water table returns to normal, some uranium is left behind in pore fluid and retained on soil particles, thus remaining as a potential source for plume re-supply if unusually high water-table elevations return. Therefore, in the past during uranium disposal, high concentrations of uranium were deposited in the smear zone (Zone 3) and can serve as a continuing current source to groundwater. Uranium storage in this zone has generally been observed in close proximity to waste disposal units (Zone 1). Presently, with the limited characterization conducted in Zone 3, there is insufficient evidence to determine the extent to which uranium contamination in this zone is present away from known waste disposal units.

- **Zone 4**, located mainly in the Hanford formation aquifer, is the uppermost hydrologic unit through which uranium migrates toward the Columbia River. The persistent uranium plume is observed in the groundwater of the upper Hanford formation. Dissolved uranium concentrations are influenced by sorption and desorption interactions with aquifer sediments depending on geochemical conditions.

- **Zone 5** is a highly dynamic zone of interaction between groundwater and Columbia River water that infiltrates the banks and channel substrate to varying degrees, depending on river stage and hydrogeologic properties of aquifer sediments. Geochemical conditions change rapidly within this zone because of chemical differences between groundwater and river water. Dilution of contaminants in groundwater typically occurs in this zone, prior to the ultimate discharge of groundwater into the Columbia River system.

Within the context of the feasibility study, the selection of remedial technologies and development of remedial strategies, the focus is on the smear zone (Zone 3) and the upper groundwater aquifer (Zone 4) where the uranium immediately affects the groundwater quality. Technologies for the lower levels of the vadose zone (Zone 2) are also considered. The interface zone between the groundwater and Columbia River (Zone 5) will be addressed incidentally by remediation of upgradient groundwater. Remediation of the waste disposal units (Zone 1) has already been completed.

The recently completed limited field investigation clarified our understanding of the uranium distribution outlined in the conceptual site model. Elevated concentrations of uranium relative to background were distributed within sediments in, slightly above, and below the water table. This zone of elevated sorbed uranium appears to correspond to a smear zone (Zone 3) reflecting the sediment levels that are influenced by groundwater-level fluctuations. Three of the four characterization boreholes were located adjacent to, but not directly within, uranium waste disposal areas (Zone 1). Excavations in such disposal areas have encountered high concentrations of process uranium above background levels in vadose zone sediments down to the water table (Zone 2). Presumably, these zones vertically beneath the disposal sites were pathways by which uranium migrated to groundwater when earlier discharges were occurring. Water samples were collected at multiple depth intervals in the groundwater column at each of four new boreholes. Analysis of these water samples indicates that dissolved uranium is present in the upper levels of the groundwater in all four locations. Groundwater concentrations exceeded the natural background concentration of uranium of approximately 10 µg/l in all four locations. Uranium concentrations in groundwater were detected as high as 202 µg/l, a concentration that is over six times the drinking water standard for uranium in groundwater. The dissolved uranium in the groundwater appears to move laterally primarily through the saturated high-permeability Hanford formation gravels and sands that are above the Ringold Formation silty sandy gravels.

The lateral distribution of uranium within the smear zone is not fully known because only four locations have been drilled. However, well-399-1-23 has the highest concentration of uranium, both in the vadose zone sediment immediately above the water table (Zone 3) and in the groundwater (Zone 4). This well is located within 23 m (75 ft) from the effluent end of the 316-5 Process Trenches. Vadose zone sediment in well 399-1-18 adjacent and downgradient of the South Process Pond, contains elevated uranium concentrations in sediments near the water table (Zone 3). The remaining two well locations, well 399-3-19 (east of the South Process Pond) and well 399-3-20, did not exhibit measurable indications of elevated uranium concentrations relative to surrounding areas in sediment or groundwater.

4.0 Regulatory Framework

The Phase III feasibility study is being conducted in accordance with the requirements described in *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA* (EPA 1988). This EPA guidance prescribes a process that includes the following tasks:

1. Establish remedial action objectives
2. Develop general response actions
3. Inventory applicable technologies and management strategies
4. Screen appropriate technologies
5. Combine technologies into alternatives
6. Preliminary screening of alternatives
7. Evaluate selected alternatives with nine criteria
8. Compare alternatives
9. Develop feasibility study report
10. Develop proposed plan.

Presently, the first four tasks have been completed and are documented in this report (Sections 4.0, 5.0, 6.0, and 7.0).

The primary remedial action objectives of the 300-FF-5 Operable Unit were established in the *Work Plan for the Phase III Feasibility Study* (DOE-RL 2005) based on the objectives stated in the record of decision for the 300 Area in 1996 (EPA 1996). These remedial action objectives are as follows.

1. Restore, to the extent possible, the groundwater aquifer to its highest and best beneficial use, which is presumed to be a drinking water supply.

2. Reduce risk to human health and the environment.

5.0 Identification and Inventory of Potential Remediation Technologies

The 1994 feasibility study (DOE-RL 1994) for groundwater treatment focused only on dissolved-phase uranium in groundwater in the saturated aquifer. The source of the contamination was assumed to be addressed by removal of contamination from vadose zone sediments as part of the 300-FF-1 Operable Unit remedial action. Ten years of groundwater monitoring and further site characterization has shown this remedial strategy to be inadequate. Consequently, the identification of remedial technologies for this Phase III feasibility study supplements groundwater control and removal technologies from the earlier feasibility study with source control and new in-situ technologies.

An inventory of potentially applicable remedial practices and technologies was conducted as part of the *Work Plan for Phase III Feasibility Study 300-FF-5 Operable Unit* (DOE-RL 2005). The technology inventory included all the technologies considered in the original 1994 Phase I and Phase II Feasibility Report (Table 4-1, DOE-RL 1994). Additional treatment technologies, particularly new and developmental in-situ treatment technologies for uranium, were also inventoried. At that time, the location, extent, and form of the uranium contamination was not known, particularly in regard to the source of the persistent uranium concentration in the groundwater. Consequently, when the first screening of technologies was conducted in 2004, only one of three screening criteria (implementability) could be applied.

Additional characterization information was available to support an updated inventory and categorization of technologies for the current technology screening. These technologies were categorized in terms of general response actions. The development of general response actions follow from the understanding of the source and mechanism by which the groundwater is contaminated by uranium. Presently, it appears that one significant cause of the persistent dissolved uranium is the long-term storage and periodic, pulse release of uranium residing in the smear zone sediments (Zone 3) and lower vadose zone sediments (Zone 2) into the groundwater (Zone 4). Subsequent identification, evaluation, and selection of remedial technologies must contend with the high permeability of the aquifer itself and treat the source of the uranium in the smear zone and possibly the lower vadose zone. The screening of prospective remediation technologies follows from this fundamental view of the problem. The updated inventory consists of 53 prospective technologies for groundwater, 6 prospective technologies for the smear zone, and 10 prospective technologies for the vadose zone. Table 1 lists the general response actions and the associated technologies considered in the technology screening. The table includes the source of information for each technology (e.g., the original remedial investigation/feasibility study, the work plan, or recent developments). No additional screening was conducted for those technologies rejected by the remedial investigation/feasibility study unless there have been relevant updates to the technology since 1995. New technologies or changed assessments on older technologies listed in the original 1994 feasibility study (DOE-RL 1994) are highlighted in yellow in Table 1.

Table 1. Inventory of Remediation Technologies or Management Approaches for Uranium (1 of 6)

General Response Action	Technology Type	Remediation Technology	Source of Information	Conclusion from 1992 RI/FS	Retained for Technology Screening
No Action	No action	No action	FS (DOE-RL 1992)	Retained as "baseline" case	Yes
Institutional Controls	Land-use restrictions	Deed restrictions	FS (DOE-RL 1992)	Retained to be used in conjunction with other process options	Yes
	Access controls	Signs and/or fences	FS (DOE-RL 1992)	Retained to be used in conjunction with other process options	Yes
	Monitoring	Monitoring	FS (DOE-RL 1992)	Retained to be used in conjunction with other process options	Yes
MNA	MNA	MNA	EPA 1999	Not explicitly listed in RI/FS but implied in 1994 ROD	Yes
Containment	Horizontal barriers	Subsurface barrier or surface cap	FS (DOE-RL 1992) and FRTR Version 4.0	NOT retained in RI/FS. Surface barriers not applicable to groundwater per se, but applicable to vadose zone.	No for groundwater; yes for vadose zone technology
	Vertical barriers	Slurry walls	FS (DOE-RL 1992)	Proven and feasible technology	Yes
		Grout walls - grout injection	FS (DOE-RL 1992)	Less effective and more costly than slurry walls	Yes
		Grout walls – deep-soil mixing	FS (DOE-RL 1992)	No more effective than slurry walls but more expensive	Yes
		Sheet piling	FS (DOE-RL 1992)	Not implementable due to rocky subsurface	No

Table 1. Inventory of Remediation Technologies or Management Approaches for Uranium (2 of 6)

General Response Action	Technology Type	Remediation Technology	Source of Information	Conclusion from 1992 RI/FS	Retained for Technology Screening
Containment	Vertical barriers	Cryogenic walls	FS (DOE-RL 1992) and DOE 1999	More expensive than slurry walls. Contemporary assessment: difficult to implement for long-term.	No
	Hydraulic containment	Pump to control or contain uranium plume	FS (DOE-RL 1992)	Feasible	Yes
Removal	Groundwater extraction	Wells	FS (DOE-RL 1992)	Established and feasible	Yes
		Interceptor trench	FS (DOE-RL 1992)	Established and feasible	Yes
	Aquifer soil dredging/excavation	Excavation with dewatering	FS (DOE-RL 1992)	Well developed and feasible. Contemporary assessment: not relevant to saturated zone uranium.	No for groundwater; yes for vadose zone technology
		Mechanical dredging	FS (DOE-RL 1992)	Well-developed and feasible. Contemporary assessment: not relevant to saturated zone uranium.	No for groundwater; yes for vadose zone technology
		Hydraulic dredging	FS (DOE-RL 1992)	Not effective for large cobbles	No

Table 1. Inventory of Remediation Technologies or Management Approaches for Uranium (3 of 6)

General Response Action	Technology Type	Remediation Technology	Source of Information	Conclusion from 1992 RI/FS	Retained for Technology Screening
Disposal	Treated groundwater	Surface water discharge	FS (DOE-RL 1992)	Feasible to Columbia River	Yes
		Subsurface discharge	FS (DOE-RL 1992)	Feasible	Yes
	Sludge and soils	Onsite disposal	FS (DOE-RL 1992)	ERDF was planned. Contemporary assessment: ERDF not large enough. Moist solid not compatible.	No
		Offsite disposal	FS (DOE-RL 1992)	Less preferred under CERCLA; no regional facility available	No
Ex-Situ Treatment of Groundwater	Separation	Gravity separation of suspended solids	FS (DOE-RL 1992)	Well established and feasible. Contemporary assessment: not relevant to dissolved uranium.	No
		Filtration of suspended solids	FS (DOE-RL 1992)	Well established and feasible. Contemporary assessment: not relevant to dissolved uranium.	No
		Ion exchange of uranium	FS (DOE-RL 1992)	Established: effective for low uranium concentrations	Yes
		Reverse osmosis	FS (DOE-RL 1992)	Effective for concentrating	Yes
		Ultrafiltration	FS (DOE-RL 1992)	Effective for high molecular weight compounds. Contemporary assessment: not effective with dissolved uranium.	No

Table 1. Inventory of Remediation Technologies or Management Approaches for Uranium (4 of 6)

General Response Action	Technology Type	Remediation Technology	Source of Information	Conclusion from 1992 RI/FS	Retained for Technology Screening
		Membrane-based coupled transport	FS (DOE-RL 1992)	Developmental	No
		Electrodialysis	FS (DOE-RL 1992)	Expensive, developmental	No
		Freeze/crystallization	FS (DOE-RL 1992)	Expensive, developmental	No
		Evaporation/distillation	FS (DOE-RL 1992)	Expensive	No
		Electrolysis	FS (DOE-RL 1992)	Expensive	No
	Chemical reaction	Precipitation	FS (DOE-RL 1992)	Effective for secondary waste stream	Yes
	Organic separation	Air stripping	FS (DOE-RL 1992)	Effective only for organics, not applicable to uranium	No
Ex-situ Treatment of Groundwater	Organic separation	Carbon adsorption	FS (DOE-RL 1992)	Effective only for organics, not with uranium	No
	Chemical reaction	Enhanced oxidation	FS (DOE-RL 1992)	Not applicable to uranium	No
		Chemical oxidation/reduction	FS (DOE-RL 1992)	Expensive	No
	Biological	Biological treatment	FS (DOE-RL 1992)	Not effective for uranium	No
	Thermal	Thermal treatment	FS (DOE-RL 1992)	Not applicable to uranium	No
In-situ Treatment	Physical	Vapor extraction	FS (DOE-RL 1992)	Not applicable to uranium	No
	Physical and chemical	In-situ flushing	FS (DOE-RL 1992) and FRTR Version 4.0	Potentially effective and feasible in so far as uranium is on sediments	Yes

Table 1. Inventory of Remediation Technologies or Management Approaches for Uranium (5 of 6)

General Response Action	Technology Type	Remediation Technology	Source of Information	Conclusion from 1992 RI/FS	Retained for Technology Screening
In-situ Treatment	In-situ precipitation/ fixation	Generic precipitation/fixation	FS (DOE-RL 1992), FRTR Version 4.0 and recent DOE-sponsored research	Formerly unproven. Contemporary assessment: see below for recent developments.	Yes
		Permeable reactive barrier – ZVI	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; reoxidation delayed but not prevented
		Permeable reactive barrier-amorphous ferric oxyhydroxide	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	Yes
		Permeable reactive barrier-hydroxyapatite	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	Yes
		Permeable reactive barrier-zeolite	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; not effective at aquifer water pH
		In-situ reactive barrier-injected polyphosphate	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	Yes
In-situ Treatment	In-situ precipitation/fixation	DART emplacement of ZVI and apatite pellets in wells	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; not applicable to Hanford formation
		In-situ reactive barrier-nanoparticle injection	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; reoxidation delayed but not prevented

Table 1. Inventory of Remediation Technologies or Management Approaches for Uranium (6 of 6)

General Response Action	Technology Type	Remediation Technology	Source of Information	Conclusion from 1992 RI/FS	Retained for Technology Screening
In-situ Treatment	In-situ precipitation/fixation	Colloidal ZVI injection	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; reoxidation delayed but not prevented
		In-situ reactive barrier-calcium citrate and sodium phosphate injection	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	Yes
		In-situ redox manipulation by dithionite injection	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; uranium reoxidizes and re-dissolves
	Biological	Microbial dissimilatory reduction of U(VI)	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; uranium reoxidizes and re-dissolves
		Anaerobic in-situ reactive zone	FRTR Version 4.0 and recent developments	New technology NOT addressed by RI/FS	No, see Table 2; uranium reoxidizes and re-dissolves

Yellow highlighting indicates new technologies or changed assessments on older technologies listed in the original feasibility study (DOE-RL 1994).
CERCLA = *Comprehensive Environmental Response, Compensation, and Liability Act.*
ERDF = Environmental Restoration Disposal Facility.
FRTR = Federal Remediation Technologies Roundtable: Screening Matrix and Reference Guide, Version 4.0: http://www.frtr.gov/matrix2/top_page.html.
FS = Feasibility study.
MNA = Monitored natural attenuation.
RI = Remedial investigation.
ROD = Record of decision.
ZVI = Zero valent iron.

6.0 Evaluation and Screening of Remedial Technologies

The screening process is presented in the following eight sections. Section 6.1 presents the remediation strategy. Geochemical considerations that control the efficacy of remedial technologies are discussed in Section 6.2, and Section 6.3 presents the screening criteria. Sections 6.4 through 6.6 present the screening of technologies for each targeted matrix.

6.1 Remediation Strategy

Presently, it appears that one significant cause of the persistent dissolved uranium is the long-term storage and periodic, pulse release of uranium residing in Zone 3 (smear zone) sediments and lower vadose zone sediments (Zone 2) into the groundwater. The high permeability of the aquifer itself would make direct extraction or treatment of groundwater inefficient. Therefore, treatment of the source of the uranium in the smear zone, and possibly the lower vadose zone, to reduce the availability of uranium to the groundwater and/or reduction of its mobility if it does reach the groundwater, appears to be a more effective remediation strategy. The challenge is how this stabilization, isolation, or interception is accomplished.

Physical encapsulation or in-situ stabilization of the uranium would have to be applied in a horizontal, planar geometry over a wide area. The typical method for contacting the subsurface is via wells or boreholes through which reagents are applied to the subsurface. The capability of such techniques to contact treatment volumes lateral to the borehole is generally very limited. Therefore, a large number of closely spaced injection points are required.

A second approach is to apply liquids to groundwater and use groundwater flows to laterally spread reagent. The reagent then reacts to stabilize or isolate uranium where contact is made. This process implies a chemical technology. The chemical technologies for treating uranium have become available for consideration only within the past decade. However, to screen appropriate chemical technologies for further consideration, an understanding of uranium chemistry is required.

6.2 Geochemical Considerations

The mobility of uranium in environmental surface and subsurface systems is highly variable, based on the geochemical environment where it is found. The principal variables affecting the environmental geochemistry of uranium are the oxidation potential (Eh), pH, temperature, composition of the aqueous pore fluid (especially the concentrations of complexing ligands such as dissolved bicarbonate/carbonate [HCO_3^-/CO_3^{2-}]), and sediment mineralogy. These five variables affect the reduction/oxidation (redox) state, aqueous complexation, precipitation/dissolution, and adsorption/desorption of uranium, which in total determines the mobility of uranium in environmental systems.

The primary variable determining the mobility of uranium in environmental systems is oxidation state. Uranium can exist in the +3, +4, +5, and +6 oxidation states in aqueous environments. Uranium(VI) and U(IV) are the most common oxidation states of uranium in natural environments. Uranium will exist in the +6 oxidation state under oxidizing to mildly reducing environments. Uranium(IV) is stable under reducing conditions and is considered relatively immobile because U(IV) forms sparingly soluble minerals. Dissolved U(III) easily oxidizes to U(IV) under most reducing conditions found in nature. The U(V) aqueous species (UO_2^+) readily disproportionates to U(IV) and U(VI).

Reducing conditions that are characteristic of many deep geologic environments are conducive to formation of sparingly soluble uranous [U(IV)] compounds, such as uraninite (UO_2) and coffinite ($USiO_4$). Such stabilization of uranium could also be promoted by creating reducing conditions using anaerobic biological process to create a reducing environment. Oxidizing conditions that tend to occur in near-surface environments such as the Hanford Site, in contrast, tend to release uranium precipitated or sorbed as U(IV) into shallow groundwaters and surface waters as the more stable uranyl, U(VI), aqueous complexes. Therefore, the problem with attempting U(IV) stabilization in shallow groundwaters, such as present in the 300-FF-5 Operable Unit, is long-term maintenance of anoxic, reducing conditions.

In the oxidizing conditions present in the shallow portion of the 300-FF-5 Operable Unit aquifer, uranium is present in the +6 [U(VI)] oxidation state, which forms a variety of aqueous complexes as a function of pH with natural organic and inorganic ligands present in the pore fluid. The presence and composition of ligands, temperature, and pH of the system will determine the environmental fate of uranium in the vadose zone and aquifer sediments beneath the 300-FF-5 Operable Unit. A key factor controlling the solubility of uranium in such oxic environments is the concentration of dissolved bicarbonate/carbonate [HCO_3^-/CO_3^{2-}]). If uranium is present as precipitated minerals in the vadose zone and aquifer sediments, atmospheric CO_2 and typical groundwater CO_2/calcite mineral equilibria, along with pH, will control the extent of solubility and adsorption of uranium in the shallow groundwater. Above pH 6, uranyl-carbonate complexes—e.g., $UO_2CO_3^0$(aq), $UO_2(CO_3)_2^{2-}$, $UO_2(CO_3)_3^{4-}$, and $Ca_2UO_2(CO_3)_3^0$(aq)—control the uranium geochemical cycle. Uranyl-carbonate complexation increases the solubility concentrations of uranium minerals and precipitates, facilitates U(IV) oxidation, and limits the adsorption of uranium to sediment minerals surfaces in oxidized waters, thereby increasing the mobility of uranium in groundwater (Langmuir 1997a and 1997b).

In addition to dissolved carbonate and hydroxide, uranium may form a number of aqueous complexes with dissolved fluoride, sulfate, and phosphate. The ranges of stability of such aqueous species as a function of pH and their ligand concentrations should be considered to formulate possible geochemical uranium management strategies. However, relative to carbonate complexes, uranyl fluoride and sulfate species are only stable under acidic pH conditions at the concentrations of fluoride and sulfate found in most groundwaters, and are not stable at the higher pH conditions associated with natural waters such as the oxic carbonate-rich, well-buffered near neutral (pH 7.5-8.5) pH groundwater of 300-FF-5 for uranium management (Langmuir 1978).

In contrast, formation of uranyl phosphate solid phases offers potential to assist in uranium management. In a pH range from 4 to 10 within which common groundwater pH conditions exist, U(VI) forms more stable solid phases with phosphate than with any other common ligand (Langmuir 1978).

The formation of uranyl-phosphate minerals is significant in terms of the uranium geochemical cycle; however, it is especially important in the context of remediation. The stability of uranyl-phosphate minerals is second only to the uranyl-vanadate minerals. However, in comparison, the prevalence of uranyl-phosphates, and in particular autunite minerals, this far exceeds that of the vanadates (Grenthe 1984; Langmuir 1978, 1997b; Smith 1984).

The geochemistry of uranium establishes a context where candidate in-situ chemical technologies may be evaluated within this screening process. Remedial strategies based on in-situ chemical stabilization will be only as effective as the geochemistry of the site permits. Such chemical technologies may be generally grouped according to the following paradigm. This framework assists in understanding the technology screening.

- *Redox Technologies* – These technologies attempt to manipulate oxidation-reduction conditions of the subsurface to reduce uranium to uranous (uranium IV) forms. The techniques include in-situ redox manipulation using sodium dithionite, zero-valent iron, microbial induced reduction, and calcium polysulfide technologies. The common deficiency of technologies in this category is that the reduced environment and corresponding uranium precipitate is easily re-oxidized over time. Consequently, over time the "treated" uranium is remobilized. It may be possible, depending upon the kinetics of the remobilization oxidation, to meet remediation goals in the saturated zone for groundwater if remobilization were slow enough to result in uranium concentrations below cleanup criteria.
- *Co-precipitated Iron Oxyhydroxide* – This technology affects only temporary stabilization because the reaction is reversed as the precipitate ages.
- *Phosphate Precipitation Technologies* – These technologies apply and modify phosphate with uranyl (uranium VI) forms to remove soluble uranium and prevent further dissolution of uranium by sequestration, immobilization, or precipitation. The resulting reaction seeks to create a stable, long-lasting reaction that removes the source of ongoing uranium contamination to the groundwater. Newly developed and developing approaches offer a variety of application techniques and reagent types. However, this group of technologies requires further development.
- *Flushing Technologies* – This group of remediation technologies uses a variety of leaching solutions to dissolve solid-phase uranium and hydraulic extraction techniques to remove the solubilized uranium with lixiviant residuals. This technology group is basically an extension of *in-situ* mining that has been practiced since the 1960's. Carbonate flushing solutions are typically employed. Subsurface stratigraphic heterogeneities make comprehensive treatment difficult to attain. Hydraulic capture and capture of the mobilized uranium can be problematic.

6.3 Screening Criteria

Potentially applicable technology types and process options were identified and screened in accordance with CERCLA guidance using effectiveness, implementability, and relative cost as criteria to eliminate those options that are the least feasible, and to retain those options that are considered most viable. The following criteria were considered in evaluating each technology under conditions specific to each treatment matrix or zone contributing to or containing the groundwater contamination. As discussed in Section 3.0, three zones were considered:

- Saturated sediments and groundwater of the upper aquifer (Zone 4).
- Smear zone (Zone 3) formed by the fluctuating water-table interface
- Lower vadose zone sediments (Zone 2).

A technology is considered *effective* if it is proven capable of or there is relatively low technical uncertainty associated with performance of the technology in the targeted matrix over the time period necessary to affect a permanent reduction of dissolved uranium in groundwater.

A technology is considered *implementable* if proven capable of being constructed and deployed in the type of the sediments found in the Hanford and Ringold Formations at the required depths below ground surface and operating at the necessary scale. The technology also must not interfere with other technologies if it does not address all of the contaminated volume, and must not pose potentially significant administrative issues (e.g., use of potentially unacceptable reagents).

The third criterion, *relative cost*, is evaluated on the technologies that passed the screen for effectiveness and implementability. The relative cost is considered by assessing whether the cost for a technology can be reasonably estimated, and whether high-cost factors for a technology render it grossly more expensive than other technologies with similar effectiveness and implementability.

Technologies are not required to address the entire volume of the operable unit if they do not operate in a way that prevents combination with another technology as part of a multiple technology approach to remediation.

6.4 Screening of Groundwater Technologies

Screening of both legacy and new technologies for groundwater is presented in Table 2. Technologies that originated in the Phase I and II feasibility study are italicized in the Table 2 listing.

The 2006 limited field investigation further confirmed the uppermost level of the unconfined aquifer associated with the Hanford formation is the principal location of dissolved uranium and has the highest concentrations of uranium in the aquifer. Depth-discrete water sampling from well 399-1-23, approximately 22.8 m (75 ft) from the south end of the 315-5 Process Trench, did have the highest uranium groundwater concentrations in Ringold Formation sediment at the Hanford/Ringold contact. This elevated occurrence of uranium in groundwater is theorized to be a residual effect of the waste discharge in the less-permeable and less-flushed Ringold Formation sediment. The uranium is the only observed exception to the general pattern of higher uranium concentrations associated with the uppermost levels of the aquifer near the water table, which coincidentally is located in the more mobile groundwater of the Hanford formation. Consequently, wide-area groundwater remediation will focus on the uppermost portions of the aquifer or the sources of uranium above the water table.

Three passive management practices, such as land-use restrictions, access controls, and monitored natural attenuation, were accepted for further consideration in the remediation alternative step of the feasibility study. These three passive actions presently form the basis of the present interim response and will be the basis of the baseline remedial alternative for the feasibility study, which will affect the least expeditious remediation of the uranium in groundwater.

Twenty-four active technologies for groundwater remediation have been identified for consideration. These technologies either involve some combination of pumping and treating groundwater ex-situ or in-situ hydraulic barriers. Treatment technologies were considered independent of the hydraulic control or extraction technologies. Recent advances in technology have brought an additional 13 technologies that focus on in-situ treatments. Since 1994, pilot-scale attempts to construct hydraulic barriers have not been successful because of large rocks in the upper sediments. Table 2 presents the results of the evaluation of these groundwater remediation technologies according to effectiveness and implementability.

The relative cost of eight implementable and effective groundwater technologies were evaluated. The preliminary economic comparison is summarized in Table 3. The very high permeability of the upper Hanford formation strata of the aquifer where the dissolved uranium contamination is located makes only limited, focused extraction pumping effective and feasible. Treatment of the extracted water ex situ is generally not cost effective unless combined with some phosphate-related, in-situ stabilization technology. Technologies that rely on water extraction, even if hydraulically successful, will only address the symptom but not the cause and source of the contamination. The naturally occurring groundwater flows far exceed the scale of engineered pumping, yet the uranium contamination of the groundwater has persisted. Presently, the two phosphate sequestration technologies appear to offer the best prospects for active treatment of dissolved uranium in the groundwater. The cost of long-term pumping with ex-situ treatment is an order of magnitude higher than the in-situ treatment technologies. The cost comparison for extensive-area pumping updated the 1994 assumptions of 28 large extraction wells deployed to attempt interception of groundwater parallel to the Columbia River. Pairing such a pumping system with the least costly ion-exchange treatment technology gives a capital cost of approximately $25 million. Annual operation and maintenance of such technology would cost approximately $7 million annually. Extended operation of such an extensive system over several decades, if effective, would require a long-term expenditure of approximately hundreds of million dollars. In-situ phosphate treatment technologies are estimated to require a relatively short-term expenditure of approximately $25 million dollars. The two phosphate technologies differ somewhat in reagent deployment, but are similar in implementation and effectiveness and relative cost. The phosphate technologies would expedite the water treatment because they can also treat the source of the uranium in the vadose zone sediments (Zone 2) and smear zone (Zone 3).

6.5 Screening of Technologies for Smear Zone Sediments Contributing to Groundwater Contamination

Screening of remediation technologies for the smear zone is presented in Table 4. Table 5 presents the final screening based upon comparison of relative cost.

The sediment in the fluctuating smear zone (Zone 3) is the conduit for lower vadose zone uranium to enter groundwater from source areas above and is potentially a repository of uranium acting as a source to groundwater contamination during high river stage. The Zone 3 vertical dimensions vary with temporal changes in the water-table level associated with changes in Columbia River water levels (hence the term "smear zone.") This interface zone between the fully saturated aquifer below and the vadose zone above consists of sediment with varying degrees of sorbed uranium and pore water containing dissolved, mobile uranium. Control or removal of uranium in this zone would prevent continuing replenishment of uranium into the upper Hanford formation aquifer where monitoring has indicated to be the primary location for dissolved uranium in the groundwater beneath the 300-FF-5 Operable Unit.

The thickness of the groundwater smear zone is approximately 2.5 to 3 m (~8 to 10 ft) and fluctuates with both the seasonal and daily Columbia River level variations. The median depth of this zone below ground surface varies between 9.75 and 12.25 m (~32 and 40 ft). Consequently, access to this zone entails passage through the overlying vadose zone that may or may not be contaminated, depending upon proximity to the original contaminant discharge and prior remediation work.

Six active technologies were identified to be considered in the screening process. One physical technology (e.g., selective excavation) was identified as being effective and technically implementable.

Though significant volumes of uncontaminated overburden would require handling, excavation of the remaining uranium-contaminated sediment may be cost effective, particularly if part of a related construction excavation. Slope stability set-back requirements, dewatering of contaminated sediment, and handling of vadose sediment overburden incur significant costs. Pressure grouting of the targeted smear zone is technically difficult to affect beyond a radius of 1 m (3.28 ft). Stabilization of the targeted zone by phosphate stabilization is judged to be effective, implementable, and economical. Application by infiltration of phosphate would be facilitated by the relatively porous, sandy sediment fill above the targeted residual zone. An ongoing pilot test is being conducted to verify the effectiveness and cost of phosphate stabilization. Other chemical and biological technologies are either ineffective due to incomplete technical development, reaction reversibility, or application difficulties.

6.6 Screening of Technologies for Vadose Zone Sediments

Screening of remediation technologies for the vadose zone is presented in Tables 6 and 7.

Uranium residuals have been encountered in soil/sediments directly below former waste disposal areas (Zone 1), such as the former discharge ponds. Contaminated sediments have been excavated from beneath the former ponds as part of the 300-FF-1 Operable Unit clean-up to a level of 267 pCi/g prior to backfill placement. Generally, the excavation depths in the pond areas did not extend to the water table. Consequently, residual uranium remains in this deeper portion of the vadose zone on sediment and in associated pore water that may migrate downward under some conditions as a source of uranium to the 300-FF-5 Operable Unit groundwater.

Ten active technologies applicable to the lower vadose zone sediments were identified and considered in the screening process. One physical technology, further excavation, was identified as being effective and technically implementable. Though significant volumes of uncontaminated overburden would require handling, excavation of the remaining uranium-contaminated sediment may be cost effective, particularly if part of a related construction excavation. The two phosphate stabilization technologies are judged to be effective, implementable, and economical. Application by infiltration of either phosphate technology would be facilitated by the relatively porous, sandy sediment fill above the targeted residual zone. Effective distribution and application of a reactive form of hydroxy apatite reagent other than liquid phosphate compounds is difficult in the relatively dry sediment. The application of a mobilizing lixivant, analogous to solution mining, would require not only application infrastructure but also an effective collection infrastructure, making the relative cost higher than phosphate-reagent stabilization technology application. Other chemical and biological technologies are either ineffective due to reaction reversibility or application difficulties.

Table 2. Technology Screen for Groundwater Remediation (1 of 6)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Passive	No action			Yes	Retained as "Baseline" case	Yes
	Institutional controls	Yes	Institutional controls and monitoring is the present interim remedy	Yes	Institutional controls and monitoring is the present interim remedy	Yes
	Monitored natural attenuation	Yes	Presently operative, but not fully effective because of continuing releases from untreated sources	Yes	Natural attenuation processes are occurring without intervention	Yes
Physical	Slurry wall containment	?	If cut off wall can be effectively inserted into less permeable zones, either containment or flow restriction could be affected	No	Large rocks and high hydraulic conductivity preclude slurry wall construction	No
	Grout walls - grout injection	?	Grout injection within a less permeable zone can effectively reduce flow and effect hydraulic control or containment. Grout wall in highly permeable zones may not be effective.	?	Proven construction technology; however, quality assurance is difficult. Construction in very high permeability Hanford aquifer would be problematic.	No
	Grout walls - deep soil mixing	?	Depth and heterogeneity of Ringold mud base layer are problematic in assuring effective containment	No	Depth to toe-in layer, large rocks and high hydraulic conductivity preclude consistent auger placement of grout	No
	Selective *hydraulic containment with pumping*	No	Focused pump and treat can be effective where hydrogeology permits moderate pumping rates. Hanford aquifer conditions preclude effective containment even at very high pumping rates. Continuous pumping from water supply well did not appreciably reduce uranium concentrations.	Yes	Proven technology. Groundwater withdrawn will require ex-situ treatment before disposal. Extremely high pumping rates would be required even for small areas.	No

Table 2. Technology Screen for Groundwater Remediation (2 of 6)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Physical	*Groundwater extraction-wells*	?	Focused groundwater extraction can be effective where hydrogeology permits moderate pumping rates. Hanford aquifer conditions generally require very high pumping rates. Continuous pumping from water supply well did not appreciably reduce uranium concentrations. Very localized pumping may be effective to facilitate in-situ treatment or flushing technologies.	Yes	Proven technology.	**Yes** Retained as groundwater flow management tool for in-situ treatment technologies. Very high permeabilities of Hanford aquifer preclude wide-scale deployment.
	Groundwater extraction-interceptor trench	?	Hanford aquifer permeability and aquifer layers call effectiveness of trench into question	No	Rocky, high permeability of aquifer would make construction of trench very problematic	No
	Treated water disposal to surface water (Columbia River)	Yes	Proven technology. Very large flows may require special diffuser or distribution system to prevent excessive scour, erosion, or ecological issues.	Yes	Proven technology. Water quality of treated water discharge will control NPDES permitting.	**Yes**
	Treated water disposal to groundwater (re-injection)	Yes	Proven technology. Care must be taken to not re-inject in location where subsurface contamination could be mobilized.	Yes	Proven technology.	**Yes**

Table 2. Technology Screen for Groundwater Remediation (3 of 6)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Chemical	*Ex-situ ion exchange*	Yes	Effective for low concentrations of uranium. Limited by effectiveness of groundwater extraction.	Yes	Proven technology. Concentrated uranium solution resulting from resin regeneration will require treatment/disposal.	**Yes**
	Ex-situ reverse osmosis	Yes	Effective for low concentrations of uranium. Limited by effectiveness of groundwater extraction.	Yes	Proven technology. Concentrated uranium solution resulting from process will require treatment/disposal.	**Yes**
	Ex-situ precipitation	Yes	Effective only for high concentrations of uranium in secondary waste streams. Limited by effectiveness of groundwater extraction.	Yes	Proven technology. Resulting waste stream will require further processing.	**Yes**
	In-situ flushing	Yes	Effective only on sorbed uranium where hydraulic contact and containment with flushing solution recovery can be obtained. Not effective on dissolved uranium per se.	No	High permeability of aquifer and focusing treatment to narrow, upper zone of saturated sediment are problematic. More properly applied to smear zone or vadose zone contamination.	**Yes, for uranium on sediments only**
	Permeable reactive barrier-ZVI	No	Short-term effectiveness of iron removal by iron possible but subject to dissolved oxygen, temperature, pH, and metal complexing agents. Long-term performance not effective due buildup of precipitates of carbonate minerals on reactive surfaces.	No	Excavation of barrier trench precluded by large rocks	No

Table 2. Technology Screen for Groundwater Remediation (4 of 6)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Chemical	Permeable reactive barrier-amorphous ferric oxyhydroxide	No	Uranium previously sorbed on amorphous ferric oxyhydroxide material tends to be desorbed with lower uranium concentrations, resulting in a re-release of uranium over the long term.	No	Excavation of barrier trench precluded by large rocks	No
	Permeable reactive barrier-hydroxyapatite	No	Least effective media for uranium removal relative to amorphous ferric oxyhydroxide or zero-valent iron (Naftz et al. 2002)	No	Excavation of barrier trench precluded by large rocks	No
	Permeable reactive barrier-zeolite	No	Efficiency and longevity of zeolite depends on sorptive capacity and specificity for uranium. Reactions that cause clogging and surface passivation are likely to be less significant because the chemical mechanism is primarily cation exchange. No uranium specific zeolites known.	No	Excavation of barrier trench precluded by large rocks	No
	In-situ reactive barrier-injected polyphosphate	?	Effectiveness controlled by application design and groundwater flow. Rapid autunite formation immobilizes uranium. Longer-term apatite formation provides backup process. Promising but not fully developed.	Yes	Multiple linear arrays of application wells could allow deployment in sediments with large boulders. Implementability remains to be demonstrated.	Yes

Table 2. Technology Screen for Groundwater Remediation (5 of 6)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Chemical	DART emplacement of ZVI and apatite pellets in wells	No	The application of the solid phase reagents requires close spacing (not more than two well diameters) of many wells. Long-term performance is compromised by buildup of deposits and precipitates on reactive media.	No	This technology assumes that the emplaced reagents have a higher permeability than the surrounding formation. The very high permeability of the Hanford formation, where most of the contamination exists, makes emplacement problematic.	No
	In-situ reactive barrier-nanoparticle injection	No	Technology in development. Effectiveness, particularly over the long term is problematic due to reoxidation and remobilization from ZVI.	Yes	Nanoparticle composition is unspecified, but zero-valent iron is the principal candidate	No
	Colloidal ZVI injection	No	Technology in development. Effectiveness, particularly over the long term is problematic. Long-term performance is not effective due buildup of precipitates of carbonate minerals on reactive surfaces.	Yes	Combine with in-situ reactive barrier by nanoparticle/ colloidal injection	No
	In-situ reactive barrier-calcium citrate and sodium phosphate injection	?	Microbial degradation of citrate over time facilitates application of phosphate to form apatite immobilization of uranium. Experimental technology in field application.	Yes	Injection of reagents in multiple wells to form an in-situ reactive barrier avoids problems with excavated trench construction	Yes

Table 2. Technology Screen for Groundwater Remediation (6 of 6)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Chemical	In-situ redox manipulation by dithionite injection	No	Application effectiveness controlled by stratigraphy. Short-term effectiveness of redox reaction controlled by presence of available iron. Long-term maintenance of reduced conditions required to maintain immobilization is problematic.	Yes	Application and injection of reagent uses multiple injection wells. Number of wells is controlled by well spacing, which remains to be determined for site conditions. Follow-up application of reagent feasible with wells.	No
Biological	Microbial dissimilatory reduction of U(VI)	No	Though short-term stabilization is likely effective, long-term stability of uranium is not effective unless continuing biological treatment is applied periodically in perpetuity	No	Long-term maintenance of biologically reduced zone is problematic	No
	Anaerobic in-situ reactive zone	No	Though short-term stabilization is likely effective, long-term stability of uranium is not effective unless continuing biological treatment is applied periodically in perpetuity. Addition of iron and/or sulfur additives delays but does not prevent re-oxidation and re-mobilization of uranium.	No	Long-term maintenance of biologically reduced zone is problematic	No

Italic text indicates technologies that originated in the Phase I and II feasibility study (DOE-RL 1994).
? = Insufficient data.
DART = Directed applied reagent technology.
NPDES = National Pollutant Discharge Elimination System.
ZVI = Zero valent iron

Table 3. Cost Screen for Groundwater Remediation Technologies (1 of 3)

Technology Type	**Technology**	**Effective?**	**Technically Implementable?**	**Retain for Further Consideration?**	**Rationale for Cost Evaluation**	**Retain for Alternative Assembly?**
Passive	*No action*	--	Yes	Yes	Continued monitoring for indefinite period with continued uranium exposure to the environment. Retain for "baseline" case.	Yes
	Institutional controls	Yes	Yes	Yes	Continued monitoring for indefinite period with continued uranium exposure to the environment. Incrementally higher operation and maintenance costs to maintain access controls; however, long-term risk of costly natural resources damage assessment.	Yes
	Monitored natural attenuation	Yes	Yes	Yes	Continued monitoring for indefinite period with continued uranium exposure to the environment. Effectively a continuation of the present interim action with the potential need for additional monitoring wells at additional expense.	Yes
Physical	Slurry wall containment	?	No	--	--	--
	Grout walls - grout injection	?	?	--	--	--
	Grout walls - deep soil mixing	?	No	--	--	--
	Selective hydraulic containment with pumping	No	Yes	--	--	--
	Groundwater extraction-interceptor trench	*?*	*No*	--	--	--
	Treated water disposal to surface water (Columbia River)	*Yes*	*Yes*	Yes	Disposal to Columbia River is less costly than re-injection. However, pumping and treatment of groundwater ex situ is at least one order of magnitude more costly than in-situ treatment.	No
	Treated water disposal to groundwater (re-injection)	*Yes*	*Yes*	Yes	More costly than discharge to Columbia River unless combined with in-situ treatment as required for hydraulic control. Very expensive ex-situ treatment costs favor re-injection in combination with an in-situ treatment.	No, would only be used where appropriate for hydraulic control of in-situ process

Table 3. Cost Screen for Groundwater Remediation Technologies (2 of 3)

Technology Type	Technology	Effective?	Technically Implementable?	Retain for Further Consideration?	Rationale for Cost Evaluation	Retain for Alternative Assembly?
Physical/ Chemical	*Groundwater extraction-wells* with in-situ treatment *(re-injection)*	Yes for make-up water	Yes	Yes	Retained only if in-situ treatment requires hydraulic control.	No, would only be used where appropriate for hydraulic control of in-situ process
Physical/ Chemical	*Groundwater extraction-wells* with ex-situ treatment *(see Treatments Below)*	? For U capture in Hanford formation	Yes	Yes	A limited system of 7 wells (350 gpm) would cost ~$800,000 without treatment. PV of 100 years operation with ion exchange ~ $60 million. Not cost effective for more than 5 years of operation.	No
Chemical	*Ex-situ ion exchange* of pumped groundwater	Yes	Yes	Yes	Small unit ~ 300 gpm: PV of 100 years operation with ion exchange ~ $60 million. Not cost effective for more than 5 years of operation. Large unit ~4000 gpm: prohibitively expensive-PV for 100 years on the order of $250 million.	No
	Ex-situ reverse osmosis of pumped groundwater	Yes	Yes	Yes	More costly than ex-situ ion exchange	No
	Ex-situ precipitation of pumped groundwater	Yes	Yes	Yes	More costly than ex-situ ion exchange	No
	In-situ flushing	Yes	No	Yes, for uranium on sediments only	In-situ flushing NOT cost effective, in high permeability aquifer due to poor control. Not applicable to thin interface zone deposits of uranium found in limited field investigation.	No
	Permeable reactive barrier-ZVI	No	No	--	--	--
	Permeable reactive barrier-amorphous ferric oxyhydroxide	No	No	--	--	--
	Permeable reactive barrier-hydroxyapatite	No	No	--	--	--
	Permeable reactive barrier-zeolite	No	No	--	--	--

Table 3. Cost Screen for Groundwater Remediation Technologies (3 of 3)

Technology Type	Technology	Effective?	Technically Implementable?	Retain for Further Consideration?	Rationale for Cost Evaluation	Retain for Alternative Assembly?
Chemical	In-situ reactive barrier-injected polyphosphate	?	Yes	Yes	In situ stabilization of uranium is generally one order of magnitude less than pump-and-treat technology. ~ $25 million depending upon extent of deployment.	Yes
	DART implacement of ZVI and apatite pellets in wells	No	Yes	--	--	--
	In-situ reactive barrier-nanoparticle injection	No	Yes	--	--	--
	Colloidal ZVI injection	No	Yes	--	--	--
	In-situ reactive barrier-calcium citrate & sodium phosphate injection	?	Yes	Yes	In situ stabilization of uranium is generally one order of magnitude less than pump-and-treat technology. ~ $25 million depending upon extent of deployment.	Yes
	In-situ redox manipulation by dithionite injection	No	Yes	--	--	--
Biological	Microbial dissimilatory reduction of U(VI)	No	No	--	--	--
	Anaerobic in-situ reactive zone	No	No	--	--	--

Italic text indicates technologies that originated in the Phase I and II feasibility study (DOE-RL 1994).
U = Uranium.
? = Insufficient data.
DART = Directed applied reagent technology.
PV = Present value.
Redox = Reduction and oxidation.
ZVI = Zero valent iron

Table 4. Technology Screen for Smear Zone Remediation (1 of 2)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Passive	No action	--	--	Yes	Retained as "baseline" case.	**Yes**
Physical	Selective excavation to water table	Yes	Deeper excavation removes uranium residuals where encountered	Yes	Implementable only for focused, localized areas. Excavation side wall stability would require handling large soil volumes and soil moisture would require dewatering processes. However, excavation is feasible.	**Yes**
	Pressure grout injection at water table with dense push rod well pattern	Yes	Grout can stabilize and isolate uranium from groundwater	No	Efficacy of technology dependent upon site conditions. If smear zone is widespread, grout injection is too localized be effective.	No
Chemical	Injection of reactive substance to form water barrier at water table	Yes	Physical mechanics of application and containment limit effectiveness. Reactive substance used determines effectiveness.	No	Physically feasible. Agent not yet identified or available.	No
	Stabilization by application of polyphosphate solution	?	Application effectiveness controlled by stratigraphy. Rapid autunite formation immobilizes uranium. Longer-term apatite formation provides backup process. Promising but not fully developed.	Yes	Polyphosphate application may be configured for differential reaction rate and delivery conditions. Dual delivery modes: percolation from surface application or timed flooding with elevated water table techniques.	**Yes**

Table 4. Technology Screen for Smear Zone Remediation (2 of 2)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Biological	Temporary bio-flushing to anaerobically stabilize uranium	?	Though short-term stabilization is likely effective, long-term stability of uranium is questionable unless continuing biological treatment is applied periodically in perpetuity.	No	Maintenance of biologically reduced zone problematic	No
	Anaerobic in-situ reactive zone	Yes	Anaerobic bioreduction has been demonstrated. However, long-term maintenance of reductive zone not proven.	No	Maintenance of biologically reduced zone problematic	No

Table 5. Cost Screen for Zone 3 (Smear Zone) Remediation Technologies

Technology Type	Technology	Effective?	Technically Implementable?	Retain for Further Consideration?	Rationale for Cost Evaluation	Retain for Alternative Assembly?
Passive	No action		Yes	Yes	Continued monitoring in perpetuity with continued uranium exposure to the environment. Retain for “baseline” case.	Yes
Physical	Selective excavation to water table	Yes	Yes	Yes	Higher relative cost compared with lowest cost technology, polyphosphate stabilization (1.8) for treating relatively thin ~15 acre smear zone.	Yes; only for small focus areas
	Pressure grout injection at water table with dense push rod well pattern	Yes	No	--	--	--
Chemical	Injection of reactive substance to form water barrier at water table	Yes	No	--	--	--
	Stabilization by application of polyphosphate solution	Yes	Yes	Yes	Lowest cost technology when applied over "prototype coverage area" based upon ~15 acre smear zone of North and South disposal areas. Relative cost factor 1.0, ~$20 million.	Yes
Biological	Temporary bio-flushing to anaerobicly stabilize uranium	?	No	--	--	--
	Anaerobic in-situ reactive zone	Yes	No	--	--	--

Table 6. Technology Screen for Vadose Zone Sediment Remediation (1 of 2)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Passive	No action			Yes	Retained as "Baseline" case	**Yes**
Physical	More extensive excavation to water table	Yes	Deeper excavation removes uranium residuals where encountered	Yes	Further excavation possible	**Yes**
	Impermeable surface cap	Yes, Partially	Reduces infiltration and associated transport of uranium from sediments above influence of water table, but not at uncovered locations	No	Wide-area hydraulic control not feasible due to very high permeabilities. Large rocks preclude cut-off walls.	No
Chemical	Vadose flushing with mobilizing agent and hydraulic extraction of solution	?	Physical flow dynamics of application controls effectiveness. Chemical used determines effectiveness.	Yes	Consider as a groundwater technology because agent collection will be in groundwater	**Yes**
	Vadose flushing with immobilizing agent-hydroxyapatite reaction	Yes	Application effectiveness controlled by stratigraphy. Hydroxyapatite reaction kinetics controls extent of effectiveness.	No	Application of hydroxyapatite in a reactive form through vadose zone not feasible	No
	Vadose flushing with immobilizing agent-polyphosphate	?	Application effectiveness controlled by stratigraphy. Rapid autunite formation immobilizes uranium. Longer-term apatite formation provides backup process. Promising but not fully developed.	Yes	Polyphosphate application may be configured for differential reaction rate and delivery conditions. Percolation from surface application may be conducted prior to or possibly after surface re-development; e.g. golf course.	**Yes**

Table 6. Technology Screen for Vadose Zone Sediment Remediation (2 of 2)

Technology Type	Technology	Effective?	Rationale for Effectiveness Screen	Technically Implementable?	Rationale For Implementability Screen	Retain for Further Consideration?
Chemical	Vadose flushing with colloidal ZVI	?	Application effectiveness controlled by stratigraphy. Short-term effectiveness of redox reaction controlled by presence of water. Long-term maintenance of reduced conditions required to maintain immobilization questionable.	No	ZVI most appropriate for groundwater not unsaturated soil. Nanoparticle ZVI will be considered as groundwater technology.	No
	Vadose flushing with dithionite solution	?	Application effectiveness controlled by stratigraphy. Short-term effectiveness of redox reaction controlled by presence of available iron. Long-term maintenance of reduced conditions required to maintain immobilization questionable.	No	Technology is proven but delivery of dithionite to unsaturated soil problematic.	No
	Vadose flushing with calcium polysulfide	No	Redox modification is not effective over the long term	Yes	Application of calcium polysulfide appears to be feasible using infiltration methods	No
	Vadose flushing with calcium citrate and sodium phosphate	?	Control and rate of microbial degradation of citrate in vadose problematic	Yes	A form of apatite technology; however, delivery technology not fully developed. Maintenance of moisture for citrate biodegradation not yet demonstrated.	Yes
Biological	Temporary bio-flushing to anaerobically stabilize uranium	No	Though short-term stabilization is likely effective, long-term stability of uranium is questionable unless continuing biological treatment is applied periodically in perpetuity	No	Maintenance of biologically reduced zone problematic	No

Table 7. Cost Screen for Vadose Zone Sediment Remediation Technologies

Technology Type	Technology	Effective?	Technically Implementable?	Retain for Further Consideration?	Rationale for Cost Evaluation	Retain for Alternative Assembly?
Passive	No action		Yes	Yes	Continued monitoring over long term with continued uranium exposure to the environment. Retain for "baseline" case.	Yes
Physical	More extensive excavation to water table	Yes	Yes	Yes	Higher relative cost compared with lowest cost technology, polyphosphate stabilization (1.8). May be cost effective in conjunction with shallow upper vadose zone excavation.	Yes, where other removal actions coincide
	Impermeable surface cap	Yes, partially	No	--	--	--
Chemical	Vadose flushing with mobilizing agent and hydraulic extraction of solution	Yes	Yes	Yes	Within high permeability Hanford aquifer, groundwater pumping for withdrawal of lixiviant solution is at least three times the cost of immobilizing agent flushing.	No
	Vadose flushing with immobilizing agent-hydroxyapatite reaction	Yes	No	--	--	--
	Vadose flushing with immobilizing agent, polyphosphate	Yes	Yes	Yes	Lowest cost technology, particularly if applied without wells.	Yes
	Vadose flushing with colloidal ZVI	?	No	--	--	--
	Vadose flushing with dithionite solution	?	No	--	--	--
	Vadose flushing with calcium polysulfide	No	Yes	--	--	--
	Vadose flushing with calcium citrate and sodium phosphate	?	Yes	Yes	Low cost technology, particularly if applied without wells. Comparable cost to (poly)phosphate percolation depending upon application process.	Yes
Biological	Temporary bio-flushing to anaerobicly stabilize uranium	No	No	No	--	--

7.0 Summary of Technology Screen

Potential remediation technologies and management practices have been identified to reduce uranium concentrations in groundwater within the 300-FF-5 Operable Unit. Because recent characterization has identified sources of uranium contributing to the groundwater contamination on sediments at the groundwater interface or "smear zone" (Zone 3) and potentially within the deep-vadose zone sediments beneath original uranium waste discharge areas, the technology inventory was expanded from the original aquifer centric scope of the Phase I and II feasibility study (DOE-RL 1994).

Fifty-three technologies or management techniques for groundwater were initially identified. Thirteen of the 53 technologies were additions to the 40 identified in the original feasibility study (DOE-RL 1994). The additions are new in-situ technologies that were not known earlier. Evaluation of these technologies on the basis of criteria from the 1994 feasibility study (DOE-RL 1994), including adjustments for 2006 conditions and with a focus on groundwater technologies, narrowed the original 53 technologies to 29 candidate technologies for groundwater. With the consolidation of 3 institutional control actions into 1 action, 27 actions and technologies were reduced to 13 using criteria of effectiveness and implementability. The 13 remaining technologies were reduced to 2 active technologies and 2 passive management strategies using the relative cost criteria.

The resulting active technologies for groundwater are as follows:

- In-situ polyphosphate treatment
- In-situ calcium citrate and sodium phosphate treatment.

The resulting passive management strategies for groundwater are as follows:

- Institutional Controls (Land-use restrictions, access controls)
- Monitored Natural Attenuation

Because the 1994 feasibility study (DOE-RL 1994) did not address the smear zone (Zone 3) where fluctuating water elevations produce a wetted layer of sediment, a new list of six prospective technologies was initially identified. The six technologies were reduced to two technologies using criteria of effectiveness and implementability. The two active technologies remained after applying relative cost criteria.

The resulting active technologies for the smear zone (Zone 3) are as follows:

- Selective excavation to the water table
- Stabilization by application of polyphosphate.

The 1994 feasibility study (DOE-RL 1994) also did not address the lower vadose zone; rather, the authors assumed that remedies deployed in the 300-FF-1 Operable Unit upper vadose zone would protect groundwater. A new list of 10 candidate technologies was identified. Using criteria of effectiveness and implementability, the 10 were reduced to 4 technologies. Three active technologies remained after applying relative cost criteria.

The resulting active technologies for the vadose zone are as follows:

- More extensive excavation of sediment to the water table
- Vadose flushing with polyphosphate immobilizing agent
- Vadose flushing with calcium citrate and sodium phosphate.

Remedial strategies will be developed by combining selected technologies into multiple alternatives based on the results of this technology screening. The alternatives will likely incorporate different assemblages, sequencing, and application areas/zones of technologies. The detailed analysis and comparison of the remedial alternatives will form the basis of the feasibility study.

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