Radioactive Waste Management Program

Sherwood Uranium Mill Project TECHNICAL EVALUATION REPORT

June, 1998

Washington State Department of
Health

Environmental Health Programs

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Contents

Abstract

The Department of Health in Washington State regulates uranium and thorium mill operations and closure. Western Nuclear, Inc. operates the Sherwood Project site, located north of Spokane, Washington on the Spokane Tribe Indian Reservation.

This Technical Evaluation Report reviews the Sherwood Project for compliance with regulations and license requirements.

Radioactive materials, wastes from the milling of uranium, have been isolated in a lined impoundment. Mill tailings were disposed in a neutral pH. Mill buildings were decommissioned and disposed in the impoundment. Contaminated soils were identified by a thorough sampling and analysis protocol and disposed in the impoundment.

The mill site was re-graded and re-vegetated, after removal of buildings, equipment, and contaminated soils.

Once filled, the impoundment was covered with more than 12.6 feet of site borrow soils and re-vegetated. A diversion channel was constructed around three, up-stream sides of the impoundment. The impoundment dam, constructed during operations, was re-graded to complement the cover design and to provide a 20%, rock-covered outslope. A rock-armored swale outlet for the impoundment cover watershed area was installed.

All impoundment and margin areas have been covered with rock armor or re-vegetated to provide structural stability. Regulations require a design that effectively controls radiological hazards for 1,000 years, to the extent reasonably achievable, and, in any case, for at least two hundred years.

The Sherwood Project closure design was evaluated against applicable regulations and against regulatory guidance and staff technical positions prepared by the U.S. Nuclear Regulatory Commission.

Remaining closure tasks include a Monitoring and Stabilization Plan to assure that construction activities have been successful, vegetation has been adequately established, and potential ground water impacts are monitored.

When all regulatory requirements are completed, the Sherwood Site will transfer to federal government responsibility. It is likely that the U.S. Department of Energy will assume responsible for access, monitoring, and custody of the radioactive materials at the Sherwood Project site. The U.S. Nuclear Regulatory Commission will be responsible for regulatory oversight. The land will remain the property of the Spokane Tribe.

Transfer of responsibility will occur when all current regulatory and license requirements are met and the required transfer agreements have been implemented.

KEY WORDS: *uranium, mill, radiation, radioactive material, tailings, closure, reclamation, cover, cap, diversion, erosion, vegetation, evapo-transpiration, regulations.*

Executive Summary

The Department of Health in the State of Washington (WDOH) regulates uranium and thorium milling operations and closure. The Sherwood Project, operated and now closed by Western Nuclear, Inc. (WNI), is reviewed herein for compliance with applicable regulations. The NRC Standard Review Plan (NRC 1993a) is used as the basis for this review.

The Sherwood Project has been reclaimed. Rock is placed in critical areas. Natural species of plants have been seeded. Ponderosa Pine trees have been planted. Re-vegetation of site soils has progressed since construction was completed in the fall of 1996.

Remaining project tasks are identified in radioactive materials license WN-I0133-1, and in the project's Monitoring and Stabilization Plan (SMI 1997). Remaining sub-tasks are:

- Structural Stability (Erosion).
- Vegetal Coverage.
- Ground Water.

This report reviews the Sherwood Project, to date, for compliance with regulation, WAC 246-252 (WAC).

This report has determined that the site has been fully reclaimed, subject to completion of the Monitoring and Stabilization Plan phase. All construction aspects have been verified for compliance with all regulatory requirements. WDOH regulations have been used for the basis of this review. In addition, NRC guidance documents have been used consistently to prepare plans and specifications.

During the plan review and concurrence phase, WDOH found that the conventional clay-barrier tailings cover design was not compatible with site-specific conditions at the Sherwood Project site. Therefore, a thick, homogeneous cover design was developed. The resulting cover design requirement is 12.6 feet of uncompacted borrow soil. A vegetated cover was required to limit infiltration into the impoundment wastes. Adequate evapotranspiration by native plant species is expected at the Sherwood Project site, due to meteorological and site-specific environmental conditions.

Additionally, WDOH also determined that dewatering of tailings was marginally feasible and that tailings were best kept saturated.

During operations, WNI placed neutralized tailings in a lined impoundment. This has resulted in no significant release of tailings constituents at monitoring wells around the impoundment. The neutralized state of tailings placement has limited the potential for hazardous or radioactive chemicals to be soluble or mobile. Keeping the tailings saturated limits the exposure of tailings to oxygen in the tailings vapor space.

Because the impoundment liner retains pore fluids and the tailings are mostly slimes near the bottom of the impoundment, there exists a natural limitation on pore fluid permeability. Release of tailings pore-space fluids is limited by the synthetic liner in the short term and by the low permeability tailings in the long term.

The constructed slope of the impoundment cover is approximately 0.25%. There is a potential that settlement will occur on the surface due to consolidation of tailings and cover materials. The thick, homogeneous cover provides sufficient load to produce settlement. However, WDOH review staff have determined that settlement of the surface provides no detrimental effect on site performance. Therefore, the effect of settlement was not included as a design requirement.

If settlement is great enough, it could produce a surface that will impound surface waters. Spring runoff could accumulate for a short term before being evaporated each summer. Company and department staff inspection of soils placed on the cover have identified sufficient fine material (clay and silt) content that moisture will not infiltrate quickly and may pond. If ponding of surface liquids occurs, it will enhance plant and animal diversity at the site.

Vegetation is a primary design requirement, as defined at the Sherwood Project. The thick, homogeneous cover design must include a reliable vegetative cover to be effective.

At the Sherwood Project site, a conventional, clay-barrier design would be breached by intrusion of Ponderosa Pine trees, unless buried very deep. Clay-barrier designs also have questions of construction feasibility. Significant quality control is necessary, as is a reliable source of low-permeability borrow soils.

Detailed water balance studies were performed based on several successional plant communities, and under several severe environmental conditions. Range fires, precipitation events, long-term changes in climate, and drought were considered. Early to late successional plant communities were evaluated. Only in the initial re-vegetation phase, directly after construction, and for a short time after a severe wild fire, was there any potential for infiltration of precipitation into the waste. This limited infiltration break-through only occurred under modeling of abnormally wet climatic periods. This is a limited likelihood over a small portion of the site longevity requirement.

This report reviews all aspects of the Sherwood Project for regulatory compliance. Each section reviews a specific portion of these requirements. In each case, performance aspects of the site are weighed against requirements and found to be in compliance. Regulatory requirements and NRC guidance reviewed together and in total also find the site in compliance with regulation.

Introduction

The Department of Health in Washington state (WDOH) has regulatory authority for oversight of the Sherwood Project site, operated by Western Nuclear, Inc. (WNI).

The property is owned by the Spokane Tribe of Indians and is located on the Spokane Tribe's reservation in northeast

Washington approximately 40 miles northwest of Spokane, Washington.

The Sherwood Project once mined and milled uranium ores for the purpose of uranium recovery. The Sherwood site operated from 1978 to 1984. Reclamation of the site has been performed since, including;

- Decommissioning of the mill buildings and equipment, and disposal in the mill tailings pond.
- Contaminated soils cleanup and disposal in the mill tailings pond.
- Construction of a diversion channel around the mill tailings impoundment.
- Reconstruction (re-grading) of an impoundment dam.
- Hardening of an impoundment outlet swale, dam surface, and groins with rock (riprap).
- Construction of a mill tailings impoundment cover.

Mill decommissioning and contaminated soil cleanup actions were performed under mill decommissioning (SMI 1997b) and radiological verification plans (SMI 1996a). Construction of diversion channel, dam embankment, and mill tailings cover were performed under tailings reclamation plans (SMI 1997a). Continuing, post-construction monitoring is performed under a monitoring and stabilization plan (SMI 1997).

The WDOH specific license, WN-I0133-1, will be terminated when all regulatory requirements have been met by WNI. When terminated, the U.S. Department of Energy (DOE), or another federal agency designated by the President, will be responsible for long-term custody of the site. The U.S. Nuclear Regulatory Commission (NRC) will provide regulatory oversight through a license.

The Technical Evaluation Report (this report) is the WDOH review for the Sherwood Project for the reclamation phase of site closure. The NRC *Standard Review Plan* (NRC 1993a) was developed for review of remedial action of inactive mill tailings sites under Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Although the Sherwood Project site is a Title II site, WDOH has adopted this NRC review method.

The NRC *Standard Review Plan* includes:

- Areas of Review.
- Acceptance Criteria.
- Review Procedures.

The *Standard Review Plan* recommends areas of review for the following subject areas:

- Geology and Seismology.
- Geotechnical Stability.

- Surface Water Hydrology and Erosion Protection.
- Water Resource Protection.
- Radon Attenuation and Site Cleanup.

The balance of this report is broken up into review areas roughly approximating the NRC guidance. WDOH has separated the Radon Attenuation and Site Cleanup activities. The titles of each section have been revised to be more consistent with site-specific actions at the Sherwood Project site. A section on Construction Considerations has been added. A Reference section is included to identify significant documents reviewed by WDOH. Appendices are included to clarify details of the geotechnical and radon flux (emanation) rate review.

When the monitoring and stabilization plan phase is complete, either this report will be augmented with an additional section, or a separate review and document will be prepared for this final reclamation phase.

Geology and Seismology

The geology and seismology section is segmented into major sub-sections. Geologic investigation includes Review of Geologic Literature, Field Geology Mapping Study, Borehole Geophysical Study, and Seismic Study. A section on Climate identifies Sherwood Project site-specific meteorology.

Geologic Investigation

The geologic investigation was designed to better understand the geologic framework in which the tailings impoundment is situated. By understanding the types of geologic materials present, their relationships to each other, and the structures that exist within the individual geologic units, it is possible to more accurately evaluate the relationship between the tailings impoundment and the associated hydrologic and ground water systems.

The geologic investigation consists of four tasks:

- Geologic literature review.
- Field geologic mapping study.
- Borehole geophysical study.
- Seismic study.

Data obtained from the geologic investigations provided the physical framework for evaluating:

- Performance of the impoundment reclamation design.
- Transport of potential contaminants in the ground water system, should they leak from the impoundment.
- Development of an effective ground water protection plan.

Review of Geologic Literature

Review of geologic literature for the Sherwood Project area provides insight into the regional geologic framework and provides a basis for a more detailed field geologic mapping study of the tailings impoundment area.

The literature review indicates that crystalline igneous rocks underlie the region. Structural deformation, including folding and faulting of the crystalline bedrock, has locally preserved some slightly younger volcanic and clastic materials in down-thrown fault blocks. Subsequent periods of volcanic activity, after the period of structural deformation, have deposited layers of ash and basalt flows. More recent glacial events have eroded the surfaces of these older rocks and deposited thick layers of sand, silt, and gravel over the eroded bedrock surface. Surface topography surrounding the Sherwood Project site consists of gently rolling sandy hills formed by the gradual erosion of glacial sedimentary deposits.

See references utilized by Shepherd Miller, Inc. for regional geology presented in Appendix P of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994b).

Regional geology described in these references was compared to more recent regional geologic mapping prepared by Washington State Department of Natural Resources (WDNR), Division of Geology (Waggoner 1990). Waggoner's map indicates the same basic suite of igneous rock types at the Sherwood Project site as described in SMI 1994b, but with different estimated ages of the rocks based upon updated information. Waggoner's map indicates strong north-south regional structural trends; different from the east-west structural trends described in SMI 1994b. Detailed mapping of the tailings impoundment area indicates that the geologic framework of the tailings impoundment area is consistent with the general geology presented on regional maps for the area.

Field Geologic Mapping Study

In order to obtain site-specific geologic data at a level of detail greater than could be derived from the geologic literature, a field geologic mapping study was initiated to supplement the geologic reconnaissance performed by Western Nuclear, Inc. during the past 16 years. See Section 3.1 and Attachment C.2 of SMI 1994. This mapping study was designed to evaluate surface geologic conditions and their potential influence on the ground water system for the tailings impoundment drainage basin. The purpose of this mapping study includes the establishment of baseline geologic conditions and the selection of areas for seismic and surface geophysical investigations.

More than 100 rock outcrops were identified during the field investigation. Lithologic, textural, and structural features were noted and recorded at 97 different outcrops. Strikes and dips of joints, slickensided surfaces, faults, and fractures were measured. Several faults and several dominant orientations of jointing and fracturing were identified in and around the tailings impoundment area. However, no continuous or large-scale faults, joints, or fractures that could influence the gross scale hydrology of the area were observed. Shear zones that appear in outcrops in the impoundment area are filled with clay. The structural geology of the Sherwood Project area, developed from the field investigation, is presented on Figure C.2.1 in *Sherwood Project, Ground Water Protection Plan, Technical Integration Report* (SMI 1995a).

Borehole Geophysical Study

A borehole geophysical study was performed on selected wells completed in the bedrock at the tailings impoundment area, to supplement the surface geologic mapping and to observe the nature of ground water flow in the open-hole portions of the wells. The study was performed using a down-hole video camera and a natural gamma probe. The down-hole camera was used both to video the inside of selected wells to check the well construction and to observe the flow of water into the wells. The observation of water flowing into the well after it had been bailed dry aided in understanding the way ground water flow occurs in the conductive bedrock. The natural gamma probe allowed confirmation of the geologic logs of older wells by detecting the difference in natural gamma radiation between the bedrock and the overlying glacial sediments.

Results of the borehole geophysical study indicate that the original geologic and well construction logs from the wells are accurate. In addition, the ground water recharging into the wells was observed to flow very slowly from only a few discrete fractures. Many adjacent fractures were dry and provided no ground water flow. This indicates that fractures in the upper bedrock are discontinuous and not all hydraulically connected.

Seismic Study

A seismic study of the tailings impoundment area was performed to map the bedrock surface and to delineate subsurface structures that may influence ground water flow. This task provides a more detailed picture of the subsurface geology and its potential influence on the tailings impoundment and the drainage basin hydrologic system. The seismic survey included more than five miles of geophysical traverses consisting of five seismic reflection survey lines totaling over 9,500 feet in length, and five seismic refraction lines totaling over 17,000 feet. The seismic line locations are presented on Figure 3.3 of Appendix P of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994b).

Results of the geologic investigation revealed that the tailings impoundment is located in a drainage basin in which both surface water and ground water flow toward the south. Seismic studies delineated the buried bedrock surface. The bedrock surface generally defines the lower portion of the subsurface drainage and approximately mirrors the surface topography prior to development at the site.

A few zones of low seismic velocity were observed in the seismic refraction lines to the east of the impoundment. However, no structures, which could influence ground water flow paths, were identified. It was not possible to correlate these few low-velocity zones with surface structures observed during field mapping.

Placement locations of monitoring wells MW-8, MW-9, and MW-10 were based on results of a previous survey conducted down-gradient from the tailings dam. This previous seismic survey showed that the bedrock surface underneath the tailings impoundment creates a southward draining basin. The basin edges correspond to the high outcrops identified during field mapping. Bedrock occurs near or at the surface on the basin edges and becomes more deeply buried toward the center of the drainage basin and toward the south of the drainage.

Bedrock depths are the greatest at the point of compliance below the tailings dam where the glacial sand cover is over 200 feet thick. This drainage basin drains to the south through a narrow, steep-sided valley in the bedrock surface directly below the tailings dam. Wells MW-8, MW-9, and MW-10 were drilled in the deepest part of the alluvial valley, and provide a check on the seismic study results and confirmed the location of bedrock surface.

Climate

The climate at the Sherwood Project site is a continental type, characterized by warm, dry summers and cold winters. The majority of precipitation occurs in the fall and winter, as rain and snow, respectively. Maximum runoff typically occurs in the spring as a result of snowmelt. Long-term average annual precipitation is estimated at 18 inches, based on a 103-year record for Spokane, and a 46-year record for Wellpinit. Evapo-transpiration substantially exceeds precipitation during most of the year. However, some runoff and infiltration during the spring is projected for the site until vegetation is established. These issues are discussed in detail later in this report and can be found in the *Sherwood Project, Re-vegetation Reclamation System Evaluation* (SMI 1995).

Geotechnical Stability

Geotechnical stability pertains to Characterization of Tailings Impoundment Stratigraphy, Slope Stability, Settlement, Liquefaction Potential, Soil Cover Engineering Parameters, and Cover Soils Hydraulic Conductivity. Characterization of Tailings Impoundment Stratigraphy includes sub-sections for Characterization of Tailings, and Foundation Stratigraphy and Stability. Slope Stability includes the Main Embankment, and Margins. Topsoil is identified under Soil Cover Engineering Parameters.

Characterization of Tailings Impoundment Stratigraphy

The stratigraphy of the tailings impoundment and underlying foundation is addressed in detail in Appendix P of the *Sherwood Project Tailings Reclamation Plan* (SMI 1994b). The structural stability of the existing disposal area, including the foundation, has not changed since original licensure. Impoundment structures were originally designed and constructed consistent with Regulatory Guide 3.11, "Design, Construction, and Inspection of Embankment Retention Systems for Uranium Mills" (NRC 1977). The initial characterization and structural stability analysis of the foundation may be found in a report prepared by D'Appolonia Consulting Engineers (D'Appolonia 1978). The main embankment dam was approved and has been inspected periodically by engineers from the Washington State Department of Ecology, Dam Safety Section.

Characterization of Tailings

Characterization studies were designed and conducted to determine the geotechnical properties of the tailings material. Characterization results provided the basis for structural stability analysis and information needed for settlement predictions.

Physical properties of the tailings were characterized using two tailings surface samples, 151 split spoon samples, and seven Shelby Tube samples obtained from ten borings. The split spoon samples were separated according to bulk composition characteristics into 246 individual samples. Grain-size distribution, Atterberg limits, natural moisture content, and radium-226 analyses were performed on 76 selected samples. Individual samples from these 10 borings were then grouped according to grain-size distribution in order to represent four tailings material types (i.e., sands, slimy sands, sandy slimes and slimes). A composite sample was obtained from each material type and then analyzed for grain-size distribution, Atterberg limits, specific gravity, 15-bar moisture content, radium-226, thorium-230, total uranium, and radon emanation.

In the spring of 1993, samples were obtained from nine additional borings in the tailings impoundment that were drilled as part of the pilot dewatering study. The borings were placed on 60-foot centers in a square configuration located at the deepest part of the tailings impoundment. The tailings profile was sampled continuously in each boring to within five feet of the impoundment liner. Samples were visually classified among four tailings material types, and selected samples were analyzed for grain size distribution and hydraulic conductivity. Although the tailings profile exhibited complex detailed stratigraphy, two general statigraphic layers were identified for the impoundment. The upper 50 to 60 feet of the tailings profile consist of sands, slimy sands, and sandy slimes, while the lower 15 to 25 feet primarily consist of slimes and sandy slimes.

Foundation Stratigraphy and Stability

Unconsolidated alluvial sands and underlying bedrock and quartz monzonite are discussed in detail in Appendix P of the *Sherwood Project Tailings Reclamation Plan* (SMI 1994b). Cross-sections illustrating the tailings impoundment and its relationship to these formations are shown in Figure 5 and Figure 6. The ground water table is primarily located in the alluvial sands underlying the tailings impoundment. At the point of compliance (POC) wells located at the toe of the tailings dam, ground water is approximately 270 feet below the impounded tailings. Review of static water levels (SWLs) over time indicates that fluctuations in the ground water elevations are such that contact with tailings is not feasible even if the 30 mil Hypalon® liner were absent or failed. Static water levels are greater than 200 feet below the impoundment.
Engineering properties of the foundation materials were evaluated in detail prior to construction. The pre-construction site investigations and testing are summarized in a 1978 report prepared by D'Appolonia Consulting Engineers, Inc.

Slope Stability

The significant slopes at the Sherwood Project site include the Main Embankment for the dam and the Margins between the diversion channel and the mill tailings cover.

Main Embankment Dam

The Main Embankment Dam was initially constructed with a 3H:1V slope configuration. During reclamation the outslope was reduced to a more gentle slope of 5H:1V. Professional engineering staff from the Dam Safety Section of Department of Ecology reviewed structural stability of the main embankment. Dam Safety engineers determined that the proposed, gentle outslope was stable and an improvement over the original dam configuration.

Static and pseudo-static slope stability analyses were performed on the longest slope length of the reconstructed 5H:1V main embankment. Analysis input parameters were obtained from the design report prepared by D'Appolonia Consulting Engineers, Inc. (D'Appolonia 1977) from typical material values and from soil characterization tests. Results of the analyses indicate that the 5H:1V main embankment is stable with a minimum factor of safety of 2.89 for static conditions and 2.29 for dynamic conditions. These factors of safety are much greater than the industry accepted values of 1.5 for static and 1.1 for dynamic conditions.

Liquefaction was also considered. Design reports were prepared that concluded that since the dam embankment cannot become saturated under any scenario, liquefaction cannot occur.

Margins

Structural analyses were performed using the PC Stable 5M computer program (Verduin et. al. 1987) to evaluate the potential for slope failure of margin areas. Four cross-sections, representing the four worst-case conditions, were selected for analysis. Input parameters were estimated using values determined from site soil characterization studies and typical material values. No phreatic surface was used in the analyses because water, which might seep from the diversion channel, will drain through the margin areas without forming a phreatic surface. Results of the analyses indicated that margin areas are stable with a calculated minimum factor of safety of 1.7 for static conditions and 1.5 for dynamic conditions. These factors of safety are greater than the industry accepted limits of 1.5 for static and 1.1 for dynamic conditions.

Liquefaction will not occur since the materials in margin areas cannot become saturated.

Settlement

Settlement could be caused by:

- The load imposed by fill required for the sub-grade elevation.
- The load from the cover material.
- The increase in effective stress if tailings were to become unsaturated.
- Liquefaction-induced settlement.

Structural stability of the reclaimed tailings impoundment surface was evaluated by using an estimate of the amount of differential settlement that could occur due to these factors. Effects of settlement could manifest in cover features in three ways:

- Ponding.
- Cracking.
- Localized surface erosion.

Settlement estimates range from less than a foot, occurring in the first year, up to over nine feet over 45 years (90% of ultimate settlement), using worse-case assumptions.

To establish a basis for settlement estimates, Shelby tube samples were split into 6-inch sections and tested for moisture content, in situ dry density, and grain-size fraction passing the # 200 sieve size. Two of the 6-inch sections were selected for consolidation testing. These sections were selected based upon a visual determination of high slimes content. This selection was intentional to provide the most conservative consolidation parameters. Results of analysis are included in Appendix L to the *Sherwood Project Tailings Reclamation Plan* (SMI 1994).

Cone penetrometer tests were performed in 1995 that show a continuous plot of tip resistance, sleeve friction, friction ratio, and pore pressure versus depth.

Settlement was estimated for tailings cover surface as a function of soil cover loading and potential dewatering of tailings.

Tailings stratigraphy, which largely controls settlement, has been identified to be highly heterogeneous in the impoundment. See Appendix A and Appendix P of the *Sherwood Project Tailings Reclamation Plan* (SMI 1994 and SMI 1994b). In order to analyze the settlement potential of the tailings materials, assignments were made for the horizons below the vertical extent of the borings but above the impoundment liner, based on the percentages of each material type observed in the borings. Since slimes have the highest consolidation potential, they were conservatively assumed to exist in the lower strata for settlement analysis, where they would be under the greatest compressive stress.

Reconstruction of the main embankment was an extension down-slope and away from the tailings impoundment. This eliminated any potential for slime zones to encroach under the dam embankment foundation.

Analysis of the thick, homogeneous cover design revealed the potential for settlement to occur that could result in ponding. The re-vegetated cover surface allows ponding only for limited time frames, in the winter and spring. Evapotranspiration of any standing water will occur in the summer and fall. In areas where ponding may occur, plant species diversity is expected. This plant diversity will enhance the ecosystem and promote adaptation to changing environmental conditions (SMI 1995).

Cracking due to differential settlement is discussed, in detail, below in the Soil Cover Engineering Parameters section. Analysis shows that the thick, homogeneous cover is erosionally stable even without vegetation. Vegetation will only enhance erosional stability.

In conclusion, the thick, homogeneous cover design is not sensitive to settlement. Settlement monitoring is not required.

Liquefaction Potential

Professional engineers from the Dam Safety Section of Department of Ecology reviewed liquefaction potential of the cover system and the main embankment. It was determined that liquefaction potential is low, especially since no component other than tailings is expected to be in a saturated state.

Liquefaction of slimes may potentially damage cover performance. However, liquefaction of slimes is not expected to produce a flow that would spill outside the limits of the impoundment (WDOE 1995a). A homogenous cover, greater than 12.6-feet thick, using local borrow materials, is not likely to be damaged even if slimes become liquefied during a seismic event. There is considerable structural stability in the cover material to prevent large-scale rafting of the cover. Even if liquefaction occurs at depth, the thick cover will contain the liquefied slimes due to the bulk of cover material over-riding the slimes. Even if some cracking of the surface were to occur, it would self-heal promptly.

The prediction of post-liquefaction displacements is a rapidly evolving field and difficult to predict. Vaid and Thomas (Vaid 1995) found in laboratory testing that immediately following the development of a liquefied condition in a saturated soil, the soil experiences a period of very low shear resistance en route to achieving its residual undrained shear strength. This low shear resistance phase appears to be a function of:

- The maximum shear strain during dynamic loading.
- The magnitude of effective confining stress immediately after the earthquake.
- The relative density (Vaid 1995).

Utilizing a methodology developed by Byrne, post-liquefaction displacements are predicted to vary from near zero to an upper bound of 9 feet for horizontal movement (Byrne, 1994). Even during a seismic event, the thickness of the cover would make eruption of liquefied slimes onto the ground surface unlikely.

Soil Cover Engineering Parameters

Sand, clay, quartz monzonite, and topsoil characterizations were conducted to determine the quantity and type of borrow materials available onsite. Appendix A and Appendix B of SMI 1994 provides data regarding soil borrow material characteristics. Additional visual descriptions of each soil borrow type are provided in staff inspection reports. See descriptions of borrow material types and their properties in internal WDOH staff correspondence (Stoffel 1996).

Fourteen borings were taken from nine potential site soil borrow sources. Approximately 50% of the boring profiles were represented by 126 split spoon samples. The split spoon samples were separated, according to bulk composition characteristics, into 149 individual samples. Sixty-three of the individual samples were submitted to the laboratory for grain-size distribution and natural moisture content analysis. Atterberg limit tests were conducted.

The majority of borrow material soil utilized in the cover was weathered quartz monzonite that was ripped during excavation of the surface water diversion channel located adjacent to the impoundment. During the ripping process, the weathered quartz monzonite easily broke down and separated into fine to coarse-grained soil. The clay fraction associated with the ripped weathered quartz monzonite and the clay layers encountered during diversion channel excavation ensures that the soil cover performance for radon attenuation is greater than the conservatively modeled design based on RADON computer code calculations, using uncompacted sand properties for input parameters. Company and department staff inspections during construction observed significant fines content (clay and silt) in cover soils placed. See the section on Radon Emanation Potential.

With a well-graded particle-size distribution, cover soils are not likely to erode over the 1,000-year design life. This is because well-graded soils are internally erosionally stable and will not allow release of fine particles to wash out or segregate from the soil matrix.

Detrimental effects of freeze-thaw are not expected. The thick, homogeneous cover design provides a self-healing benefit from freeze-thaw effects. Cracking due to settlement and shrinkage is not likely (SMI 1995).

Topsoil

Seven growth media (topsoil) stockpiles were sampled to evaluate suitability for vegetation growth. All samples were analyzed for typical chemical and physical plant growth parameters; including texture, organic matter, pH, electrical conductivity, and macro and micro plant nutrients. Supplemental fertilizer requirements were developed.

Results of the characterization revealed that sufficient topsoil was available to provide a minimum of 6 inches of topsoil placement. Supplemental fertilizer applications were made to help establish self-sustaining vegetation.

Cover Soils Hydraulic Conductivity

Hydraulic conductivity requirements for traditional clay-barriers are typically specified as a maximum permeability of 10^{-7} cm/sec.

Analysis performed for the thick, homogeneous cover design revealed that this specific requirement is not necessary in order to achieve the desired infiltration and radon emanation rate limits.

Extensive water balance and vegetation productivity analyses determined that infiltration could be effectively limited by enhanced evapo-transpiration (ET) associated with natural vegetation.

Modeling results indicate that enhanced evapo-transpiration can achieve better performance than a clay-barrier design (SMI 1995). Worst-case conditions such as before vegetation is established or after a forest fire were incorporated into the model. Even under worst-case conditions, the amount of predicted infiltration will not adversely impact average site performance over the long term.

The thick, homogeneous, vegetated cover also has the benefit of being stable for the design requirement of 1,000 years, without active maintenance. The thick cover avoids performance issues that arise if a clay-barrier design is used. The Sherwood site is located in a Ponderosa Pine forest. Ponderosa Pine trees would intrude and damage a clay-barrier.

The required cover design thickness was derived from modeling radon emanation rates using the RADON computer code (NRC 1989) and determining the thickness required to achieve the radon emanation rate regulatory limit. Soil density specifications were selected as uncompacted (except construction traffic) sandy soil values, to be conservative and to eliminate construction compaction and associated quality control requirements. In practice, some compaction occurs due to construction equipment traffic and settlement.

Limiting infiltration rates through the cover and into the waste is a regulatory requirement and design goal. A clay-barrier design attains this goal, in principle, by limiting the maximum flow (infiltration) rate through the soil cover. The thick, homogeneous soil barrier has greater permeability and can potentially pass a greater amount of water for a given period of time. However, productive soils in an environment conducive to well-established vegetation can eliminate most, if not all, expected precipitation by evapo-transpiration. Modeling of the thick, homogeneous cover for water balance was performed (SMI 1995).

Long-term climatic conditions, and natural vegetal succession, consistent with site conditions and adjacent natural vegetation settings, were used to predict seasonal water balance of the productive zone of the soil (upper few feet of the soil within the root zone of natural species). Except for a short period just after the initial re-vegetation period, there was no net infiltration past the root zone under any reasonable or likely occurrences expected in the long-term. Therefore, a thick, homogeneous cover meets the design goal of limiting infiltration into the waste.

Surface Water Hydraulics

Surface Water Hydraulics includes sections for Hydrologic Description, Flood Flow Rate Determination, Flood Flow Depths, Velocities, and Shear Stresses, and Erosion Protection. Flood flow rates are based on the Probable Maximum Precipitation (PMP) Estimates and the Probable Maximum Flood (PMF) Estimates. Erosion Protection considers the TDA surface, Margin Slopes, Diversion Channel, the TDA Swale Apron, and the beneficial affect of Natural Vegetation.

Hydrologic Description

The only source of continuously flowing surface water in the vicinity of the tailings impoundment is the Spokane River, located approximately 700 feet below the lowest elevation of the reclaimed site and a distance of approximately one mile south of the Sherwood Project site. There are no continuous or ephemeral streams in the vicinity of the tailings disposal area (TDA) that could provide continuous runon from a surrounding watershed.

A diversion channel has been constructed around the west, north, and east sides of the impoundment surface, effectively cutting off the potential for runon to the impoundment from higher elevations during flood events. The outlet of the diversion channel is located approximately 600 feet east of the southeast corner of the TDA. The size of the watershed that could contribute water to the diversion channel is approximately 700 acres (SMI 1994).

During reclamation plan development, WNI's tailings impoundment up-slope watersheds were evaluated. Several small but distinct basins were identified that under extreme conditions could possibly provide drainage into confluences along the diversion channel flow path. These basins are delineated in Figure 2 in Appendix D of *Sherwood Project, Tailings Reclamation Plan* (SMI 1994).

The primary source of surface water drainage on the TDA is from direct precipitation onto the impoundment surface and the adjoining margins of the diversion channel. The southern boundary of the TDA is an impoundment-dam structure with rock-covered outslopes (5H:1V). The impoundment cover slopes toward the east and then south. Drainage of the impoundment surface is mostly adjacent to the impoundment surface to the east. An outlet swale was constructed southeast of the impoundment surface at the east end of the impoundment dam. This outlet drains any potential runoff from approximately 167 acres of the TDA cover (SMI 1995f).

Flood Flow Rate Determination

WAC 246-252-030, Criterion 6, requires structural stability of the impounded tailings for 1,000 years to the extent reasonably achievable, and in any case for 200 years. Guidance developed by the NRC recommends conservative hydraulic design bases (NRC 1990). The design basis event for erosion protection is the Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) events. These criteria are based on the maximum precipitation and flood flow rates that could possibly occur. Determination of flood flow rates is necessary to evaluate structural integrity. PMP events must be characterized in order to prepare flood flow hydrographs needed to determine flow rates and subsequently for structural evaluations.

Probable Maximum Precipitation (PMP) Estimates

The Probable Maximum Precipitation event was estimated using Hydrometeorological Report Number 43 (USDC 1966). A 6-hour PMP storm of 11.5 inches was identified as the maximum precipitation event that could possibly occur for the Sherwood Project site. The 6-hour PMP was subdivided into one-minute time increments and evaluated using the HEC-1 program

(COE 1991) to obtain the temporal precipitation rate distribution for the design storm.

It has been shown that when the rainfall rate peaks near the center of the storm event duration, the most conservative (largest) PMF peak flood discharge is produced. This method was used. In addition, the 6-hour design storm was converted from a 24-hour event, resulting in conservatively higher rainfall intensities (18 inches per hour peak precipitation intensity).

Probable Maximum Flood (PMF) Estimates

The Probable Maximum Flood is dependent on the characteristics of the PMP event, the hydraulic characteristics of the watershed (surface roughness and terrain), and on surface water balance characteristics (infiltration, surface water storage, evapo-transpiration, and runoff) prevailing at the time of the event.

Two procedures were used to estimate PMF peak discharges for the site. The HEC-1 (COE 1991) computer program was used for both the TDA and surrounding watershed. The TDA was also analyzed using the Modified Rational Method (Chow 1964). The Modified Rational Method is recommended by the NRC in *Final Staff Technical Position - Design of Erosion-Protection Covers for Stabilization of Uranium Mill Tailings Sites* (NRC 1990).

Basin watershed surface roughness characteristics were determined using the U.S. Soil Conservation Service Curve Number (CN) (USBR 1977). CN values were estimated by considering each type of surface condition (soil and vegetation) prevalent for each basin. A CN value of 78 was determined to be appropriate for the site. This CN value is consistent with a "fair range/pasture land" soil and vegetation condition. The Sherwood Project site and surrounding watershed basin is consistent with this description.

After rainfall occurs over a drainage area, there is a delay in time (the lag time) between the occurrence of precipitation at the surface and peak runoff at any particular location downstream. Lag times were estimated using a procedure developed by the U.S. Soil Conservation Service (SCS 1985). This method is typically used for flood flow estimates for small watersheds.

Soil moisture at the beginning of the PMP event was assumed to be near saturation. This is consistent with Antecedent Moisture Condition (AMC) III (Nelson et. al. 1986). This assumption is considered conservative, since it allows no water balance consideration for potential infiltration, surface ponding, or evapo-transpiration. All precipitation therefore results in surface runoff. AMC III was used in modeling flood flow using the HEC-1 computer program.

The Modified Rational Method (Chow 1964) uses a coefficient (C) that represents a multiplier accounting for water balance losses. For example, C = 1.0 indicates 100% runoff (no infiltration, surface ponding, or evapo-transpiration). C = 0.8 indicates 80% runoff. C = 1.0 (100% runoff) was used in modeling flood flow rates at the Sherwood Project site, using the Modified Rational Method. Three candidate surface cross-sections were evaluated to determine the worst-case maximum design discharge for the TDA surface. See Figure 1, Appendix G of

Sherwood Project Tailings Reclamation Plan (SMI 1994).

The Corps of Engineer's HEC-2 computer program (COE, 1991a) was used to estimate the peak discharge for the diversion channel. This program provides maximum flood flow rates, flow depths, and velocities. Peak discharge for design purposes (PMF) for the diversion channel was estimated at 5325 cfs (cubic feet per second) (SMI 1994). Maximum tailings disposal area swale outlet flood flow rates was estimated at 720 cfs (SMI 1995f).

Flood Flow Depths, Velocities, and Shear Stresses

After peak discharges (PMF) are estimated, flood flow depths, velocities, and surface shear stresses are determined for those discharges. These parameters provide the basis for determining what, if any, erosion protection features are needed. Vegetation coverage and/or rock of adequate size and depth are provided, by design, to mitigate peak flood flow impacts from erosional defects.

Water surface depths and flood flow velocities were estimated using two procedures. For the TDA surface and all embankment and margin slopes, Manning's Equation (Chow 1959) was used. For the diversion channel, the HEC-2 (COE 1991b) computer program was used. Both methods are recommended by the NRC in NUREG/CR-4620 (NRC 1990).

Erosion Protection

Peak flood flow discharges, flood flow depths, velocities, and surface shear stresses were determined for the TDA surface, margin slopes, margin apron/toe, diversion channel, and dam embankment outslope. Surface shear stresses were used as input for design of surface protection features.

Soil slopes were analyzed to ensure that the length of the slope does not exceed a critical distance where gullying could occur. If so, potential erosional defects are mitigated by design features, such as minimum vegetal coverage or placement of rock (riprap). A summary of erosion protection design requirements is contained in *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996).

TDA Surface

The surface of the impoundment (TDA) is designed with a relatively flat slope of 0.25%. A minimum vegetated soil cover is adequate for erosion protection of this slope. Vegetation enhances evapotranspiration, and minimizes potential infiltration. In NRC guidance (NRC 1990), the minimum slope recommended for reclaimed TDA surfaces is 2%. This recommendation is made in order to enhance runoff and minimize infiltration. The Sherwood Project design is not expected to produce significant infiltration rates.

For erosion protection, flatter slopes are preferred. Therefore, the Sherwood Project TDA surface slope design of 0.25% is adequate.

Calculations using the NRC/Horton Method (NRC 1990), confirmed that the TDA surface is erosionally stable with minimal vegetation and without riprap or rock mulch.

Expected vegetation coverage for the TDA surface will promote ET and serve to make the cover erosionally stable with a considerable factor of safety.

Margin Slopes

The Sherwood Project TDA is located in a small watershed basin. There are up-gradient slopes (margin slopes) to the west, north, and east of the TDA. A down-gradient impoundment dam embankment outslope is located to the south. The margin slopes transition the area between the higher elevation diversion channel and the TDA surface. Margin slope design ranges from 3H:1V at the west and north, to 5H:1V at the east. See Figure 4 of the *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996) for final construction topography and margin slope configurations.

Margin slopes were analyzed to be adequately erosionally stable if a 39% vegetal coverage is attained under worst-case conditions and locations. Other conditions and locations have a somewhat lesser erosional stability requirement. Some locations have inherently erosionally stable soils (large sand, gravel or natural bedrock). No riprap or rock mulch is required, so long as vegetal coverage is assured, where needed. See Appendix A - Vegetal Coverage for details of the evaluation of vegetal coverage requirements for margin slopes. Statistically-based monitoring data are used to evaluate vegetation coverage after reclamation construction completion.

Methods identified in the *Sherwood Project, Monitoring and Stabilization Plan* (SMI 1997) are used to perform vegetation coverage monitoring.

By design, riprap is placed in a 10-foot transition zone between margin slopes and the TDA surface. Three-inch diameter (D_{50}) riprap was placed. See Detail 2 on Sheet 6 of the Reclamation Drawings (SMI 1996).

Diversion Channel

The diversion channel is a prominent feature of the Tailings Reclamation Plan design. The design of the diversion channel is quite conservative in relation to the flood flow design basis (PMF). The surface roughness (Manning's n Number), used in the design development, directly influences expected flow depth and velocity conditions. Projections indicate that just after construction, design flood flow velocities may be as high as 4.5 to 6.0 feet per second, and flood flow depths will be moderate in the diversion channel, as designed. After many years, natural reforestation is expected. Projected design flow velocities are then expected to be as low as 1.5 to 2.0 feet per second, and flood flow depths are expected to be much higher. Flood flow rates are the product of flow velocity and flow cross-sectional area; a function of flow depth and geometry of the channel. The diversion channel design is provided with rock erosion protection (riprap) in the lower portion of the channel to resist high flood flow velocities and shear stresses. The upper portion of the channel is not protected with rock, since flood flow velocities are expected to be considerably less.

A larger diversion channel cross-sectional area is needed for slower flood flow velocities that would occur after reforestation. The diversion channel is designed to contain the discharge (PMF) under worst-case conditions. See *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996) for details of the diversion channel design.

Confluences occur along the diversion channel where discharges from each watershed basin intercept the main diversion channel. Confluences have additional design requirements. Design analyses have determined that these locations have greater velocities due to greater slopes from intercepting basin stream flows. Calculations of the Froude Number (near 1.0) indicate that there is critical flow at these confluences. (A Froude Number near 1.0 indicates a turbulent flow condition and the possible occurrence of hydraulic jumps and standing waves.) This condition requires increased erosion protection. Rock size requirements for the diversion channel in the vicinity of the confluences are significantly increased over the nominal rock size requirement for the balance of the channel (SMI 1996). See Appendix B, Rock and Filter Sizing and Gradation, for specific analytical justification for diversion channel riprap requirements. See *Sherwood Project, Revised Technical Specifications and Executive Summary* (SMI 1996) for detailed specifications for diversion channel rock protection.

Sedimentation of the diversion channel was evaluated to determine if any significant loss of diversion channel cross-sectional area might occur over the design period (1,000 years). If so, the channel might possibly be breached by flood flows that may occur in the future. If breached, the diversion channel might erode and allow diversion channel flood flow to escape the channel, flow across the TDA surface, and exit through the TDA Swale outfall. The diversion channel design was evaluated for cross-sectional area adequacy, including potential for sedimentation.

Soil deposition in the diversion channel was evaluated. Initial evaluation used flood flow runoff rates from a 10-year storm. Sedimentation rates were predicted using the computer code SEDCAD+ (Civil Software Design 1992). Storms with various return intervals were then considered, including the 10-year, 20, 50, 100, 200, and 500-year storms, and summed to evaluate the entire spectrum of possible storm events. See Table 1.1 of *Sherwood Project Responses to WDOH Comments on the December 1994 Tailings Reclamation Plan* (SMI 1995e) for projections.

The HEC-6 computer program (COE 1993) was also used to evaluate sediment transport and deposition. An inherently conservative limitation to the use of the HEC-6 computer program is that it was developed to predict steady-state (continuous flow rate) sediment build-up, such as occurs behind a flood control impoundment dam. HEC-6 calculations predict, under expected potential infiltration conditions, that there is no flood flow expected to occur in the diversion channel (and thus no flushing of sediment) except for 100-year or larger flood flow events. Without sediment flushing, sedimentation of approximately 1.5 feet at the bottom of the diversion channel is expected, based on the analysis.

Sedimentation is expected to occur at the transitions (confluences) from the relatively steep slopes of the watershed basins to the relatively shallow (0.25 - 0.75%) slope of the main diversion channel. This amount of deposition is not expected to significantly reduce the diversion channel flow cross-sectional area, nor allow for any potential increase in the potential for breach of the diversion channel. See Table 1.5 of the *Sherwood Project Responses to WDOH Comments on the December 1994 Tailings Reclamation Plan* (SMI 1995e). The diversion channel configuration includes an adequate freeboard for the worst-case flood flow with predicted sedimentation build-up, and for a slow-flowing reforested channel.

Professional engineers from WDOE analyzed the unlikely scenario where flood flow breaches the diversion channel, flows over the TDA surface, and out the TDA swale outfall. They concluded that the TDA swale outfall has sufficient emergency flow capacity to handle this additional flow, according to their risk-based criteria.

Riprap of the diversion channels and the associated confluences from the eight drainage sub-basins was analyzed using methods referenced in the *Final Staff Technical Position - Design of Erosion Protection Covers for Stabilization of Uranium Mill Tailings Sites* (NRC 1990). Bends in the diversion channel (radius of curvature) were analyzed using techniques found in *Hydraulic Design of Flood Control Channels* (COE 1970). Shear stresses produced by the PMF flow are compared to allowable shear stresses, based upon an assumed riprap size. For the diversion-channel design bend-radius at the Sherwood Project, these shear stresses proved to be insignificant.

Riprap sizes were selected to be equivalent to or greater than required by analysis. Design specifications allowed for larger riprap sizes for the ease of construction. Diversion channel design includes rock-protection placement one foot above the projected PMF flow depth determined by analysis, as an added factor of protection.

The diversion channel design includes larger rock sizes 50 feet up- and down-slope of each confluence, consistent with the larger rock size requirement of the confluence. See Appendix E of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994), and the Confluence Erosion Protection Appendix in the *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996).

The outfall of the diversion channel represents the transition from the engineered channel to the natural drainage surface. Without adequate protection, this transition may erode and headcut up-slope back into the diversion channel. If this occurs, it might eventually affect the adequate dispersal of flood discharges away from the TDA surface. A possible mitigation alternative is an outfall apron of heavy rock erosion protection. If acceptable, erosion may be allowed to occur.

A geomorphic report was prepared to evaluate erosion potential at the diversion channel outfall (SMI 1995f). An outfall apron was deemed unnecessary. The diversion channel outlet is located approximately 600 feet to the east of the TDA swale outfall. The great extent of the diversion channel margin soil mass, as well as the distance from the TDA surface, is considered adequate protection.

Review by professional engineers at the WDOE concurred that a diversion channel outfall apron is unnecessary (WDOE 1995).

TDA Swale Apron

The TDA swale outfall from the TDA surface requires erosion protection from potential headcutting that might result from erosional scouring at the transition to natural ground. There is considerable rock protection provided by design for the general swale outfall region. The swale outfall is approximately 200 feet wide with rock provided approximately 200 feet upstream of the slope transition at the TDA swale outfall to natural ground. A heavy-rock swale outfall apron is provided at this transition in slope, and extends down and under the natural soil. See *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996) for design details. The swale width and the prevalence of vegetation in the natural ground slope will prevent significant scouring. Vegetation of the TDA surface over time will also significantly reduce the potential for runoff at high flood flow rates.

Natural Vegetation

Wherever erosional stability is not provided by rock, either: (1) vegetation will succeed; (2) soils will not support vegetation, yet remain erosionally stable; or (3) vegetation will not succeed and erosion will occur. For the Sherwood Project, natural site conditions encourage vegetation success. This is evident from the surrounding habitat and the natural vegetation in the area. Even in areas where rock is provided, vegetation is likely to encroach over the long term.

In many cases, natural slopes are erosionally stable even without erosion protection from vegetation, either because of short or shallow slopes, or because of inherently stable soils or bedrock. Some slopes require vegetation for adequate erosional stability. In all cases, prevalence of vegetation is considered an enhancement of reclamation performance, either for erosion protection, or for enhanced evapo-transpiration and reduced infiltration, and runoff.

Soil placement on the TDA surface and the TDA margin slopes includes approximately 1 foot thickness (or more) of topsoil. This soil was either harvested from excavated surfaces during construction, or during initial site development and operations. Topsoil at the Sherwood Project is a rich, productive, sandy loam soil, with considerable amounts of fine silts and clays.

Of all project surfaces, the TDA margin slopes require the greatest vegetal coverage for adequate erosional stability. Analysis indicates that 39% coverage is necessary for vegetation alone (without rock) to provide adequate surface shear stresses to resist the worst-case design storm (PMF) flood flows, velocities, and shear stresses. This requirement is conservative in that the impact of storm flow rates and velocities is greatest at the bottom portion of slopes and at areas of greatest total elevation drop. There are several areas of the TDA margin slopes that have natural bedrock, firm weathered bedrock, or soils with predominantly large particle sizes; all of which have enhanced natural erosional stability, in addition to that provided by vegetation. There are some areas of the margin slope that may be susceptibility to erosion. These areas must have adequate vegetation to prevent erosion from occurring or recurring. See Appendix A, Vegetal Coverage, for details of vegetal stress analysis.

When evaluating the *Sherwood Tailings Reclamation Plan* (SMI 1994), it was discovered that for a design to be valid for a 1,000-year period, the design must consider and be complementary to the natural processes likely to occur. Vegetation will develop at the Sherwood Project site with site-specific plant and animal community diversity. Although there will be variations with time and natural environmental processes, vegetation will be less dependent on the initial selection of vegetation species or application methods and more on the local ecology. For this reason, it was determined that any vegetation species and application method is appropriate and adequate, so long as short-term erosional stability is attained. Specific re-vegetation methods are not expected to affect long-term performance.

Vegetation design was selected from natural species that prevail in the area of the Sherwood Project site. Rye grain was seeded as a cover crop during initial re-vegetation. Straw mulch was added on the TDA surface. Topsoil is amended with fertilizer. Ponderosa Pine trees were planted on the TDA surface.

Water Resources Protection

Water Resources Protection includes sub-sections on Mill Tailings Impoundment Investigation, Basin Hydrologic Evaluation, and Leak Detection Monitoring Program. Mill Tailings Impoundment Investigation considers Tailings Material Sample Collection and Analysis, Pumping Test and Pilot Dewatering Program, and Tailings Impoundment Water Quality. Basin Hydrologic Evaluation is divided into Ground Water Monitoring System, Ground Water Occurrence and Flow Rate, and the Integrated Site Model.

Reclamation design at the Sherwood Project incorporates a thick homogeneous cover, greater than 12.6 feet thick, over saturated tailings. Several ground water investigations, data analyses, and modeling efforts were conducted in order to established that the reclamation design will meet long-term objectives of protecting ground water, consistent with regulatory requirements of *Chapter 246-252*, Criterion 5 and Criterion 6 (d) (WAC).

The reclamation cover design has the performance benefit of expected high rates of evapo-transpiration and low infiltration rates, as shown by water balance analysis and predictions of vegetation production. Evapo-transpiration analysis is presented in *Sherwood Project, Re-vegetation Reclamation System Evaluation, prepared for Western Nuclear, Inc.* (SMI 1995c).

Under conservative assumptions, water balance analysis shows that a relatively small net infiltration of precipitation is only likely in the first few years while vegetation is being established.

Infiltration is not expected to occur over the long term.

Ground water impact analysis predicts that even with very conservative assumptions, tailings liquid export from potential liner overtopping and/or bottom release from a fully failed impoundment liner will not cause ground water quality impacts in excess of health-based regulatory limits. The ground water impact analysis is presented in Appendix P of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994), and in the *Sherwood Project, Ground Water Protection Plan Technical Integration Report* (SMI 1995a).

After an initial stabilization period, no net infiltration is expected, and therefore little or no potential for release of tailings liquid is expected. For the design longevity requirement of 1,000 years, expected average ground water impacts are bounded by conservative assumptions and an analytical result that demonstrates compliance to regulatory requirements in the unlikely "worst-case" of total liner failure.

WAC, Chapter 246 - 252, Criterion 5 (n) (iii) requires dewatering of tailings to minimize seepage, unless tests show that tailings are not amenable to a dewatering system. After conducting detailed tailings material characterization analyses, WNI conducted a pilot-dewatering program that determined that long-term dewatering of the tailings is only marginally feasible. Owing to low permeability associated with the fine-grained tailings material, studies indicate that dewatering wells have small capture zones.

Lenticular, discontinuous, coarse-grained layers that are limited in aerial extent and bounded by fine-grained layers in the tailings impoundment indicate that the effectiveness of long-term dewatering would probably diminish over time as "negative boundaries" are encountered. See *Sherwood Project, Tailings Reclamation Plan, Appendix P* (SMI 1994b).

Chemical studies conducted on tailings material indicate that keeping the tailings saturated has long-term benefits for ground water quality. Saturated tailings experience significantly reduced oxygen contact and therefore reduced acid generation potential. Saturated tailings are expected to remain relatively moist over time, owing to the fine-grained lenses and slimes within the tailings, and to the impervious liner that will limit water export from the tailings. Moist conditions tend to optimize the oxidation-reduction reactions and pH of the tailings to limit ground water impacts well below regulatory limits.

Neutral pH causes metal ions to remain relatively insoluble, when compared with more acidic conditions. The thickness of the cover also enhances the chemical stability of the tailings by effectively limiting the diffusion of oxygen and therefore limiting the oxidation potential. Vegetation and productive soils promote microbial activity; which consumes oxygen in the upper portion of the cover and therefore limits introduction of oxygen at depth. See *Sherwood Project, Technical Integration Report* (SMI 1995a).

Mill Tailings Impoundment Investigation

The Sherwood tailings impoundment contains approximately 100 million cubic feet (9.9 million tons) of uranium mill tailings material and approximately 9.9 million cubic feet (74 million gallons) of drainable water. See Attachments D.1, D.2 and D.3 of Appendix P of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994). A 30-mil (0.030 inch thick) B.F. Goodrich Hypalon® liner underlies the tailings.

A tailings impoundment investigation was performed to:

- Identify the constituents of regulatory concern within the tailings impoundment that might potentially impact the ground water system, if the impoundment were to leak.
- Evaluate dewatering of the tailings as a potential reclamation alternative.

The tailings impoundment investigation consisted of five principal tasks:

- Tailings material sampling and analysis.
- Tailings impoundment pumping testing and pilot dewatering study.
- Evaluation of tailings impoundment water quality.
- Tailings dewatering feasibility analysis.
- Evaluation of long-term impacts from tailings pore water release potential.

Tailings Material Sample Collection and Analysis

Operational design of the tailings impoundment included lining the tailings impoundment with a 30-mil Hypalon® synthetic membrane and adding lime to the mill tailings before disposal in the impoundment. The impoundment was lined to prevent leakage of tailings pore water and contamination of the ground water system. Lime was added to the tailings liquor prior to disposal in the tailings impoundment, in order to maintain a neutral pH solution. A neutral pH environment enhances precipitation of metals and minimizes the solution of metal ions from the tailings into the tailings pore water.

The existing tailings pore fluid pH is approximately 6.5. Metal ion concentrations in the tailings fluid have been effectively minimized. These factors have significantly reduced the metal ion and radionuclide source concentrations in the tailings pore water and greatly reduced the threat of potential impacts to ground water.

Tailings material sampling and analyses were performed in order to characterize the tailings. Modeling was performed for tailings dewatering from pumping, and for drainage from a potential liner failure. Results developed from these analyses are presented in Appendix A and Appendix P of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994). These results were then used in the tailings dewatering feasibility analysis and in development of the ground water protection plan.

Detailed study of tailings stratigraphy was performed using boring-log sample data to characterize stratigraphic control on tailings pore water flow. The distribution of tailings sands and slimes in the impoundment was found to be very complex, with individual tailings layers thinly bedded and discontinuous. This complexity prevents development of a small-scale stratigraphic model for the entire impoundment. However, identification of large-scale stratification of the tailings is implied from the data.

The lower 15 to 25 feet of the impounded tailings consist mostly of low permeability slime and sandy slime. The upper 50 to 60 feet consist mostly of sands and slimy sand with some sandy slimes and relatively few slimes. See

Section 4.1 and Attachment D.4 of Appendix P (SMI 1994).

Representative hydraulic properties of the tailings were developed to model potential dewatering of the tailings materials. Over 1,000 feet of continuous borings within the tailings were used to develop an empirical relationship between the grain size distribution and the permeability of tailings. In this empirical relationship, the percent of tailings-material passing the # 200 sieve size was correlated in 36 laboratory falling head permeability tests. See Attachments D.5 and D.6 to *Appendix P* (SMI 1994). This relationship was then applied to the average percent of each tailings material type found in the tailings borehole profiles. Weighted average vertical and horizontal permeability values were then determined for the two principal tailings layers identified by the tailings stratigraphic characterization study described above. Average horizontal hydraulic conductivities of 9.6 x 10^{-5} cm/s and 2.6 x 10^{-5} cm/s were determined for the upper and lower tailings layers, respectively. Average vertical hydraulic conductivities of 1.8 x 10^{-5} cm/s and 4.2 x 10^{-6} cm/s were determined for the upper and lower tailings layers, respectively. See Attachment D.6 to *Appendix P* (SMI 1994). These values were incorporated into the tailings dewatering feasibility analysis and evaluation of potential long-term groundwater impacts.

Pumping Test and Pilot Dewatering Program

Two field-scale tests were performed in the tailings impoundment to develop hydrologic data used in the dewatering feasibility analysis and in evaluation of potential long-term groundwater impacts. These tests consisted of a 147-hour pumping test followed by a seven-month, pilot-scale, dewatering program.

The pumping test in the tailings material was performed to provide a field-scale check on laboratory permeability tests and to determine the tailings residual saturation values; i.e., how much water remains in the tailings after gravity drainage as a result of dewatering pumping or potential liner failure. The pilot dewatering program was performed to evaluate the practical aspects of full-scale tailings dewatering, such as costs, maintenance, and achievable pumping rates.

The 147-hour pumping test included eight observation wells and one pumping well. Permeability was evaluated using the method developed by Neuman (Neuman 1975). An average specific yield of 0.1 for the tailings profile and a permeability value of 1.4 x 10^{-5} cm/s were obtained from the pumping test. See Attachments D.2 and D.8 to *Appendix P* (SMI 1994). These results were incorporated into the tailings dewatering feasibility study and in the evaluation of potential long-term groundwater impacts.

The pilot dewatering program consisted of continuously pumping nine 2-inch diameter wells. These wells were installed in the deepest portion of the impoundment, in a square grid pattern with 60 feet of horizontal separation.

Pumping was performed for a period of approximately seven months. Data collected from this pilot program included pumping flow rate, water depth (static water level), frequency of pump changes, maintenance, and downtime. For pilot dewatering program results, see

Section 4.2 and Attachment D.9 of *Appendix P* (SMI 1994).

The pilot dewatering program evaluation showed that partial dewatering of the tailings could be achieved. However, the formation of precipitates on pump impellers and in flow meters reduced pumping efficiency, resulting in long-term average pumping rates of only 2.38 gpm (gallons per minute). It was determined that regular maintenance of five hours per week would be required for each pumping well, and the support of two full-time staff to maintain each group of 10 wells would be required to support an effective dewatering program.

Therefore, even though dewatering is marginally technically feasible, it is not economically feasible or practical, considering the limited potential benefit that would be achieved.

Tailings Impoundment Water Quality

Tailings pore water quality was evaluated in two phases:

- Current pore water quality.
- Hypothetical pore water quality, resulting if tailings become unsaturated and oxidize.

Existing tailings pore water quality was evaluated by sampling of the tailings pore water from a well installed in the deepest portion of the impoundment and screened over the full depth of the saturated tailings. This tailings pore water sample was analyzed for all constituents listed in 40 CFR 264, Appendix IX. Results of this sample analysis indicate that tailings pore water pH is near neutral (approximately 6.5) because lime was added during tailings effluent disposal in the impoundment. Tailings pore water is in a reduced state (Eh < 100 mv).

Overall, tailings pore water quality is very good and contains no volatile or semi-volatile organic compounds, herbicides, pesticides, or PCB's. Constituents of potential regulatory concern, as defined in *Chapter 246-252* (WAC), found within the tailings pore water above drinking water standards, are: arsenic, nickel, thallium, uranium, radium-226, and radium-228.

A second phase of tailings pore-water quality evaluation consisted of geochemical testing of the tailings using static acid-base accounting procedures, column tests, and computer program modeling of the geochemical system. These tests and analyses provide insight into the potential evolution of the tailings and tailings pore water system if the tailings were to become unsaturated and oxidize. Tailings might become oxidized only if they became less than saturated and if sufficient access to oxygen became available in the vapor pore space.

Acid-base accounting test procedures indicate that tailings have a potential to create acidic conditions. The net neutralizing potential (NNP) of the tailings was found to be -2.4 tons $CaCO_3$/Kt to -4.0 tons $CaCO_3$/Kt. The neutralizing potential (NP): acid producing (AP) ratio was found to be 0.20 to 0.50. For details of the evaluation, see Section 4.3.2 of *Appendix P* (SMI 1994). NNP values less than 20 tons $CaCO_3$/Kt and NP:AP ratios less than 3 indicate that tailings material has the potential to create acidic conditions.

Column tests were performed on three columns, each filled with representative compacted tailings samples. Two of the columns were inoculated with the acidophilic bacteria Thiobacillus ferrooxidans, which accelerates the oxidation of ferrous iron (Fe^{+2}) to ferric iron (Fe^{+3}).

The columns were saturated with deionized water, allowed to drain for 24 hours, and then aerated with water-saturated air. The columns were aerated for 10 weeks, flushed six times with deionized water, aerated again for an additional 10 weeks, and flushed six times again. Effluent samples from the 10 and 20-week flushings were analyzed for pH, 10 metals (As, Ba, Cd, Cr, Fe, Mg, Mo, Ni, Pb, and Se), 2 anions (SO_4, and Cl), and 2 radionuclides (uranium and radium-226). During the 20-week tests, the pH of the columns decreased to 3.6. The constituents Cd, Ni, radium-226, and uranium all showed ten-fold increases over initial concentrations in the tailings pore water, while the remaining constituents either showed evidence of early rinse out behavior and/or were not affected by the oxidation reactions or lower pH conditions. See Section 4.3.2 of *Appendix P* (SMI 1994) for evaluation results.

Geochemical modeling of tailings water was conducted to determine if column testing realistically represented oxidation that could occur from the limited oxygen available. It was assumed that dewatering of the tailings would allow influx of a limited amount of oxygen, which would then be available for reaction with the tailings material. With dewatering pumping, air (and oxygen) would enter vertically through the well bore and laterally through the well screens and into the tailings pore space.

The geochemical code PHREEQE (Parkhurst et. al., 1980) was used to model the chemistry of the column leachates and the tailings pore water. Geochemical modeling steps were designed to:

- Calculate the mineral equilibrium of the column leachates and tailings pore water.
- Model the effect of the introduction of oxygen to the tailings / tailings pore water system.

The goal of the first step was to determine which tailings minerals were in equilibrium with respect to the tailings pore water. The goal of the second step was to determine if:

- Column tests realistically represented potential oxidation that might occur during dewatering of the tailings impoundment.
- The effect that addition of oxygen in smaller proportions than used in column testing improves tailings pore water quality.

Geochemical models produced initial values in close agreement with observed values of the tailings pore water quality. These models are therefore expected to adequately represent the tailings pore water system and were qualified for use in modeling impacts of incremental addition of oxygen to the tailings pore water due to dewatering.

With the addition of incremental oxygen concentrations, the models show that, as the concentrations of incremental oxygen increase, the pE increases and the pH decreases. As pE increases and pH decreases, a substantial increase in concentrations of dissolved uranium and dissolved nickel occurs. Modeling results indicate that if air fills open pore spaces created during dewatering and if available oxygen is completely consumed, then dissolved uranium and nickel concentrations would increase by up to four orders of magnitude.

Both the column tests and the three modeled pore water scenarios suggest that tailings pore water quality would degrade significantly with tailings dewatering caused by oxidation and acidification of tailings. Comparison of column tests with geochemical modeling shows that column tests contain similar or lower concentrations of uranium and nickel than the concentrations predicted by modeling results. Geochemical modeling predictions exceed tailings pore water quality degradation observed in the column tests by one to two orders of magnitude.

It is evident, from results of tests and modeling, that dewatering would significantly degrade tailings pore water quality and increase potential for adverse ground water impacts.

Basin Hydrologic Evaluation

A basin hydrologic evaluation was performed to characterize physical parameters, which control ground water occurrence, flow, and potential transport of contaminants. Results of this evaluation, combined with results of the geologic investigation and the tailings impoundment investigation described above, provide the technical basis for the development of the Sherwood Project Ground Water Protection Plan. This evaluation includes review of the currently existing ground water monitoring system, identification of the hydro-stratigraphic units in which ground water was found to occur, estimates of ground water flow rates, and an evaluation of recharge to the drainage basin (SMI 1994b).

Ground Water Monitoring System

The tailings impoundment drainage basin consists of approximately 700 acres of gently rolling hills with mostly sandy soil cover underlain by igneous bedrock. The basin, which is surrounded on the north, east, and west sides by high bedrock, drains to the south. The hydrologic conditions and ground water quality of the basin have been monitored by a series of 10 monitoring wells installed both in the alluvium and in the underlying bedrock.

Monitoring wells MW-2, MW-2a and MW-2b are situated up-gradient from the tailings impoundment and constitute background monitoring locations. Wells MW-4, MW-5, MW-6, MW-8, MW-9, and MW-10 are located near the toe of the tailings impoundment dam and constitute down-gradient, monitoring locations. MW-1 and MW-3 are located laterally, east and west of the tailings impoundment, respectively. See Section 5.1 of *Appendix P* to the 12/94 TRP (SMI 1994).

Ground Water Occurrence and Flow Rates

Data from aquifer tests performed on selected wells and analysis of the well boring logs indicate that ground water occurs in two hydro-stratigraphic units: the alluvium, which lies on top of the bedrock surface, and the conductive bedrock. The second hydro-stratigraphic unit, the conductive bedrock, includes the weathered bedrock in the upper portion and unweathered or competent bedrock below. See Figures 5 and 6 for representative cross-sections of the Sherwood Project site. See the *Sherwood Project, Ground Water Protection Plan and Technical Integration Report* (SMI, 1995d).

Core logs and packer aquifer test data in the weathered zone and upper portions of the unweathered bedrock indicate that a zone of conductive bedrock with relatively uniform hydraulic conductivity exists to a depth of approximately 50 feet below the top of the bedrock surface. See Section 5.2.2 of *Appendix P* (SMI 1994). This conductive zone is formed from a network of small joints and fractures in the weathered bedrock and portions of the unweathered bedrock. Hydrologic data indicate that the bedrock has no significant hydraulic conductivity at depths greater than 50 feet below the top of the bedrock surface. Average permeability rates were calculated to be 1.4×10^{-2} cm/s for the alluvium and 1.5×10^{-5} cm/s for the conductive rock (SMI 1994).

Ground water in these two hydro-stratigraphic units flows to the south through a narrow bedrock valley located approximately 200 feet beneath the toe of the impoundment dam. See Figure 1.1 "Tailings Impoundment Drainage Basin," in *Appendix P* (SMI 1994).

Flow in the conductive bedrock zone occurs at a much slower rate than in the alluvium, due to the lower hydraulic conductivity of the bedrock unit. Well MW-4, screened in the conductive bedrock zone, and MW-10, screened in the alluvium, monitor these two hydro-stratigraphic units at the point of compliance (POC). See Figure 1 "Cross-section and Well Locations" (SMI 1995d).

Ground water flow rates were estimated for both hydro-stratigraphic units by integrating seismic data developed from:

- The geologic investigation in section 3.0 of *Appendix P* (SMI 1994).
- Ground water elevation data from the monitoring wells.
- The *Sherwood Project, Annual Environmental Monitoring Program Report for 1994* (SMI 1995g).
- Hydrologic properties of the hydro-stratigraphic units developed from aquifer tests. See Section 5.2.2 of *Appendix P* (SMI 1994).

The thickness of each hydro-stratigraphic unit was determined from static water levels using the monitoring wells and the location of the alluvial and bedrock materials from seismic data. Flow gradients were based on the difference in observed water levels between monitoring locations and were modeled to be approximately equal to the slope of the bedrock surface. Application of Darcy's Law ($Q = KiA$) for saturated flow in porous media allowed calculation of the flow rate in each hydro-stratigraphic unit. The average ground water flow rate in the alluvium was calculated to be 218 gallons per minute (gpm). The average ground water flow rate in the conductive bedrock was calculated to be 1.5 gpm. Therefore, overall ground water flow from the tailings impoundment drainage basin is approximately 220 gpm.

Integrated Site Model

Effectiveness of ground water protection features was evaluated using predictive ground water modeling techniques. Estimates were made of potential long-term impacts for a postulated release of tailings impoundment pore water. The modeling approach developed for this evaluation is called the Integrated Site Model (ISM). The ISM employs the computer program SOLUTE, version 3.0 (Beljin and Heijde 1993), to model contaminant transport in the ground water system below the tailings impoundment.

The ISM combines the physical framework developed during the site geologic investigation, source concentrations, and leakage rate data developed in the tailings impoundment investigation, and hydro-stratigraphic unit geometry and hydrologic properties developed during the basin hydrologic evaluation to predict ground water quality. This predictive model is used to evaluate tailings impoundment operational and reclamation design elements for relative ground water protection performance. The ISM is also used to predict potential long-term impacts to the environment from potential liner leakage.

The subroutine SLUG2D within the computer program SOLUTE was used to develop and calibrate the ISM. The ISM calibration consisted of modeling a February 4, 1984 release of approximately 100,000 gallons of tailings fluid of which 20,000 to 80,000 gallons were pumped back into the impoundment and 80,000 to 20,000 gallons infiltrated into the ground water system. See Attachment F.1 of *Appendix P* (SMI 1994). This event was detected in the down-gradient monitoring well MW-4. ISM model input included concentrations in the tailings fluid, estimated volume of fluid release to the ground water system, hydraulic properties and geometry of the hydro-stratigraphic unit, and concentrations observed in the down-gradient monitoring well MW-4.

Concentrations in the tailings fluid were represented by sample analyses presented in Section 4.3.1 of *Appendix P* (SMI 1994). The rate of leakage equaled the rate of infiltration (10.25 gpm), as calculated in Attachment D.17 to *Appendix P* (SMI 1994). To be representative of impoundment liner leakage, this scenario would require an impoundment liner failure equivalent to 2,700 square feet or 100 individual leakage areas 27 square feet each. The *Sherwood Project, Re-vegetation Reclamation System Evaluation* (SMI 1995c) concluded that much less net infiltration would pass through the thick soil reclamation cover. Therefore, the estimated 10.25 gpm net infiltration is conservative. The ISM calibration consisted of varying the dispersivity values in the model for each constituent until the modeled concentrations matched the concentrations observed in well MW-4. See Table F.2.2, Summary of Predicted Concentrations Down-Gradient of the Tailing Impoundment, in *Appendix P* (SMI 1994).

Results of the ISM calibration indicate that the dispersivity values fall within the range of typical dispersivity values observed for alluvial material. Only transport of the groundwater fluid in the alluvium was modeled because tailings fluid that might escape the impoundment would travel primarily in the alluvial hydro-stratigraphic unit with very little migration into the less permeable conductive bedrock unit. In addition, 99% of the vapor pore space occurs in the alluvial hydrostatic unit.

An oxidation front would only penetrate the tailings to depths where excess oxygen would persist after bio-chemical reduction reactions are satisfied, and oxygen diffusion would exist.

Oxygen diffusion rates through the drained tailings would be very slow. High residual moisture content of the tailings after gravity drainage would allow very little pore volume for vapors and gases. Diffusion rates would require continuous pores pathways through which oxygen could diffuse, which is unlikely.

Layers of slimes within the tailings pile would essentially stop further vertical penetration of the oxidation front into the tailings profile, due to their extremely high residual saturation moisture contents. Oxidation-reduction chemical reactions and microbial activity near the tailings surface would rapidly consume oxygen in the air filling the drained pores, where air might enter the tailings. Therefore, even if the tailings were to drain, pore space at depth would receive very little oxygen at very slow rates.

Movement of an oxidation front downward through the tailings would be quite slow, even under conditions of gravity drainage. The intact synthetic membrane liner surrounds the lower and lateral surfaces of the impoundment, precluding the flux of oxygen into the tailings through these surfaces.

For all hypothetical ground water impact scenarios, the ISM model predicts that long-term, steady-state hazardous-constituent concentrations at the down-gradient wells for a worst-case leakage scenario would remain below health-based regulatory limits. Therefore, *Appendix P* (SMI 1994) calculations demonstrate that both operational and reclamation design elements effectively protect ground water quality. For a description of pore water quality, see page 26 and *Sherwood Project, Technical Integration Report* (SMI 1995a).

A 12.6-foot thick, homogeneous reclamation cover (SMI 1995d) allows less infiltration than predicted for a conventional compacted clay reclamation cover system.

Appendix P (SMI 1994) ISM modeling is based on a conventional, compacted-clay reclamation-cover design. Therefore, the ISM analysis predicts conservative, upper bound estimates of potential ground water impacts for a 12.6-foot thick, homogeneous reclamation cover design.

Leak Detection Monitoring Program

The development of leak detection monitoring program requirements entails review of tailings impoundment operational and reclamation design elements and evaluation of reclamation design performance predictions for ground water transport. Modeling (described above) evaluated worst-case tailings impoundment leakage scenarios and subsequent effects on water quality at the point of compliance (POC).

Development of a leak-detection monitoring-program requires review of existing ground water monitoring system configuration and environmental monitoring data from the ground water quality database.

Sherwood Project site area background ground water quality values were developed.

Surface reclamation design of the tailings impoundment includes:

- Placement of a 12.6 foot thick, homogeneous, soil cover over the tailings (SMI 1996).
- Re-vegetating the soil cover (SMI 1995c).
- Maintaining a favorable geochemical environment within the tailings.
- Enlarging the diversion channel system; which circumscribes the impoundment.

A thick, homogeneous, reclamation-cover design replaced the conventional, compacted-clay cover design modeled in *Appendix P* (SMI 1994b). Modeling of the conventional, reclamation-cover design provides a conservative over-estimation of potential ground water impacts. Therefore, it is expected that performance of the vegetated, thick, homogeneous, reclamation-cover will further limit the amount of precipitation and oxygen; which may enter the tailings.

The Leak Detection Monitoring Program is described in the *Sherwood Project, Ground Water Protection Plan, Technical Integration Report* (SMI 1995d) and in the *Sherwood Project, Monitoring and Stabilization Plan*, (SMI 1997). The Leak Detection Monitoring Program provides for prompt detection and reporting of anomalous ground water concentrations and potential leakage. The program has been implemented in two phases:

- Monitoring during final reclamation construction activities.
- Post-construction monitoring.

The Leak Detection Monitoring Program includes monitoring of up-gradient monitoring well MW-2b and down-gradient monitoring wells: MW-4 and MW-10. Monitoring well MW-2b was installed to provide long-term up-gradient water quality data for the tailings impoundment drainage basin. Monitoring wells MW-4 and MW-10 provide leak detection monitoring for the tailings impoundment drainage basin. Monitoring well MW-4 proved effective for detecting past tailings fluid releases during milling operations. Monitoring Well MW-10 is also located down-gradient, is constructed in the shallow aquifer, and is screened in the alluvium at the deepest portion of the subsurface drainage basin.

Monthly water level measurements are made for each monitoring well.

Quarterly ground water quality samples are collected from each monitoring well and analyzed for the following parameters; static water level, total dissolved solids, electrical conductivity, temperature, pH, uranium (natural), sulfate, chloride, and nickel.

Ground water monitoring will continue at the Sherwood Project site at least until the WDOH, Radioactive Materials License has been terminated.

Selection of leakage monitoring constituents is limited by the relatively good quality of pore water in the impoundment. Few constituents are present at higher concentrations and with sufficient mobility to provide prompt detection of a potential release, without significant retardation. Leak detection indicators must also be generally absent or exist at relatively low natural background concentrations.

Chloride is selected as a leak-detection-monitoring constituent because it is the most conservatively transported constituent, exhibiting no retardation. Chloride would be the first constituent to arrive at the point of compliance (POC), should leakage occur. Chloride is present in the impoundment in concentrations of approximately 291 mg/l and in natural background ground water in low concentrations of approximately 6 mg/l. (Note: the EPA-based drinking water standard is 250 mg/l.)

Sulfate is also a leak-detection-monitoring constituent because of the relatively high concentration in the impoundment fluids, approximately 6,195 mg/l, and relatively low background concentration in ground water, approximately 17 mg/l. The high source concentration and relatively conservative transport makes sulfate an appropriate indicator parameter.

Nickel is selected as one of the dissolved metals present in the tailings pore water, which would exhibit relatively conservative transport in the environment. Few metals are present in measurable concentrations in the tailings pore fluid, because of the neutral pH and reduced condition of the tailings solution.

Radionuclides of radium and uranium are not selected as leak-detection monitoring constituents because of their relatively retarded rates of ground water transport and high natural background ground water concentrations.

If any leak-detection monitoring constituents are confirmed to be anomalous, an intermediate-level monitoring program is implemented.

Intermediate monitoring consists of weekly monitoring of monitoring well static water level (SWL) and monthly ground water quality sampling and analysis for the following parameters: total dissolved solids, uranium (natural), electrical conductivity, temperature, pH, chloride, sulfate, and nickel.

A decision to proceed to compliance monitoring or to return to normal leak detection monitoring is made based on an evaluation of monitoring data obtained after a six-month observation period.

Compliance monitoring consists of quarterly monitoring for the following hazardous constituents: arsenic, nickel, thallium, Ra-226, Ra-228, uranium (natural); and the following secondary parameters: static water level, total dissolved solids, pH, electrical conductivity, temperature, chloride, and sulfate.

If compliance monitoring indicates that applicable ground water regulatory standards for hazardous constituents have been exceeded, or that constituent UCL (upper control limit) have been exceeded, then a corrective action plan will be developed. Provisions of WAC 246-252-030 Criterion 5 (m) will be used, based on site-specific conditions at that time. See Table 1 (SMI 1997) for detailed descriptions of specific leak detection protocols. See Table 2, Summary of Leak Detection and Compliance Monitoring Ground Water Standards, in *Sherwood Project, Monitoring and Stabilization Plan* (SMI 1997).

Radon Emanation Potential

Radon Emanation Potential is broken into sub-sections on Background Information, Cover Thickness Calculations, and Radon Flux (Emanation) Rate Modeling. Radon Flux Rate Modeling is further divided into Long-Term Moisture Saturation, Long-Term Average Moisture, Radon Diffusion Coefficient, and Estimating Diffusion Coefficients. Applicable formulas are given.

Radon-222 is a chemically-inert gas and a radionuclide with a 3.8-day half-life. Radon-222 exists as the result of natural disintegration of radium-226. Radium-226 is prevalent in uranium mill tailings.

Radon's unique chemical property of existing primarily as an inert gas means that radon gas diffusion through the cover must be mitigated to prevent its release into the air where it may expose the public.

Radon is primarily mitigated at uranium mill tailings facilities, by burial under sufficient soil of proper characteristics to control radon gaseous emanation from the surface.

Design of radon covers is performed by analytical methods that predict radon gas emanation from the soil cover surface, based on radium-226 concentrations in the tailings and on design features of the cover.

An evaluation was performed on the thick, homogeneous cover design constructed at the Sherwood Project site.

The thick, homogeneous, cover design, submitted by Western Nuclear, Inc., is analyzed in Appendix 6, "Radon Barrier Design," of the *Sherwood Project, Re-vegetation Reclamation System Evaluation* (SMI 1995c). The reclamation cover is designed to meet regulatory requirements from Washington Administrative Code 246-252-030 (3) (WAC), as it relates to control of radon emanation from uranium mill tailings.

Regulations set limits on the rate of radon-222 gas emanation from the surface of uranium mill tailings covers to values no greater than 20 pCi/m^2-sec, averaged over the cover, as verified using the RADON computer model (NRC 1989) (WAC).

The RADON computer model verification process is intended to serve the following:

- Evaluate computer program input parameters used for the RADON computer model and estimate minimum cover design features (e.g., cover thickness) required for the Sherwood Project site cover.

- Using the methodologies and guidelines provided in the Radon Attenuation Handbook, NUREG/CR 3533 (NRC 1984), and the NRC Regulatory Guide 3.64 (NRC 1986), estimate the parameters required to perform a hand calculation to verify RADON computer model results and to provide independent estimates of minimum cover design features.

- Perform a sensitivity analysis for cover design features, using a range of values for input parameters (e.g., saturation moisture content, clay content, soil density, long-term average moisture content, etc.) in order to understand the relative factor of safety in the analysis and in the design.

Background Information

Since uranium mill tailings contain most of the decay products of the radioactive decay of uranium and some residual uranium (most of the uranium is removed during milling), they represent a potential for exposure to radiation by several pathways. The most important gaseous emission pathway is Radon-222 emanating from the surface.

Radium-226 in the tailings decays by alpha particle emission and becomes Radon-222, a radioactive noble gas, which is itself an alpha emitter, having a half-life of 3.8 days. Radon-222 decay progeny are short-lived, particulate isotopes, with a mean half-life of about 30 minutes.

Radon is heavier than air and partially soluble in water. Although it is chemically inert, it will attach to dust or other particulates dispersed in the air. These properties play an important role in the behavior of radon gas and influence its impact upon the environment.

Once produced, radon-222 gas is found in the vapor pore spaces between the grains of tailings material. It then diffuses through the tailings and cover materials to the surface. Some radon gas reaches the surface and some undergoes radioactive decay en-route. Any decay en-route results in decay progeny isotopes, none of which are naturally gaseous in nature. As particulates, these decay products are trapped in the radon cover and naturally decay to stable isotopes in a short time.

Radon-222 gas that reaches the surface escapes into the air above, where it mixes into the passing air-stream by natural turbulence.

Because of the presence of long-lived uranium-238, uranium-234, and thorium-230 in the tailings, radium-226 inventory concentration will remain nearly constant (in equilibrium) for thousands of years.

The scope of the tailings inventory and remedial actions required for their control vary with each site and must therefore be determined specifically for each uranium mill site.

WAC 246-252-030, Criterion 6 (WAC) requires, in part, an earthen cover over tailings or wastes designed to limit atmospheric releases of Radon-222 (from uranium byproduct material) such that the concentration of Rn-222 shall not exceed an average release rate of 20 pico-curies per square meter per second. This release rate limitation is consistent with NRC regulations in 10 CFR 40 and EPA regulations in 40 CFR 192.

In developing an adequate cover design for the Sherwood Project, WNI evaluated a number of design alternatives. The *Sherwood Project, Tailings Reclamation Plan* (SMI 1994) proposed a compacted-clay barrier design. During the plan review process, WDOH staff became concerned that natural vegetation could intrude through the compacted, clay-barrier during the 1,000-year design life.

Since the climax vegetation community at the Sherwood Project is expected to be Ponderosa Pine trees, the potential for trees to adversely affect the radon attenuation properties of a near-surface compacted-clay barrier layers was an important consideration. This potential impact appeared likely under site-specific conditions prevalent at the Sherwood Project site.

Adverse bio-intrusion effects were also found at several sites closed by the U.S. Department of Energy (DOE). These UMTRA, title II sites have experienced bio-intrusion of compacted-clay barriers. As a result, active maintenance has been required to mitigate potential bio-intrusion effects (DOE 1992).

WDOH regulations require the cover design to remain effective without the use of active maintenance (WAC).

A compacted-clay barrier design was initially proposed by WNI in section A.5, "Radon Attenuation," of Appendix A of the *Sherwood Project, Tailings Reclamation Plan* (SMI 1994). After staff review and comment, WNI revised their proposal in Appendix 6, "Radon Barrier Design," of Sherwood Project, *Re-vegetation Reclamation System Evaluation* (SMI 1995c). A thick, homogeneous cover that incorporates the establishment of a Ponderosa Pine community was eventually adopted.

The compacted-clay barrier was replaced with a thick, homogeneous, cover design that relies on vegetation for evapotranspiration of precipitation for infiltration control. Soil thickness provides radon emanation rate control and adequate depth to mitigate the effect of deep root penetration.

Cover thickness was evaluated using uncompacted (except by construction traffic) sandy soil properties. Uncompacted sand borrow material fill was chosen as cover material to avoid the potential for detrimental effects of bio-intrusion, freeze/thaw, and seismic events. Uncompacted sand also has construction benefits compared with a compacted-clay barrier.

A cover design thickness of 12.6 feet of uncompacted sand soil is the required cover design resulting from the conservative application of the RADON computer program, using the regulatory emanation rate limit of 20 pCi/m^2-sec of radon-222 from Washington Administrative Code 246-252 (WAC).

The RADON computer program was developed by the NRC (NRC 1989). Compliance with the RADON computer program's conservative predictions is expected to assure long-term conformance with the standard. Input parameters are conservatively chosen because of the considerable extent of the design life (1,000 years) criteria for the project. The cover design protocol, established by NRC Regulatory Guide (NRC 1989a), allows only conservative, worst-case assumptions for input parameters. As a result, the analytical approach is considered highly conservative and produces a cover thickness that is robust in meeting long-term requirements.

Cover Thickness Calculations

The thickness of earthen cover materials required to reduce radon flux (emanation) rates to acceptable levels depends upon cover material properties and thickness in retarding the release of radon gas. Retardation is limited by the rate of diffusion through the cover.

Since radon-222 has a relatively short half-life (3.8 days), retardation effects in the cover allow for radon decay prior to release from the surface. Daughter decay products are solid particulates.

The parameter that characterizes radon transport in the soil is called the diffusion coefficient. Retardation of radon-222 gas diffusion within cover materials is accomplished by:

- Providing adequate cover thickness.
- Employing cover materials with sufficiently limiting diffusion coefficients.
- Reducing cover material porosity by adequate compaction of cover materials.
- Increasing long-term moisture content of the cover materials by including sufficient fine soil content.

Thus, the diffusion coefficient for radon gas diffusion in the cover is a key parameter determining cover design effectiveness.

The basis for radon flux (emanation) rates and minimum cover thickness calculations presented in this analysis is one-dimensional, steady-state gas-diffusion theory. Only vertical diffusion is considered because the horizontal dimensions of tailings piles are large compared to the typical mean radon diffusion length (cover thickness), and edge effects are therefore limited.

Short-term, or seasonal, variations in flux rates are ignored because regulatory requirements address only long-term average radon flux exposure.

Advective transport, the externally forced movement of radon, also affects radon gas flux. Advective forces are considered minimal for uranium mill tailings sites because of the inherently inert characteristics of tailings materials. Tailings are primarily fine (slimes) to coarse (sand) soils, either partially or fully saturated with liquid water.

There are generally no biodegradable constituents that might generate organic soil gases that could enhance advective gas flow rates, or pressurize the tailings. Chemical reactions within the tailings pore space are generally not expected to produce gaseous chemical compositions or increased vapor pressure.

Advective driving forces are considered negligible and therefore advective transport effects are neglected.

The one-dimensional, steady-state diffusion equation appropriate for radon flux determinations (NRC 1989, and NRC 1989a) is:

$$\mathbf{D(d^2C / dx^2) - AC + RpEA/n = 0} \quad (1)$$

where:

D = diffusion coefficient for radon in the total pore space (cm^2s^{-1})
C = radon activity concentration in the total pore space ($pCi\ cm^{-3}$)
A = radon decay constant ($2.1x10^{-6}s^{-1}$)
R = specific activity of radium-226 ($pCi\ g^{-1}$)
p = dry bulk density of soil or tailings ($g\ cm^{-3}$)
E = radon emanation coefficient (dimensionless)
n = soil or tailings porosity (dimensionless)

Radon flux is related to the radon activity concentration gradient by:

$$\mathbf{J = -10^4Dn\ (dC/\ dx)} \quad (2)$$

where:

J = radon flux (pCi $m^{-2}s^{-1}$)
10^4 = units conversion (cm^2/m^2)

Solutions to Equation (1) are obtained by applying boundary conditions for the system being analyzed, and solving for surface radon flux. For a thick, bare (tailings with no cover) tailings source, boundary conditions are typically chosen as:

- A specified radon concentration at the bare tailings/air surface.
- Zero radon flux at the base of the tailings.

For tailings covers consisting of multiple layers of different material properties, additional boundary conditions for each layer interface are:

- Continuity in radon concentration.
- Continuity in radon flux, across the interface.

Individual layers are defined by the occurrence of distinct changes in radium content, soil texture, compaction, moisture, or tailings or cover material properties.

Solutions to Equations (1) and (2) can be used to calculate radon flux from the surface, for a given set of tailings and cover parameters. Thickness of cover needed to achieve a specified radon flux can thus be determined.

WDOH Concurrence Review of Radon Flux Rates

Radon flux (emanation) rates were estimated for Sherwood Project site designs by WNI in order to prepare cover design thickness requirements for the construction plans and specifications. These designs and the radon flux rate analysis have been reviewed thoroughly by WDOH staff for concurrence with WNI design and analysis. The RADON code has been used to verify the final design thickness requirement.

See Appendix C - Radon Flux (Emanation) Rate Modeling for a discussion of the important parameters influencing radon-222 emanation rates.

Realistic Flux Rate Modeling

In addition, WNI prepared an evaluation of radon flux (emanation) rates based on "realistic" assumptions for RADON code input parameters. WDOH requested this analysis to be performed in order to evaluate the extent of the safety margin inherent in the conservative nature of RADON code default values and conservative parameter selection protocols (NRC 1989 and NRC 1989a).

Results of this "realistic case" analysis show an expected average radon flux (emanation) rate of only 0.13 pCi/m^3-s through the final cover. This rate is only expected during time periods when soil moisture storage is at a minimum (only about six months per year). For the balance of the year, when the moisture content is higher, there is no radon flux expected (SMI 1996c). This is well below the required limit of 20 pCi/m^3-s (WAC).

Radon-222 Flux Measurements

WNI performed Radon-222 flux measurements on the tailings impoundment after final cover placement. Measurements were performed to comply with requirements of 10 CFR 40, Appendix A, Criterion 6 of the federal Clean Air Act. Sampling was performed using the Large Area Activated Charcoal Canister (LAACC) method. Measurement was performed October 2-3, 1996. The surface was dry. No vegetation was present on the just completed construction surfaces. Weather was favorable. The lined impoundment surface area of approximately 80 acres was measured.

The mean Radon-222 flux rate for the Sherwood Project tailings impoundment was measured at 0.51 +/- 0.03 pCi/m^3-s. The laboratory Practical Quantitative Limit (PQL) was 0.5 pCi/m^3-s, and the maximum measured value was 0.7 pCi/m^3-s (WNI 1996).

Measured flux rates are consistent with results of the realistic analysis performed by WNI and reviewed by WDOH.

Contaminated Soil Cleanup

Contaminated Soil Cleanup is sub-divided into Site Characterization, Soil Cleanup Verification, and Thorium and Uranium Sampling and Analysis. Site Characterization includes Background Values for Radium, Thorium, and Uranium, Sampling to Determine the Aerial Extent and Depth of Contaminated Soils, and Cleanup Standards. Soil Cleanup Verification covers Sampling and Analysis Procedures, Statistical Procedures, Quality Assurance and Quality Control, and Completeness of Data.

Soil cleanup at the Sherwood Project site is mandated by regulation (WAC), in order that completed reclamation will not result in excess exposure to the public. To that end, soil is measured, removed if above predetermined values, and deposited in the tailings impoundment. Soil contamination of the surface may not exceed 5 pCi/g of Ra-226, in excess of site background values, when the site has been cleaned up. The impoundment cover may not be constructed of materials in excess of site background values. Contaminated soils were disposed of below the impoundment cover.

Site Characterization

Site characterization entails two main tasks. First, background radioactive material concentrations must be obtained for the general area. Then, the site must be evaluated to determine the likely aerial extent and depth of contaminated soils. NRC-based cleanup standards (WAC) are used throughout as the basis for cleanup activities. Once site characterization is completed, a detailed plan of sampling and cleanup is developed.

Background Values for Radium, Thorium, and Uranium

Page 8.15 of NUREG/CR-5849 (NRC 1993) discusses the protocol for determining statistical adequacy of background soil concentrations. This protocol requires that whenever background concentrations exceed 10% of a cleanup standard, the background characterization effort must demonstrate that enough samples were taken to adequately determine average background concentrations. The minimum number of samples is given by equation 8.22 of the NUREG (NRC 1993). This protocol was used for Ra-226, Th-228, Th-230, and Th-232. Compliance with the protocol in tables C.5 through C.7 was verified for each of the Sherwood Project site soil types and shown in the *Sherwood Project, Radiological Verification Program* (SMI 1994a).

Uranium was not part of the background determination. However, after the background characterization was performed, it became necessary to address natural uranium in the soil cleanup. The approach taken was to assume that background uranium concentrations were in secular equilibrium with radium, resulting in background total uranium activity twice that of Ra-226. This assumption proved to be reasonable and consistent with both the Tum Tum background data taken for the pre-reclamation radiological surveys, and historical environmental sampling results prepared by Washington State Department of Health. See Table B.1, Appendix B of the *Sherwood Project, Radiological Verification Program* (SMI 1994a) for data from the pre-reclamation radiological survey.

Sampling to Determine the Aerial Extent and Depth of Contaminated Soils

According to the NUREG (NRC 1993) in Chapters 2 and 3, an adequate characterization of the aerial extent of contaminated soil includes a review of historical site activities and characterization surveys. Sherwood Project characterization activities are summarized in Chapter 2 of Volume 2 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a), and discussed in detail in Chapter 2 and Appendix B of the *Sherwood Project, Radiological Verification Program* (SMI 1994a).

First, in the pre-reclamation radiological survey, historical knowledge of operations was used to identify six sub-site areas. Subsequent work is documented in the *Sherwood Project, Radiological Verification Program* (SMI 1994a). The pre-reclamation survey is located in Appendix B. The correlation study is located in Appendix G. Results were consistent with historical expectations of contamination and contamination-free areas. These results led to the determination of primary, secondary, tertiary, and ancillary areas as shown in Chapter 2 of Volume 2 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a). These classifications led to determinations of the extent and nature of sampling applied to each of the area types during cleanup and verification.

Second, pre-reclamation survey and correlation studies included laboratory analysis of approximately 100 grids and 200 samples. Sampling locations were distributed widely over the site, based partly on historical operations data.

Cleanup Standards

Throughout the soil cleanup activities at the Sherwood Project, methods and procedures have strictly adhered to NRC standards for cleanup action levels and performance methods, for uranium, thorium, and radium.

Soil Cleanup Verification

It is the responsibility of the site operator to clean up soil contamination exceeding soil cleanup standards. There is also an operator verification responsibility required to assure that soil cleanup has been adequately accomplished. WDOH, as the oversight regulator, must verify that cleanup has been adequately performed and verified by the site operator.

There are four elements necessity to assure soil cleanup verification. These include sampling and laboratory analysis procedures, statistical procedures, QA/QC, and completeness of the data.

Sampling and Analysis Procedures

There were three primary methods employed for sampling and laboratory analysis. These were in-field measurements with a portable NaI (Tl) detector, onsite measurements of composite samples with a NaI (Tl) detector, and laboratory measurements with isotopic analysis for radium, thorium, and uranium.

Onsite measurements utilized a demonstrated statistical correlation between gamma-counts and radium concentrations and a statistical association between radium and thorium. These techniques are consistent with NRC approved techniques documented in Chapters 4 - 6 of the NUREG (NRC 1993).

Each of the more than 4,000 grids were sampled for both Ra-226 and Th-230 through either laboratory analysis or a demonstrated association with onsite measurements.

Uranium measurements, by contrast, were performed after compliance was demonstrated for all grids to radium and thorium standards. Sampling and analysis for uranium focused on areas of highest likely contamination and on association with radium and thorium. Uranium measurements were used to demonstrate that low radium concentrations imply low uranium concentrations.

Statistical Procedures

A primary requirement of NUREG/CR-5849 is that sampling data must demonstrate that each grid meets NRC standards with a 95% or greater confidence. This implies that the sampling mean plus two standard deviations is less than the standard. See Chapter 8 of the NUREG (NRC 1993). Statistical treatment of measurement technique was specifically designed to meet this requirement. Onsite measurement "action levels" were set so that if a particular grid were measured at or below the action level, then there was 95% or greater confidence that NRC standards were met. Laboratory measurement results plus two standard deviations (95% confidence limit) for the laboratory measurement technique were compared to NRC standards. These protocols are documented in Volume 2 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a).

Another major statistical procedure was the use of correlation between field measurements and laboratory measurements. This technique is widely employed in radiological verification and has been documented, for example, in the "Bendix" report (Bendix 1984). Validity of in-field measurements depends upon correlation of laboratory Ra-226 measurements with in-field measurements, and the association of Th-230 with Ra-226. In locations where either the correlation or association was not valid, laboratory analysis was performed. Correlation analysis is carefully documented in Appendix G of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a).

It was determined statistically, through evaluation of sampling results, that the association of uranium with radium and thorium was valid in areas of natural soil deposits. Process areas (mill site) were sampled 100%for uranium due to the potential that equilibrium concentrations may have been disturbed.

Quality Assurance and Quality Control

There are two QA/QC programs of relevance. One is WNI's QA/QC program. This includes activities in the field, at their contract laboratory, and data management and analysis. The other is WDOH's verification "splits" and inter-comparisons.

QA/QC results are extensively documented in Chapters 5 and 6 of Volume 2, and in Appendix A of Volume 4 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a).

QA/QC soil samples include matrix spikes, blanks, and duplicates, with each batch submitted to the laboratory. Spikes employed NIST-traceable standards. They also submitted blind performance-evaluation samples prepared from onsite soils. In addition, their contract laboratory has its own internal QA/QC program.

QA/QC for onsite field measurements includes calibrations, thrice-daily performance checks, and maintenance of control charts. These steps meet requirements of Chapter 5 of the NUREG (NRC 1993). Documentation for WNI's Quality Assurance Program is available in Chapter 3 of Volume 2, and in Appendix A of Volume 4 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a).

External Quality Assurance includes sample splits and result inter-comparisons with WDOH. In-field splits and inter-comparisons are documented in Chapter 6 of Volume 2 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a).

Gamma-survey split samples were evaluated by WNI and by WDOH. A paired t-test was used to evaluate the relative bias of the two data sets. The two data sets passed the paired t-test.

In addition to comparing gamma-survey data, a comparison was made of WNI's laboratory data to WDOH's laboratory data for Ra-226, Th-230, and U-238. Results of these tests are documented in Chapter 5 of Volume 2 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a).

Ra-226 populations were in agreement, while U-238 results are biased high and Th-230 results are biased low.

Completeness of Data

Soil verification data are contained in Appendices A and B of Volumes 4 - 9 of *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a). These volumes contain data records and results regarding soil analyses.

Thorium and Uranium Sampling and Analysis

Recognition of issues associated with Th-230 occurred early in the cleanup planning. In fact, much of the verification plan was based on Th-230 and its contribution to in-growth of Ra-226. Each grid on the site was (effectively) sampled for Th-230 through either laboratory analysis or via association with Ra-226. The sampling, analysis, and QA/QC discussed above are more than adequate to demonstrate compliance with NRC standards for Th-230.

Uranium was addressed after all grids met the radium and thorium standards. First, sampling locations for 100 grids were focused upon areas of highest likely contamination, based upon historical records. This identified areas where uranium was, and was not, in statistical association with radium. In those areas where an association held, compliance was demonstrated using association with radium or gamma-count values. In areas where an association did not hold, each grid was sampled and analyzed for uranium. In all, approximately 200 grid samples were analyzed in the laboratory for uranium.

WDOH Verification

Department staff evaluated and approved the *Sherwood Project, Radiological Verification Program* (SMI 1994a) prior to the commencement of the soil cleanup activities. During company sampling and analysis, department staff performed radiation surveys, took over 100 soil samples, and performed independent laboratory analysis. Department staff evaluated the applicability of background material concentrations and mineralogy. Site inspections were performed to verify compliance with plans and specifications. Results documented in *Sherwood Project, Radiological Verification Completion Report* (SMI 1996a) were thoroughly reviewed by department staff.

Construction Considerations

Construction Considerations has sub-sections on Materials of Construction, Quality Assurance and Quality Control, Quality Control Records, and Vegetation. The Materials of Construction portion describes Riprap, Filter Material, Rock Placement, and Filter Placement. Quality Assurance and Quality Control is divided into Tolerances, Rock Durability, Rock Gradation, Rock Thickness, Diversion Channels, Margins, Confluences, Embankment Outslopes, and Vegetation.

Construction was authorized after the Sherwood Project closure plan was approved, environmental review was completed, and technical specifications and drawings for site reclamation were submitted and approved.

The tailings impoundment area was covered by a minimum of 12.6 feet of site borrow soils.

A large diversion channel was constructed around the tailings impoundment on the west, north, and east.

The impoundment dam on the south side of the tailings area was lowered to conform to final grade, and pushed out to a shallow 5H:1V slope.

Riprap was placed in all areas found by analysis to require rock surface-protection from erosion.

Monitoring wells were either abandoned or adjusted to meet the new elevations resulting from construction.

A lined solution holding pond, just north of the tailings area, was reclaimed by excavation of the liner and contents and placement in the lined tailings area. This area was covered with soil to a compatible grade elevation with that of the covered tailings area.

Each of the design elements was evaluated during construction for compliance with design drawings and specifications. WNI performed quality control evaluations through use of daily and weekly reports, inspections, and quality assurance audits. WDOH staff performed verification inspections and audits on approximately a weekly basis. Over 50 individual inspections were performed during construction.

A completion report of the construction was prepared by WNI and submitted to WDOH for review and concurrence. The *Sherwood Project Construction Completion Report* (SMI 1997a) details all aspects of construction and compliance to applicable requirements. Where specific compliance was not attained, corrective actions were performed, or justifications provided that the underlying regulatory requirements were met.

Materials of Construction

Specific requirements for construction are noted in the following sections:

Riprap

Riprap consists of sized angular basalt or quartz monzonite obtained from a tested, onsite, rock source or an alternate, approved, rock source. After passing petrographic analysis, riprap must meet the rock scoring criteria discussed in Appendix D of the *Staff Technical Position on Erosion Protection* (NRC, 1990). Riprap material must be resistant to abrasion and weathering, and free from cracks, seams, soils, and other defects that could tend to increase weathering by water and frost action. Riprap must be well-graded and sized as specified for each particular site area, as shown in Table 2A of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

For ease of rock production during construction, actual sizes of riprap used were limited to D_{50} of 3", 6", and 15", even though design requirements indicated that smaller rock could be used in many locations.

Filter Material

Two sizes of filter material are specified in Table 2B of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

Rock Placement

Rock (riprap) is placed at locations and grades as shown on reclamation plan drawings. Rock is placed in a manner to prevent segregation and provide a desired rock thickness. Non-conforming rock must be either reworked, or removed and replaced, as necessary.

Filter Placement

Each filter layer is placed in one lift and tracked in place by appropriate heavy equipment. Where more than one layer is required, each layer is placed in a manner that prevents segregation. Filter material that does not meet quality control requirements must be either reworked, or removed and replaced, as necessary.

Quality Assurance and Quality Control

Quality control was provided onsite by WNI. Daily and weekly status reports, inspection reports, and field inspections were performed.

Surveying was provided by an independent licensed engineer for construction grades and cut points.

Rock-size, gradation, and quality evaluations were provided by an independent geotechnical laboratory and field inspected.

The corporate office of WNI performed an independent Quality Assurance evaluation of operations and construction at the Sherwood Project site by audit. A corrective action program was instituted as defined in the *Construction Component Quality Plan* (SMI 1996b).

Specific requirements for quality control are noted in the following sections:

Tolerances

All elevation and thickness specifications are given in the *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996). Elevation and thickness tolerances are measured on a 100-foot center grid system. Rock thickness is measured every 100 linear feet along the channel, margin toe, and embankment groin. Vegetation productivity is measured on the impoundment cover and margins to ensure successful re-vegetation. Vegetation success and productivity measures are identified in the *Monitoring and Stabilization Plan* (SMI 1997).

Rock Durability

As specified in Table 3 of the *Revised Executive Summary and Technical Specifications* (SMI 1996), durability testing of the rock used for riprap and filter material includes the following series of ASTM laboratory tests:

- Petrographic analysis (initially only).
- Bulk Specific Gravity and Absorption.
- Sodium Sulfate Soundness.
- Los Angeles Abrasion.
- Schmidt Hammer Rebound.

The rock qualification test program follows the testing requirement listed in the *Staff Technical Position on Erosion Protection* (NRC, 1990).

At a minimum, a test series is performed before use. This is followed by testing for each additional 10,000 cubic yards of rock produced from a particular source. More frequent testing, including petrographic analysis, may be conducted if it is suspected that the rock has changed substantially from the rock that was previously tested. Any visual change that is noted will be recorded.

Petrographic analysis is required as a first step in qualifying a rock source.

Rock Gradation

Gradation testing of riprap and filter material includes, at a minimum, an initial test followed by additional testing for each additional 10,000 cubic yards of rock. Gradation testing must be performed for each riprap and filter size. A minimum of three gradation tests is required for riprap sizes having less than 30,000 cubic yards of production.

Rock Thickness

The thickness of riprap, and filters are measured in accordance to Table 3 of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

Diversion Channels

Cross-sectional areas and channel bottom low-points are measured every 100 feet in accordance with Table 3 of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

Margins

Slopes of the margins are graded in accordance with Figure 4 of the Final Drawings. Slopes are surveyed every 100 feet, in accordance with Table 3 of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

Confluences

Slopes of confluences and placement of riprap in the diversion channel, and up the confluences, are surveyed in accordance with Table 3 of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

Embankment Outslopes

Slope surveys are performed on 100-foot grids on the impoundment dam face. See Table 3 of the *Revised Executive Summary and Technical Specifications* (SMI 1996).

Vegetation

Vegetation is specified in design requirements and provided by seeding, mulching, and enhancement farming practices, as needed to initiate vegetation after construction completion.

Evaluation of vegetation performance is provided by measurement of percent live vegetal coverage. Vegetation success is evaluated in the *Monitoring and Stabilization Plan* (SMI 1997).

If insufficient vegetal coverage exists in any area, alternate erosion protection must be provided, such as reduced slopes, placement of riprap, or use of other geotechnical materials or techniques.

Quality Control Records

Weekly inspection reports are maintained showing construction progress, details of construction activities performed, and corrective action decisions. Volumes of materials placed and the number of field and laboratory tests performed on each material are summarized weekly.

Quality Control Records are generated verifying specific requirements listed in *Sherwood Project, Revised Executive Summary and Technical Specification* (SMI 1996). The following QA Records are maintained:

- Petrographic analysis of riprap.
- Rock durability tests.

- Rock gradation tests for each size of riprap.
- Rock placement and thickness verification.
- Rock gradation.
- Tailings surface sub-grade elevation.
- Final cover elevation.
- Diversion channel alignment points (E-W, N-S, and elevation).
- Final diversion channel cross-sectional areas.
- Extent of riprap placement in the confluences.
- Slopes of margins.
- Slopes of diversion channel.
- Slopes of confluences.
- Main embankment outslopes.

Quality Control Records are maintained in a secure location and made readily available for inspection or audit by authorized inspectors.

A construction completion report is required upon completion of the construction phase of the Sherwood Project (SMI 1997a).

Vegetation

All construction surfaces not covered with rock erosion protection materials are vegetated. The impoundment cover, outlet swale, margins surrounding the tailings surface, and upper portions of the diversion channel walls are seeded with natural species to enhance the natural succession of vegetation.

The tailings top surface was analyzed and found to be erosionally stable, with only vegetation and without riprap. Ponderosa Pine saplings are planted on an eight-foot center grid. The outlet swale is riprap-protected. The last 30 feet of the swale has a natural soil cover over a substantial riprap and filter layer. The natural soil portion of the outlet swale is re-vegetated with native species. The impoundment margins and the upper portion of the diversion channel walls are also re-vegetated.

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Appendices

Two appendices are included. Appendix A describes the Vegetal Coverage evaluation analysis performed by WNI and verified by WDOH. Appendix B similarly describes Rock and Filter Sizing, Durability and Gradation. Appendix B is divided into Rock and Filter Sizing, and Rock Durability and Gradation.

Appendix A - Vegetal Coverage

The licensee proposes to re-vegetate margin areas between the diversion channel and the tailings impoundment cover surface. In support of this proposal, three vegetative test plots were established in areas surrounding the impoundment. These test plots had slopes that were comparable to the slope of the impoundment cover. See Appendix M of *Sherwood Project, Tailings Reclamation Plan* (SMI 1994). Detailed cataloging of cover material was performed to determine the amount of live cover, rock, and litter (dead cover). Field measurements yielded approximately 40% live cover over three test plots.

The Staff Technical Position on Erosion Protection (NRC 1990) allows full credit in allowable vegetal stress only if expected (or actual) vegetal cover is significantly above a 30% cutoff and preferably above 70% vegetal cover. Since field-testing resulted in 40% vegetal cover, a 75% reduction {(70-40)/(70-30)} in allowable vegetal stress was imposed by WDOH staff.

This reduced allowable vegetal stress level is significant for steeper slopes (i.e., 33% slopes or 3H:1V grades). Stress calculations for two different margin slopes determined that maximum vegetal stress is less than allowable on 20% slopes, but greater than allowable on 33% slopes. Therefore, vegetal coverage field measurements are required after construction completion to assure erosional stability.

If steeper slopes are not successfully re-vegetated to provide for adequate erosional stability, redesign may be required, either by adjustments in grade, placement of riprap, or use of other geotechnical materials or techniques.

Appendix B - Rock and Filter Sizing, Durability, and Gradation

Detailed review of rock and filter sizing, durability, and gradation is included here to augment discussions in the text on geotechnical stability.

Rock and Filter Sizing

In sizing riprap, median stone diameter (D_{50}) is estimated using either the Safety Factors Method or the Stephenson Method. According the *Staff Technical Position on Erosion Protection* (NRC 1990), the Safety Factors Method is appropriate for surfaces with a slope < 10%. The Stephenson Method is used for embankments with a slope > 10%.

Riprap sizes, from 1 inch to 15 inches, were estimated for various applications on the Sherwood Project site.

Analytical checks of D_{50} riprap sizes were found to be adequate and, in several cases, larger than required.

Riprap gradation is specified as rock that is well-graded throughout the layer thickness and placed in a manner that will minimize degradation and separation of the material.

Riprap is used to minimize potential for erosion of the underlying soil. Whenever underlying soils are of such a gradation that there is danger that fines may be washed out through the voids in the riprap, a layer of graded gravel (filter) is placed beneath the riprap. Gradation of the filter should be coarser than the underlying soil, but finer than riprap. Depending on riprap and fine soil gradation, more than one filter layer may be needed.

Placement of filter material is specified beneath riprap in the diversion ditch in appropriate locations and with minimum thickness. See Table 5.2.4 and Table 2A of *Sherwood Project, Revised Executive Summary and Technical Specifications* (SMI 1996). The design filter (D_{15}/d_{85}) ratio is less than 5, which is the maximum acceptable value quoted in the literature.

Durability and Gradation

Rock durability is defined as the ability of rock to withstand the forces of weathering.

In order to assure that rock used for erosion protection remains effective for up to 1,000 years, as required by Criterion 6 of WAC 246-252-030 (WAC), potential rock sources are tested and evaluated. An acceptable procedure for making this determination is presented in Appendix D of the Staff Technical Position on Erosion Protection (NRC 1990). After initial laboratory testing, this procedure specifies a minimum score, depending on the location where the rock will be placed.

Rock scoring 80 or greater indicates high quality rock that can used for any application. Rock scores between 65 and 80 indicate less durable rock that can still be used for any application, provided that the riprap is appropriately oversized. Rock scoring less than 65 cannot be used for critical areas such as diversion ditches, and poorly drained toes and aprons. However, rock scoring between 50 and 65 can be used in non-critical areas, provided it is properly oversized. Rock scoring less than 50 is not acceptable for use.

An initial required test, the petrographic examination (ASTM C 295), was performed on samples of basalt and quartz monzonite rock. The examination results indicated a lack of smectites and thus that the rock source was qualified for further evaluation and testing.

Rock samples were then tested for Bulk Specific Gravity and Absorption (ASTM C 127), Sodium Sulfate Soundness (ASTM C 88), Los Angeles Abrasion (ASTM C 535), and Schmidt Hammer Rebound (ASTM C 805).

Rock testing and evaluation indicated that the proposed dense basalt is of very high quality for all samples sent to the lab. Only one offsite basalt source failed critical area use (scored less than 80 but greater than 65), but could be used for non-critical use with appropriate oversizing. Most basalt samples scored in the 86-93 range.

Initially, quartz monzonite samples tested were found to be unacceptable. Petrographic analysis on one quartz monzonite sample indicated that clays were present, which disqualifies that source.

Evaluation of an established bench within the reclaimed mine produced a higher quality rock source. The exposed rock face was a hard quartz monzonite.

Samples sent to the lab resulted in a "fair" rating for smectites (expanded lattice clays). Rock durability tests were performed on this rock source. Initial petrographic test results indicated that the quartz monzonite source on the mine bench was adequate.

Rock durability test scores for the mine bench quartz monzonite source averaged 80, including pre-production tests and tests every 10,000 cubic yards. The lowest score was 78 and the highest score was 81. The quartz monzonite rock source was sampled and tested for durability 11 times.

Construction was concluded with rock from both basalt and quartz monzonite sources. Rock placement was generally oversized by a significant amount. Filter sizing was appropriately adjusted to compensate for the rock-size actually placed.

Appendix C - Radon Flux (Emanation) Rate Modeling

Over the past several years, the NRC has refined the diffusion model to estimate radon flux. The RAECOM computer program is documented in NUREG/CR-3533 (NRC 1989). This reference establishes the analytical approach recommended for design of earthen covers for radon flux attenuation. The RADON computer program is an interactive BASIC version of the FORTRAN computer program RAECON.

The RADON computer program was used to analyze cover designs for the Sherwood Project. The model runs on a personal computer (PC), and follows the guidance presented in the Regulatory Guide (NRC 1989) and the Radon Attenuation Handbook, NUREG/CR-3533 (NRC 1989a). These references describe methods acceptable to NRC for radon flux calculations through earthen covers and for calculating minimum cover thickness needed to meet regulatory standards. These references suggest methods for obtaining various input parameters used for calculating radon flux and earthen cover thickness, and suggest default values for certain parameters.

Long Term Moisture Saturation

Moisture saturation is the relative portion of the soil void space taken up by moisture. The moisture content of earthen materials has been shown to markedly affect radon gas diffusion, radionuclide transport, structural stability, and productivity of vegetation. Because these effects are primary considerations in cover design performance, and since performance must persist for very long time periods, long-term average moisture content in covers and tailings at uranium mill tailings sites is of particular interest.

There are several available analytical models for evaluating soil moisture saturation (NRC 1989a). By combining equations (14) and (15) in Section 4.4, NUREG/CR-3533 (NRC 1989a), the following equation is obtained:

$$\mathbf{m = m_r\,(1 - (0.7+f_{cm})^2\,/H^2) + (0.7+f_{cm})^2/H^2} \qquad (3)$$

where:

$$\mathbf{m_r = 0.124P^{1/2} - 0.0012E - 0.04 + 0.156f_{cm})} \qquad (4)$$

and, where:

m = long-term moisture saturation (affected by depth to the water table) (vol./vol.)
m_r = residual long-term moisture saturation (unaffected by depth to the water table) (vol./vol.)
P = annual precipitation (in.) = 18.2 inches
E = annual lake evaporation (in.) = 25 inches
f_{cm} = the fraction of soil passing through a US Standard Sieve # 200
H = depth to water table (ft.) = 120 feet

Long-term moisture saturation, m, is a function of P, E, H, and f_{cm}. Assuming annual precipitation (P), annual lake evaporation (E), and depth of water table are consistent over a long period, long-term moisture saturation is then seen to vary primarily with f_{cm}, the fraction of soil passing through a US Standard Sieve # 200. It is evident in practice and from analysis that increases in f_{cm} produces increases in long-term moisture saturation, and reduction in radon flux rates.

Alternatively, greater soil fines (percent passing the # 200 sieve) produce greater long-term moisture saturation and less cover thickness in meeting radon flux rate limits.

Long Term Average Moisture

Moisture content is the ratio, in soil, of moisture to dry solids, by weight. There are several acceptable methods for predicting the long-term soil moisture content for use in radon cover design analysis. One recommended method is to measure moisture content at cover material borrow sites and to make adjustments, if needed, for differences in placement conditions between the borrow site and the disposal site.

NRC guidance references (NRC 1989, and NRC 1989a) recommend that soil moisture for the candidate cover materials, w_c, be measured from samples obtained from soil depths of 120 to 500 cm. Shallow samples of the soil are excluded because of seasonal variability in their moisture content. Samples close to the water table are also excluded to avoid bias from moisture due to capillary effects.

NRC guidance (NRC 1989a) recommends a conservative default value for long-term average moisture content as the wilting point of soils. Permanent wilting of vegetation occurs at relatively low values of long-term moisture content. The wilting point can be determined by laboratory soil testing or from empirical relationships, such as those recommended by Rawls and Brakensiek (NRC 1989a). The established empirical relationship predicts volumetric moisture content of the soil using 15 bars (soil moisture tension), or the following equation:

$$\mathbf{Q = 0.026 + 0.005z + 0.0158y} \qquad (5)$$

where:

Q = permanent wilting point of soil (wt./wt.)
z = % clay in the soil (100 wt./wt.)
y = % organic matter in the soil (100 wt./wt.)

Because Q is determined as the permanent wilting point of the soil, NRC guidance (NRC 1989) considers that this value is a reasonable lower bound for the soil moisture content over the long term.

The wilting point is the soil moisture content at which soil can no longer supply water at a rate sufficient to maintain plant life. The tension of the soil water when permanent wilting occurs is species-specific, but is conservatively estimated to be 15 times atmospheric pressure.

Long-term average moisture for the candidate cover material, w_c, is related to Q by the following equation:

$$\mathbf{w_c = 100Qp_w/p_{ds}} \qquad (6)$$

where:

p_w = density of water (1.0 g/cc)
p_{ds} = density of dry solids (1.69 g/cc)

NRC guidance (NRC 1989a) recommends use of a default value for tailings long-term average moisture, w_t. Radon cover thickness calculations are not as sensitive to tailings moisture content as to cover moisture content. Unless documented alternative information is furnished, a default value of w_t = 6% is recommended for tailings moisture content, for arid western sites.

The Radon Diffusion Coefficient

The degree of radon flux reduction provided by a tailings cover depends on the time required for the radon to diffuse through the cover, and thus to partially decay in it. Therefore, the diffusion coefficient of the soil is of central importance to determine the required cover thickness to achieve a given radon flux reduction. It is therefore advantageous to know as accurately as possible the diffusion coefficient of the candidate cover material.

The diffusion coefficient is most accurately determined by direct measurement. Measurable quantities in determining the diffusion coefficient are the radon flux and the tailings radium concentration. The diffusion coefficient can be calculated from any combination of two measurements of flux and concentration; which directly involve the cover and the source, respectively.

Radon diffusion coefficients can be measured either in the laboratory or the field. Field measurements offer the advantage of exposure to actual wind, sun, rain, and other significant environmental parameters; which may affect the soil moisture content and its diffusion coefficient.

In addition to soil moisture content, other soil parameters, such as soil compaction (bulk density), may have a significant influence on the value of the diffusion coefficient. It is important that the highest practical compaction be achieved for earthen covers over the tailings so that maximum radon attenuation is obtained.

Estimating Diffusion Coefficients

It is often desirable to estimate diffusion coefficients of materials under various conditions for which measured values are not available. This can be done with either complex models based upon physical characteristics of the soil, or using empirical correlation based upon measured values. Soil moisture and compaction (bulk density) are important factors in the development of diffusion coefficients for a given soil cover material.

A theoretical model has been developed for estimating radon diffusion coefficients (NRC 1989). The formalism considers the detailed composition of the pore fluid as well as a statistical definition of the pore structure of the material. The pore fluid is modeled as a two-phase mixture of water and vapor, with radon diffusion occurring in both phases, and with radon exchange occurring between the water and the vapor. The pore structure is modeled from the measured pore-size distribution of the soil, and described by weighted-average combinations of single and composite pores. Soil parameters required to estimate a radon diffusion coefficient are thus the moisture, the packing density, and the pore-size distribution.

Empirically determined correlations for estimating diffusion coefficients have the advantage of being simple and easy to use, with a minimal amount of information needed. The recommended correlation, using long-term moisture saturation, m, is:

$$\mathbf{D = 0.07\ e^{-4(m - mp2 + m5)}} \tag{7}$$

The exponential argument in the correlation is a simple power series in m, where the first term defines the general downward slope. The second term contains the porosity influence and also causes a more gradual decrease, with moisture in the pore-filling region. The final term in the exponential argument accounts for major pore blockage near saturation and causes the more rapid decreases needed in this region.

The relationship between moisture saturation, m, and the commonly-measured moisture content, w, is:

$$\mathbf{m = 100w/(1/p - 1/g)} \qquad (8)$$

where:

p = soil dry bulk density (g cm^{-3})
g = specific gravity of dry soil solids (g cm^{-3})
w = moisture content (%) (wt./wt/)