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Natural and Engineered Features Supporting Environmental Performance of Idaho National Laboratory's Remote-Handled Low-Level Waste Disposal Facility – 19436

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ABSTRACT

The Idaho National Laboratory's (INL's) Remote-Handled Low-Level Waste (RH LLW) Disposal Facility has been designed and constructed to receive waste generated at the INL site in support of the US DOE Office of Nuclear Energy (NE) and Naval Reactors (NR) missions. The facility has been designed to receive legacy RH LLW currently in storage at INL facilities and new waste generated by nuclear research programs. RH LLW to be received at the facility is solid waste consisting of surface contaminated materials; ion exchange resins used to purify cooling and canal water; and activated metal components generated during reactor core change outs and Naval spent fuel management; and nuclear R&D. Disposal of INL's RH LLW poses unique disposal challenges due to high radiation levels (contact rates up to 600 Sv/hr [60,000 Rem/hr]) that require remote handling and adequate shielding for transportation and disposal. The facility has been designed to meet the requirements of DOE Order 435.1, *Radioactive Waste Management* [1], including the all-pathways dose, air pathway dose, inadvertent intruder doses, and radon emissions limits.

This paper presents an overview of natural and engineered design features that support the safety case and enhance the environmental performance of the facility. These features include location selection, use of reinforced pre-cast concrete vaults; a robust hydraulic drainage system; use of steel waste canisters for waste disposal; the facility monitoring system; facility layout; and crediting waste forms. The facility performance assessment (PA) [2] developed to meet the requirements of DOE Order 435.1, credits each of these protective features. Releases from waste forms disposed of at this facility are limited by corrosion of the steel waste canisters which will ultimately allow contact with infiltrating water followed by transport of radionuclides from the vault system. The steel waste canisters were credited for their ability to limit water contact with the waste based on the demonstrated ability of the reinforced pre-caste concrete vaults to provide long-term structural protection of the steel waste canisters. Verification of hydraulic and concrete performance was conducted through laboratory data, field infiltration tests supported by a robust monitoring system, and numerical modeling. Releases into the vault system from activated metals are based on site-specific corrosion data. Radionuclide transport from the vault system from all waste forms is based on site-specific climatological, hydrologic, and stratigraphic data.

At INL, the groundwater pathway historically and appropriately has received the most attention. By crediting aspects of the natural system, the engineered vault system, and the waste, estimated radiologic doses via the groundwater pathway are minimal. Air pathway doses were reduced by differentially crediting corrosion of aluminum and stainless steel activated metals resulting in the pathway being screened out of the PA. Groundwater and inadvertent intruder doses were reduced through selective facility layout. This paper provides an overview of the system-wide protective features incorporated into the facility design along with an extensive reference list to supporting technical papers and analyses that provide data and interpretation.

INTRODUCTION

In 1948, the Atomic Energy Commission (AEC), predecessor to the DOE, established the National Reactor Testing Station, now known as the INL Site. Here, the AEC and DOE built, tested, and operated fifty-two test reactors, support facilities, and equipment. Today, INL is a multi-program laboratory that supports

DOE missions and business lines of nuclear energy research, energy resources, science and technology, and national security.

The INL Site occupies approximately 2,305 km^2 (890 mi^2) of mostly undeveloped, high desert terrain in southeastern Idaho (Figure 1). Underlying the INL Site is the Snake River Plain Aquifer (SRPA); one of the most productive aquifers in the United States which serves as the drinking water supply source for much of southeastern Idaho. During the 70-year history of the INL Site, operations conducted in support of nuclear reactor testing and the cold-war have resulted in releases of radionuclides at land surface and into the underlying SRPA.

Since 1952, the Radioactive Waste Management Complex (RWMC) has accepted the bulk of INL's contact and remote-handled low-level waste for disposal. In accordance with environmental restoration commitments under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) [3], the RWMC is undergoing closure and active waste disposal operations are being phased out.

The RH LLW Disposal Facility was constructed to provide replacement RH LLW disposal capability and support cost-effective, efficient operations in support of INL's nuclear energy mission and the Naval Nuclear Propulsion Program.

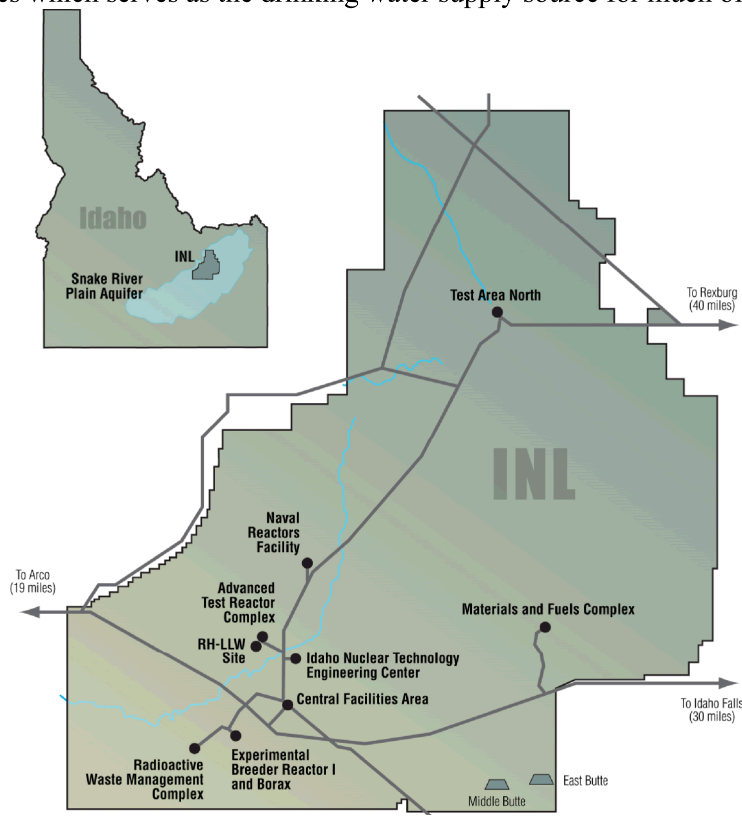

Fig. 1. Map of facilities showing RH LLW Disposal Facility.

FACILITY DESCRIPTION

The RH LLW Disposal Facility was constructed 0.5 km southwest of the Advanced Test Reactor (ATR) Complex (Figure 1) and is comprised of an administration building; a maintenance building; and the vault yard (Figure 2). The below grade vault yard provides twenty years of waste disposal operations capacity with five disposal vault configurations in four vault arrays supporting six different cask/canister system configurations (Figure 3). There are a total of 446 waste disposal vaults that will accommodate disposal of a total of 939 stainless steel radioactive waste canisters. Each disposal vault is constructed of a base component, a riser component, and a vault shield plug. Together with the perimeter blocks, construction of the vault yard required precise placement of more than 1,600 individual components weighing between 13.6 and 22.7 metric tons (15 and 25 tons).

The vault walls are constructed of 15.2-cm (6-inch) thick reinforced concrete while the shield plugs are nominally 1.52-m (5-ft) thick. The facility is designed to accommodate canisters with contact radiation dose rates as high as 600 Sv/hr (60,000 Rem/hr).

Fig. 2. RH LLW Disposal Facility showing administration and maintenance building (background) and vault yard (foreground). The Advanced Test Reactor Complex is in the far background.

Fig. 3. Vault yard construction showing four all vault arrays.

NATURAL AND ENGINEERED FEATURES SUPPORTING ENVIRONMENAL PERFORMANCE

Standard DOE-STD-5002-2017 [4] provides guidance for meeting DOE's requirements for waste management contained in DOE Order 435.1 [1].

The Standard represents implementation of recommendations and standards for radioactive waste disposal, especially as they relate to the "safety case" for a disposal facility. The safety case is a collection of arguments and evidence supporting safe disposal of waste and the concept provides a way to address, acknowledge, and document that evidence to provide defense-in-depth. Key contributors to the defense-in-depth approach include natural and engineered features as part of the design of the total system. The standard states that these features may also be integrated into the facility performance assessment (PA); a documented evaluation that provides DOE with a reasonable expectation that disposal will meet the radiological performance objectives established in DOE Order 435.1 [1]. The following sections describe these features and how they contribute to defense-in-depth and how some were incorporated into the PA.

Natural Features and Site Selection

Many natural features of the INL impact the safety case in a positive way by combining to limit the potential for release and transport of radionuclides to potential receptors; especially via the groundwater pathway. Natural features of the INL and specifically the RH LLW site that contribute to the protectiveness of the facility include:

- **Semiarid environment**: The INL is a high desert environment that experiences on average 22 cm of precipitation annually. The high evapotranspiration rates result in relatively low (~1 cm/yr) net infiltration through undisturbed soils. In disturbed unvegetated soils, the infiltration rate approaches 10 cm/yr. At these low infiltration rates, radionuclide migration to the aquifer can takes tens of years to hundreds of thousands of years, depending on the radionuclide.
- **Distance above the aquifer** – Depth to the aquifer at the INL Site ranges from about 65 m at the northern end to about 190 m at the southern end. The base of the RH LLW facility is located about 143 m above the aquifer. The depth to the aquifer provides additional dispersion/dilution and more time for radionuclides to decay before reaching the aquifer and potential receptors.
- **Surface Alluvium** – Prior to final site selection, coreholes were drilled through the alluvium to the upper basalt contact. Cores were logged and correlated to determine sedimentary structure in the alluvium and core material was sent to an independent laboratory to determine grain size, texture, moisture content, and cation exchange capacity [5]. Sorption properties of alluvium and vadose zone sediments were also analyzed [6]. The results provided information necessary for the construction of the facility (i.e., geotechnical, seismic response, structural integrity) and the total thickness of alluvium. The alluvium thickness at the RH LLW site ranges from 13.5 m to 17.5 m. Even with the vaults extending 7 m into the surface alluvium, there remains 7 m to 9 m of alluvium between the base of the vaults and the first basalt contact. This alluvium serves to retard radionuclide transport and results in lower radionuclide fluxes to the vadose zone.
- **Vadose Zone Stratigraphy and Hydrology** – The vadose zone at INL is comprised of basalt sequences separated by sedimentary deposits. The basalt layers are typically fractured and highly transmissive to water. Functionally, they do little to inhibit the migration of radionuclides because they have high hydraulic conductivity, low effective porosity, and very little sorptive capacity. Interbed presence and structure controls the migration rate of water and radionuclides. In order to retard migration, the interbeds must be laterally continuous at the scale of the RH LLW Disposal Facility. The interbeds near ATR are relatively continuous and the thickness is relatively constant [6]. The total interbed thickness below the RH LLW disposal facility and the aquifer is approximately 22 m. Soil texture consists of sands, silty-sands, and clays with some gravel, which increases the sorption capacity and retards radionuclide migration.
- **Surface Water Hydrology** – The facility is located about 1.3 km from the Big Lost River channel. There are no other sources of surface water within that distance including man-made infiltration ponds, playas, or wetlands. The facility is also outside the 10,000-year flood plain of the Big Lost River [7]. To provide additional protection against flooding during and after a probable maximum precipitation event, the surface of the vault yard is about 1.5 m above the natural grade, well above the possible ponded water elevation from natural rainfall events and above the floodwater elevation predicted to occur following a probable maximum precipitation event or the probable maximum flood.
- **Aquifer Transport** – Water velocities in the aquifer near the RH LLW facility are higher than to the south and east. The Darcy velocity near the RH LLW Disposal Facility is estimated to be about 16 m/yr. Higher velocities near the facility location contribute to more dilution in the aquifer, reducing concentrations and doses to potential downgradient groundwater users.

- **Demographics and Land Use** – The RH LLW facility is located approximately 16 km from the INL Site boundary in the direction of groundwater flow and 18 km from the INL maximally exposed individual (MEI) location for atmospheric radionuclide emissions. Restricted public access on the INL Site limits exposure during the institutional control period.

To enhance the impact of these natural features, a site-selection process was executed to choose the best site based on environmental impact and other considerations. The site selection study [8] identified and evaluated 34 potential sites for the RH LLW Disposal Facility. These sites were screened against "must" criteria related to proximity to faults, floodplains and wetlands. The remaining sites were then ranked against 21 "want" criteria from 4 areas: Geology, Hydrology, Land Use, and Natural Resources. The "want" criteria were assigned weighting factors based on overall impact to facility design, construction, operation, or performance; technical feasibility of mitigating impacts; and cost associated with mitigating impacts. The siting study recommended two sites that scored significantly higher than others and both sites were included in the Environmental Assessment (EA) [9]. While the EA determined that both candidate sites were protective of the aquifer, one site was preferred because its slightly higher elevation, greater distance from the Big Lost River, and thicker sediment provided greater protection of the aquifer and lower dose estimates. In addition, the preferred site had less potential for cumulative groundwater impacts, a composite analysis concern.

Engineered and Facility Design Features

Several features were identified or designed into the facility to enhance the protectiveness of the facility. These include waste form, waste canister, vault system and design, drainage system, engineered cover, facility layout and monitoring system.

Waste Form

While not an engineered or design feature, waste characteristics play a large role in mitigating potential human exposure and environmental consequences. The disposal facility will accept three primary types of RH LLW: (1) activated metals, (2) ion-exchange resins, and (3) surface-contaminated waste materials. These are solid waste forms (liquids and gases are not accepted) with integral contamination and/or surface contamination. These waste forms and the characteristics that inhibit release from the facility are described below.

- **Activated metals –** Activated metal components are a significant portion of the waste destined for disposal at the RH LLW facility. These mostly reactor core components are primarily stainless steel, Inconel (i.e., nickel-chromium based alloy), and Zircaloy (high zirconium alloys), with a smaller fraction of aluminum. Cement used throughout the vault system is certain to raise the pH above native soil conditions, which will decrease the relative corrosion rate of the steel reinforcement used in vault fabrication and of activated metal waste until the soluble carbonates are leached from the cement. Although corrosion of the activated metal waste and waste canisters was credited in the PA, this pH effect was not considered in determining corrosion rates for the activated metals.

  Corrosion of activated metals was assumed to be a first-order process, allowing release to be modeled by the fraction of activity released per unit time. The corrosion rate used in the PA is based on the corrosion rate of Type 316L stainless steel coupons buried in INL soils adjusted to account for sensitization. This rate, 9.18E+04 yr/mm, combined with a surface-area-to-volume ratio for typical INL-type reactor components (0.535/cm) results in a fractional corrosion rate of 5.83E-07 yr^{-1}.

  The small amount of activated aluminum contains 90% of the total tritium inventory. Tritium is not a significant contributor to the groundwater pathway, but is for the air pathway. Therefore, aluminum corrosion rates were used to determine tritium release rates for the air pathway analysis. The air pathway however was screened out due to low dose estimates (< 0.001 mSv/yr [0.1 mrem/yr]).

- **Resins –** Ion-exchange resins are polystyrene or ceramic beads used to purify reactor cooling and canal water as part of routine operations at NRF and ATR Complex. Release of radionuclides from ion-exchange resins is assumed to be controlled by simple-linear equilibrium desorption that accounts for the impact of resin degradation and the presence of cement on the geochemical environment. Release from the resins occurs only after the canisters have failed and water contacts the resin. Both radionuclide desorption from resins and waste canister failure were credited in the PA.
- **Surface-contaminated waste materials –** Surface-contaminated materials include cellulosics, plastics, metal grindings, etc., from materials examination in hot cells. Activated metal components may also have radionuclide contamination on the surface. The radionuclides become mobile as the waste is contacted by infiltrating water, which happens after the waste canisters have failed. Waste canister failure was credited in the PA.

Stainless Steel Waste Canisters

All waste materials will be placed in robust steel canisters at the generator facilities and transported to the RH LLW Facility in a shipping cask. Canister characteristics that enhance the protectiveness of the facility include:

- **Canister thicknesses –S**teel canisters planned for disposal at the facility have a minimum side-wall thickness of 10 gauge (0.342 cm [0.1345 inches]). Typically, the canister tops and bottoms are thicker (up to 1.9 cm [0.75 inches] thick).
- **Canister composition –** All waste will be disposed of in corrosion-resistant stainless steel. The NRF canisters (55-ton and Large Concept Canister [LCC]) and Nuclear Packaging (NuPac) waste canisters will be made of Type 316L stainless. Existing Hot Fuel Examination Facility (HFEF) canisters are constructed of Type 304 stainless steel. Newly-procured canisters will be Type 316L stainless steel; however, for performance modeling, all HFEF canisters were assumed to be Type 304 stainless. Waste received in carbon steel waste canisters with carbon steel overpacks will be placed in Modified Facility Transfer Container (MFTC) vaults with a Type 316L stainless steel liner and covered with a Type 316L stainless steel lid.
- **Hydraulic performance –** Stainless steel canisters are expected to remain structurally intact, degrading only through corrosion, based on analysis provided in [10] [11] and Appendix B of the PA [2]. The mean canister life was determined by assuming corrosion proceeds equally from both inside and outside the canister and failure (i.e., loss of hydraulic containment) occurs when 50% of the wall thickness has corroded (in other words, when corrosion advances one quarter of the wall thickness from each side). For conservatism, Type 316L stainless steel canisters were assigned a failure rate representative of general corrosion of Type 304 stainless steel resulting in a mean canister life of 24,700 years (standard deviation = 2880 years). This is nearly an order-of-magnitude less than the lifetime of Type 316L stainless steel canisters. Existing Type 304 stainless steel HFEF canisters were assumed to be sensitized and subject to tunneling corrosion. Therefore, a conservative estimate of the mean canister life (150 years, standard deviation = 50 years) was assigned to these canisters which is less than the calculated life of carbon steel canisters.

  Only the outer stainless steel canisters are credited in the PA (many canister configurations include both an inner and outer waste can) for limiting water contact with the waste. Corrosion of the steel canisters and activated metal waste will be a function of environmental conditions. Initially, it is expected that corrosion will progress at rates representative of a suspended-in-air vault environment, transitioning to rates representative of a buried-in concrete or soil environment. The time period for this transition and net corrosion rate depends on the degradation rate of the concrete. With or without significant concrete degradation, the cement vault environment is expected to raise the pore-water pH beneath the vault system, which will decrease the corrosion rates relative to buried-in-soil conditions.

Vault System

The RH LLW concrete vault system provides structural protection of the waste canisters by supporting operational loads and the final engineered cover (see [10], [11] and Appendix D of the PA [2]). It also protects the canisters from corrosion by limiting water contact although this was not credited in the PA. The vault system design was based on lessons learned from existing facilities at INL. Elements of the improved design include concrete specifically formulated for increased longevity, thicker vault walls, component mating surfaces that limit ingress of infiltrating water and holes in the base that allow condensation or unintended infiltration to drain. Key elements of the vault design include:

- **Precast reinforced concrete vault components –** Each disposal vault is constructed of a base, a riser, and a vault shield plug (Figure 4). Base sections are constructed of a 40.6-cm (16-inch) thick hexagonal base and an integral riser section, an upper riser and shield plug (Figure 4). The hexagonal base and plugs allows close packing of the vaults and provides structural stability of the vault array. Lower and upper riser side walls are 15.2-cm (6-inches) thick as required by the facility performance specification [12]. The cylindrical shape of the risers is self-supporting, providing increased structural support over rectangular designs. The overlapped mating surface between the risers and between the upper riser and plug limit the ability of water to enter the vault. The base also has drain holes to allow any water imbibing into the vault or condensation forming in the vault to drain freely.

  Vault shield plugs are removable to support waste disposal. They are a minimum of 1.52-m (5-ft) thick based on radiation worker exposure safety calculations. There is a nominally 1.9-cm (0.75-inch) wide gap between plugs after installation. The gap between the plugs will, over time, allow water to infiltrate between the vault plugs and pass through the pea gravel infill between the vault riser sections (see next section). The low porosity, low-permeability concrete will greatly limit the transmission of water into the vault. The internal volume of the vaults relative to the volume of the steel waste canisters was limited to 25% through design and construction to limit void space and potential subsidence. The air gap provided by the void space will mitigate contact of any imbibed water with the steel waste canister as long as the vault and canister remain intact.

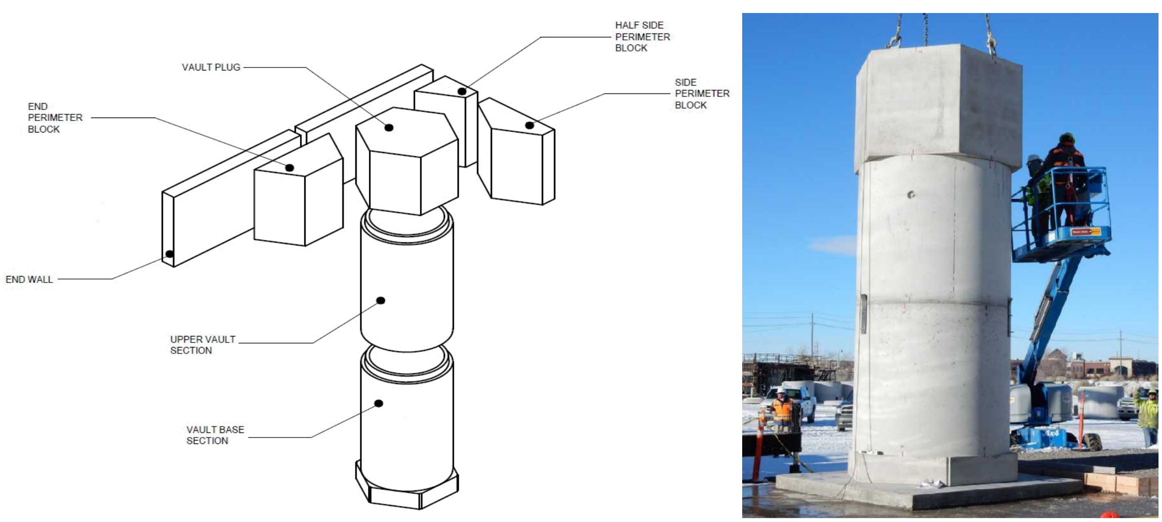

Fig. 4. Schematic of typical vault and perimeter components, and photo of NuPac vault fit-up test.

- **High-quality concrete –** The high-quality, steel-reinforced concrete is expected to protect the waste canisters and maintain the functionality of the engineered cover well into and feasibly beyond the 1,000-year compliance period. [11]. Two concrete mix designs were selected for use in vault components [13], [14]. Mix design 2 contains an air-entraining admixture to mitigate freeze/thaw degradation and was used for vault plugs and perimeter blocks located above the frost line. Mix design 3 was used for vault bases and risers located below the frost line. The reduced air gives mix design 3 a higher density, higher compressive strength and lower permeability. Each mix was designed to achieve a minimum 28-day compressive strength of 34.5 MPa (5,000 psi). The average compressive strength ranged from 44.1 MPa (6,400 psi) for plugs and perimeter blocks, to 53.1 MPa (7,700 psi) for bases and upper risers.

Concrete mixes were also designed to minimize degradation through carbonation, sulfate attack, alkali-aggregate reaction (including alkali-carbonate reaction and alkali-silica reactions), and freeze-thaw cracking. This was done through a combination of careful selection and testing of cement, aggregates (rocks, pozzolans, fly ash and slag), and admixtures (accelerators, water reducers, and lithium). Concrete samples were subjected to rigorous testing for strength, chemical composition, porosity, permeability/hydraulic conductivity and chloride diffusivity. The concrete was also analyzed for exposure to radiation. All concrete components were subject to strict quality assurance including inspections for defects and damage. Age related impacts are also managed by operations including restricting use of deleterious chemicals, operational controls and continued inspections.

Table I contains a summary of concrete test results and input parameters for the concrete service life analysis performed to support the PA. This included numerical simulations of water movement through the drainage materials under a range of precipitation/infiltration conditions. This evaluation is summarized in the next section, *Hydraulic Drainage System*.

TABLE I. Summary of Concrete Design Values and Test Results [13].

Bounding Design Parameter Description	Bounding Parameter Design Value	Testing Standard or Source	Test Results
Maximum water/cementitious material ratio (w/cm)[a]	0.40	Batch ticket	0.38
Minimum 28 day compressive strength[a]	34.5 MPa (5,000 psi)	ASTM[b] C39-14	46.9 MPa (6,800 psi)
Cement Type [for Class S2]	Type II/V	CMTR[c]	Not applicable
Air content for plugs, perimeter blocks & end walls [for Class F2]	Class F2 5% ± 1.5%	ASTM C231-14	5.8%
Air content for other precast concrete vault components [for Class F1]	Class F0 N/A	ASTM[b] C231-14	N/A but test result was 3.0%
Reactions with aggregate	Expansion < 0.10% at 16 days	ASTM[b] C1260-14	0.02% expansion at 16 days
Chloride ion in concrete test samples [related to Class C2]	Max water-soluble chloride ion (Cl^-) content as wt% of cement = 0.15	ASTM[b] C1218-99	RH LLW site pore-water max chloride content = 0.0083%
Concrete rate of water absorption [related to Class P1]	No value	ASTM[b] C1585-13	Average secondary rate for Mix 2 = 1.6x10 $mm/s^{1/2}$
Concrete porosity [related to permeability and chloride ion penetration resistance]	No value	ASTM[b] C642-13	Permeable pore space = 12.8% voids
Ion diffusion coefficient [related to chloride ion penetration & Class C2]	Goal < 8×10^{-12} m^2/sec	ASTM[b] C1202-12	Average = 1.65×10^{-12} m^2/sec
Permeability [related to Class P1]	No value	API RP 40[d]	Gas permeability = 3.4×10^{-8} cm/s at 28 days[e]

a. Related to several durability requirements.
b. ASTM = ASTM International, formerly American Society for Testing and Materials.
c. CMTR = Certified Material Test Report
d. API RP 40 = American Petroleum Institute Recommended Practice for Core Analysis

e. Liquid permeability should be less by at least one order of magnitude and will decrease with curing time.

Hydraulic Drainage System

The RH LLW Disposal Facility hydraulic drainage system was designed to allow water to pass easily and quickly through, around, and away from the vault arrays in order to limit accumulation of moisture next to the vaults and waste canisters (Figure 5). This type drainage system with steel-canister waste containment was evaluated against a traditional hydraulic containment system (geosynthetic membrane with leachate collection), and geochemical liner systems used to retard radionuclide migration (see [15] and Appendix C of the PA [2]). The hydraulic drainage system was the preferred option based on dose potential, performance risk, and maintenance concerns.

The hydraulic drainage system was designed to accommodate infiltration rates up to and including the probable maximum precipitation event without raising the saturation of materials adjacent to the vaults above 70% [16]. Key components of this robust drainage system include:

- **Pea gravel infill** – Pea gravel was placed between the cylindrical concrete vault sections. The highly porous media placed between the vaults allows free drainage of water between the vaults. By not holding water adjacent to the vaults for an extended period, water is very unlikely to imbibe into the concrete. The pea gravel placed between the vault risers provides additional structural stability to the vault array and radiation shielding.
- **Drainage course beneath the vaults** – This relatively clean (i.e., few fines) coarse material beneath the vaults serves as (1) a leveling layer and (2) as a water storage layer. The leveling layer is necessary to allow vaults to stand upright while maintaining the plug gap tolerances. The water storage and infiltration characteristics are necessary because precipitation and snowmelt during operations will be focused into the small area between the vault plugs and bottoms, being transmitted rapidly by the pea gravel. The drainage course which extends out a minimum of 3 m beyond the vault array was designed with sufficient storage capacity and hydraulic conductivity to accommodate a probable maximum precipitation event.
- **Perimeter drainage material** – A coarse material with few fines has been placed in a column around the perimeter of each vault array to promote rapid drainage of water and act as a capillary barrier, inhibiting water in the alluvial fill and crushed-gravel base course from being imbibed into the concrete vault walls (see [10], [11] and Appendix D of the PA [2]). This material also supports the perimeter blocks.
- **Crushed gravel base course** – The crushed gravel base course sits atop the perimeter drainage material and supports the perimeter blocks at the top of the vault array and the surface road base. This material contains a mix of fine and course materials and has been highly compacted. The contrast between this material and the perimeter drainage material creates a capillary barrier, diverting the bulk of precipitation or snowmelt away from the vault surfaces and into the alluvial fill as demonstrated through field tests and numerical simulation.
- **Alluvial fill** – The native alluvium excavated from the vault area and used to backfill the volume around the drainage materials contains a mix of fine and course materials. The fine fraction provides higher capillary suction than the perimeter drainage material, which preferentially results in flow into the alluvial fill. The material contrast acts like a capillary barrier between the perimeter drainage material and the alluvial fill.
- **Geotextile fabric** – Geotextile fabric was placed horizontally between the undisturbed subbase and crushed gravel base course and vertically between perimeter drainage gravel and the compacted alluvial backfill to within one foot below the bottom of the perimeter components. At this elevation, the geotextile fabric was pulled over the perimeter drainage gravel and extended up the sides of the

perimeter blocks to the vault yard surface. The geotextile fabric inhibits migration of fines into the coarse drainage materials. The material is permeable and allows water to pass through easily.

- **Surface road base** – The surface road base is the same material as the crushed gravel base course and allows the dense packing required to support transport vehicles. The apron around the perimeter of the vaults slopes away from the vaults, promoting drainage of onsite water away from the vaults.

  An evaluation of the concrete vaults and drainage system was performed with the TOUGHREACT model before final design using estimated properties/parameters and a limited set of measured hydraulic data, and after construction using as-built hydraulic properties. The initial evaluation predicted expected rates of water propagation under a range of precipitation/infiltration conditions, expected residual saturations in materials adjacent to the vaults, and residence time for wetting fronts infiltrating through the vault system. The results were used to predict saturations and rate of propagation of wetting fronts into concrete which was used to determine the expected number of pore-volumes passing through the concrete as a function of time. The evaluation was conducted for a range of hydraulic and concrete properties; therefore, it also served as the sensitivity analysis for evaluation of the as-built vault system.

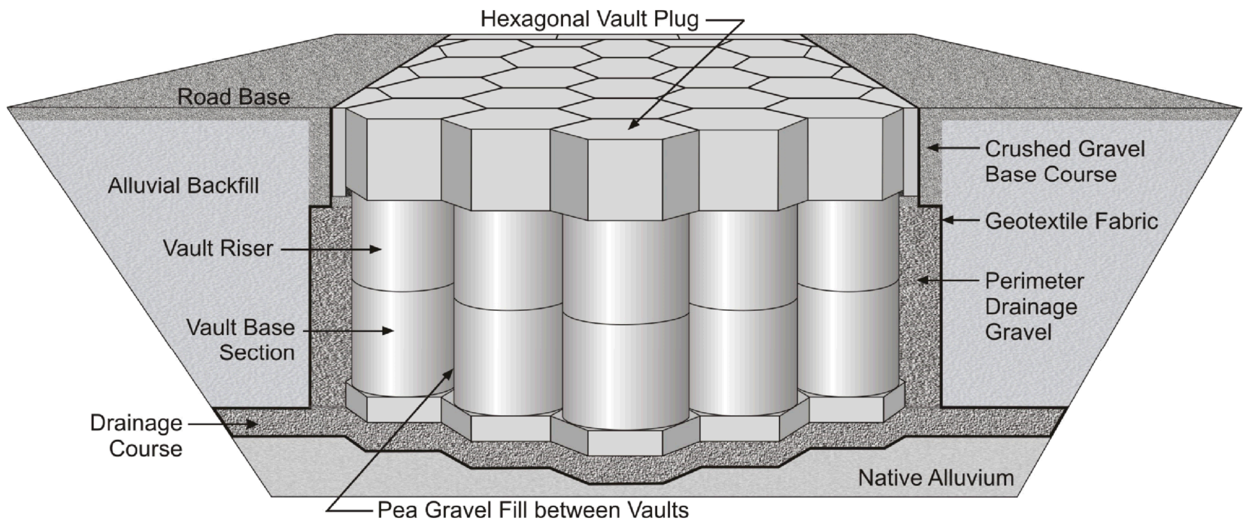

Fig. 5. Vault components in an array showing elements of the drainage system.

Analyses of the as-built vault and drainage system were also performed with the help of a refined model parameterized with a more complete data set to provide a final assessment of hydraulic and concrete performance of the vault system. These analyses (see [10], [11] and Appendix D of the PA [2]) provide confidence that the vault system meets or exceeds the requirements specified in the facility technical and functional requirements [16] and performance specification [12]. Based on the performance of the hydraulic drainage system and concrete vault components, it is very likely the concrete vaults will perform their intended functions throughout the 1,000-year period of performance required by DOE Order 435.1.

Facility Layout

Facility layout was an important factor in reducing the maximum potential groundwater pathway dose by consideration of the following:

- **Facility orientation** – The long-dimension of the vault arrays were oriented nearly perpendicular to the groundwater flow direction. Water movement in the vadose zone is gravity dominated and expected to occur nearly vertically downward with little dispersion. The vault arrays are long relative to the lateral expected dispersion in the vadose zone. This serves to dilute radionuclides fluxes to the aquifer resulting in lower concentrations and doses.

- **Vault array placement** – The predicted groundwater pathway dose from the facility depends not only on how much contamination gets to the aquifer, but when and where it arrives. Thought was given to placement of each vault array based on the radionuclide inventory, waste forms and canister types in each, in an effort to spread out the contamination physically and temporally to decrease the predicted maximum groundwater pathway dose.

  Even though there were 246 radionuclides in the facility inventory, only 14 were retained for full analysis in the PA after screening, and of those only Tc-99, C-14 and I-129 contributed markedly to the estimated dose. Tc-99 was the highest dose contributor. About 38% of the Tc-99 inventory is in ATR resins (NuPac array), 11% in surface-contaminated waste in HFEF canisters (HFEF-LCC array) and 49% in surface-contaminated in MFTC canisters (MFTC array). Although desorption from resins will cause radionuclides to be released later than from surface-contaminated waste (thereby reducing peak flux and dose), by placing the NuPac array on the west side and the HFEF and MFTC vaults on the east side, the Tc-99 contamination is also separated physically which lessens dose. Although the HFEF and MFTC vaults are on the east side and aligned with the groundwater flow direction, the HFEF canisters are Type 304 stainless steel and the MFTC canisters and Type 316L stainless steel which takes longer to corrode. By accounting for this difference in canister life, the peak fluxes from these two populations will reach the aquifer at different times decreasing the overall effective dose.

  Most of the C-14 is contained in activated metals with the bulk in LCC and 55-ton canisters. Doses were reduced by placing the 55-ton vault array on the west side and the LCC array on the east side. Nearly all of the I-129 inventory is in ATR resins (NuPac array). Although release from resins is delayed compared to surface-contamination, I-129 transport is largely unimpeded due to low sorption. Therefore, the NuPac array was placed on the west side away from most of the surface contaminated waste in the MFTC array on the east side to separate contaminants that are expected to arrive at the aquifer sooner than others. The NuPac vaults were also separated from the activated metals due to the potential for degradation of the resins in the presence of high radiation fields.

- **Intruder Pathway** – Intrusion calculations typically average waste inventories over the facility area. Separation of the vault arrays, as described above, allowed a larger area to be credited in the calculation of intruder doses.

Engineered Cover

An engineered cover will be placed on the RH LLW Disposal Facility after the vaults have been filled. In the PA [2], it was assumed that the facility would be covered at the end of Phase I operations (i.e., at the end of the 20-year operational period). Engineered covers at INL have been designed for several facilities, including the RWMC Subsurface Disposal Area and the Idaho CERCLA Disposal Facility (ICDF). The final cover design for the RH LLW Disposal Facility will be designed incorporating lessons learned from the RWMC and ICDF cover designs, which will be emplaced well before the RH LLW Disposal Facility cover. Prior emplacement of these covers will allow monitoring and assessment of performance prior to emplacing the RH LLW Disposal Facility cover. Using state-of-the-art knowledge at time of closure, the final cover will be designed to do the following:

- **Limit biotic (i.e., plant and animal) intrusion** – The cover thickness after long-term erosion will be sufficient to prevent plant roots and burrowing animals from reaching the tops of the vault plugs.

- **Reduce infiltration** – The cover will be configured to divert surface water away from the vaults and will extend beyond the boundary of the facility. The cover will be designed to limit water infiltration into the vault system, thereby reducing the potential for waste transport from the vault.

- **Remain functionally intact for hundreds of years** –The PA assumes the cover will limit the net infiltration rate to no more than 0.1 cm/yr for 500 years after closure. For the remainder of the compliance period (i.e., 500 to 1,000 years after closure), the cover is assumed to degrade and the infiltration rate returns to the background infiltration rate of 1 cm/yr. Practically, the cover is expected to remain functional well into and feasibly beyond the compliance period.

Facility Monitoring System

The facility has been equipped with a robust monitoring system [17] that supports the defense-in-depth concept by helping confirm the facility is in compliance and performing as expected. Compliance monitoring is conducted at the facility point of compliance, roughly 100 meters downgradient of the facility boundary in the Snake River Plain Aquifer with two wells. An upgradient well is also used to allow discrimination of contamination not from the facility. Annual compliance monitoring is conducted in accordance with the facility monitoring plan.

The facility is also equipped with a sophisticated near-field monitoring system comprised of a total of twenty-two instrumented tubes and monitoring wells installed in the backfill material adjacent to the vaults and in the upper sedimentary interbed. The monitoring system includes advanced tensiometers (for water detection), water content reflectometers (for water detection), thermocouples (for temperature measurement), and lysimeters (for water sample collection). Many instruments were installed in the backfill material as the vaults were installed (Figure 6).

Instruments in wells drilled after construction were placed at depths extending from the base of the vault arrays to sedimentary interbeds at a depth of approximately 53 meters (175 feet). Each is connected to a data logger connected to a wireless data transmission system, which allows access to data from a computer located in the Administration Building. The near-field vadose zone monitoring system will be used for performance monitoring, allowing validation of water drainage through the vault system and collection of vadose zone water samples, should water be present.

Fig. 6. Monitoring wells (right) and instrument installation during vault construction (left).

Upon completion of construction, eight infiltration tests were conducted to test the monitoring system and validate the as-built performance of the drainage system. Water was applied over square areas (2.43 m x 2.43 m [8 ft x 8 ft]) immediately adjacent to each vault array around instrumented tubes and wells at rates of 5.2 to 7.0 cm/hr (2.0 to 2.8 inches/hr) for 10 to 24 hours. These application rates are akin to a 100-year precipitation event. Data collected during the tests (Figure 7) show the perimeter drainage gravel adjacent to the vaults did not reach saturated conditions during most tests. If it became saturated, it was only for a brief time while water was being applied. Overall the water content in the perimeter drainage gravel and drainage course materials returned to near residual values within a few days of the test. In some tests there was no observable increase in moisture content of the drainage course. These tests confirmed the drainage system is highly effective at transmitting water and limiting accumulation of water in backfill materials, even at high infiltration rates. Data collected during the infiltration tests were used to calibrate models used to confirm the as-built performance of the facility, support concrete durability estimates, and inform the PA model (Figure 8).

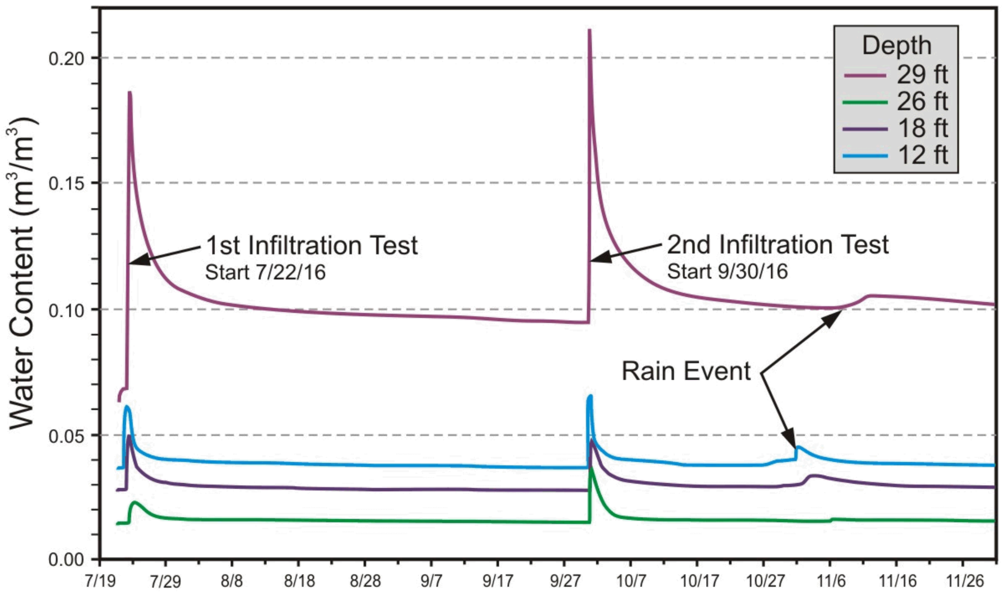

Fig. 7. Water content calculated using measured permittivity and calibration curves during first and second infiltration tests at PA vaults.

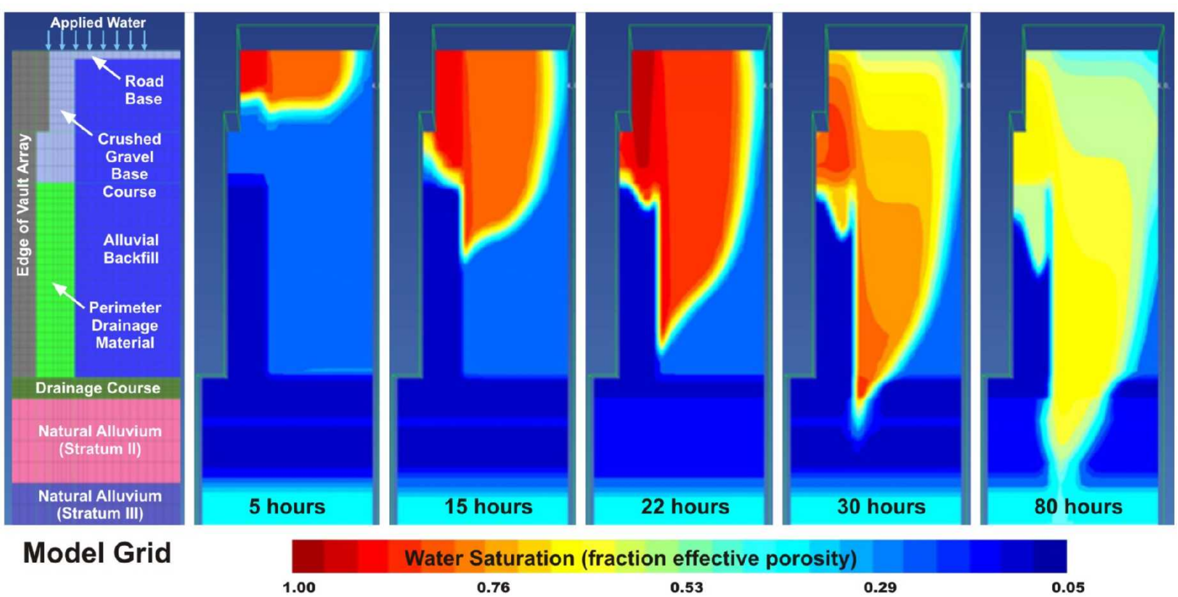

Fig. 8. Modeled water saturations after start of first characterization test at the PA vaults. Results are for a vertical slice through the center of the water application area. Water was applied for 24 hours.

CONCLUSIONS

The RH LLW PA [2] is a very thorough analysis of potential impacts/risks posed by the disposal facility to the public and to the environment from all exposure pathways. Despite many conservative assumptions, the PA results are much lower than performance objectives (see insert).

Even conservative parameters examined during the sensitivity analysis and a robust Monte-Carlo uncertainty analysis indicate that the facility will be protective under a wide range of conditions.

Predicted potential impacts are low relative to performance objectives for a facility of this type in large part due to crediting many of the natural, design, and waste features in the PA that provide a more realistic measure of facility impacts. This was accomplished by extensive investigation, data collection, simulation, quality control, and other evidence supporting methods. Important features credited and integrated into the RH LLW PA include: the natural environment, location selection, use of reinforced pre-cast concrete vaults; a robust hydraulic drainage system; waste forms, use of corrosion resistant waste canisters for waste disposal; and facility layout.

RH LLW Disposal Facility PA Results

- All-pathway (GW) peak dose compliance period, 4.4E-06 mSv/yr (4.4E-04 mrem/yr), Year 3039, (Tc-99)
- All-pathway (GW) peak dose post-compliance period, 6.4E-03 mSv/yr (0.64 mrem/yr) Year 21740, (Tc-99)
- Air pathway (screened out)
- Biotic pathway (screened out)
- Acute intruder peak dose, 0.032 mSv (3.2 mrem)
- Chronic intruder peak dose, 0.054 mSv/yr (5.4 mrem/yr)
- Radon peak flux = 5.6E-08 $Bq/m^2/s$ (1.5E-06 $pCi/m^2/s$) compliance period; 3.7E-06 $Bq/m^2/s$ (1.0E-04 $pCi/m^2/s$) post-compliance period

Functionally, the arid environment and thick vadose zone at the INL provides a significant level of protection to human health and the environment. Contaminant mobility was influenced by selecting a site with maximum sediment thickness. Flood potential was also minimized through site selection and design.

The RH LLW Disposal Facility has been designed to rapidly transmit water through the vault system and accommodate the probable maximum precipitation event. Based on the highly performing hydraulic drainage system and high-quality concrete vault components, there is strong evidence the concrete vaults will perform their intended functions of waste canister protection and support for the engineered cover throughout the 1,000-year period of performance. Performance of the drainage system was demonstrated through field characterization tests, laboratory characterization data, and numerical modeling.

The waste canisters and the activated metal waste forms are highly corrosion resistant steels. Aided by the protection of the concrete vaults, the stainless steel canisters are expected to remain structurally intact, degrading only through corrosion. Activated metal waste forms (stainless steel, Inconel, Zircaloy and aluminum) release radionuclides only as the metal corrodes. Corrosion rates for both canisters and metal waste were identified based on: expected temporal performance of the concrete vault system; conditions local to the vaults affecting corrosion rates; INL site-specific data for steel coupons buried in soils and suspended in a concrete vault environment; sensitized and annealed buried coupon data from other sites; and other corrosion data. These corrosion rates result in slow radionuclide release rates for activated metals; and waste canisters that could last hundreds to thousands of years.

The RH LLW Disposal Facility layout was selected to reduce dose by orienting the long-dimension of the vault arrays perpendicular to the groundwater flow direction, and strategically placing vault arrays based on radionuclide inventory, waste forms and canister types to dilute doses both physically and temporally.

Identification and robust analysis of features and factors in support of the defense-in-depth concept helped build the safety case for the RH LLW Disposal Facility, and helped build confidence that the facility will perform as expected. Incorporation of the features into the facility design and integration into the PA resulted in low predicted doses and was key in helping obtain operational authority. The low doses also allow operational flexibility in the future to meet unforeseen waste disposal challenges.

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