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SITE CHARACTERIZATION AND PERFORMANCE ASSESSMENT FOR A LOW-LEVEL RADIOACTIVE WASTE MANAGEMENT SITE IN THE AMERICAN SOUTHWEST

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ABSTRACT

The Area 5 Radioactive Waste Management Site (RWMS), located 105 km northwest of the city of Las Vegas in southern Nevada, has been used for the disposal of low-level radioactive waste since 1961. The site is located in the Mohave Desert of the American Southwest, an extremely arid region receiving as little as 0.1 m yr^{-1} of precipitation. Site characterization studies have measured the physical, hydrologic, and geochemical properties of core samples collected from 10 shallow boreholes and 3 deep boreholes that extend through the unsaturated zone to the uppermost aquifer. Results indicate that the unsaturated zone consists of 240 m of dry alluvial sediments and is remarkably uniform with respect to most physical parameters. Measurements of saturated hydraulic conductivity with depth showed no evidence of trends, layering, or anisotropy. Parameters for hydraulic functions were not highly variable and exhibited little trend with depth. Water potential profiles indicate that water movement in the upper alluvium is upward, except immediately following a precipitation event. Below the evaporative zone, the liquid flux was downward and of the same order of magnitude as the upward thermal vapor flux induced by the geothermal gradient. The extreme climatic conditions at the site reduce or eliminate many radionuclide release and transport mechanisms. Downward transport of radionuclides to the uppermost aquifer appears unlikely under current climatic conditions. Important radionuclide transport pathways appear to be limited to upward diffusion and advection of gases and biologically-mediated transport. Conceptual models of disposal site performance have been developed based on site characterization studies. The limited transport pathways and limited land use potential of the site provide reasonable assurance that regulatory performance objectives can be met.

GENERAL SITE DESCRIPTION

The Nevada Test Site (NTS) is a United States of America (USA), U.S. Department of Energy (USDOE) facility occupying 3.5×10^9 m^2 of desert in the American Southwest. It is located in the state of Nevada about 375 km northeast of Los Angeles, California and 105 km northwest of Las Vegas. The terrain is typical of much of the Basin and Range Physiographic Province in the states of Nevada, Arizona, and Utah, which is a province of intervening valleys and ranges, all nearly parallel and trending roughly north-south. The NTS's primary mission from 1951 to 1992 was to serve as the USA nuclear weapons test site. In addition, since 1961 the USDOE has operated a low-level waste (LLW) disposal site, the Area 5 RWMS, that accepts low-level radioactive and mixed waste from USA Government facilities nationwide.

DISCLAIMER

The Area 5 RWMS is located in a closed alluvial filled basin along the eastern boundary of the NTS. The location is within the arid northern Mohave Desert, where average annual precipitation is only 0.1 m. Average temperatures are characterized by large daily ranges. Average temperatures for the warmest and coldest hours in January are 12 and minus 3 degrees C and 36 and 17 degrees C in July.

The RWMS is currently used to dispose of defense low-level radioactive waste generated by the USDOE. Low-level radioactive waste is disposed of in steel or wooden boxes in shallow (<5 m) unlined landfill cells. Some high-specific activity wastes or wastes capable of releasing volatile species (HTO, ^{222}Rn) have been segregated and buried at greater depth. In recent years, the most significant waste streams on a volume basis are actinide contaminated wastes generated by decommissioning or environmental remediation projects. Most activity is received in a small number of waste streams containing ^{3}H and U in relatively concentrated forms that are not economically recoverable. Fission and activation products are insignificant. Stabilized waste forms occur, but unstabilized heterogenous waste forms are most common. A coordinate system is used to establish the location of each package. A database is maintained that identifies the location, package number, and the generator information for each waste package. Filled trenches are covered with an interim 2.4 m earthen cover. This cover remains in place until final closure of the trench. The final closure cover is designed to isolate the waste by inhibiting movement of gas or water through the waste.

SITE CHARACTERIZATION AND PERFORMANCE ASSESSMENT PROGRAMS

USDOE waste management standards require operators of waste disposal sites to implement a site characterization program and to prepare a performance assessment. A performance assessment is a systematic analysis of the potential risks posed by waste management systems to the public and the environment, and a comparison of those risks to the established performance objectives. Current performance objectives are that offsite individuals shall not receive effective dose equivalents greater than 2.5×10^{-4} Sv yr^{-1} from all pathways, 1.0×10^{-4} Sv yr^{-1} from airborne emissions, and ^{222}Rn emissions must be less than 0.74 Bq m^{-2} s^{-1}. Groundwater resources must be protected as required by local governments, which usually require that doses from groundwater consumption be less than 0.4×10^{-4} Sv yr^{-1}. Finally, the activity concentration of wastes disposed of at the site must not exceed levels that would cause inadvertent human intruders to receive doses greater than 1.0×10^{-3} Sv.

Performance assessments identify the likely natural processes and events that affect the disposal system, examine the effects of these processes and events on the performance of the disposal system, and estimate potential exposures for a period of 10,000 years with consideration for the associated uncertainties. Although compliance with the performance objectives is not required beyond 10,000 years, the analysis will be extended in time under environmental conditions projected at 10,000 years to display the peak in the dose curve.

Performance assessments need not provide complete assurance that the performance objectives will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projections of performance. Proof of the future performance of a disposal system is not to be had, in the ordinary sense of the word, in situations that deal with much shorter time frames. Instead, what is required is reasonable assurance that compliance with the performance objectives is likely to be achieved.

Analysis of the disposal system provided must include the source term, the possible pathways with the associated scenarios, assumptions, and the methodology employed. A discussion of the sensitivity of the analysis to key model assumptions, scenarios, and parameters must be included along with discussions of the uncertainty resulting from inaccuracies and limitations in the available data, uncertainty associated with the assumptions made, and uncertainty associated with the time frame of analysis.

The performance assessment must also evaluate the design and closure requirements of the disposal unit including the required depth of burial and cap design specifications. Analysis results are also to be used to set waste acceptance criteria such as activity concentration limits, waste form stability requirements, and allowable percentage of liquids in the waste. Results should guide the design and implementation of environmental monitoring and site characterization programs.

USDOE performance assessments do not assess risks from exposure to chemical toxicants and do not address risks encountered during operation of the site. These issues are addressed in separate assessments.

HYDROGEOLOGICAL SITE CHARACTERIZATION

A number of field studies have been performed to describe the near surface geologic environment. In addition to surface analyses, three subsurface investigations were conducted to provide core and drill cuttings for laboratory testing and characterization of important physical, geochemical, and hydrologic properties that could affect unsaturated flow and transport on a macroscopic field scale, as well as the hydrologic and chemical character of the uppermost aquifer beneath the Area 5 RWMS. Subsurface samples were collected from shallow trenches and from boreholes drilled by rotary air methods.

Geologic Character of the Frenchman Basin and Near Surface

Frenchman Flat Basin is a classic example of Great Basin topography. It is an arid basin enclosed by mountain ranges of moderate elevation (more than 1600 m). The lowest part of the basin is occupied by a dry playa called Frenchman Lake at an elevation of less than 940 m. Frenchman Flat serves as the ultimate drainage for approximately 1.3×10^{12} m^2 of surrounding territory.

The facility is built upon alluvial detritus derived from slope erosion of the Tertiary volcanics exposed in the nearby Massachusetts Mountain and Halfpint Range to the immediate north. All of the deposits are unconsolidated and are caused by water-based erosion. The relative percent of materials falling into the gravel, sand, and silt/clay size fractions were determined from analyses on 2100 core samples at 0.76 m intervals to be 20% gravel, 70% sand, and less than 5% silt. The depth of alluvium varies from zero at the edges of the basin to approximately 600 m in the center near Frenchman Playa, and is estimated to be between 360 to 460 m thick directly beneath the Area 5 RWMS. Below the alluvium lies a layer of interbedded Tertiary ash-flow and ash-fall tuff estimated at over 550 m thick, underlain by an undetermined thickness of Paleozoic Carbonates down to the Precambrian basement.

Hydrologic Character of the Frenchman Basin and Near Surface

The high desert climate limits the occurrence and movement of water on the surface, thus, there are no perennial or intermittent streams within the vicinity of Frenchman Flat. Rainfall events that are strong enough to produce surface runoff are very few in number and seldom result in enough moisture to produce runoff into the basins and valley floors, thus, recharge through the valley floors is generally assumed to be insignificant (1). The intense evapotranspiration characteristic of the present climate causes most surficial water to evaporate. These factors dictate the regional hydrologic behavior, an arid intermittent surface regime of extremely limited extent and a deep subsurface (groundwater) flow regime, which plays the dominant role in movement of water throughout the area. The topmost hydrologic unit beneath the Area 5 RWMS is defined as the valley-fill or alluvial aquifer.

Well cuttings and drill logs from three deep boreholes indicate that the unsaturated zone is extremely dry and at least 240 m thick. This dry zone beneath the Area 5 RWMS serves as the primary natural geologic barrier that inhibits the potential migration of nuclides in solution from the waste site.

The following conclusions regarding the properties of the vadose zone were drawn from the field characterization and laboratory data:

- The thick alluvial deposits are lithologically and mineralogically homogeneous and do not contain extensive layering of secondary carbonate.

- The alluvium is virtually homogeneous with respect to particle size distribution, and is characterized as a well-graded medium sand with gravel and a small amount of fines.

- The hydrologic properties of the alluvium are generally homogeneous and isotropic. This includes porosity, saturated hydraulic conductivity, moisture retention, and unsaturated hydraulic conductivity.

- Water content of the alluvium is very low near the surface and increases only slightly with depth (from 5% at the surface to about 10% at a depth of 37 m). This indicates that the entire alluvial vadose zone is in a very dry state.

- Water potential measurements (a measure of the strength of the driving force causing fluid flow) show a large positive gradient in the upper portion of the alluvium (indicating a tendency for water to flow up towards the surface) because of the large value of potential evapotranspiration at the land surface. The upwards potential exists throughout the upper 35 m of alluvium, with the largest upwards gradients in the top 9 m.

- Very little, if any, liquid flow is occurring within the upper 35 m of the vadose zone because the unsaturated hydraulic conductivity values are so small. These values are extremely small due to the very low water contents in the alluvium.

- Finally, depth profiles showing an enrichment near the surface of stable chloride and bromide, as well as the heavier naturally occurring isotopes of hydrogen and oxygen, provide strong evidence that evaporation is the dominant hydrologic process in the upper vadose zone. Water that exists deeper in the vadose zone probably entered the system under a much wetter climate.

HYDROLOGIC MODEL

Observation of the current system indicates that hydrology and climate are the primary factors defining the behavior of the system and its waste isolation performance. The site characterization data suggest that the small amount of liquid water infiltrating at the surface during infrequent rainfall events (diffuse recharge) does not migrate down to the water table, but rather tends to stay close to the surface and evaporate or transpire through plant respiration. This conclusion is in accord with similar studies in other arid regions which also show a tendency for net upward movement of liquid from the vadose zone (2,3,4).

Transient Infiltration Model

It is apparent that the isotropic homogeneous hydrologic characteristics of the alluvium and the lack of horizontal variation in the water potential profiles indicate that an one-dimensional analysis should be sufficient to determine the magnitude of water flux in the near surface alluvium. UNSAT2, a two-dimensional, unsaturated flow computer code that has been well established in the literature (5) was used to model the soil moisture profile in the near surface of the alluvium by applying 14 years of daily rainfall data and daily evapotranspiration rate calculated from the Penman equation (6).

Results from the simulation indicate that liquid water movement is restricted to the topmost 40 to 60 cm of alluvium, due to the high evaporative demand at the surface. The results add support to the proposition that under current climatic conditions all of the water entering the near surface due to rainfall is recycled back into the atmosphere.

Upward Advection and Diffusion Model

Since downward advection of moisture appears unlikely, the possibility of upward movement was investigated. Estimates were made using hydrologic conditions and characteristics typical of the alluvium.

The calculations show that the total time for liquid water to travel 2.4 m up from the estimated top horizon of emplaced waste to the land surface (based on matric potential as the only driving force) is about 5×10^8 years. This extremely long period of travel time is the result of very low water content values in the alluvium. The alluvium is so dry that a continuous phase of liquid between grain boundaries does not exist, thus the unsaturated hydraulic conductivity and travel times are extremely small. Based on these calculations, upward advection of liquid water driven by the matric potential gradient is not a concern , under these base case conditions, with respect to the transport of nuclides out of the waste cells.

Upwards diffusion through the top 2.4 m of alluvium is influenced by the moisture content of the soil, as well as the concentration gradient, and can be described by Fick's first law adapted for unsaturated media. However, the diffusion coefficient is also dependent on the moisture content of the alluvium and is near zero at the observed water content. Because the upwards diffusion in the alluvial pore spaces requires a continuous phase of liquid water in which to take place, it is apparent that diffusion will not yield any significant additional flux of nuclides away from the system under the present dry conditions. This conclusion is supported in the literature by studies involving Cl^{-1} in Ca saturated systems where zero transmission was observed at water contents of 0.077 to 0.155 in a loam soil (7).

CONCEPTUAL MODELS OF SITE PERFORMANCE

Reasonable assurance of compliance with the performance objectives is provided by analyzing a limited number of deterministic scenarios. Scenarios were developed by screening comprehensive lists of events and processes. Items were eliminated based on probability of occurrence, significance of the consequence, and applicability to the site and governing regulations. Remaining items were assembled into a compliance scenario and several uncertainty scenarios. The compliance scenario represents the best estimate of the future performance of the site and is analyzed to determine compliance with the performance objectives. Uncertainty scenarios include processes or events believed to be credible, but very unlikely. Uncertainty scenarios are analyzed to bound site performance.

Compliance Scenario

The compliance scenario represents the most likely future state of the disposal site. It includes no low probability disruptive events and assumes that the waste disposal cells and their caps remain intact and undisturbed throughout the 10,000-year compliance period. Waste forms disposed of at the site are extremely heterogenous and in most instances unstabilized. Therefore, no credit is taken for waste packaging or waste form. Radionuclides are assumed to be available for transport at the end of disposal operations. The site is located within an area of aggrading alluvial sediments. Closure caps are expected to be buried by alluvial sediments in 6,000 to 30,000 years. All water-mediated transport pathways have been eliminated from the compliance scenario. Preliminary modeling of hydrological processes described above have eliminated downward and upward advective transport of moisture and diffusion of solutes in soil pore water. All remaining release pathways assumed for the compliance scenario involve upward transport to the near surface environment by mechanisms not involving water movement. The only physical transport mechanism assumed is diffusion and advection of gases such as HTO, ^{14}C, ^{85}Kr, and ^{222}Rn. Several biologically-mediated release pathways are assumed. Native flora are assumed to repopulate the site and transport radionuclides to the near surface. Although local fossorial vertebrates rarely burrow to the depth of buried waste, 2.4 m, invertebrate species such as ants and termites are assumed to be capable of reaching waste and transporting contamination to the surface.

Transport pathways acting in the near surface accessible environment are dependent on human land use of the site. Rural areas of southern Nevada support very low population densities ($< 0.5\ km^{-2}$) because of the lack of water resources and poor soils. Current land uses are limited to grazing (mostly seasonal), irrigation-based agriculture, and mining. Cultivation of irrigated crops is limited to areas where surface water or near surface (< 30 m) groundwater is available. The nearest location where water is available for irrigation is 14 km from the site. Economically, significant mineral resources including oil and gas are not known to occur anywhere on the NTS. The most likely future use of the site is grazing, based on current land usage patterns and resource availability. Therefore, the compliance scenario assumes that the site is used as open rangeland and tended by a resident residing at the nearest water source, 14 km from the site. Exposure pathways assumed for this land use include ingestion of beef from cattle grazing on the site and direct exposure by external irradiation and inhalation during transient occupation of the site.

Intruder Scenarios

The DOE LLW Management Performance Objectives require analysis of risk to inadvertant human intruders. These analyses are performed to determine the concentration limits of waste that can be disposed of in the near surface environment where direct human contact with waste is possible. Historically, USDOE and USNRC performance assessments have limited these analyses to three acute exposure scenarios involving exposure to waste while digging or drilling at the site, and three chronic exposure scenarios where the intruder homesteads on the contaminated site after exhuming or exposing buried waste (8). These scenarios were adopted for the performance assessment with modifications to reflect the land use limitations of this extremely arid site.

Uncertainty Scenarios

Uncertainty scenarios consider events or processes considered credible for the site, but too unlikely to be included in the compliance scenario. Events and processes retained for development of uncertainty scenarios are essentially low probability disruptive events that are not considered in human intrusion scenarios. Events retained for consideration include irrigation, flash flood channeling to the depth of buried waste, and enhanced infiltration in subsidence depressions.

SITE PERFORMANCE

Analysis of the compliance scenarios indicates that the waste disposal site is reasonably likely to meet all the performance objectives for 10,000 years. Near-term performance is dominated by the release of HTO. Long-term performance is dominated by actinides and their progeny (^{240}Pu, ^{239}Pu, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{232}Th, ^{235}U, ^{231}Pa and ^{227}Ac). The limited agricultural uses of the desert environment make inhalation and external irraditation the most important exposure routes.

Near-term predictions of site performance should be instructive to site environmental monitoring programs. Performance assessment modeling predicts that near-term releases should be limited to gaseous emissions of HTO and uptake of ^{3}H, ^{14}C, and uranium by plants. Site environmental monitoring consists of a groundwater monitoring program, air monitoring, soil monitoring, and vegetation monitoring. Consistent with performance assessment results, the groundwater monitoring and soil monitoring programs have not detected any releases to date. These two media are not expected to be contaminated within the institutional life time of the facility. Groundwater monitoring in particular, could be replaced by near field vadose zone monitoring of moisture content and volatile species. The air monitoring program has detected HTO at levels less than 1% of USDOE offsite release limits. Measurement of other gaseous species such as ^{14}C and ^{222}Rn are not now performed because of the low site inventory for these radionuclides. Monitoring of vegetation has detected only low levels of ^{3}H contamination suggesting that waste containers remain largely intact. Vegetation monitoring should be continued as an early indicator of container failure.

Site characterization studies and performance assessment have shown that the arid nature of the Area 5 RWMS offers unique performance enhancing advantages. Most importantly minuscule or nonexistent recharge eliminates troublesome groundwater release pathways. Exposure pathways are further reduced by the limited biological productivity and land use potential.

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