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APPLICATION OF PATHWAYS ANALYSES FOR SITE PERFORMANCE PREDICTION FOR THE GAS CENTRIFUGE ENRICHMENT PLANT AND OAK RIDGE CENTRAL WASTE DISPOSAL FACILITY*

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ABSTRACT

The suitability of the Gas Centrifuge Enrichment Plant and
the Oak Ridge Central Waste Disposal Facility for shallow-
land burial of low-level radioactive waste is evaluated us-
ing pathways analyses. The analyses rely on conservative
scenarios to describe the generation and migration of con-
tamination and the potential human exposure to the waste.
Conceptual and numerical models are developed using data
from comprehensive laboratory and field investigations and
are used to simulate the long-term transport of contamina-
tion to man. Conservatism is built into the analyses when
assumptions concerning future events have to be made or
when uncertainties concerning site or waste characteristics
exist. Maximum potential doses to man are calculated and
compared to the appropriate standards. The sites are found
to provide adequate buffer to persons outside the DOE reser-
vations. Conclusions concerning site capacity and site ac-
ceptability are drawn. In reaching these conclusions, some
consideration is given to the uncertainties and conserva-
tisms involved in the analyses. Analytical methods to
quantitatively assess the probability of future events to
occur and the sensitivity of the results to data uncertainty
may prove useful in relaxing some of the conservatism built
into the analyses. The applicability of such methods to
pathways analyses is briefly discussed.

INTRODUCTION

Solid low-level radioactive waste will be generated during operation
of the Gas Centrifuge Enrichment Plant (GCEP) under development on the DOE
Portsmouth Reservation, Piketon, Ohio, and by normal activities of the
three plants, the Oak Ridge National Laboratory (ORNL), the Y-12 Production
Plant (Y-12), and the Oak Ridge Gaseous Diffusion Plant (ORGDP), located on
the DOE Oak Ridge Reservation, Oak Ridge, Tennessee. These wastes, as per
DOE Order 5820,[1] may be disposed of at Low-Level Waste (LLW) disposal sites.
Two sites, the GCEP Landfill site, a 9-ha (20-acre) tract of land located
0.8 km north of the gaseous diffusion plant, and the Oak Ridge Central Waste
Disposal Facility (CWDF) site, an area of about 235-ha (500-acre) located on

West Chestnut Ridge 2 km west of ORNL and 2 km southeast of ORGDP, are under consideration for shallow-land burial of these wastes. Guidance for establishing site suitability requirements and performance objectives for land burial of radioactive wastes are provided in DOE Order 5820[1] and DOE Order 5480.[2] New disposal sites are to be selected in compliance with applicable federal, state, and local laws and regulations. Additional site selection criteria should address, as appropriate, the following:

(1) Size, including disposal and administrative areas, and buffer zones;

(2) Hydrogeologic characteristics which permit disposal completely above or completely below the transition zone (the zone between the unsaturated and saturated zones) and reliable prediction and control of radionuclide migration;

(3) Potential impacts of natural hazards such as floods, erosion, tornadoes, earthquakes, and volcanoes on site performance; and

(4) Impacts on current and projected population distributions and displaced families or businesses; land use, resource development plans and nearby public facilities (i.e., parks, schools, and streets); accessibility to transportation routes, and utilities; and the location of waste generators.

Consequently, characterization of the geologic, hydrologic and geographic systems of a potential host site, as performed for the GCEP landfill site[3] and the Oak Ridge CWDF site,[4] is necessary for analysis of the site suitability. Additionally, a buffer zone must be established within the site boundary, beyond which unrestricted public activity is allowed. The buffer zone, identified using predictions of radionuclide migration, is a three-dimensional zone outside which doses to man and radionuclide concentrations will not exceed regulatory limits. Therefore, for verification of the acceptability of a potential site, it is necessary to perform a dose to man pathways analysis for waste likely to emanate from the disposal facility. A pathways analysis includes a detailed characterization of the waste, the development of scenarios describing future events, the development of conceptual models based on the site characterization studies, modeling of the site performance and an analysis of the dose to man receivable from the transport of contamination. Pathways of greatest potential for producing high doses to man are examined in the greatest detail. Since site acceptability requires a system analysis of both wastes and site characteristics, the results are also utilized to specify the allowable volume, radionuclide concentrations and composition of the waste that can be buried, and to determine what operational controls must be maintained. This paper presents the results of pathways analyses used for determination of the acceptability of the GCEP landfill site and the Oak Ridge CWDF site for development of waste disposal facilities.

APPROACH TO PATHWAYS ANALYSES

The purpose of the pathways analyses presented here is to verify the acceptability of DOE sites for disposal of solid low-level radioactive

waste. Hence, the DOE guidance for establishing LLW site performance objectives[2] is used as the primary basis for the studies. Supporting literature[5,6,7] is also used to provide a framework for the analyses.

The principal thrust of a pathways analysis is the study of the exposure pathways to man for waste buried at a proposed site. Pathways of most concern for shallow-land burial disposal sites are (1) inadvertent intrusion into the waste and its subsequent intake by inhalation and ingestion and (2) groundwater and surface water transport of leachate from the waste and subsequent use of the contaminated water for irrigation and drinking.[5] As illustrated in Fig. 1, wind and water erosion are processes of transit that can result in environmental exposures. The intruder pathway may occur after site closure and involve either direct contact (e.g. someone searching for artifacts) or indirect contact with the waste (e.g., agricultural activities). In general, intruder-exposure pathways depend on and limit the maximum concentration of the radionuclides in the buried waste and are not site specific. Conversely, ground-water migration of leachate from the waste (Fig. 1) depends on site-specific parameters and tends to limit the total radionuclide quantity disposed of.
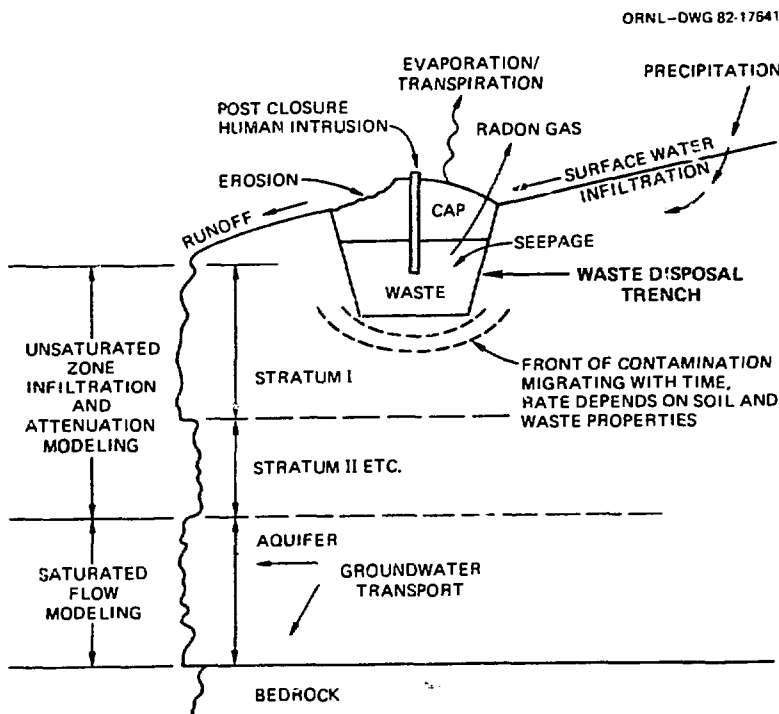

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Figure 1. Schematic of low-level waste shallow land burial area and exposure pathways.

The selection of and consideration given to each pathway and the calculation of the resultant dose are affected by site-specific factors and characteristics of the waste. These are fixed quantities that must be determined as accurately as possible to provide realistic input to the calculations. The comprehensive field investigations of the geology and geohydrology of the sites provide the framework and some of the site-specific information needed for the pathways analyses. In the course of performing the analysis, however, major uncertainties concerning site-specific parameters are pointed out and assumptions concerning future events have to be made. Since the regulations require calculations of doses to man at points of maximum probable exposure, the pathways analyses rely on conservative approaches; that is, when site-specific information or data concerning future events are unknown or uncertain, the values of the corresponding basic parameters are chosen to maximize intake or exposure to man.

Two time periods are considered in the analyses: (1) an institutional control period for the first 100 years following site closure and (2) a performance period (post institutional period) of at least 400 years following the institutional control period. Since scientific analysis cannot forecast events for such intervals, scenarios of future development are constructed to provide a basis for the analyses. During institutional controls, it is assumed that inadvertent intrusion can be prevented and that if public exposure occurs, it will result from off-site migration of contamination. The site is also assumed to be properly operated and maintained under design conditions. Under design conditions, the piezometric surface is always below the waste disposal trenches. Engineering features, such as trench caps and surface drainage systems, are included to prevent the infiltration of surface water into the trenches. Side wall drains, capillary barriers or drainage blankets are designed to prevent the migration of moisture from the undisturbed soil into the trenches by capillary transport. Therefore, under design conditions that are expected to prevail during the 100-year period of administrative control following trench closure, generation of leachate in the trenches would be minimal and migration of contamination into the soil would not be significant. Consequently, the analyses of the groundwater pathways consider that during the period of administrative controls, only a fraction of the total disposed activity could be released to the environment before implementation of remedial actions. After institutional controls, inadvertent intruders may enter the site. The analyses consider that an inadvertent intruder lives on the site and consumes food produced from farming activities. External and internal doses to an inadvertent intruder could result from (1) direct exposure to contaminated soils and materials, (2) inhalation of contaminated dust particles suspended in air by various activities, (3) ingestion of food crops grown in contaminated soil, and (4) ingestion of contaminated groundwater from an on-site well. When maintenance of the site ceases, rapid degradation of the engineering features is assumed. The integrity of the trench caps and drainage systems could be compromised due to subsidence, cracking, erosion, human intrusion or other unexpected courses. This would result in infiltration of water into the trenches and saturation of a portion of the waste. Following such an event (hereafter referred to as the wetting event) leachate would be generated and could migrate out of the trenches into the soil. A conservative approach considers that leachate generation

occurs rapidly and simultaneously at all trenches and that the total disposed activity could be released to the environment. Public exposure could result from migration of the leachate through the soil to aquifers and surface water systems and contamination of a public water supply. In the analyses, the nearest potential public water supply is chosen as the point of potential public exposure.

The methodology used for estimating the doses receivable through these pathways is described in Adams and Rogers[8] and Killough and McKay.[9] Doses from external exposure are calculated as annual dose using dose conversion factors prepared by Kocher.[10] Doses from internal exposure to inhaled and ingested radionuclides are calculated as 50-year dose commitments using dose conversion factors included in Dunning.[11] The annual dose from radionuclides released from the site to a person outside the site boundary must not exceed the following: 25 mrem/y to the whole body, 75 mrem/y to the thyroid, and 25 mrem/y to any other organ.[5] Maximum permissible doses to persons inside the buffer zone (i.e., the inadvertent intruder) must be as low as reasonably achievable within the following standard: 500 mrem/y to the whole body, gonads or bone marrow, and 1500 mrem/y to any other organ.[2] These performance objectives are used in the analyses to identify the buffer zones and determine the maximum burial concentrations of radionuclides.

PORTSMOUTH GCEP WASTE PATHWAYS ANALYSIS

The proposed GCEP landfill site is located on the DOE Portsmouth Reservation, Piketon, Ohio, about 0.8 km north of the gas diffusion plant (Fig. 2). The waste to be disposed of at the site will include failed equipment, spent alumina and trash and will be contaminated with low-enriched uranium at an average assay of 1% ^{235}U. The projected volume is 7.1×10^3 m^3. Waste samples were used to provide laboratory estimates of leach rates and distribution coefficients with site soils and groundwater samples.[12] The laboratory tests were performed using batch tests with the distribution coefficient determined for a range of pH and leachate concentrations.

The proposed low-level waste disposal site lies at the eastern edge of the old Portsmouth River valley fill on gently sloping land with slopes of 2-12%. The flatter portion of the site lies on lacustrine soils and the steeper slopes lie on the flank of a bedrock hill at the eastern edge of the site. Surface drainage flows into Little Beaver Creek. Characterization of site geologic conditions was accomplished by completion of drilling, sampling, and testing programs.[3] A total of twenty six exploratory borings were drilled in the study area which encompassed approximately 12 ha. PVC well casings were installed in twelve of the boreholes, two of which were grouted into the bedrock. One three-well cluster was installed to test for confined aquifer conditions in the soils. Soil samples were subjected to a number of physical and chemical tests.

The site is underlain by bedrock of Mississipian age including, in ascending sequence, the Bedford shale (thickness of 26 m), the Berea sandstone (thickness of 7-9 m), Sunbury shale (thickness of 6.5 m), and the Cuyahoga shale (thickness of 27 m). The Portsmouth River alluvium is
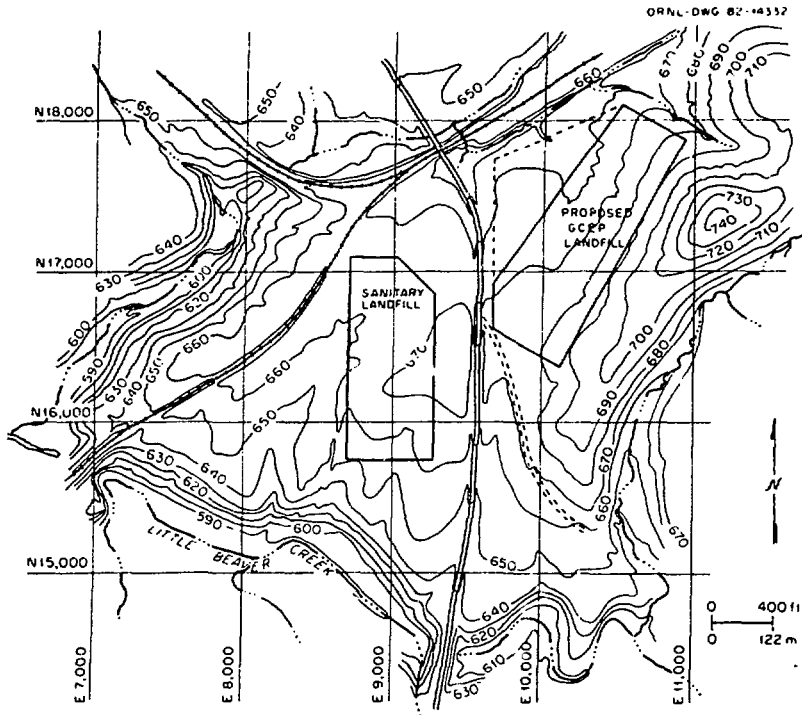
Figure 2. Proposed GCEP low-level waste landfill.

composed primarily of the Minford silt with a relatively thin layer of
Gallia sand. The alluvial deposits range in thickness from 2 to 13 m over
the site. Aquifers exist in both bedrock and soil formations. Capillarity
in the alluvial soils results in elevated moisture contents in the alluvium
with most of the hydrodynamic transport occurring at the interface between
the Minford silt and the Gallia sand. The groundwater beneath the site
ultimately discharges to Little Beaver Creek and its unnamed tributary to
the northwest of the site which discharge to the Scioto River approximately
5 km downstream. The Scioto River with an accompanying alluvium is a major
surface water supply, including drinking water.

Field and laboratory investigations were performed to determine the
hydrologic characteristics of the abandoned Portsmouth River alluvium.
Field measurements of the hydraulic conductivity of the unsaturated zone
were determined using falling head permeability tests. Field measurements
of the hydraulic conductivity of the saturated zone were determined by slug
tests conducted in the piezometers installed in the site area. Values of
saturated hydraulic conductivity varied from 6.6×10^{-6} cm/s to 6.6×10^{-3}
cm/s. Laboratory values were measured in the range from 3.1×10^{-8} cm/s to
7.3×10^{-7} cm/s with a ratio of horizontal to vertical permeability of 2 to
4. Unsaturated permeabilities were determined by pressure plate tests and
by permeability and moisture characteristic cells. These tests confirmed

that the soils had high field capacities, low effective porosities and a low hydraulic conductivity that decreases rapidly with a decrease in moisture content. A tracer test was performed in a three-well cluster to determine the dispersivity of the alluvial aquifer using the method developed by Lenda and Zuber.[12] The dispersivity was determined to be less than 0.5 m and the aquifer was shown to have a low yield with a limited thickness contributing to the transport of water. The porosity of the soils was about 42%. Effective porosity of the Gallia sand was estimated to be 21%. The effective porosity of the soils was estimated to be from 9% to 13%.

Recharge to the alluvial aquifer occurs on the upland soils adjacent to the site with estimated infiltration rates of 9.9 cm/y, primarily from December to April. Infiltration in the site area was estimated to be 0.25 cm/y primarily during April and May. The piezometric surface was monitored to determine the seasonal variations. The high water table during the month of April was found to reach shallow depths, varying from 3 m to 7 m over the site area, and precluding the development of deep disposal trenches. These shallow-water table conditions also suggest that the time scales associated with the vertical migration of radionuclides from the bottom of the trenches to the saturated zone are small compared to those associated with horizontal migration in the saturated zone and, therefore, that the main buffer at the site resides in the horizontal transport in the aquifer. For this reason and because the major groundwater flow occurs in a very confined zone at the interface of the Milford silt and the Gallia sand, a two-dimensional vertically-averaged model was used to represent the hydrodynamic transport at the site.

The groundwater code utilized for analyzing site performance was the U.S. Geological Survey Method-of-Characteristics code.[13] The code originally did not include the effects of adsorption of solutes by soils. Since this phenomenon is known to be of importance in the transport of solute contaminants in aquifers, the code was modified to include the effects of adsorption.[14] The modification of the code allowed the distribution coefficient to be specified as a function of time to reflect the variations of the distribution coefficient as a function of leachate concentration observed during the waste characterization studies. The study area, grid layout, and boundary conditions used for the groundwater model are shown in Fig. 3. The constant head grid cells were specified according to the data describing the piezometric surface obtained from the monitoring program for high water table conditions. The aquifer parameters were specified by using the data collected from the field and laboratory studies or by the use of submodels appropriate for the site area. In this process, a conservative approach was followed when uncertainties existed concerning basic parameters or their areal distribution over the grid. The hydrodynamic portion of the model computed a piezometric surface that compared favorably with the monitoring data. The average groundwater velocity was computed to be 29.5 m/y as compared to 19.5 m/y determined during the field investigation. The groundwater discharge to Little Beaver Creek was computed to be 1.66×10^7 L/y.

Because of uncertainties in the interpretation of the leach rate tests, two scenarios were developed having conservative assumptions that allowed
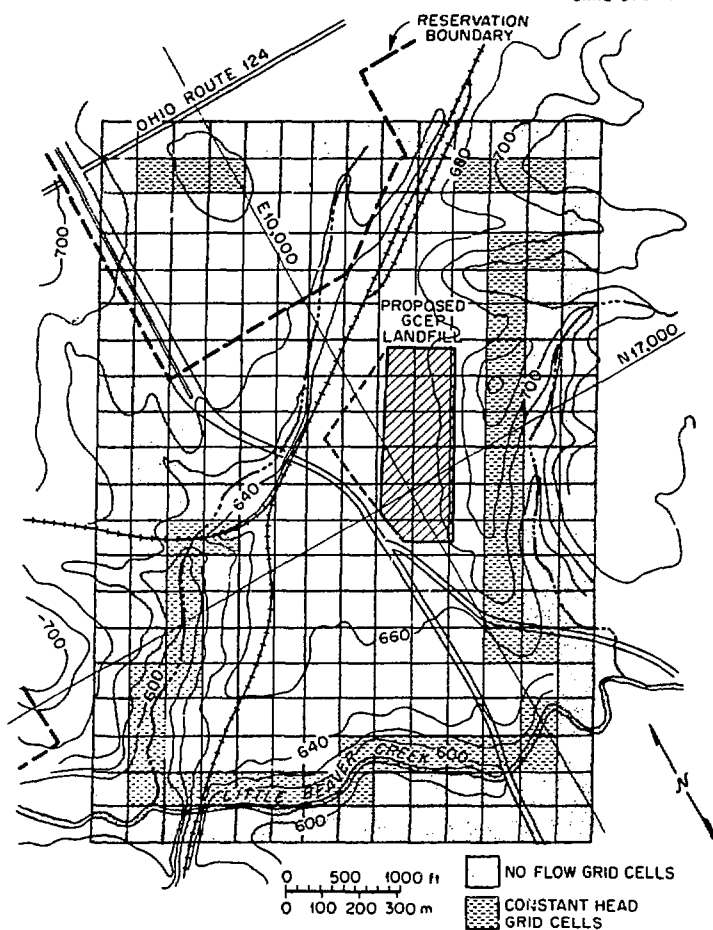
Figure 3. Study area, grid layout and boundary conditions for
modelling site area.

for the generation of contaminated leachate and the transport through the
alluvial aquifer. For one scenario, the generation of leachate was assumed
to occur at a constant rate at a concentration of 26.7 mg/L of uranium
until the entire uranium inventory entered solution. For the second
scenario, one-third of the uranium is assumed to go into solution immedi-
ately with the remaining uranium entering solution at a concentration of
26.7 mg/L with a constant rate. The leachate entered the alluvial aquifer
at a rate corresponding to the vertical permeability of the site soils.
The maximum concentration and the two leaching scenarios were developed to
reflect the results of the waste characterization studies.[12] Concentra-
tions of 500, 625, and 750 g of uranium per cubic meter of waste were con-
sidered. The soil and waste in the burial trenches were assumed to be in
equal parts and the porosity of the compacted waste was assumed to be 50%.
Conservative values of the distribution coefficient (4-50) were specified
based on the maximum concentration of uranium in the aquifer.

The groundwater model was run for a simulation period of 400 years to provide insight into site performance for a total simulation period of 500 years. Simulations of the transport of contamination from the waste disposal area were performed for various concentrations of uranium in the waste and for each of the scenarios discussed above. Figure 4 shows the results of a 400-year simulation for the first scenario and a waste concentration of 625 g of U/m^3. These results indicate that contamination will be transported through the aquifer in a confined zone and be discharged to the unnamed tributary to Little Beaver Creek. Figure 5 shows the maximum concentration of the groundwater discharged to the unnamed tributary during the simulation as the concentration of uranium in the waste is varied for the two scenarios considered for analysis. These results are utilized in the dose analysis which follows and the determination of site acceptability.

The maximum potential dose to the public receivable from the nearest public drinking water source (the Scioto River) was determined based on the discharge of contaminated groundwater from the alluvial aquifer at a concentration of 750 µg/L diluted by the stream flow of Little Beaver Creek and the Scioto River. The 50-year total body dose commitment was determined to be 1.3×10^{-2} mrem and the corresponding highest dose to organ was determined to be 7.5×10^{-2} mrem (endosteal cells of the bone). These calculations assumed an average enrichment of 1.0% of $235U$ in the waste and in the contaminated groundwater.

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CONCENTRATION (MICROGRAMS/LITERS)   1000 FT.

× - 2000
■ - 1000
▽ - 500
◇ - 100
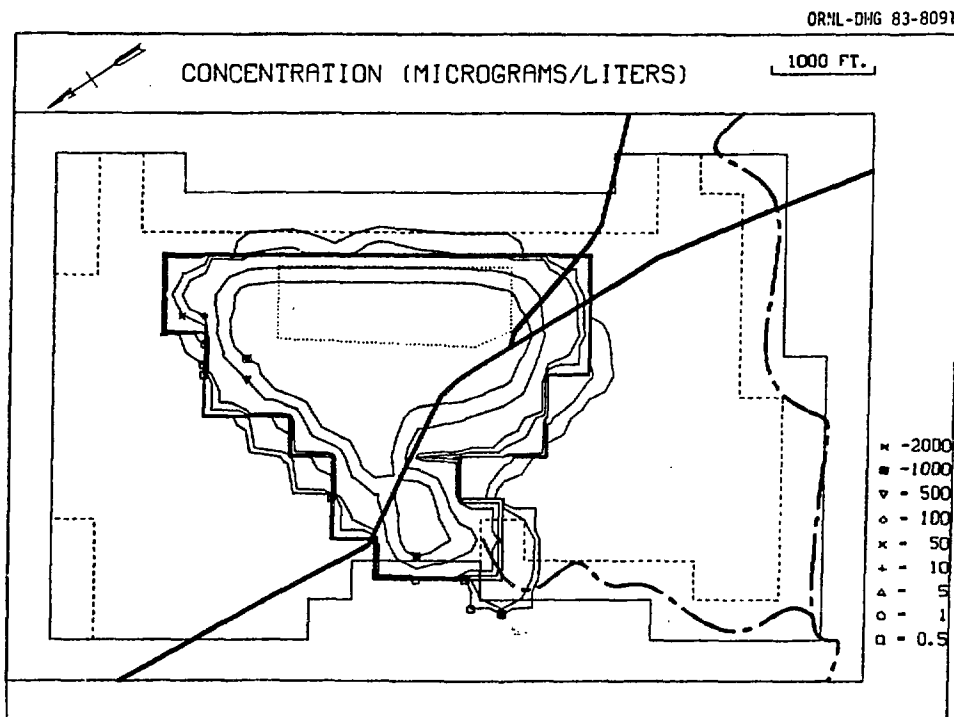× - 50
+ - 10
△ - 5
○ - 1
□ - 0.5

Figure 4. Uranium concentration in aquifer for a concentration of 625 g of U/m^3 of waste at 400 years of simulation time.
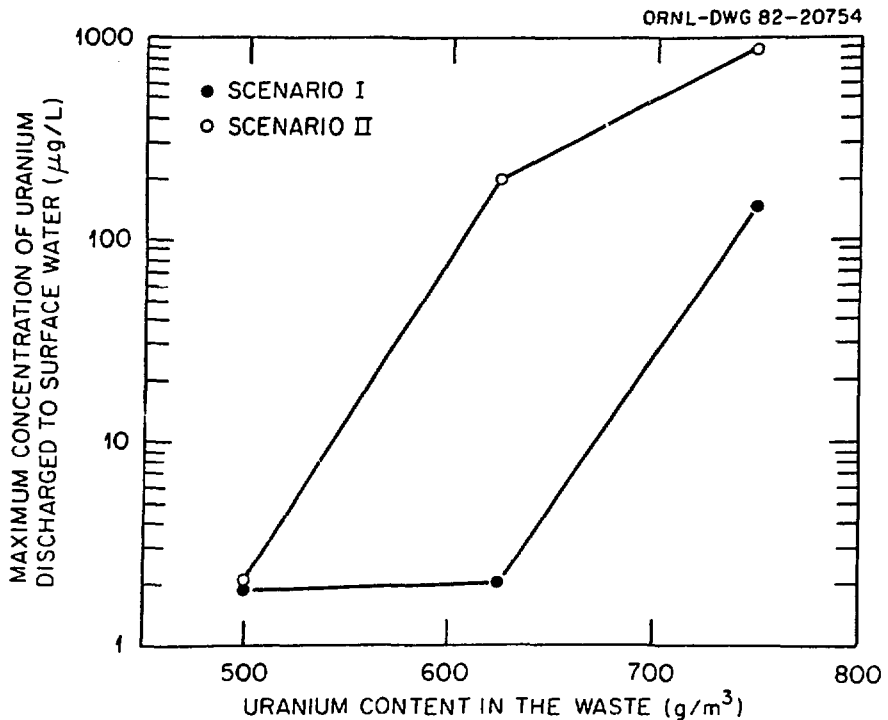
Figure 5. Maximum uranium concentration discharged to surface water during simulation period for various uranium contents in the waste.

For uranium concentrations in the waste of 750 g $/m^3$, the 50-year dose commitments to the inadvertent intruder from the direct intrusion pathways, i.e., direct exposure to contaminated soils and materials, ingestion of food crop grown on contaminated soil, and inhalation of resuspended particles, were calculated to be 0.4 mrem to the total body and 3.7 mrem to the organ with the highest dose (lungs). Since the alluvial aquifer underlying the site is of very low yield, the dose commitments to the inadvertent intruder from ingestion of contaminated groundwater depend on both the probable geographic location of a well with respect to the contaminated groundwater and the amount of water that could be derived from such a well for consumption. Fifty-year dose commitments were calculated to be 164 mrem for the total body and 980 mrem to the organ with highest dose (endosteal cell of the bone) for a well located at a point of maximum probable exposure.

Dose commitments that could be received by terrestrial biota such as birds and mammals from surface and airborne radionuclides or by burrowing animals were also investigated. The maximum dose receivable was estimated to be 5 mrem/year.

In summary, disposal of uranium-contaminated waste at the proposed GECP landfill site could result in radiological doses to persons outside the site area or to an inadvertent intruder following site closure and

institutional controls. The potential doses to the general public from the nearest drinking water supply and to the inadvertent intruder from the direct intrusion pathways are low. The groundwater pathway to an inadvertent intruder is the limiting pathway for determining the capacity of the proposed site with potential doses approaching regulatory limits for uranium concentrations in the waste exceeding 1000 g /m^3. The site is found favorable for shallow-land burial of waste with characteristics matching those considered in this study. The contaminant plume within the aquifer beneath the proposed site (see Fig. 4) is limited to an area that is relatively insensitive to the waste burial concentration. This area is recommended to be defined as a buffer zone which would permit unrestricted activity outside of its perimeter.

OAK RIDGE CWDF PATHWAYS ANALYSIS

The West Chestnut Ridge site, an area of about 235 ha (500 acres) located on the DOE Oak Ridge reservation, is the proposed location of the Oak Ridge Central Waste Disposal Facility (CWDF). Wastes to be disposed at the CWDF are solid, low-level, radioactive wastes generated by the three DOE Oak Ridge plants: the Oak Ridge National Laboratory (ORNL), the Y-12 Production Plant (Y-12) and the Oak Ridge Gaseous Diffusion Plant (ORGDP). Out of a yearly volume of 22,700 m^3 projected for disposal, about 12,000 m^3/y will originate from known routine activities and 10,700 m^3/y is expected from various decomissioning activities or activities of future facilities. The waste characterization, therefore, essentially relies on available information on the routinely produced waste and on expected contents and characteristics for the nonroutine waste.

For the direct intrusion type pathways (e.g. digging into a trench, home reclamation on a trench, gardening), which depend on the maximum concentration of radionuclides at any arbitrary location at the site, the source terms were based on the maximum concentration of radionuclides that may be in any specific and future waste stream. For the water pathways, the portion of the waste (about 7,000 m^3/y) that will be disposed of with little or no containment in bulk or baled form (while the remaining part will consist of fixed sludges or wastes grouted in a concrete mixture) is of most concern. These wastes, also referred to as unstabilized wastes,[6] are most likely to experience slumping, subsidence, degradation and therefore much higher percolation rates and leaching rates than stabilized wastes. Consequently, the characteristics of these wastes were used to produce conservative source terms for the water pathways analysis. Since it is assumed that leaching occurs in all trenches simultaneously, the water pathways source terms reflect average concentrations of radionuclide in the unstabilized wastes. The composition, in percent of the total activity, of the buried unstabilized waste mass at 100 years following trench closure is shown in Fig. 6.

The West Chestnut Ridge site is located in the western portion of the Valley and Ridge Physiographic Province. The site includes three discontinuous ridge lines separated by valleys containing perennial and ephemeral or wet season flow channels. Bedrock beneath the site is cherty dolomite and limestone of the Conasauga and Knox Groups. Formations which subcrop

TYPICAL UNIT WASTE MASS

Tc-99 (16.8%)
C-14 (8.4%)
Pu-239 (0.5%)
Pu-238 (0.1%)
U-234 (0.0%)
U-235 (1.0%)
Zr-93 (8.4%)
U-238 (11.4%)
Sn-121m (1.2%)
H-3 (3.3%)
Am-241 (0.2%)
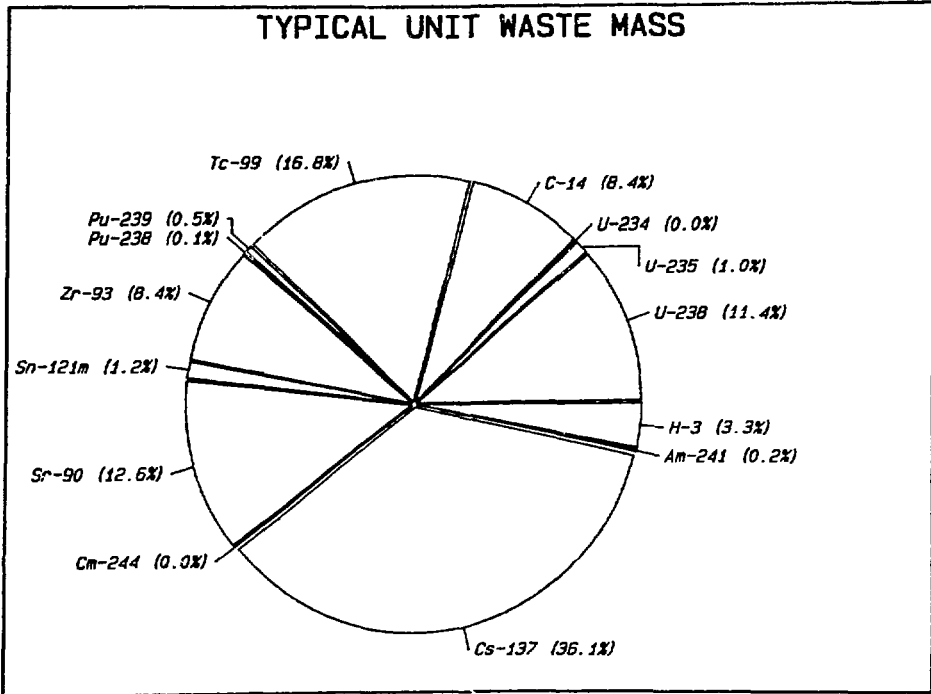Sr-90 (12.6%)
Cm-244 (0.0%)
Cs-137 (36.1%)

Figure 6.   Percent composition of the CWDF unstabilized waste.

the site include the Copper Ridge Dolomite, the Chepultepec Dolomite, the Longview Dolomite, and the Newala Formation (Fig. 7). Bedrock generally strikes N 50-60° E. Measured dips in the area range from 25° to 35° to the southeast. Figure 7 shows locations of exploratory boreholes and traces of karst zones observed in field mapping. The karst zones show a strong stratigraphically controlled orientation and karst development is discontinuous in individual zones along strike. The site bedrock conditions are defined as follows. Residual soils of variable thickness typically overlie a zone of cavernous carbonate bedrock with mud and gravel filled cavities. The thickness of this cavernous zone ranges from 0 to more than 30 m. The zone of cavernous bedrock is the most active weathering zone. Residual soils above this zone have been deeply leached and are essentially devoid of carbonate minerals. Relatively unweathered rock conditions are found below the cavernous zone.

Characterization studies of the site geohydrologic system have included field and laboratory testing of soil permeability, field measurements of bedrock permeability, laboratory measurement of soil moisture characteristics and permeability under unsaturated conditions, water table fluctuation monitoring in observation wells, aerial thermal sensing to identify groundwater emanations, precipitation measurements, surface water flow monitoring, tracer testing and water budget calculations.[4] Shallow unconfined aquifers occur below the West Chestnut Ridge site in both the soil and the weathered bedrock zone. These aquifers are localized with
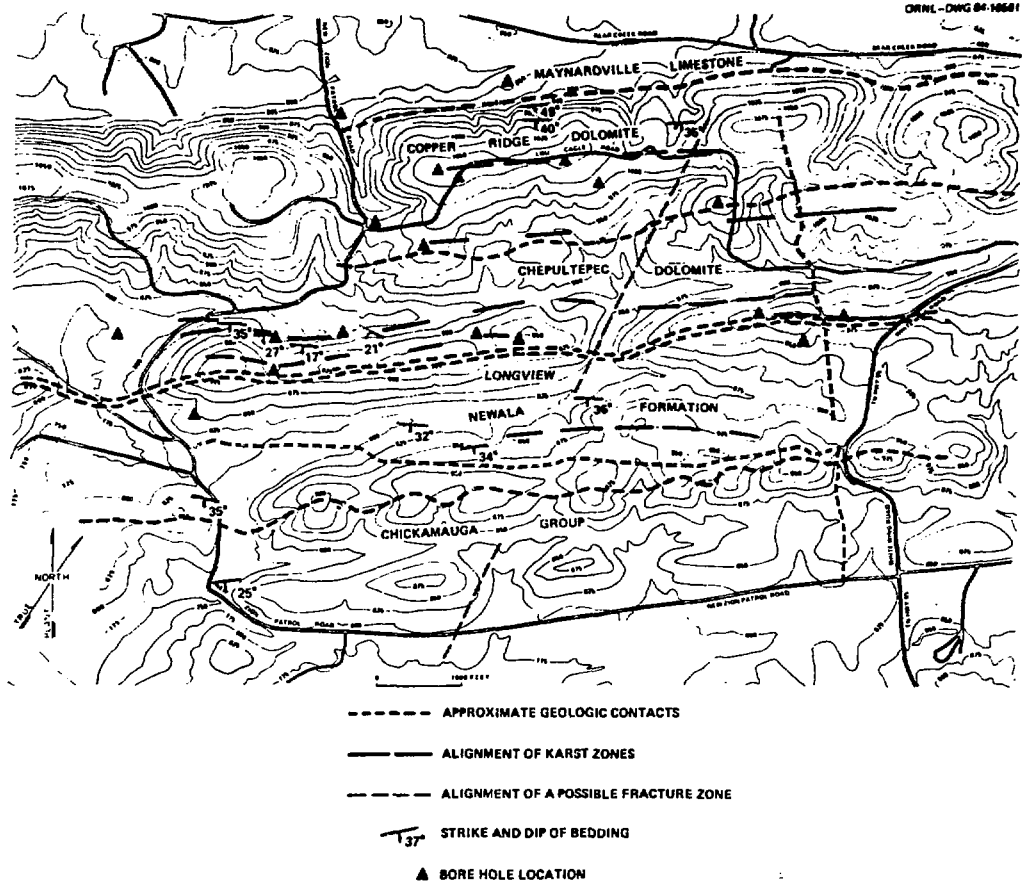
Figure 7. Areal geologic map of the West Chestnut Ridge Site.

recharge occurring in the higher elevations. Within both the soil and
bedrock aquifers, flow is from the higher topographic areas toward the
lower areas. Gradients indicate flow toward the nearest perennial surface
water features. Apparent water divides are located beneath the ridges on
the site. Rapid well responses to precipitation events indicate that
transmission of water through site soils and bedrock occurs rapidly. Pre-
cipitation which falls at rates below the vertical infiltration capacity of
the residuum infiltrates through the residuum into the bedrock aquifer.
When the vertical infiltration capacity of the residuum is exceeded during
a precipitation event, lateral quickflow occurs in the upper soil horizons
and ephemeral surface flow occurs where the quickflow emerges to the sur-
face. This phenomenon occurs during the winter and spring seasons and
causes infiltration of saturated pulses through the residuum. Water move-
ment in the weathered bedrock and bedrock aquifer is strongly controlled by
the locations and orientations of cavities. The primary orientations of
cavity systems are controlled by local bedding orientation and the orienta-
tion of penetrative joints and fractures which are widened by dissolution.

The actual groundwater flow paths in the bedrock and weathered bedrock zones are expected to resemble rectangular or trellis drainage patterns with long runs parallel to strike and cross-strike channels leading to another strike controlled zone or to emanation in a surface stream. The influence of stratigraphic controls on groundwater movement has been demonstrated on the site by performance of a tracer test in the ephemeral stream located in the middle portion of the Chepultepec Dolomite. Dye tracer was introduced into the aquifer by way of a disappearing stream and was detected in surface water approximately 1.5-3 km away. Travel rate within the traced flow path is on the order of 200-360 m/d. Flow in this portion of the site is thought to represent the upper bound of groundwater movement for the site.

The results of the field permeability tests indicate that the zone including the top of unweathered bedrock and the weathered bedrock is the major transmissive unit for horizontal transport at the site. The permeability estimates for this zone were about 2.0×10^{-4} cm/s. This high permeability value is attributed to flow in fractures and/or open bedding planes. Flow through the residual soils is mainly vertical, although lateral flow paths may occur in residuum where predominantly gravelly zones have formed by weathering of bedded cherts or where sandy zones in bedrock persist in the residuum. The considerable scatter observed in the data of the soil local permeability tests around a mean value of about 2.0×10^{-6} cm/s is consistent with the highly variable nature of the soil itself; however, the rapid response of the soil wells to storm events, combined with the mapping of numerous sinkholes, solution pan features and dolines at the site, suggests that preferential vertical flow paths occur in the soil layer and that permeability values in the upper range of the test results (10^{-5} to 10^{-4} cm/s) better represent the pervious character of the residuum layer.

Two major creeks, Grassy Creek to the north and Ish Creek to the south, and an ephemeral or wet season channel, the New Zion Creek in the central valley, constitute the surface drainage system for the site. The extremely variable flow rates of these streams preclude their use as dependable water supplies. The nearest dependable water supply is the Clinch River. Surface drainage from the site eventually discharges into the Clinch River. The streambeds of the creeks act as collectors and discharge pathways to the Clinch River for both the surface water system and the groundwater which flows downdip in the site unconfined aquifers. A strong interaction between surface and subsurface water flows occurs in the discharge pathways. The quantity of groundwater discharged to individual streambeds on site and the associated dilution factors could not be established with the existing data. However, a minimum factor for dilution of the maximum amount of contaminated water that may occur over the entire site by the Clinch River flow was estimated to be 2.4×10^3.[15]

The dominant water pathway to an inadvertent intruder would result from consumption of well water. DOE regulations[2] specify that analyses of potential exposure should be based on doses to individuals at points of maximum probable exposure. Consequently, the assumption is made that the intruder well is located in the region of maximum radionuclide concentration predicted in the uppermost tappable water bearing zone. For the CWDF

shallow-land burial site, the region that is expected to experience maximum radionuclide concentration is that located directly underneath the trenches, and the uppermost tappable water bearing zone is the weathered bedrock aquifer. To quantify potential exposure to the public and to the inadvertent intruder, dose calculations should, therefore, be made based on radionuclides concentrations at two locations — a hypothetical water supply point in the Clinch River downstream of the CWDF, and a hypothetical point in the weathered bedrock aquifer located directly underneath a trench area. To simulate the migration of radionuclides from a trench bottom to the intruder well point in the weathered bedrock aquifer, a typical two-dimensional vertical cross section was used. The cross section was located in an area representative of the site conditions, parallel to the expected groundwater flow, and in such a way that it intercepted a large number of trenches (sources), a large number of wells (data points), and collector areas (discharge locations) as defined by the alluvium of the creeks. Figure 8 shows a schematic design of the conceptual model on the cross section. The conceptual model was based on a generalized geologic profile and consisted of a three-layer system including a soil layer, a transmissive layer, and a sound rock layer. The upper layer, bounded by the ground surface on top and the top of the weathered bedrock zone on the bottom, represents the soil layer. In this layer, the materials have relatively low hydraulic conductivities and high adsorption characteristics. Migration of radionuclides in this layer is expected to be mainly vertical and associated with time scales that are quite larger than those of the other layers. This layer constitutes the main buffer layer for radionuclide migration. Underlying the soil layer is a transmissive zone characterized by high hydraulic conductivity values and very low adsorption characteristics. This layer corresponds to the cavernous zone where weathering processes are the most active. Groundwater flows in that zone are controlled by solution cavities, bedding planes and discrete joints in the bedrock. Parameters defining the local properties of the materials in that zone (hydraulic conductivity, porosity, thickness of the layer, distribution factors, etc.) are expected to vary by orders of magnitudes over short distances. Fingering of the migration patterns are expected to occur and to be controlled by fracture orientation. Rapid horizontal transport of contamination fronts in discrete channels and preferential flow paths, as experienced during the tracer test, is also expected. These short travel times and low retardation factors in the aquifer will result in transport of the radionuclides from the intruder well point to the Clinch River which, on a pathways analysis time scale, can be considered as instantaneous. Each radionuclide, however, was assumed to be diluted by the minimum dilution factor of 2.4×10^3 during that transport.

The groundwater code utilized for analyzing site performance was the FEMWATER-FEMWASTE code.[16],[17] The code was modified to include the effects of concentration dependent adsorption coefficients observed during the waste characterization studies.[18] The unsaturated and saturated zone parameters were specified by using the data collected from the field and laboratory studies.[4],[18] Adjustments of the parameters were made using transient simulations of seasonal water table fluctuations until the computed piezometric surface compared favorably with the monitoring data. Since no data on leaching characteristics from the waste were available, it was conservatively assumed that the waste was in soluble form and that the
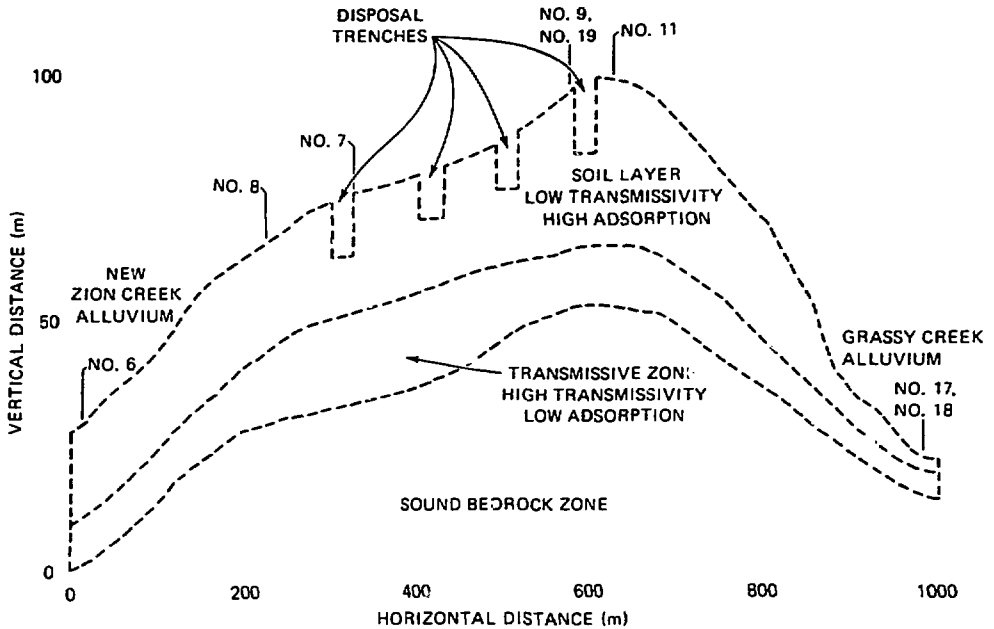
Figure 8. Schematic representation of the conceptual model.

radionuclides rapidly dissolved when the waste was saturated with water. Solubility limits in CWDF groundwater were calculated for some nuclides[15] and were used as upper bound values for concentration of these nuclides in the leachate. Leaching was assumed to occur until the total mass of the nuclides was removed from the waste. The nuclides for which solubility limits do not apply are assumed to dissolve completely during the first rapid wetting event. The nuclides for which solubility limits apply are assumed to dissolve at their solubility limit in a series of identical rapid wetting events. Infiltration of the leachate in the soil occurred at a rate corresponding to the vertical permeability of the soils. Based on the results of the geochemical program on retardation of radionuclides by soil,[18] the radionuclides were divided into seven groups. Each group was selected to conservatively represent a subset of radionuclides on the basis of mass anticipated in the waste, mobility in the soil/groundwater system and toxicity. The methodology used as a guide for the selection consisted of ranking the nuclides according to their "hazards rating" HR calculated as:

$$HR_i = \frac{Q_i}{Rd_i \times MCP_i}$$

where Q_i is the expected content in the waste, Rd_i is the retardation factor, and MCP_i is the maximum permissible concentration of the nuclide i given in App. B of NRC 10 CFR 20. Based on this analysis, seven radionuclides (Sr-90, Tc-99, Cs-137, H-3, C-14, Cm-244, and U-238) that were representative of general classes of radionuclides in the wastes were selected for detailed study in the water pathways analysis. Using a conservative approach, the results for these seven radionuclides were extrapolated to the other radionuclides.

Groups 1 through 6, with H-3, Tc-99, C-14, Sr-90, Cm-244 and Cs-137 as respective representative radionuclides, used constant Kd values of 0, 1, 10, 690, 1200 and 11,000, respectively. These were conservative values based upon the laboratory batch tests.[18] The nuclides of the seventh group, with U-238 as representative nuclide, exhibited adsorption characteristics that are a strong function of the nuclide concentration over the range of concentration of interest here and were treated with concentration dependent Kd values. Figure 9 shows the results of the numerical simulations for groups 1 through 3, the only groups that reached a maximum concentration in the aquifer within the first 1000 years. This figure shows the maximum dimensionless concentration in the aquifer (the ratio of the concentration in the aquifer to the leachate concentration) versus time after the wetting event assuming that the nuclides do not decay. These
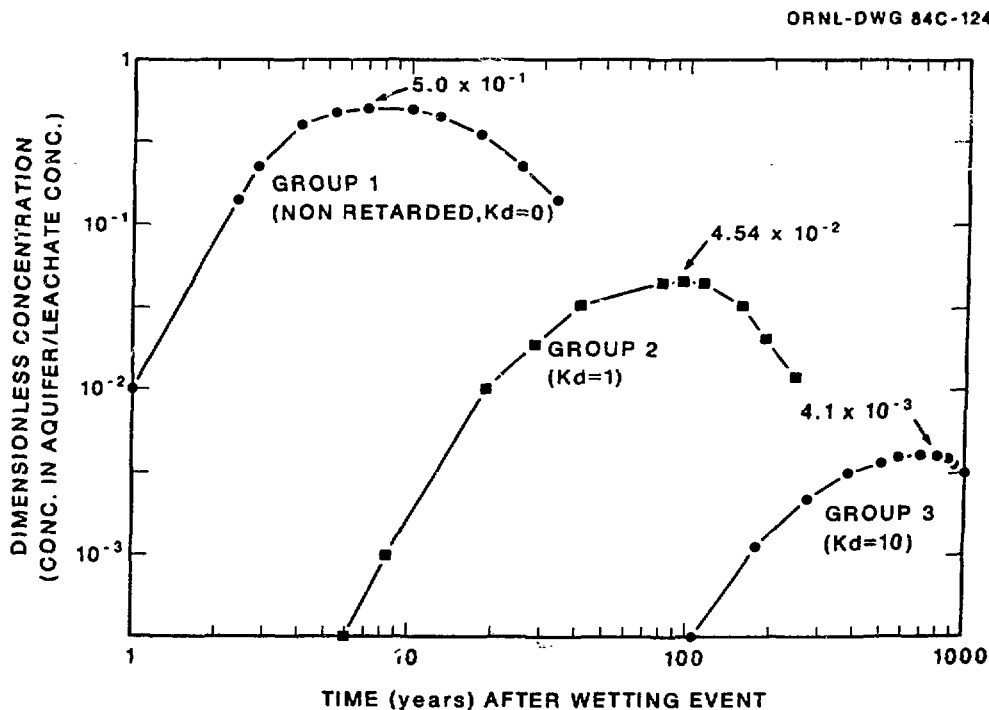
ORNL-DWG 84C-12473

Figure 9. Maximum dimensionless concentration in the aquifer versus time for group 1 through 3, assuming no decay of the nuclides.

concentrations, scaled with the appropriate leachate concentration and decay constant for each nuclide, provide the maximum concentrations that may occur at the intruder well. The peak value of these concentrations were used in the dose analysis.

Based on the maximum radionuclide concentration in the aquifer and a dilution factor of 2.4×10^3 of the aquifer discharge by the combined stream flows of the creeks and the Clinch River, the maximum levels of radioactivity that could contaminate the nearest potential public drinking water supply (Clinch River) were estimated. The doses from drinking this water from the Clinch River were derived. The total-body dose of 0.079 mrem/y and the highest organ dose of 1.05 mrem/y (bone) were mostly due to uranium nuclides (96%) and were well below the 25-mrem/y regulatory dose limits. The levels of radioactivity of the uranium nuclides in the Clinch River are also well below the EPA standard limit of 10 pCi/L. The total doses to the inadvertent intruder from the inhalation of contaminated dust were about 80% attributable to uranium nuclides. The maximum total-body dose was 5.3 mrem/y while the highest organ dose was 130 mrem/y to the lungs. For the ingestion of contaminated foodcrop pathway, approximately 52% of the total-body dose of 210 mrem/y was due to C-14 and 16% to uranium nuclides. The highest organ dose of 920 mrem/y was due primarily to uranium nuclides (48%) and Sr-90 (36%). The maximum doses resulting from direct gamma exposure of the inadvertent intruder were 160 mrem/y to the total body and 180 mrem/y to the bone and were due almost entirely to C-137 (97%). For the ingestion of contaminated groundwater pathway, it was conservatively assumed that the well was drilled near a trench. Using peak values of the radionuclide concentrations in the aquifer, a total-body dose of 189 mrem/y and a highest organ dose (bone) of 2470 mrem/y were calculated. At the end of the 500 y performance period, these doses decreased to 22 mrem/y and 280 mrem/y, respectively. About 97% of the total doses were due to uranium nuclides. Maximum dose commitments receivable by biota other than man were estimated to be 1 rem/y.

In summary, the potential dose commitments to the general public were a small fraction of that allowed under present regulations and the pathway to the general public is not a limiting factor for determining site capacity of the CWDF. In the analysis of the inadvertent intruder pathways, direct exposure to contaminated soil, ingestion of foodcrop and consumption of contaminated groundwater resulted in similar whole body dose commitments which approached the regulatory limits for the reference source terms used in the study. Hence, the results for these pathways were used as guidance to determine maximum burial concentration for each radionuclide. The significant doses resulting from disposal of the long-lived radionuclides (C-14, Tc-99, U-234, U-235, U-238) are not expected to vary with time. For those nuclides, the concentrations used in this study were, therefore, recommended as maximum waste concentrations. Significant doses from short-lived radionuclides (H-3, Sr-90, Cs-137) were calculated from the direct intrusion pathways. Based on the fact that exposure through these pathways can be prevented during administrative controls and resulting doses will decrease considerably during the performance period following institutional controls, concentration values matching those considered in this study were recommended as maximum waste concentrations. Based on the results of this analysis, tracer test data, and site characterization

data,[4] the predicted zone of groundwater contamination in the shallow
aquifers was contained within a relatively small area. This area was inde-
pendent of waste burial concentrations and was bounded by Ish Creek to the
East, Tennessee Highway 95 and Bear Creek Road to the North, Grassy Creek
to the Northwest, New Zion Patrol Road and the subterranean portion of New
Zion Creek to the West, and the Clinch River to the South. There appears
to be adequate buffer space around this area and the disposal site so that
human use of the region beyond the DOE reservation boundary should be
unrestricted.

DISCUSSION OF THE RESULTS

The pathways analyses presented above have provided considerable in-
sight for estimating the suitability of the two sites under consideration
for low-level radioactive waste disposal. Even under the most conserva-
tive conditions, buffer zones have been established within the DOE reserva-
tions, outside which public activity could be unrestricted. Additionally,
the site characterization has provided data to address the DOE site selec-
tion criteria (DOE Order 5820). Consequently, the sites were found favor-
able for development of low-level waste disposal facilities. Based on the
results of the pathways analyses, recommendations for site design and site
development were made. An area of most concern during site development and
site operation deals with site capacity. Since the pathways analyses were
performed using a large degree of conservatism, the preliminary recommenda-
tions concerning site capacity are also extremely conservative. Conserva-
tism generally is built into the analyses when assumptions concerning
future events have to be made or when uncertainties concerning site or
waste characteristics exist. In order to reduce this conservatism, the
analyses should be coupled with in-depth quantitative analyses of (1) the
probability of scenarios describing future events to occur, and (2) the
uncertainties involved in the analyses. The results of the pathways analy-
ses could, therefore, be interpreted in a less restrictive manner for de-
termining site capacity.

The inherent conservatism built into a pathways analysis can generally
be reduced, or at least more quantitatively analyzed, by using established
sensitivity and uncertainty analysis methodologies. The uncertainties pre-
sent in these analyses are broken down into three categories. Systematic
errors arising from approximations in the conceptual modeling of the prob-
lem, modelling uncertainties arising from approximations in the mathematical
description of the physics or engineering problem, and data uncertainties
arising from statistical or distributional behavior of the modelling data
and parameters. Uncertainties of the first two kinds are most difficult to
estimate and propagate and limited theoretical help is available to avoid
the use of engineering judgement. The data uncertainty area, however, can
be dealt with in a systematic and quantitative way with established methods.
These latter procedures are usually broken down into two steps. The first
step is sensitivitiy analysis to determine the important modeling parame-
ters in a pathways problem and the second an uncertainty assessment and
propagation exercise to determine the overall pathways uncertainties
arising from the most important parameter uncertainties. Several estab-
lished methodologies are available for performing these studies, the two

chief ones being statistical experimental designs and adjoint sensitivity
theory. The statistical approach is based on the generation of systematic
perturbations in the model data base and analyzing the statistical changes
in model results. Adjoint theory utilizes efficient computational methods
for determining model sensitivities (i.e. derivatives of results with
respect to model parameters) and then approximating the functional behavior
of the results through power series or interpolation schemes to estimate
model uncertainties. Both methodologies are appropriate to large scale
uncertainty analysis problems with some additional problem dependent modi-
fications. The methodologies have already been successfully applied to
similar problems in the high level waste isolation research program.

CONCLUSION

Pathways analyses such as those presented in this paper provide useful
tools for evaluating the suitability of proposed sites for hosting low
level waste disposal facilities. The analyses require comprehensive in-
vestigation of the sites. The results are useful in interpreting the per-
formance of the sites and in developing design criteria for site develop-
ment. However, the analyses remain conservative in nature. They require
the development of scenarios incorporating conservative assumptions of
future development, waste characteristics and site characteristics. The
interpretation of the results for determining site capacity is complicated
by the uncertainties inherent to the analysis of the geohydrologic system
of the site, the geochemical behavior of the waste, and the forecasting of
events hundreds of years in the future. The use of analytical methods to
quantitatively assess the probability of future events to occur and the
sensitivity of the results to data uncertainty may prove useful in relaxing
some of the conservatism built into the analyses. Future investigations
include the development and the application of such methods to pathways
analyses.

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