THREE-DIMENSIONAL SIMULATION OF GROUND WATER FLOW AND CONTAMINANT TRANSPORT AT THE REACTOR AREAS OF THE SAVANNAH RIVER SITE

Mark D. Taylor
CDM Federal Programs Corporation
2030 Powers Ferry Road, Suite 490
Atlanta, Georgia 30339

John S. Haselow
Westinghouse Savannah River Company
Building 773-42A
Aiken, South Carolina 29802

ABSTRACT

A three-dimensional ground water flow and contaminant transport model, with a heterogeneous and anisotropic hydraulic conductivity field, was developed to simulate the transport of radionuclides in ground water emanating from the K, L, and P reactor areas of the Savannah River Site in South Carolina. The model was developed to help evaluate the potential impacts to human health and the environment as a result of continuing operation of the idled K, L, and P reactors. The results of this study were then used to prepare an Environmental Information Document for the Department of Energy, and subsequently, an Environmental Impact Statement, which is required for any major federal action under the National Environmental Policy Act.

The simulations indicate that the greatest subsurface environmental impacts under normal reactor operations result from the release of tritium. Tritium is the only radionuclide for which simulated ground water concentrations exceed the drinking water standard at a significant distance from the discharge points. Other radionuclides are discharged in concentrations below drinking water standards or decay to concentrations below the drinking water standards before they are significantly transported.

INTRODUCTION

The Westinghouse Savannah River Company, under contract to the United States Department of Energy (DOE), has prepared an Environmental Information Document (EID) as part of the regulatory process for continuing operation of three idled nuclear reactors at the Savannah River Site (1). The SRS is a major DOE facility located near Aiken, South Carolina, which produces nuclear materials for national defense and civilian purposes. The three reactors are identified as the K, L, and P reactors, and their locations at the SRS are shown in Fig. 1. To provide information to fulfill the requirements of the National Environmental Policy Act (NEPA), the potential consequences to human health and the environment resulting from continuing operation of the three reactors were evaluated. One potential consequence of operating the reactors is discharges of radionuclides, mainly tritiated water, to unlined seepage basins during normal reactor operation. Unlined seepage basins have been used in the past as receptors of disassembly rinse water. While the radionuclides move through the ground water system underlying the SRS, significant radioactive decay occurs. Additionally, the radionuclides are adsorbed by the soil matrix. To estimate the extent of radioactive decay and adsorption, and to evaluate the potential subsurface environmental impacts of these seepage basin discharges, a three-dimensional ground water flow and contaminant transport model was developed to simulate the movement of radionuclides in the ground water system at each reactor area. This paper describes the development, calibration, and simulation results of the ground water flow and contaminant transport model developed for the EID.

HYDROGEOLOGY

Three distinct hydrogeologic systems underlie the SRS: (1) the Coastal Plain sediments where ground water flows through porous sands, clays, and limestones, (2) the crystalline metamorphic rock beneath the Coastal Plain sediments where ground water flows through small fractures in schist, gneiss, and quartzite, and (3) the Dunbarton Triassic Basin within the crystalline metamorphic rock where ground water flows through intergranular spaces in indurated mudstones, siltstones, sandstones, and conglomerates (2). This study focused solely on the Coastal Plain sediments aquifer system, because: 1) this system is isolated from the other two systems by a dense clay aquitard, and 2) the other two systems produce extremely low yields of poor-quality water at the SRS.

The Coastal Plain sediments with many interbedded clay, silt, and sand lenses form a complex three-dimensional flow system. However, on a regional basis, the aquifer system can be divided into six main hydrostratigraphic units, which encompass several geologic stratigraphic units as shown in Fig. 2. The Cape Fear Formation is a dense clay which acts as the base aquitard of the system. Overlying the base aquitard is the regional Cretaceous age aquifer (Aquifer 1). This hydrostratigraphic unit is composed of unconsolidated sediments from the Middendorf and Black

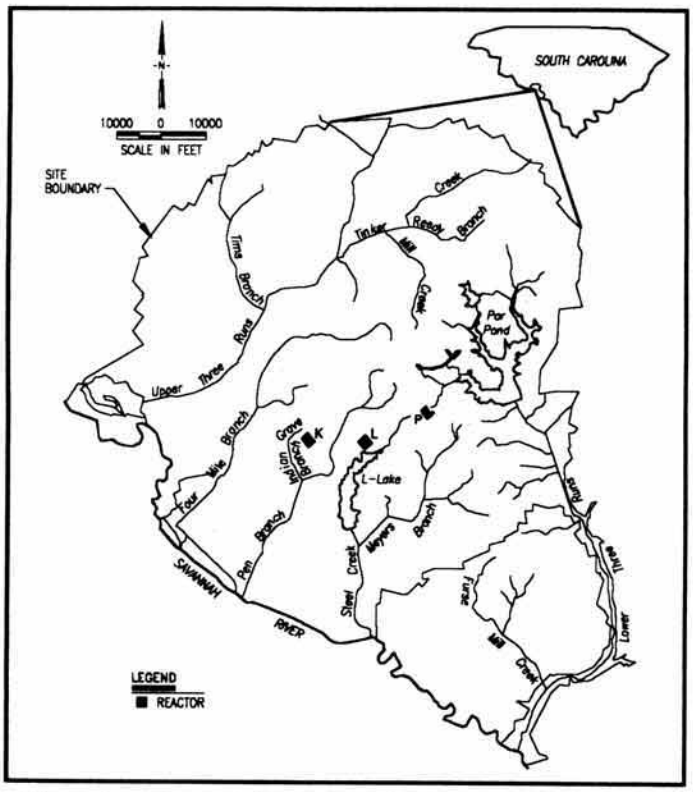

Fig. 1. Locations of the K, L, and P Reactors at the Savannah River site.

HYDROGEOLOGIC UNIT	STRATIGRAPHIC UNIT(S)
Water Table	Upland Tobacco Road Dry Branch Clinchfield
"Santee" Aquitard	Santee
Aquifer 2 or Tertiary Age	Congaree Four Mile Snapp
"Ellenton" Aquitard	Ellenton and 20 feet of Steel Creek
Aquifer 1 or Cretaceous Age	Steel Creek Black Creek Middendorf
Base Aquitard	Cape Fear

Fig. 2. Stratigraphic and hydrostratigraphic units of the coastal plain sediments aquifer system.

Creek Formations and the Steel Creek Member of the Peedee Formation. Aquifer 1 is approximately 500 feet thick and is an excellent source of high quality water and can sustain yields of up to 1800 gallons per minute (gpm) in water supply wells (2).

The upper 20 feet, on average, of the Steel Creek Member is a dense silty clay of low permeability. This 20-foot thick silty clay unit, combined with the Ellenton Member of the Rhems Formation overlying it, forms a leaky aquitard (the "Ellenton" Aquitard) which is approximately 100 feet thick. Although the Ellenton Member does contain some coarse sand lenses, the clay lenses throughout the unit make it an effective aquitard. Overlying the Ellenton Aquitard is a second aquifer (Aquifer 2) comprised of the Snapp Member of the Williamsburg Formation, the Fourmile Member of the Fishburne Formation, and the Congaree Formation, all of Tertiary age. This hydrostratigraphic unit is approximately 100 feet thick and consists predominantly of fine to medium and medium to coarse, well sorted sands. This aquifer is not nearly as prolific as Aquifer 1, but can sustain yields up to 200 gpm in water supply wells.

Overlying Aquifer 2 is the Santee Formation, which is on average 50 feet thick and acts as a leaky aquitard at the SRS (the "Santee" Aquitard). The Santee Formation elsewhere in the Coastal Plain is usually calcareous and highly transmissive, but at the SRS it is mostly fine, silty material with interbedded clays and cemented limestones. The clays occasionally contain glauconite, and as a result this unit is sometimes called the "green clay." Overlying the "Santee" Aquitard is the water table hydrostratigraphic unit, which is not an aquifer by strict definition because of its low water producing capabilities. Several wells screened in the water table unit at the SRS cannot sustain 1 gpm of flow. Nevertheless, it is a distinct and important hydrostratigraphic feature at the SRS since any contaminants entering the aquifer system at the surface must first flow through the water table unit before entering other hydrostratigraphic units or discharging to surface waters. The thickness of the water table unit varies greatly (from 0 to 200 feet) across the site due to the changing topography.

Regionally, ground water flow in the Coastal Plain sediments is seaward (toward the Atlantic Ocean). At the SRS, however, the general ground water flow direction is influenced by the Savannah River and its tributaries which provide surface water drainage for the SRS. As a result, ground water at the SRS generally flows from northeast to southwest toward the Savannah River, particularly in the lower aquifer units. Locally, ground water flow in the water table unit is highly variable because of the undulated topography and the presence of many small dissecting creeks and marshy areas at the SRS. At the K reactor site, ground water in the water table unit flows from the reactor area toward the south and west where it discharges into Indian

Grave Branch Creek. At the L reactor site, ground water flows from the reactor area toward the south where it discharges into L-Lake, and toward the west where it discharges into Pen Branch Creek. At the P reactor site, a local "high" in the water table surface causes ground water to flow in all directions from the P reactor area. Surface water discharge points are Steel Creek to the southwest, Meyers Branch Creek to the southeast, and Par Pond and its tributary to the northeast. At all three reactor sites, the hydraulic head in the water table unit is higher than the hydraulic head in Aquifer 2. Thus, ground water also moves downward from the water table unit, through the "Santee" Aquitard, into Aquifer 2.

Vertical flow between Aquifer 1 and Aquifer 2 is variable across the SRS. In some areas of the SRS, the hydraulic gradient, and hence vertical flow, is downward from Aquifer 2 to Aquifer 1. In other areas, vertical flow is upward from Aquifer 1 to Aquifer 2. This upward flow gradient has previously been referred to as a "head reversal" and prevents water in Aquifer 2 from entering Aquifer 1 in those areas. Note, however, that below the K, L, and P reactor areas, there is no "head reversal" so that Aquifer 2 is recharging Aquifer 1 in these areas.

MODEL DEVELOPMENT AND CALIBRATION

The ground water flow and contaminant tranport model codes used in this study were the DYNFLOW (DYNamic ground water FLOW simulation) and DYNTRACK (DYNamic particle TRACKing) computer programs developed by Camp Dresser & McKee Inc. in 1982. These codes have been peer reviewed and validated by the International Ground Water Modeling Center at the Holcomb Research Institute, and have been accepted by the U.S. Environmental Protection Agency (EPA) for use on Superfund sites. DYNFLOW uses a Galerkin finite element formulation to solve the partial differential equation that describes the transient, three-dimensional flow of a homogeneous incompressible fluid through a heterogeneous, anisotropic porous medium. The program uses linear finite element basis functions and incorporates induced infiltration from streams, artificial and natural recharge or discharge, and heterogeneous and anisotropic hydraulic properties. The program manages both linear (confined) and nonlinear (unconfined) aquifer flow conditions, and has special routines to allow a change from a confined to unconfined situation. The program also has a "rising water" scheme to allow drainage to local streams if the potentiometric head in a phreatic aquifer rises to the elevation of the stream bed or land surface. DYNTRACK simulates three-dimensional contaminant transport in the saturated zone of an aquifer, and uses the same three-dimensional finite element grid discretization used for DYNFLOW. DYNTRACK uses the random walk method to solve the contaminant transport equation and can model contaminant movement for conservative constituents with dispersion, as well as first-order decay and/or adsorption. Thus, DYNTRACK permits the evaluation of complicated contaminant transport problems.

The finite element grid used in this analysis is superimposed on a base map of the SRS in Figure 3. The grid was developed to adequately represent all significant physical features such as streams, lakes, the Savannah River, faults, wells, and the three reactor areas. The grid consists of 701 nodes and 1349 elements. A variable size grid system is used so that aquifer impacts can be evaluated over a large area while still maintaining sufficient detail within the reactor areas. The grid network is more dense around the reactor areas where radionuclides are released. A dense element network in these areas allows the head distribution to be calculated at a degree of resolution that is suitable for simulating the transport of radionuclides from the seepage basins.

The aquifer system is vertically discretized into seven levels of nodes that define six layers and five hydrostratigraphic units (Aquifer 1 is divided in half). The seven node levels represent the following hydrostratigraphic unit boundaries:

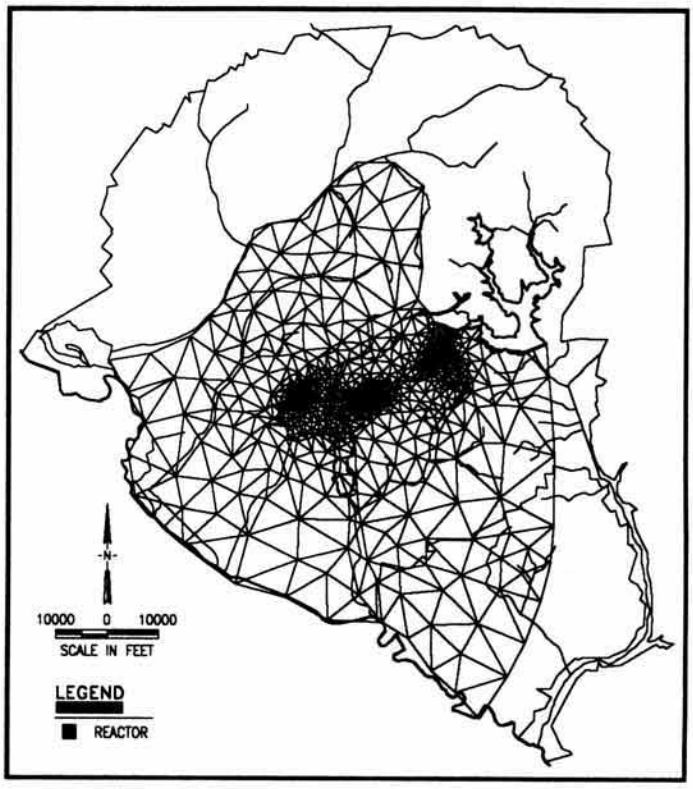

Fig. 3. Ground water model finite element grid.

- Level 1 - Top of the Base Aquitard
- Level 2 - Middle of the Aquifer 1
- Level 3 - Top of Aquifer 1
- Level 4 - Top of the "Ellenton" Aquitard
- Level 5 - Top of Aquifer 2
- Level 6 - Top of the "Santee" Aquitard
- Level 7 - Land Surface (top of water table unit)

The size of the model area was selected based on the prevailing boundary conditions. DYNFLOW can simulate specified head and specified flux boundary conditions. Ideally, the model boundaries are chosen so that they coincide with actual, stable hydrologic boundaries (e.g., oceans, rivers, etc.). Since only a few truly stable hydrologic boundaries exist at the SRS (i.e., the Savannah River and Upper Three Runs Creek), the remaining model boundaries are located far enough away from the reactor sites so that conditions imposed on the boundaries do not significantly alter the simulation results within the areas of interest, as long as the conditions imposed are realistic.

Boundary conditions imposed on the model vary between a specified head condition and a "no flow" condition, whichever is more representative of observed ground water flow conditions in each aquifer and aquitard. The distribution of specified heads along the model borders was estimated based on averages of quarterly observation well data from 1986 to 1989, as well as surface water measurements taken along the Savannah River and other surface water features at the SRS. At the bottom of the model (Level 1), a vertical "no flow" condition is specified at every node in the model, thus preventing any leakage in or out of the model through the base aquitard. Streams and swampy areas located in the interior of the model grid are represented through a "rising" head boundary condition. In these areas, the water table is allowed to rise to land surface, but not above it. If the water table is driven above the land surface, a discharge flux sufficient to keep the water table at land surface is introduced. This discharge flux represents a surface discharge of water which is lost from the ground water system as surface flow.

Aquifer stresses are incorporated in the model to account for precipitation and aquifer withdrawal. Based on previous studies performed at the SRS, rainfall recharge is estimated to be 15 inches per year. This recharge is applied uniformly over the entire model area. Aquifer pumping rates applied in the model are based on well production flows measured during the first quarter in 1989 which represent recent and anticipated future use at the SRS.

The flow model was calibrated under steady-state conditions using average observed water levels for the period 1986 to 1989 for wells located throughout the SRS. The assumption inherent in this calibration is that the average observed water levels calculated represent steady-state water levels for the rainfall recharge and ground water pumpage stress conditions imposed. *Generally, the seasonal* water level fluctuations do not appear to be more than a few feet so that the calculated average water levels will not be significantly different from the real values. Additionally, although pumpage at the SRS has steadily decreased, it does not appear to have varied significantly over the past few years nor does it appear to have any significant impact on ground water levels because production is significantly below the capacity of the aquifer system. Rainfall for the period 1986 to 1989 also did not vary significantly from average annual rainfall. Therefore, the average observed water levels used for calibration of the flow model are believed to be representative of steady-state water levels for the stress conditions imposed.

Prior to and during calibration of the flow model, property zones (areas with the same hydraulic properties) were established for each of the hydrostratigraphic units. For instance, in the water table unit and in the "Santee" Aquitard, three property zones, one for each of the three reactor areas, were established to isolate these areas from the rest of the SRS during calibration, because these areas are the areas of most concern in this study. By isolating the three areas, each could be addressed separately during calibration. Following each calibration run, a mass balance check was performed to assure that flows in and out of the model balanced with at most a 1% difference. The simulated water levels and flow patterns were then compared to the observed water levels and flow patterns, both visually and statistically, to help evaluate the set of input parameters (hydraulic conductivities). In addition, a parameter optimization program developed specifically for DYNFLOW was used to help guide the calibration process. During this process, however, the value of individual hydraulic conductivities was kept within realistic limits, based on the results of aquifer performance tests, grain size analyses, and observed past movement of contaminants at the SRS.

A summary of the statistics for the flow model calibration results is presented in Table I. Model results compare quite favorably to the observed data. As is usual in such a modeling study, a few wells show large differences between observed and simulated water levels, but these differences can be attributed to unknown local heterogeneities which could not be incorporated in the model. These differences, although possibly important on a very local scale, are not as significant with regard to the reactor site scale of the model, and should not invalidate the results of this study.

Because of the lack of observed transient contaminant transport data at the SRS, calibration of the contaminant transport properties was not possible. Instead, best estimates of the contaminant transport properties for the SRS,

TABLE I

Ground Water Flow Model Calibration Summary Statistics

Unit	Average Water Level Difference (feet)	Standard Deviation of Differences (feet)
Water Table	0.38	3.86
Aquifer 2	-0.40	2.04
Aquifer 1	-0.80	2.24
Overall	-0.19	3.01

as identified by Looney et al. (3), were used in the model in this study.

SIMULATION RESULTS

The average annual activity loading rates and discharge concentrations for the nine radionuclides of concern in this study are presented in Table II. The activity loading rates were calculated based on records of releases at the C, K, and P reactor seepage basins for the years 1984 to 1986 (1).

TABLE II

Average Reactor Seepage Basin Loading Rates And Discharge Concentrations Compared With EPA Drinking Water Standards

Radionuclide	Average Seepage Basin Loading Rate (Ci/yr)	Average Seepage Basin Discharge Concentration (pCi/l)	EPA Drinking Water Standard (pCi/l)
Tritium	4030	200,000,000	20,000
Cobalt-60	0.00171	86	200
Strontium-90	0.00034	17	8
Ruthenium-106	0.00096	48	300
Antimony-125	0.00227	114	4000
Cesium-134	0.00312	156	80
Cesium-137	0.03183	1590	100
Cerium-144	0.01373	685	80
Polonium-147	0.00293	146	1600

The concentrations were calculated based on the activity loading rates and an average observed reactor discharge of 2×10^7 liters/year. Also included in Table II are proposed concentrations for the nine radionuclides of concern that EPA allows in drinking water. EPA standard 40 CFR 141.16 specifies that drinking water may contain no concentration of radionuclides that yields a radiation dose over 4 millirem/year. Note that the concentrations presented in Table II represent a radiation dose of 4 millirem/year on an individual basis. If more than one radionuclide is present in the drinking water, the concentration of each radionuclide must be reduced so that the total exposure is less than 4 millirem/year.

Based on the contaminant transport properties, source concentrations, and EPA drinking water standards for the nine radionuclides of concern, the radionuclides to be further analyzed with the contaminant transport model were narrowed down to tritium (H-3), strontium-90 (SR-90), and cesium-137 (CS-137). Four of the radionuclides (cobalt-60, ruthenium-106, antimony-125, and polonium-147) were not considered further because they are released at concentrations at least two times below drinking water standards, and they are significantly retarded as they move through the soil. The two other radionuclides (cesium-134 and cerium-144) were not considered further because comparison of the contaminant transport properties and source strengths of these two radionuclides with that of cesium-137 indicates that the subsurface environmental impacts from cesium-137 will in all regards be greater. Both cesium-134 and cerium-144 have shorter half-lives than cesium-137, and are released at lower concentrations relative to their EPA drinking water standards. In addition, the retardation factor for cerium-144 is greater than that of cesium-137, while the retardation factor for cesium-134 is equivalent to that of cesium-137. Analysis of the subsurface impacts of tritium, strontium-90, and cesium-137 therefore provides a worst case environmental consequences evaluation since they represent the more mobile, persistent, and/or strongest (concentration) of the nine radionuclides of concern. The impact of the six other radionuclides will be less than that of the three selected radionuclides.

To further provide a worst case impacts analysis, the contaminant transport model simulations included a steady source loading rate at each of the seepage basins with radionuclides being released directly into the ground water system. No allowance was made for decay and retardation as the radionuclides move through the unsaturated zone, which is from 10 to 30 feet thick at the reactor areas. The model was run until a steady-state plume for concentrations above 1/100 of the drinking water standard was reached. This standard was chosen as a conservative criterion for impact evaluation. Steady-state plume simulations were achievable because the loss of contamination from the ground water system through surface water discharge and

radioactive decay eventually balances with the rate of radionuclide loading to the ground water system.

Ground Water Impacts

Based on the model simulation results, the greatest simulated subsurface environmental impacts result from the release of tritium. Tritium is the only radionuclide for which simulated ground water concentrations are above the drinking water standard at a significant distance from each of the reactor seepage basins. In addition, tritium is the only radionuclide for which the simulated steady-state plume for 1/100 of the drinking water standard intercepts a surface water body and/or moves down into Aquifer 2. Retardation of the other radionuclides prevents them from moving significantly before they decay to concentrations well below drinking water standards.

The simulated steady-state water table tritium plumes are shown in Figures 4 through 8. At the K reactor, steady-state was achieved in approximately 70 years. Both the 200 picocuries per liter (pCi/l) and 20,000 pCi/l tritium contours extend to Indian Grave Branch Creek in the water table unit, and slightly beyond the creek in Aquifer 2. At the L reactor, steady-state was achieved in approximately 15 years. Both the 200 pCi/l and 20,000 pCi/l tritium contours are completely intercepted by L-Lake in the water table unit. No tritium moves down into Aquifer 2 at the L reactor site. At

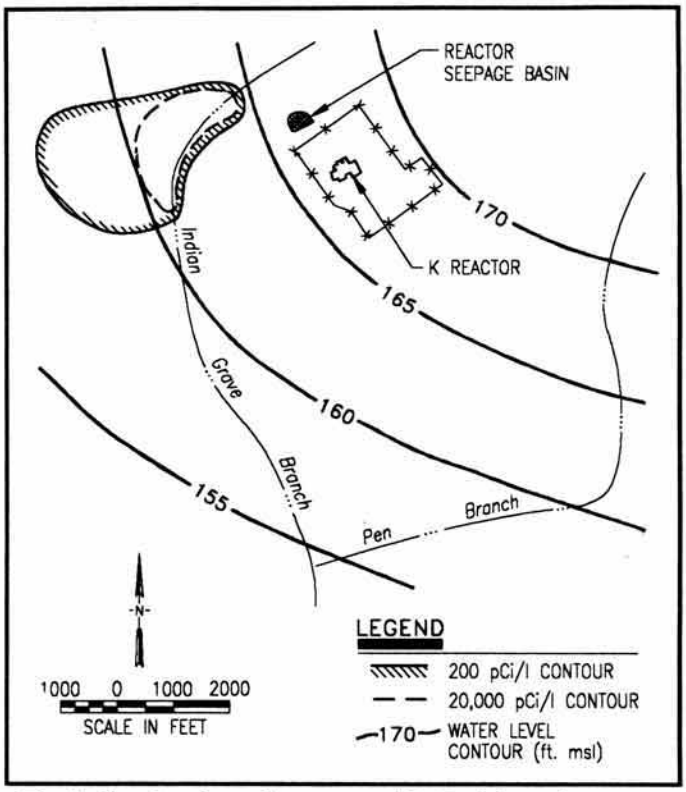

Fig. 5. Simulated steady-state aquifer 2 tritium plume from the K reactor seepage basin.

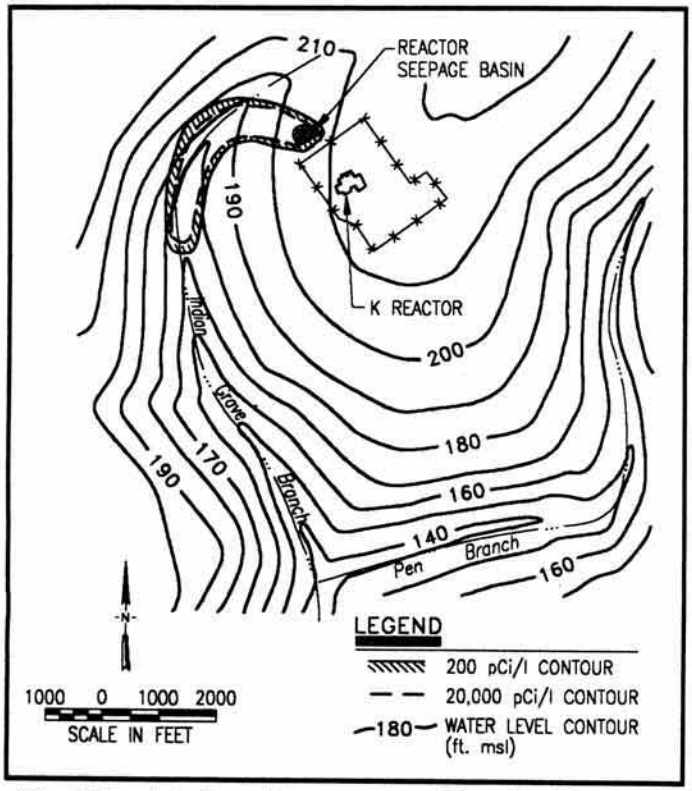

Fig. 4. Simulated steady-state water table unit tritium plume from the K reactor seepage basin.

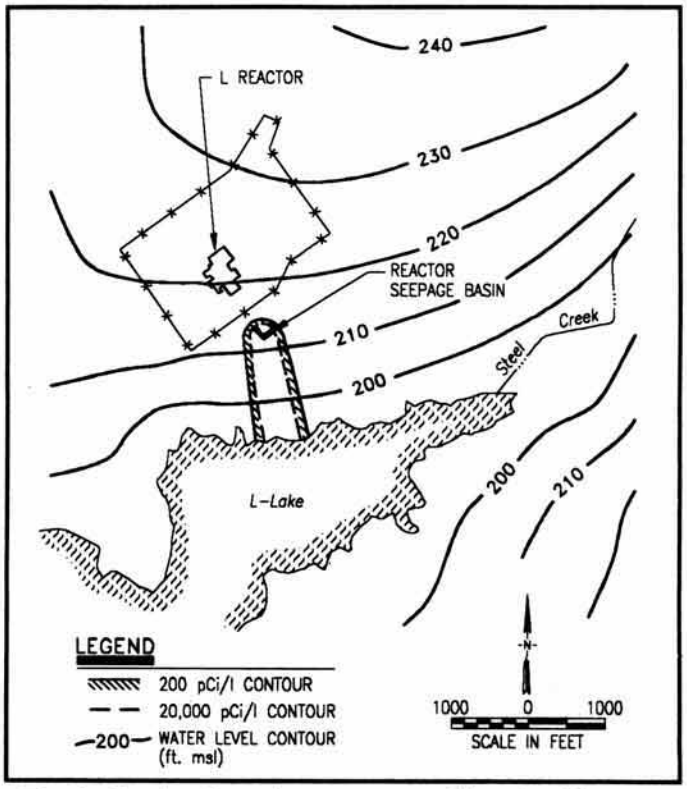

Fig. 6. Simulated steady-state water table unit tritium plume from the L reactor seepage basin.

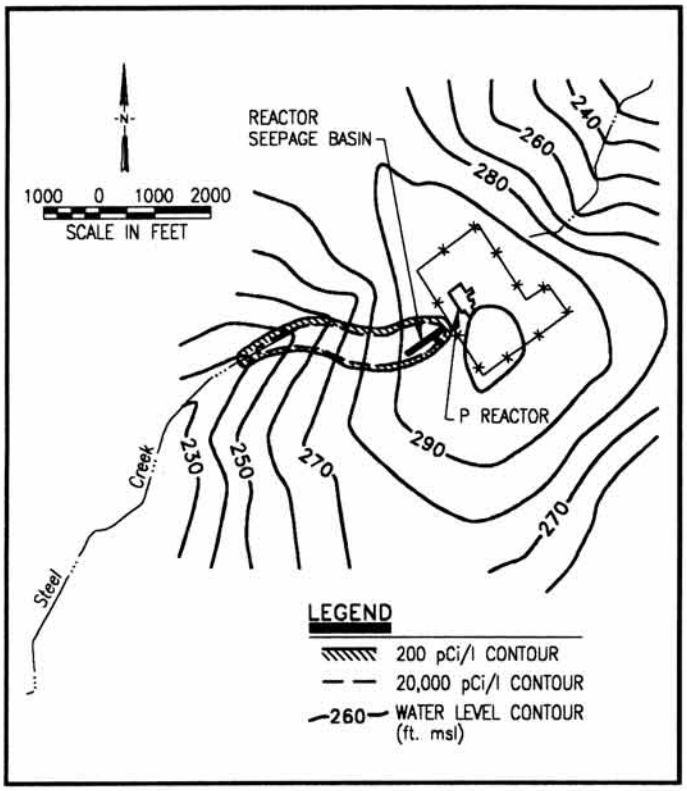

Fig. 7. Simulated steady-state water table unit tritium plume from the P reactor seepage basin.

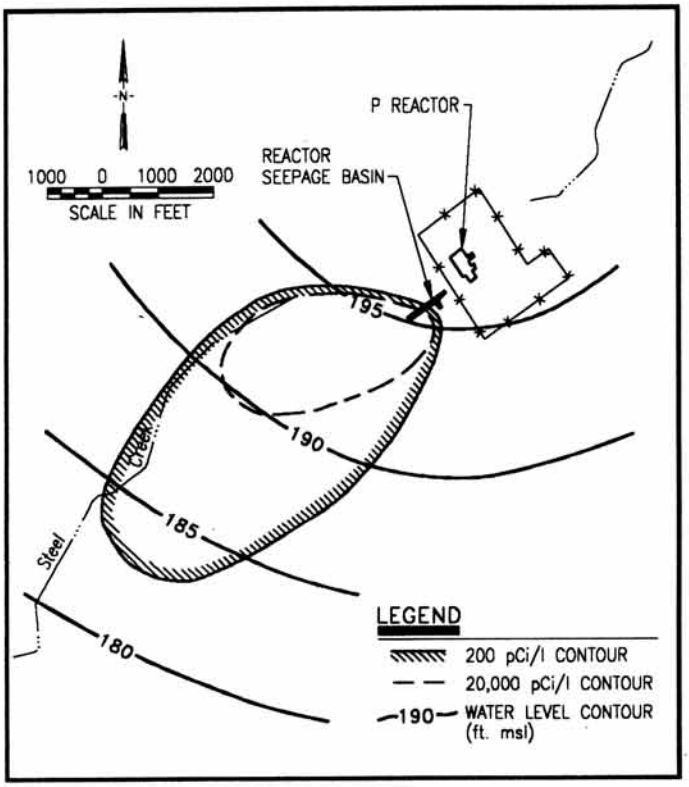

Fig. 8. Simulated steady-state aquifer 2 tritium plume from the P reactor seepage basin.

the P reactor, steady-state was achieved in approximately 120 years. Both the 200 pCi/l and 20,000 pCi/l tritium contours extend to Steel Creek in the water table unit, and further down-gradient in Aquifer 2.

A cross-section taken along the main axis of the simulated tritium plume at the K reactor is shown in Figure 9. This cross-section demonstrates how the simulated tritium plume moves underneath and past the nearest surface water body at the K reactor site. At the L reactor site, migration of tritium is limited to the water table unit. At the P reactor site tritium also migrates downward, underneath the nearest surface water body, and into Aquifer 2, similar to the K reactor site. At none of the three sites, however, does tritium migrate down any further than Aquifer 2 at concentrations above 1/100 of the drinking water standard.

Surface Water Impacts

The simulated steady-state tritium ground water to surface water activity fluxes are presented in Table III. Also presented in Table III are the ground water discharges to surface water along the reaches where tritium is discharged, and the average ground water discharge concentration of tritium at the three reactor sites. At the L reactor site, most of the tritium (67%) eventually leaves the ground water system through surface water discharge to L-Lake. Model simulations indicate that tritium reaches L-Lake within 5 years after release to the L reactor seepage basin. The

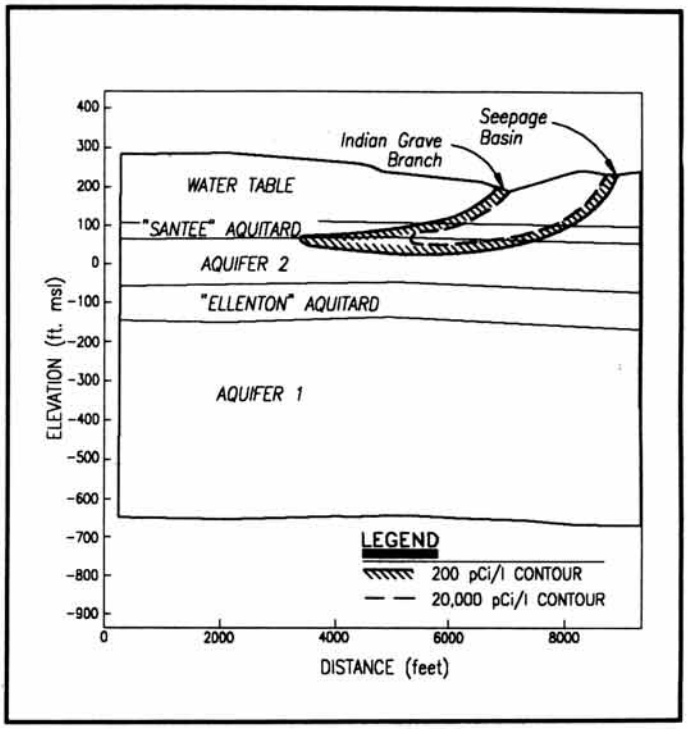

Fig. 9. Simulated steady-state tritium plume cross-section from the K reactor seepage basin (*taken along the main axis of the plume*).

TABLE III

Simulated Steady-State Tritium Ground Water to Surface Water Activity Fluxes at the K, L, and P Reactor Areas

Flux	K Area	L Area	P Area
Mass Inflow to Seepage Basin (Ci/yr)	4030	4030	4030
Radioactive Decay (Ci/yr)	2490	1320	4020
Mass Outflow to Surface Water (Ci/yr)	1540	2710	10
Contaminated Ground Water Discharge to Surface Water (ft^3/day)	68,500	9530	30,000
Average Ground Water Discharge Concentration of Tritium (pCi/ml)	2200	28,000	32

remaining tritium (33%) leaves the subsurface system through radioactive decay. At the K reactor site, some of the tritium (38%) eventually leaves the ground water system through surface water discharge to Indian Grave Branch Creek, but most of the tritium (62%) is lost through radioactive decay. Model simulations indicate that tritium reaches Indian Grave Branch Creek within 6 years after release to the K reactor seepage basin. At the P reactor site, very little tritium (0.2%) is lost through surface water discharge to Steel Creek, while the majority (99.8%) is eventually lost through radioactive decay. Model simulations indicate that what little tritium does discharge into Steel Creek reaches the creek within 30 years after discharge to the P reactor seepage basin. The primary reason most of the tritium eventually leaves the ground water system through radioactive decay instead of surface water discharge at the K and P reactor sites, is because most of the tritium migrates downward before it moves horizontally to a surface water discharge feature at these sites. At the L reactor site, however, horizontal ground water velocities are greater than at the K and P reactor sites, and the surface water discharge feature (L-Lake) is closer to the seepage basin, thus allowing more tritium to exit the ground water system through surface water discharge.

Based on tritium concentration measurements for surface waters at the SRS in 1988, significant dilution of tritium entering surface waters at the reactor sites occurs (4). Environmental monitoring at the Savannah River Site in 1988 indicates average tritium concentrations in Indian Grave Branch Creek were about 6,500 pCi/ml which is consistent with the ground water simulations of transport from the K reactor seepage basin. However, this stream flows to the more prolific Pen Branch Creek where tritium concentrations dropped to an average of 2.3 pCi/ml. Monitoring of Steel Creek upstream from L-Lake is also consistent with simulations of transport from the P reactor basins as average recent tritium concentrations are about 91 pCi/ml. Significant dilution occurs at L-Lake as evidenced by the decrease of 1988 tritium concentrations downstream of L-Lake in Steel Creek. The tritium concentrations at this location averaged about 2.7 pCi/ml. L reactor has not operated at significant power levels for over 20 years, so it is difficult to determine its historical impact on surface waters. All of these surface water features discharge to the Savannah River, where the 1988 tritium concentrations downstream averaged about 3.4 pCi/ml. Upstream from the SRS, the average tritium concentration in the Savannah River in 1988 was about 0.27 pCi/ml.

SUMMARY AND CONCLUSIONS

The continued release of radionuclides to the K, L, and P reactor seepage basins at the Savannah River Plant will impact ground water and surface waters at these three nuclear reactor sites. Based on the results of this three-dimensional ground water flow and contaminant transport study, the greatest environmental impacts will occur with the release of tritium. The information obtained from this modeling study was used to prepare an Environmental Information Document for the DOE. The DOE considered all information contained in the Environmental Information Document and developed a condensed Environmental Impact Statement. As required by NEPA, a formal decision regarding the management of reactor disassembly basin discharge water must be made by the DOE. In making this decision, the DOE must consider the ground water impact from radionuclide discharge to the seepage basins, and that environmental regulations no longer allow the use of unlined seepage basins for waste disposal, but that there is not an economically feasible separation process for tritiated water.

REFERENCES

1. J.S. HASELOW, V. PRICE, D.E. STEPHENSON, H.W. BLEDSOE, and B.B. LOONEY, "Reactor Operation Environmental Information Document, Volume 1, Geology, Seismology, and Subsurface Hydrology," WSRC-RP-89-0815, Westinghouse Savannah River Company, Aiken, South Carolina (1989).
2. G.E. SIPLE, "Geology and Ground Water of the Savannah River Plant and Vicinity, South Carolina," United States Geological Survey Water Supply Paper 1841 (1967).

3. B.B. LOONEY, M.W. GRANT, and C.M. KING, "Estimation of Geochemical Parameters for Assessing Subsurface Transport at the Savannah River Plant," DPST-85-904, E. I. duPont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina (1987).

4. H.A. DAVIS, D.K. MARTIN, and J.L. TODD, "Savannah River Site Environmental Report of 1988," WSRC-RP-89-59-1, Westinghouse Savannah River Company, Aiken, South Carolina (1989).