

Appendix 2

**Final Report to Citizens Advisory Board Concerning
Corrective Measures to Remediate the Old Radioactive Waste
Burial Ground**

**by Independent Scientific Peer Review Team
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Task Order No. GA0050

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FINAL REPORT TO CITIZEN ADVISORY BOARD
CONCERNING CORRECTIVE MEASURES TO REMEDIATE
THE OLD RADIOACTIVE WASTE BURIAL GROUND

BY

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Executive Summary

On December 1, 1999, the Education, Research and Development Association of Georgia Universities (ERDA) signed a contract with the Westinghouse Savannah River Company (WSRC) to provide an independent scientific peer review (ISPR) of the human health consequences to individuals at several locations in Four Mile Branch and the Savannah River. Specifically two areas of interest were requested: (1) provide an estimate of surface water contamination for Constituents of Interest (COIs) from waste buried in the Old Radioactive Waste Burial Ground (ORWBG); and (2) determine health risk at various locations impacted by the surface contamination originating in ORWBG and flowing to Four Mile Branch (FMB).

Initially a Gaussian-source plume model was employed. This model was found inappropriate because the burial ground size was large and the seep line was relatively too close to the ORWBG.

The model that was finally adopted comprised a burial ground that had a length of 1,000 feet, a width of 3,500 feet, and a depth of 16 feet. The burial ground was situated over a vadose zone 35 feet thick. Below the vadose zone was a 22 foot-thick aquifer flowing at 160 feet per year. The model accounts for aquifer transport including advection, dispersion, solute partitioning to aquifer solids and liquids, and radioactive decay. The model calculates a vertically averaged concentration over the plume thickness as a function of time and location. In essence the problem was reduced to a horizontal-plane-source with the contamination being carried in the direction of the aquifer flow.

The model was calibrated with the amount of tritium measured each year that is transported to FMB from ORWBG dating back to 1968. The calculated results and measurements are in good agreement and indicate that peak release of tritium to FMB from ORWBG occurred in 1989. The calculated release of tritium to FMB show that a person during the year 2000 drinking 2.2 liters per day from water collected at the seep line which feeds FMB would receive a committed effective dose equivalent (CEDE)¹ of 51 mrem per year. The dose rate at sampling point FM-6 for the same year drops to 3.4 mrem/year. This drop in dose rate is due to only the increase in the volume of water that flows through FMB at point FM-6. Distance from the seep line to FM-6 is not responsible for the drop. The same calculations indicate that by 2007 the concentration of tritium at the seep line would go below the EPA limit for drinking water of 20,000 pCi/L.

¹ The committed effective dose equivalent (CEDE) may be defined as the life-time effective dose impacted to all tissues and organs from an intake of a known amount of radioactive material.

The same model as calibrated for tritium was used for the other fifteen COIs which were deemed of importance in the CMS/FS study. The results show that the highest dose rate at the seep line comes from I¹²⁹ (9.41 mrem) and that would occur two hundred years after 1952 (2152).

Neptunium-237 and C¹⁴ produced yearly dose rates of 6.18 and 4.96 mrem/year respectively at peak concentration. Of course, peak concentrations occur at different times for different nuclides. For example for Np²³⁷ and for C¹⁴ peak concentration occur 800 years after 1952 (2752). For plutonium peak concentration occurs some 80,000 years after 1952 and for Tc⁹⁹ peak concentration occurs in 2003.

For non-radioactive COIs such as Cd, Hg, Pb and VOCs, the calculated values are relatively close to but all remained below EPA limits. For example, the EPA limit for mercury is 2 g/L. The calculated concentration at the seep line is 1.4 g/L. For VOCs the EPA limit is 0.1 mg/L. The calculated concentration is 0.093 mg/L. The EPA limit/calculated values for Cd and Pb are 5.0/0.33 g/L and 15.0/0.63 g/L respectively. Even though ISPR members believe that the calculations yielded conservative values, i.e. calculated values should be higher than measured values, nevertheless to be more confident in the validity of the model to predict accurate results, it would be necessary to calibrate the model for each nuclide.

A key parameter in the model is the partition coefficient, K_d^2 . Calculated results are highly dependent on the value K_d used for each nuclide. One straightforward method for calibration is to use measured values of the pollutants at specific locations with known flow rates as a function of time, as was done for tritium. Calibration for each nuclide would generate confidence in the results obtained and would render decision-making on environmental remediation much easier with perhaps significant savings in cost.

Finally based on the analyses detailed in this report, the ISPR members unanimously make the following recommendations:

(1) Tritium is the major contributor to health risk at the seep line of FMB, contributing 51 mrem for drinking one's entire water needs for a whole year taken from the seep line in year 2000. However, since the seep line is within government-controlled access areas and since in 5-10 years³ the tritium concentration at the seep line is expected to decline to levels below EPA

² The partition coefficient, K_d , is defined as the ratio of the waste in solid form in units of Ci/Kg to the concentration of the waste in the liquid in units of Ci/L.

³ The range of 5-10 years is included to allow for possible error in the calculations. The calculated date when the concentration of tritium dips below 20,000 pCi/year is 2007.

requirements (i.e. < 20,000 pCi/L), no corrective action of any kind to remediate the tritium concentration in FMB is recommended.

(2) In order to extend the recommendation concerning corrective action(s) to the other COIs, calibration of the model using measured concentration of each COI at known flow rates at specific points along FMB must be undertaken immediately. No measured data of COI nuclides, other than H³, was provided to the ISPR team for analysis and calibration. Additionally measured concentrations of constituents must be evaluated for consistency and place of origin. Remedial action may or may not be needed for COIs other than tritium. However, without the additional calibration, the ISPR team is not able to give a definite recommendation on the other COIs.

Introduction

On December 1, 1999, the Education, Research & Development Association of Georgia Universities (ERDA) signed a contract with the Westinghouse Savannah River Company to provide an independent scientific peer review of the human health consequences to individuals at several locations in Four Mile Branch and the Savannah River. Specifically two areas of interest were requested: (1) provide a simplified estimate of surface water stream concentration for constituents of interest (COIs) from waste buried in the Old Radioactive Waste Burial Ground (ORWBG); and (2) use the concentrations to determine the potential incremental health risk to various receptors at several locations down the path of surface water flow, that include several locations in the Savannah River.

The Old Radioactive Waste Burial Ground (ORWBG) at the Savannah River Site (SRS) consists of three areas that operated from 1952 through 1974 (see map in Appendix). The original, central portion is approximately 36 acres in size and operated from 1952 through the early 1960's. The east portion is 15 acres in size and received waste from 1961-72, while the west portion is 26 acres in size and operated from 1961-74. Tritium disposal in the west portion occurred between 1961 and 1972.

Tritium disposal occurred in three major waste forms: bulk waste, spent melts and reactive beds. Tritium in bulk waste (i.e. job control waste, waste oils and mercury, and used equipment and components) is readily leachable while tritium in spent melts (i.e. lithium-aluminum alloy that was heated to remove most of the tritium) is not readily released to infiltrating water. Reactive beds such as magnesium and other beds were used to convert tritiated water to elemental tritium and to concentrate the tritium. Most of the spent melts were disposed of in the east landfill, while tritium bulk waste was primarily disposed of in the west landfill. (Source: WSRC-RP-97, Rev. 1.1, October, 1998)

In addition to tritium the other radioactive Constituents of Interest (COIs) included in this report are cesium-137 (Cs^{137}), plutonium-238 (Pu^{238}), plutonium-239 (Pu^{239}), strontium-90 (Sr^{90}), uranium-235 (U^{235}), uranium-238 (U^{238}), carbon-14 (C^{14}), cobalt-60 (Co^{60}), technetium-99 (Tc^{99}), Iodine-129 (I^{129}), and neptunium-237 (Np^{237}). Non-radioactive COIs included are cadmium (Cd), mercury (Hg), lead (Pb), and VOCs.

The selected locations of study that were specified in the scope of work were (1) the seep line of Four-Mile Branch, (2) Road C, (3) FM-6, (4) across from the Vogle Plant, (5) the highway 301 bridge, and (6) RM-60.9, approximately 20-30 miles upstream from Beaufort-Jasper. During the study, it was discovered that no data are available for the area across from the Vogle plant.

The Education, Research & Development Association of Georgia Universities (ERDA) is pleased to submit this final report prepared by the Independent Scientific Peer Review Panel describing a mathematical model of transport of pollutants from the Old Radioactive Waste Burial Ground to the Four Mile Branch Creek. The model was developed by one of the panel members (Dr. Randall J. Charbeneau) and was used to calculate the concentrations of constituents of interest (COIs) in groundwater beneath and downgradient of the Burial Ground, along the seeps to Four Mile Creek (FMC), and in the FMC water. The calculations are based on an inventory of COIs that was delivered to the ORWBG during its 22-year period of operations (1952–1974). Based on the constituent inventory that is present, the model calculates the release to the vadose zone and subsequent transport to groundwater flowing beneath the ORWBG.

In an earlier analysis we used a Gaussian-source plume model to describe aquifer transport, including advection, dispersion, solute partitioning to aquifer solids, dilution and radioactive decay. Calibration of the Gaussian-source plume model to this data lead to unrealistic parameter estimates that are believed to be associated with representation of the source geometry. The earlier model assumed that the source may be represented by a linear boundary of finite width transverse to the direction of flow. It is difficult to place this boundary at a fixed distance from FMC, which also must be represented as a linear boundary. The primary difficulty is that the length of the source (the landfill) in the direction of groundwater flow is significant compared to the distance from the source to the receptor (FMC and its drainage seeps).

Subsequent to that analysis we received data of measured tritium mass flux to FMC (1). An alternative model was formulated and developed that incorporates the finite size of the landfill both in length and width. This is a Horizontal-Plane-Source model (HPS) that describes aquifer transport, including advection, dispersion, solute partitioning to aquifer solids, and radioactive decay. Creek water concentration is calculated by dilution of the mass flux to the creek with the creek discharge. Dose rate calculations to a person drinking 2.2 liters per day from Four Mile Creek for a whole year are included for all the radioactive COIs that make it through the vadose zone.

A sketch of the geometrical relationship of the Old Radioactive Waste Burial Ground (henceforth referred to as burial facility or simply facility) to the vadose zone and the aquifer beneath it is shown in Figure 1 (taken from reference 2). The Burial Facility is shown occupying the volume of a rectangular box. Leachate from the facility moves downward through the vadose zone and enters the aquifer within a rectangular area. The contaminant penetrates the aquifer and is carried down gradient towards an exposure location, which is shown as a well in this figure. In the model used herein, the contaminant plume is captured by FMC and mixes with the creek water. Dose calculations are based on the concentrations at the seep line and in creek

water. The following sections describe the inventory model, the model for leachate generation and vadose zone transport, the Horizontal-Plane-source plume model for aquifer transport, and the mixing model that provides estimates of COI concentrations in the creek.

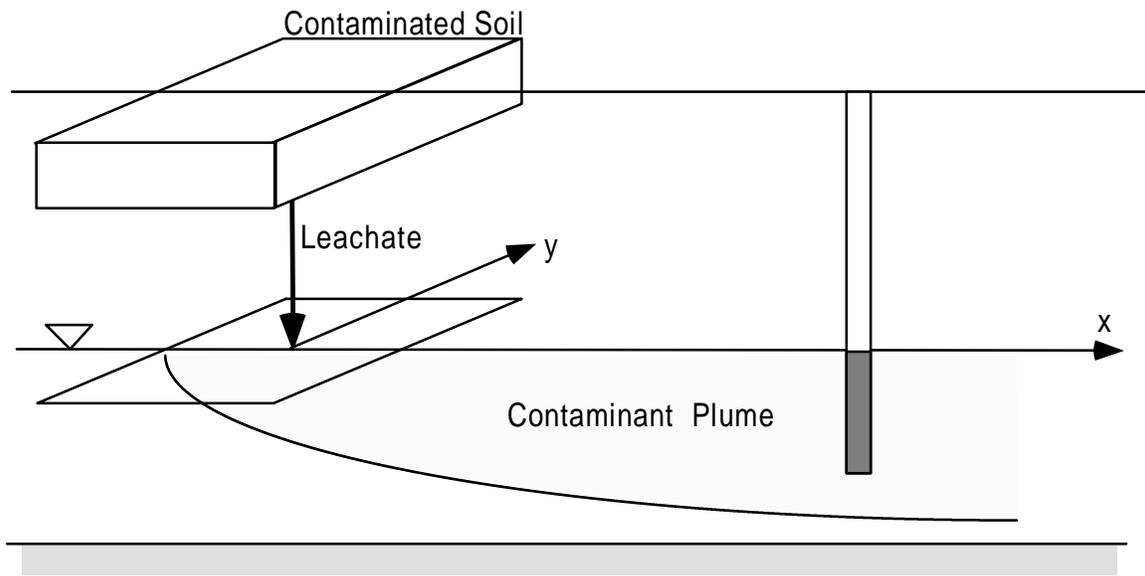


Figure 1. Groundwater Exposures from the ORWBG

Model for the COI Inventory within the ORWBG

Historical records provide only very general data that may be used to estimate the amounts of the various COIs that were disposed of within the ORWBG. These data consist of estimates of the total inventory I_o (Ci) that was delivered to the facility during its period of operation Δt_o (22 years). For this analysis it is assumed that the inventory delivery rate \dot{I} (Ci/yr) increased linearly through time during a ramping period of duration Δt_R , and then remained constant at a rate \dot{I}_m for the remaining duration of operations $\Delta t_R < t < \Delta t_o$. This assumed delivery-rate schedule is shown in Figure 2.

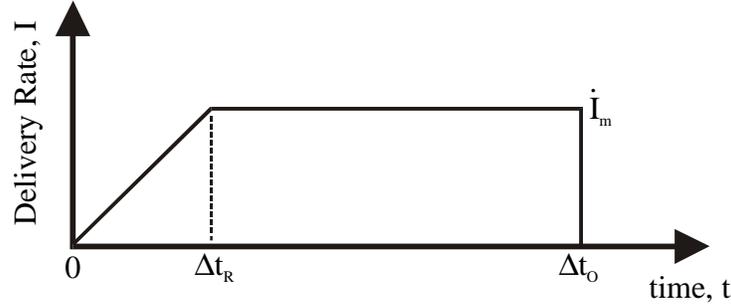


Figure 2. Assumed Inventory Delivery-Rate Schedule

Balance considerations show that $I_o = \frac{1}{2} \dot{I}_m \Delta t_R + \dot{I}_m (\Delta t_O - \Delta t_R)$, and thus

$$\dot{I}_m = \frac{I_o}{\Delta t_O - \frac{1}{2} \Delta t_R} \quad (1)$$

Equation (1) relates the maximum COI disposal rate to the total delivered inventory, the duration of facility operation, and the duration of the ramping period.

During the period of operation (1952-74) and following post-closure period, the nuclide inventory is lost from the ORWBG through radioactive decay and leaching. The COI leaching model is based on movement of water that infiltrates through the facility at a rate q_f (ft/yr) contacting a fraction f_L of the nuclide inventory, and transporting the COI from the facility as leachate. The facility waste has a volumetric water content θ_{waste} and bulk density ρ_{waste} (kg/L), and the COI partitions between the waste solids and water with partition coefficient K_d^w (L/kg). L_{waste} is the vertical thickness of the disposed waste in the Burial Ground. The COI release rate \dot{m}_f (Ci/yr) as leachate from the ORWBG that has an inventory $I(t)$ in curies at time t is calculated from

$$\dot{m}_f(t) = \lambda_L I(t) \quad (2)$$

In equation (2), the leach-rate constant λ_L is calculated from

$$\lambda_L = \frac{q_f f_L}{(\rho_{waste} + r_{waste} K_d^w) L_{waste}} \quad (3)$$

In equation (3), the variable q_f is the average annual infiltration rate, which is the average annual rainfall less subtractions that include average runoff and evapotranspiration. The factor f_L is dimensionless and accounts for the fraction of waste in contact with water and hence accounts for the mass transfer from waste to percolating water. For simplicity and because other data are not available, a value $f_L = 1.0$ is assumed for all simulations.

The partition coefficient K_d is defined as the ration of the concentration of the waste in solid form in units of Ci/Kg to the concentration of the waste in the liquid in units of Ci/L.

$$K_d = \frac{C_{waste} (Ci / Kg)}{C_{waste} (Ci / L)}$$

The COI inventory at time t , $I(t)$, is found by solving the following series of continuity equations that relate the change in inventory to its delivery rate and its loss rate due to radioactive decay and leaching. During the period of increasing delivery rate (ramping period), $0 < t < \Delta t_R$, the balance equation is

$$\frac{dI}{dt} = \dot{I}_m \frac{t}{\Delta t_R} - I_f I \quad ; \quad I(0) = 0 \quad (4)$$

In equation (4), the facility loss-rate I_f includes losses from radioactive decay and leaching, $\lambda_f = \lambda_D + \lambda_L$, where λ_D is the isotopic decay constant. Solving equation (4) gives the inventory

$$I(t) = \frac{\dot{I}_m}{\Delta t_R \lambda_f^2} [\lambda_f t - (1 - e^{-\lambda_f t})] \quad ; \quad 0 \leq t \leq \Delta t_R \quad (5)$$

During the subsequent period of operation with a constant delivery rate, $\Delta t_R < t < \Delta t_O$, the inventory balance equation is

$$\frac{dI}{dt} = \dot{I}_m - \lambda_f I \quad ; \quad I(\Delta t_R) = \frac{\dot{I}_m}{\lambda_f} - \frac{\dot{I}_m}{\Delta t_R \lambda_f^2} (1 - e^{-\lambda_f \Delta t_R}) \quad (6)$$

Solving equation (6) gives

$$I(t) = \frac{\dot{I}_m}{\lambda_f} - \frac{\dot{I}_m}{\Delta t_R \lambda_f^2} (e^{\lambda_f \Delta t_R} - 1) e^{-\lambda_f t} \quad ; \quad \Delta t_R \leq t \leq \Delta t_O \quad (7)$$

The maximum inventory I_{max} occurs at $t = \Delta t_O$.

$$I_{max} = \frac{\dot{I}_m}{\lambda_f} - \frac{\dot{I}_m}{\Delta t_R \lambda_f^2} (e^{\lambda_f \Delta t_R} - 1) e^{-\lambda_f \Delta t_O} \quad (8)$$

Following closure of the facility, there is no inventory delivery rate, and the inventory decreases due to both leaching and decay, resulting in the inventory model

$$I(t) = I_{max} e^{-\lambda_f (t - \Delta t_O)} \quad ; \quad t \geq \Delta t_O \quad (9)$$

Equations (5), (7) and (9) provide the model for determining the COI inventory through time.

Leachate Generation and Vadose Zone Transport

The previous section presents a mathematical model for predicting the ORWBG facility inventory of a COI as a function of time. Estimates of groundwater and creek concentrations of various COIs require calculation of leachate generation from the facility and vadose zone transport to groundwater flowing beneath the facility. Equations (2) and (3) provide the model for leachate generation. According to equation (2) the leachate generation rate (Ci/yr) is proportional to the facility inventory. The leach-rate constant is determined by the values of the variables in Eq(3) that characterize the facility.

A simple (and appropriate) model for vadose zone transport is to assume advection transport based on the facility infiltration rate q_f , the vadose zone volumetric water content θ_{vz} , and the thickness of the vadose zone L_{vz} . The nuclide travel time through the vadose zone is calculated from (see reference 2, Equation 9.6.11)

$$\Delta t_{vz} = \frac{(\theta_{vz} + \rho_b K_d) L_{vz}}{q_f} \quad (10)$$

In equation (10), ρ_b is the soil bulk density and K_d is the soil-water partition coefficient for the nuclide in the vadose zone.

The leachate supply-rate to the water table (Ci/yr) is calculated from

$$\dot{m}_{wt}(t) = \lambda_L I(t - \Delta t_{vz}) e^{-\lambda_D \Delta t_{vz}} \quad (11)$$

Comparison of equations (2) and (11) show that the leachate supply-rate to the water table is equal to the leachate generation rate at an earlier time, multiplied by a factor that accounts for losses due to decay during the time of vadose zone transport.

Horizontal-Plane-Source Plume Groundwater Transport Model

The Horizontal-plane-source (HPS) plume model allows for representation of one-dimensional flow, longitudinal and transverse horizontal and vertical dispersion, linear sorption, isotopic radioactive decay, finite-size source zone, and a time-variable source release. Figure 1 shows the geometry of the model used. The model calculates the vertically averaged concentration $c(x,y,t)$ at any location and time. The model is setup with the direction of flow corresponding to the x-axis. The aquifer transport equation may be developed using mass conservation principles (see reference 2), and is given by

$$R \frac{\partial c}{\partial t} + v \frac{\partial c}{\partial x} + \lambda_D c = D_{xx} \frac{\partial^2 c}{\partial x^2} + D_{yy} \frac{\partial^2 c}{\partial y^2} \quad (12)$$

In equation (12), R is the retardation factor ($R = 1 + \rho_b K_d / n$, where n is the aquifer porosity), which may be interpreted as the ratio of the velocity of groundwater to the average solute velocity. The parameter v is the aquifer seepage velocity that is assumed to occur in the x-direction. The parameters D_{xx} and D_{yy} are the longitudinal and transverse dispersion coefficients, and are equal to the product of the longitudinal and transverse dispersivities and the seepage velocity, respectively (i.e., $D_{xx} = a_L v$; $D_{yy} = a_T v$, where a_L and a_T are the longitudinal and transverse dispersivity). The concentration $c(x,y,t)$ in equation (12) represents the vertically average concentration over the aquifer thickness H .

For this model the source is represented by an initial value problem where a contaminant of unit mass is initially uniformly distributed within a box of length L in the direction of groundwater flow, width W transverse to this direction, and thickness H . This corresponds to an

instantaneous release or “spill” of unit mass. The mathematical solution for this spill model is given by (see reference 2, Section 8.7.6)

$$c_s(x, y, t) = \frac{1}{4nRHLW} \left\{ \operatorname{erf} \left(\frac{x - v't + L/2}{\sqrt{4D_{xx}' t}} \right) - \operatorname{erf} \left(\frac{x - v't - L/2}{\sqrt{4D_{xx}' t}} \right) \right\} \cdot \left\{ \operatorname{erf} \left(\frac{y + W/2}{\sqrt{4D_{yy}' t}} \right) - \operatorname{erf} \left(\frac{y - W/2}{\sqrt{4D_{yy}' t}} \right) \right\} \cdot e^{-\lambda_p t} \quad (13)$$

In equation (13), v' is the retarded seepage velocity ($v' = v/R$) and D_{ii}' is the retarded dispersion coefficient.

Equation (13) gives the concentration at location (x,y) and time t due to a release of unit mass uniformly over a rectangle of length L and width W centered at the origin $(x=0,y=0)$ at time zero. The solution for the contaminant plume corresponding to the time-variable release rate from the ORWBG given by Equation (11) is found through convolution of Equations (11) and (13):

$$c_p(x, y, t) = \int_0^t \dot{m}_{wt}(\tau) c_s(x, y, t - \tau) d\tau \quad (14)$$

Flux to Four Mile Creek and Creek Concentration

For this model representation, the Four Mile Creek is treated as a linear boundary at a distance $x = X_c$ from the middle of the ORWBG. It is assumed that all of the nuclide activity (and COI mass) that passes this boundary enters the creek system. This transport rate (Ci/yr) is calculated by integrating the advection flux crossing the linear boundary representing the creek. Due to symmetry this is given by

$$\dot{m}_c(t) = 2 n v H \int_0^{y_{max}} c_p(X_c, y, t) dy \quad (15)$$

If Q_c is the average discharge (L^3/year) in Four Mile Creek, then the creek water concentration immediately downstream of the region of seepage from the ORWBG is calculated from

$$c_c(t) = \frac{\dot{m}_c(t)}{Q_c} \quad (16)$$

Equations (1) through (16) provide the mathematical model for estimating the concentrations and mass flux of COIs in the aquifer beneath the ORWBG and in FMC.

Model Implementation

The theoretical model was implemented through an Excel workbook. The convolution integral of Equation (14) and the quadrature of Equation (15) are evaluated using a module that is written to implement Simpson's rule with user selected convergence criteria. In particular, since Equation (15) utilizes the solution from Equation (14), calculation of the mass flux to FMC and the corresponding creek concentration requires a double quadrature using Simpson's rule.

The Excel solution workbook has one worksheet requiring user-supplied data (see Figure 3). The required data are highlighted in gray (blue on the computer worksheet). The data entry occurs in blocks. The first block requires *inventory* and *nuclide decay* data (the total delivered inventory I_0 , the duration of inventory delivery rate ramping Δt_R , duration of facility operation t_0 , and the nuclide half-life $T_{1/2}$).

The second block requires *nuclide leaching* parameters corresponding to the facility infiltration rate q_f , leaching factor f_L , facility waste water content w_{waste} and bulk density ρ_{waste} , nuclide-waste soil-water partition coefficient K_d^w , and waste thickness L_{waste} . Because other information is not available, the value of K_d^w was assumed to be the same as the aquifer K_d value; that is, no credit is taken for an advanced waste form. This assumption is arbitrary and may be adjusted as better knowledge of the waste form is gained.

The third block (*Vadose Zone*) requires the vadose zone thickness beneath the burial grounds L_{vz} and the water content in the vadose zone w_{vz} . This data is used with the inventory and leaching data to calculate the nuclide flux to the water table following opening of the ORWBG (1952).

The fourth block (*Aquifer Parameters*) requires groundwater transport parameters including the aquifer Darcy velocity, q_x , the porosity n , the longitudinal and transverse dispersivities a_L and a_T , the length L and width W of the ORWBG source zone, the plume thickness H , and the aquifer bulk density ρ_b and distribution coefficient K_d . The aquifer seepage velocity v is calculated from values of q_x and n .

The remaining data include the *Creek Discharge* Q_c and the quadrature *Integral Convergence Criteria*. The parameters ϵ_1 and ϵ_2 determine the convergence for Simpson's algorithm for Equations (14) and (15), respectively.

Delivered Inventory and Nuclide Decay

I_0 (Ci)	1.48E+03	λ_D (yr ⁻¹)	0.0000
Δt_R (yr)	0.05	I_m (Ci/yr)	76
Δt_0 (yr)	22		
$T_{1/2}$ (yr)	2.44E+04		

Summary

Total Flux to Water Table (Ci) =	5.39E+02
Total Flux to Creek (Ci) =	1.07E+02
Maximum Flux to Water Table (Ci/yr) =	6.09E-02
Maximum Flux to Creek (Ci/yr) =	2.41E-03
Maximum Creek Concentration (pCi/L) =	3.15E-01

Leaching

q_r (ft/yr)	1.25	λ_L (yr ⁻¹)	8.875E-05
f_l	1.00	I_{max} (Ci)	1473
θ_{waste}	0.25		
ρ_{waste} (kg/L)	1.6		
K_d^w (L/kg)	550		
L_{waste} (ft)	16		

Vadose Zone

L_{vz} (ft)	35	Δt_{vz} (yr)	24645.6
θ_{vz}	0.2		

Aquifer Parameters

q_s (ft/yr)	40	R	3521
n	0.25	D_{xx}' (ft ² /yr)	6.1346208
a_L (ft)	135	D_{yy}' (ft ² /yr)	1
a_T (ft)	17	v_x' (ft/yr)	0.045
L (ft)	1000	c_0/M (ft ⁻³)	3.69E-12
W (ft)	3500		
H (ft)	22		
ρ_b (kg/L)	1.6		
K_d (L/kg)	550		

Creek Discharge

Q_c (m ³ /yr)	7.80E+06
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Integral Convergence Criteria

ϵ_1	0.01	Local Concentration
ϵ_2	0.1	Creek Flux

Figure 3. Data Entry Form for Model

Four separate worksheets show the results from the model calculations. The *Inventory* sheet, which follows the *Data* worksheet, shows the landfill nuclide inventory and mass flux to the water table through a user-specified time interval. The *Profile* worksheet shows the plume concentration distribution along a user-specified range of plume length (x_{\min} to x_{\max}) at a selected transverse location (y -coordinate) and time. The *XSection* worksheet shows the concentration distribution across the plume cross-section at a given user-specified x -location and time for the range $-y_{\max} < y < y_{\max}$. This worksheet is used to verify that the y -range in the creek-flux calculation is appropriate. The last worksheet, *Flux*, presents the calculations for the constituent flux to the creek and the resulting creek concentration, where the user selects the distance to the linear-creek-boundary X_c and time range.

For the non-radioactive COIs, i.e. cadmium, mercury, lead, and VOCS, the input is in kilograms quantities rather than curies. Consequently the output unit is also kg instead of what is labeled as curies. The concentration to the water table and the creek should be in units of pkg/L, or ng/L (nanograms per liter) instead of pCi/L.

Calibration of Tritium in FMC

A. Assumptions

For purposes of model calibration, an assumption was made that the west landfill is primarily responsible for tritium leachate to Four Mile Branch Creek (FMC). The measured mass flux (Ci/yr) in the FMC was used to calibrate the model. Physical parameters, primarily the source term, were adjusted in order to produce the observed timing of the release and mass flux to the creek. Only the west landfill was modeled over the twelve-year period 1961-72. Approximately 2M Ci of tritium were disposed of prior to this time period (1952-60), and not all of the tritium that was disposed of during this period is in a leachable form. (Source: WSRC-RP-97-00127, Rev. 1.1, PE-6, Oct., 1998) The effective distance from the center of the west landfill to the nearest point of FMC is assumed to be 2600 ft, and the burial ground is assumed to have a length $L = 1100$ ft. in the direction of groundwater flow towards FMC, a width $W = 1000$ ft., and a depth of 16 ft.

B. Calculations vs. Measured Results

Figure 4 shows the measured tritium flux to FMC along with the calculated results. The solid line represents calculated values. The diamonds represent measured data, taken from reference 1. The calculation gives a flux of 6800 Ci/yr in 1990, which compares with a measured tritium flux to FMC of 6420 Ci/yr in 1991. The measured and calculated fluxes in 1998 are 3490 and 3600

Ci/yr, respectively. With an average creek discharge of 7,800,000 m³/yr at a point below the seep line, this corresponds to a calculated creek concentration of 430,000 pCi/L.

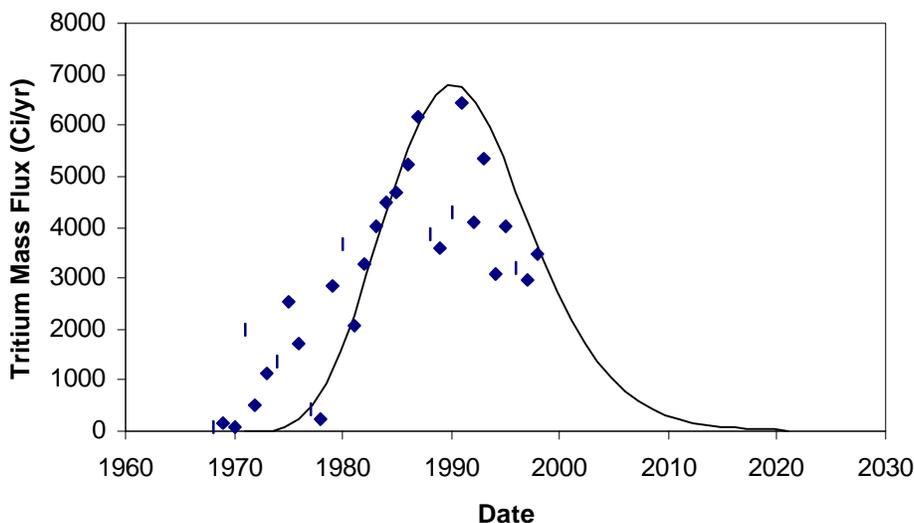


Figure 4. Comparison of Observed Data and Model Simulation For Tritium in Four Mile Branch Creek

Measured flow rates and tritium concentration at FM-6 for 1997, 1998 and 1999 were as follows:

Table 1. Measured Flow Rates and Concentration at FM-6 for 1997 – 1999		
	Flow Rate m ³ /year	Concentration pCi/L
FM-6 (1997)	2.28 x 10 ⁷	2.16 x 10 ⁵
FM-6 (1998)	3.76 x 10 ⁷	1.86 x 10 ⁵
FM-6 (1999)	1.81 x 10 ⁷	1.94x 10 ⁵
Three Year Average	2.62 x 10 ⁷	1.98 x 10 ⁵
Source: Data supplied by Peter Fledderman of WSRC. ISPR members are grateful for Mr. Fledderman's assistance.		

$$\begin{aligned} \text{Aver Ci/year} &= \frac{2.62 \times 10^7 \text{ meter}^3}{\text{year}} \times \frac{1000 \text{ L}}{\text{m}^3} \times 2.02 \times 10^5 \frac{\text{pCi}}{\text{L}} \\ &= 5.187 \times 10^{15} \frac{\text{pCi}}{\text{year}} \end{aligned}$$

or 5,187 Ci/year

According to data supplied by Lee Poe (CAB) the fraction of total tritium that reaches FM-6 that originated at ORWBG is 60% of the total. Consequently ORWBG contribution to the total flux at FM-6 is

$$0.6 \times 5,187 \frac{\text{Ci}}{\text{year}} = 3,112 \frac{\text{Ci}}{\text{year}}.$$

This number should be compared with a calculated value of 2,710 Ci/year for 1999.

The basic input data that were used in the calculations shown in Figure 4 are presented in Table 2. It is assumed that the inventory was delivered at a uniform rate over the 12-year period (1961-72, inclusive) and Δt_R is set to a small number (0.05 yrs). Within the vadose zone and aquifer, tritium is assumed to be present as tritiated water, and its partition function is set to zero ($K_d = K_d^w = 0.0$). The aquifer volume flux (Darcy velocity) and effective porosity result in a seepage velocity (average linear velocity of groundwater flow) of 160 ft/yr. Dispersion parameters are estimated using average values from the formulation presented in background documents for EPA's Composite Model for Landfills (reference 2, Eq. 8.5.9). Based on a distance of 2100 ft from the down gradient edge of the landfill to the receptor, the estimated dispersivities are $a_L = 135$ ft, $a_T = 17$ ft, and $a_v = 0.85$ ft. Furthermore, at the receptor the aquifer is assumed to be vertically mixed (see Eq. 8.7.33c, reference 2). A two-dimensional model formulation was used, as presented in Eq. 13.

The data in Table 2 determine the timing of the tritium flux to FMC. The inventory that is available for leaching is determined by adjusting the total delivered inventory, I_0 , to match the peak observed flux to FMC, resulting in a tritium leaching-inventory delivered to the west burial ground of 475,000 Ci.

Table 2. Basic Data Used in Tritium Calibration Simulation

<i>Operational Data</i>	
Inventory delivery ramping time, Δt_R	0.05 years
ORWBG duration of operations, Δt_O	12 years
<i>Leaching and Waste Data</i>	
Facility infiltration rate, q_f	1.25 ft/yr
Leaching fraction, f_L	1.0
Volumetric water content, θ_{waste}	0.25
Bulk density, ρ_{waste}	1.6 kg/L
Thickness, L_{waste}	16 ft
<i>Vadose Zone Data</i>	
Thickness, L_{vz}	35 ft
Volumetric water content, θ_{vz}	0.20
<i>Aquifer Data</i>	
Darcy velocity, q_x	40 ft/yr
Effective Porosity, n	0.25
Longitudinal dispersivity, a_L	135 ft
Transverse dispersivity, a_T	17 ft
Plume thickness, H	22 ft
Bulk density, ρ_b	1.6 kg/L
<i>Creek Data</i>	
Distance from center of ORWBG, X_c	2600 ft
Discharge, Q_c	$7.8(10^5) \text{ m}^3/\text{yr}$

The tritium “leaching-inventory” for the west landfill of the ORWBG is shown in Figure 5. While 475,000 Ci are delivered over the 12-year period, the maximum inventory in year twelve is 106,000 Ci because of decay (tritium half-life = 12.4 years). At any time, the release rate from the facility is equal to the product of the inventory and the leach-rate constant (see Eq. 2).

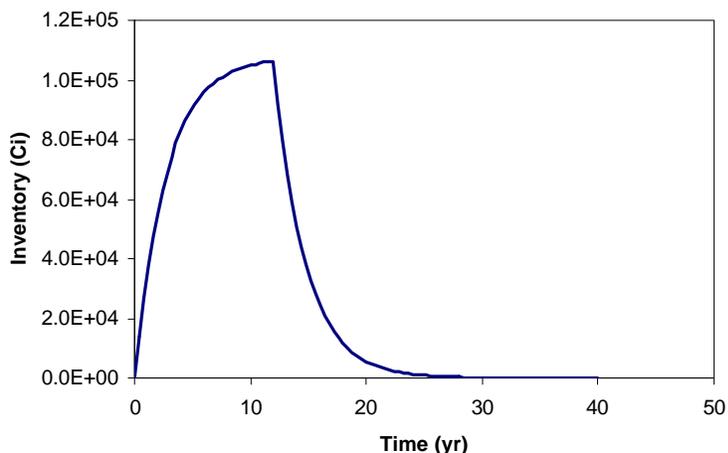


Figure 5. ORWBG Facility Inventory Estimates for Tritium (leaching inventory for the west landfill) beginning in 1961

The simulated tritium plume centerline concentration is shown in Figure 6 for the year 1998.

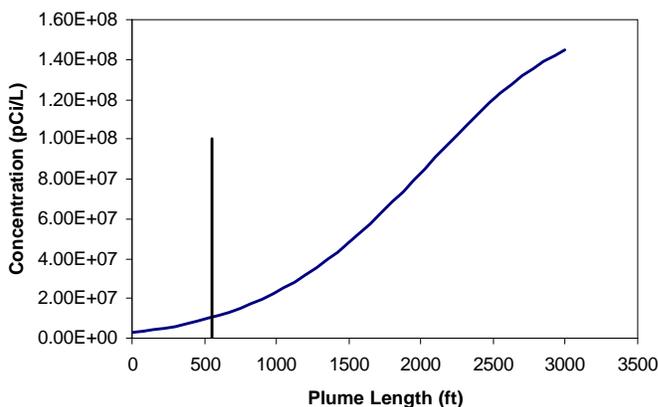


Figure 6.
Prediction of the 1998 Tritium Concentration
along the Plume Centerline

The vertical line marks the downgradient edge of the landfill. The concentration beneath the landfill is approximately $3(10^6)$ pCi/L, while the concentration at a distance of 1500 ft from the landfill exceeds 10^8 pCi/L.

The tritium plume cross-section concentration along FMC ($X_c = 2600$ ft) is shown in Figure 7. The effective plume width is approximately 3000 ft ($y_{max} = 1500$ ft), and this value is used in calculating the creek flux using Eq. 15.

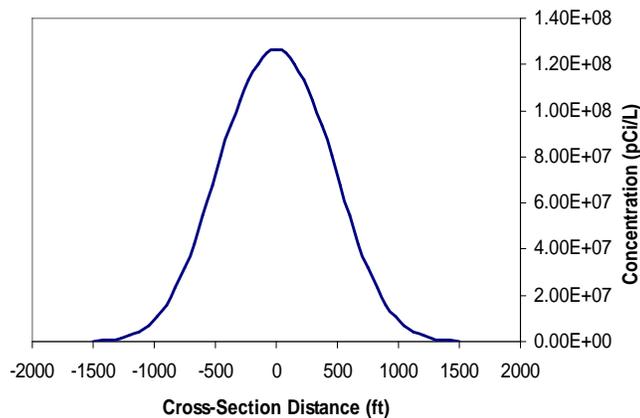


Figure 7. Predicted FMC Groundwater Seepage Concentration for Tritium in 1998

Another set of input parameters for the calculation of tritium transport to Four Mile Branch from ORWBG were used for purposes of comparison with the somewhat arbitrary adjustment of the source inventory used above in order to obtain agreement with measured tritium concentration in FMB. This set of input parameters comprise a tritium source inventory of 3,014,457 curies, a ramping period of $t_R = 5$ years and $t_O = 20$ years (1952-1972) based on data found in WSRC-RP-98, Rev. March 1999. The length L and width W of the facility were 1,000 and 35,000 feet. All other parameters are the same as reported in Table 2, and as used for other COIs that are described below. With this calculation the maximum flux to FM was 35,800 Ci/year occurring in 1987. The tritium concentration at FM-6 for 1998 was 3.2×10^5 pCi/L. This value exceeds the value of 1.16×10^5 pCi/L measured during 1998 after adjustment for ORWBG contribution. Measured concentration at FM-6 includes sources originating at places other than ORWBG. In fact it was estimated that only 60% of the total at FM-6 originates at ORWBG.

A third set of calculations for tritium transport to FMB from ORWBG were performed under identical conditions as the first set except that the source inventory was increased to 1,000,000 curies. The justification for the increase to one million curies is as follows:

- (1) The tritium plume in the water table seems to be limited to the southwest area of the burial ground (see WSRC-RP-97-00127, Rev. 1.1 Redline Oct. 1, 1998, Vol. 1., Fig. 23,

pp. 2-69). Note that no plume appears to flow from the center or the east side of ORWBG toward FMB.

- (2) The history of the tritium disposal in ORWBG, as cited in WSRC-RP-97-00127 Rev. 1.1, Redline Oct. 1, 1998 Vol. II, p. E-4, indicate that 2 million curies of tritium were buried prior to 1960 primarily in the central portions of ORWBG. Beginning in 1961 and ending 1972 one more million curies were buried in the west portion of ORWBG.

Complete input data and output results for this set of calculations are appended. The maximum tritium concentration in FMB at a flow rate of $7.8 \times 10^6 \text{ m}^3/\text{year}$ is $1.80 \times 10^6 \text{ pCi/L}$ and occurs in 1988. Since the 10 year average flow rate at the seepline is $2.22 \times 10^6 \text{ m}^3/\text{year}$. The corresponding maximum 1988 seepline concentration is

$$1.80 \times 10^6 \text{ pCi/L} \times \frac{7.8 \times 10^6}{2.22 \times 10^6} \quad \text{or}$$

$6.32 \times 10^6 \text{ pCi/L}$. For the year 2000, the seepline concentration drops to $2.34 \times 10^6 \text{ pCi/L}$ and at FM-6, the concentration drops to $1.59 \times 10^5 \text{ pCi/L}$. This compares with measured values of $1.94 \times 10^5 \text{ pCi/L}$. However, the contribution from ORWBG to the measured value is $0.6 \times 1.94 \times 10^5 \text{ pCi/L}$ or $1.16 \times 10^5 \text{ pCi/L}$. Consequently the calculation using 1 million curies over predict the concentration of tritium at FM-6 by about 37%.

Calculated Results for Other COIs

Measured concentrations were not available to the ISPR team for calibration of solute transport for other Constituents of Interest (COIs). Thus the hydrogeologic parameters that were used in the calibration of the tritium flux to FMC, were used for other COIs as well. However, the entire ORWBG landfills were considered. The ORWBG length was reduced from 1100 ft. to 1000 ft. to account for the fact that ORWBG is not a rectangle. The width used was 3500 ft. Furthermore, the entire disposed inventory was assumed to be leachable, and unless other data were available, it was assumed that $\Delta t_O = 22$ years with a 5-year ramping period ($\Delta t_R = 5$ years).

The plume width along FMC is shown in Figure 8 for Pu-239 at a time of 70,000 years after 1952. This figure shows that a value $y_{\text{max}} = 2600 \text{ ft}$ may be used for the FMC mass flux calculation, and this is assumed for other nuclides as well.

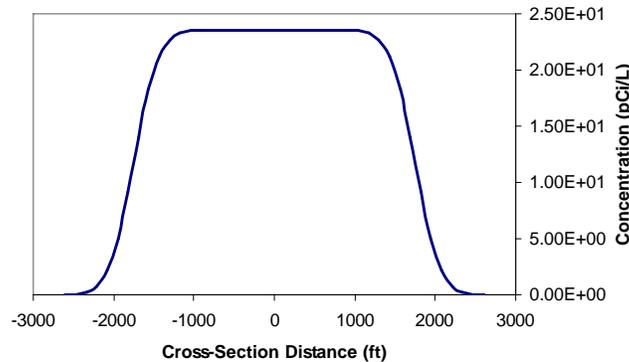


Figure 8. Predicted FMC Groundwater Seepage Concentration for Pu-239
With ORWBG Width of 3500 ft at Time 70,000 Years

The source inventory, half-life and distribution coefficients for the COIs are presented in Table 3, which also presents summary results for the calculation. K_d values are generally taken from Thibault et al. (4) for a sandy soil. For Pu^{238} , the travel time to the creek is very long, the same as for Pu^{239} , but because the half-life is relatively short (87 years) compared to 24360 years for Pu^{239} , no Pu^{238} gets to the creek. This result is governed primarily by the K_d value used, in this case 550 L/kg. Similar results are found for Cs^{137} , Sr^{90} , and Co^{60} . Furthermore, for plutonium and lead in FMC, the travel time exceeds 10,000 years.

VOCs are typically considered to be trichloroethylene (TCE). TCE and other chlorinated solvents are known to undergo biodegradation through metabolic pathways, where the enzymes that promote electron transfer are supplied during biodegradation of a primary substrate. Effective half-lives for cometabolism are uncertain, and a very conservative estimate of 100 years is assumed (5). The VOC partition coefficient is based on hydrophobic character and partitioning on soil organic carbon. A small soil organic carbon fraction of 0.1% was assumed.

Discussion

The peak concentration of tritium from the ORWBG in FMC was calculated to occur in 1989, which corresponds well with observed data since these data were used for calibration of the model. The peak H-3 concentration was about 870,000 pCi/L. The calculated current (year

1999) concentration at FM-6 is approximately 8.3×10^4 pCi/L, and the concentration from the ORWBG should drop to 2,000 pCi/L by 2015. Note that 2,000 pCi/L is 10 times lower than the EPA standard of 20,000 pCi/L which is predicted to occur in 2007. Site land controls prevent exposure to tritium through ingestion by drinking water from FMC, and this will continue for the time period during which tritium presents somewhat of a risk through subsurface transport pathways. The model predicts that the time of peak concentration for both Tc-99 and VOCs occur in year 2003. VOCs have been measured in groundwater beyond the ORWBG. Information on concentrations of these COIs in FMC are not available at present. Potential exposures from these and other COIs are small and manageable, and as the following section shows, do not really present a risk.

Furthermore, the model for exposure to COIs from the ORWBG in FMC and beyond is conservative, i.e. calculated values are higher than measured values. Measured data also show that tritium has leached from the east landfill, and indeed the concentrations beneath the entire landfill are significant. However, tritium has not migrated from the central or east parts of ORWBG to FMC. It would appear that this landfill is located closer to, or on top of, the groundwater divide that is known to exist. However, the model assumes a high seepage velocity typical of the location of the west landfill for the entire ORWBG, resulting in a conservative (high) estimate of the exposure concentration in FMC.

Table 3. Input Parameters and Calculation Results

Constituents of Interest (COIs)	SOURCE INVENTORY (Curies)	HALF-LIFE (Years)	K _d (L/kg)	Transport to Water Table (Curies)	Transport to FMC (Curies)	Peak Conc. in FMC (pCi/L)	Time to Peak Conc. (Years)
H ³	475,000	12.4	0	295,000	114,000	872,000	29 (1989)*
Cs ¹³⁷	58,660	30	15	0.0011	--	--	1200
Pu ²³⁸	20,514	87.7	550	--	--	--	80,000
Pu ²³⁹	1,475	24,360	550	539	107	0.310	80,000
Sr ⁹⁰	58,660	29.12	15	0.00069	--	--	1200
U ²³⁵	0.60	7.1x10 ⁸	35	0.60	0.60	0.022	6000
U ²³⁸	14.8	4.51x10 ⁹	35	14.8	14.8	0.53	6000
C ¹⁴	3,778	5,730	5	3,620	3,380	840	800
Co ⁶⁰	1,960,400	5.27	10	--	--	--	600
Tc ⁹⁹	12	213,000	0.1	12.0	12.0	53	52 (2003)*
I ¹²⁹	10.6	1.57x10 ⁷	1	10.6	10.6	12	200
Np ²³⁷	1.99	2.14x10 ⁶	5	1.99	1.99	0.49	800
Cd	1,591 kg	10 ¹⁰	6	1590	1590	0.33 µg/L	1000
Hg	10,998 kg	10 ¹⁰	10	11,000	11,000	1.4 µg/L	1700
Pb	50,000 kg	10 ¹⁰	100	50,000	50,000	0.63 µg/L	16,000
VOCs	28,200 kg	100	0.1	25,400	20,700	93 µg/L	52 (2003)*

Dose Calculations

Dr. Michael T. Ryan performed the dose calculations. Dose conversion factors in Sv/Bq, taken from EPAA-520/1-88-020, September 1988 are listed in Tables 3A and 3B for inhalation and ingestion respectively. The f_1 factor is the GI track uptake fraction.

The committed effective dose equivalent (CEDE) calculation for tritium based on ingestion of 2.2 liters of water for 365 days at various locations in FMB and the Savannah River are listed in Table 4 for the year 2000. The committed effective dose equivalent is defined as the sum, over all impacted tissues and organs, of the product of the committed dose equivalent and a weighting factor that incorporates the sensitivity of the tissue/organ into the body dose determination. The committed dose equivalent is defined as the dose equivalent to organs or tissues that will be received from an intake of radioactive material by an individual during a 50-year period following the intake. According to our calculation the maximum possible concentration in FMB occurred in 1989. Consequently, the calculated values in Table 4 are for the year 2000. The dose rate at the seep line is 51 mrem per year. The dose rate at FM-6 drops to 3.4 mrem/year. The dose rate at highway 301 Bridge drops to 0.01 mrem/year and at station RM-60.9 (some 20-30 miles upriver from Jasper-Beaufort is 0.009 mrem/year. It is noted that the values in Table 4 drop further by a factor of 40 for the year 2015.

The decrease in dose rates from the seep line to RM-60.9 and all the points in between is due to dilution of the tritium concentration caused by the increase in the volumetric water flow rates. No tritium is assumed to be lost along the way.

Dose rate standards are as follows:

- from all pathways = 100 mrem/year
- air pathways = 10 mrem/year
- drinking water pathways = 4 mrem/year

Natural background dose rates from all sources is equal to 300 mrem.

Other COIs CEDE calculations are listed in Table 5 for the same locations listed in Table 4 and as stipulated in the Scope of Work. Note that at no time does the yearly dose rate of any of the COIs exceed 10 mrem. The values listed in Table 5 are the maximum possible dose rates caused by drinking the water for a year and this maximum possible occurs at different times for each isotope.

Table 3A. Dose Conversion Factors and Other Dose Calculation Parameters for SRS ORWBG

limiting DCF's are in **bold**

Radionuclide	fI	Inhalation Class	Gonad	CEDE Inhalation SV/Bq					Remainder	Effective
				Breast	Lung	R Marrow	B Surface	Thyroid		
H-3	1.00E+00	Water Vapor	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11
C-14	1.00E+00	Labeled Organic Compounds	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10
C-14	1.00E+00	Carbon Monoxide	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13
C-14	1.00E+00	Carbon Dioxide	6.36E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12
Cl-36 (D)	1.00E+00	per associated element	5.04E-10	5.04E-10	1.33E-09	5.04E-10	5.04E-10	5.04E-10	5.14E-10	6.06E-10
Cl-36 (W)	1.00E+00	per associated element	5.04E-10	5.04E-10	4.56E-08	5.04E-10	5.04E-10	5.04E-10	5.36E-10	5.93E-09
Co-60	5.00E-02	oxides, hydroxides, halides, nitrates	4.09E-09	4.16E-09	3.57E-08	4.25E-09	3.54E-09	3.72E-09	7.65E-09	8.94E-09
Co-60	3.00E-01	all other compounds	4.76E-09	1.84E-08	3.45E-07	1.72E-08	1.35E-08	1.62E-08	3.60E-08	5.91E-08
Sr-90	3.00E-01	SrTiO ₃	2.64E-09	2.64E-09	3.73E-09	3.36E-07	7.27E-07	2.64E-09	3.36E-09	6.47E-08
Sr-90	1.00E-02	all other compounds	2.69E-10	2.69E-10	2.86E-06	3.26E-08	7.09E-08	2.69E-10	5.73E-09	3.51E-07
Tc-99 (D)	8.00E-01	Oxides, halides, hydroxides, nitrates	4.52E-11	4.52E-11	3.51E-10	4.52E-11	4.52E-11	1.21E-09	5.78E-10	2.77E-10
Tc-99(W)	8.00E-01	all other compounds	3.99E-11	3.99E-11	1.67E-08	3.99E-11	3.99E-11	1.07E-09	6.26E-10	2.25E-09
I-129 (D)	1.00E+00	all compounds	8.69E-11	2.09E-10	3.14E-10	1.40E-10	1.38E-10	1.56E-06	1.18E-10	4.69E-08

Table 3A. Dose Conversion Factors and Other Dose Calculation Parameters for SRS ORWBG (cont'd)

Radionuclide	f1	Inhalation Class	Gonad	CEDE Inhalation SV/Bq						Effective
				Breast	Lung	R Marrow	B Surface	Thyroid	Remainder	
Cs-137	1.00E+00	all compounds	3.28E-12	4.02E-12	1.59E-10	3.95E-12	3.55E-12	3.57E-12	2.06E-11	2.74E-11
Np-237(W)	1.00E-03	all compounds	2.96E-05	1.69E-08	1.61E-05	2.62E-04	3.27E-03	1.34E-08	2.34E-05	1.46E-04
U-235	5.00E-02	UO ₂ , U ₃ O ₈	2.37E-08	2.38E-08	2.95E-07	6.58E-07	1.01E-05	2.37E-08	8.59E-07	6.85E-07
U-235	5.00E-02	UO ₃ , UF ₄ , UCl ₄	7.24E-09	7.33E-09	1.48E-05	1.98E-07	3.05E-06	7.22E-09	2.65E-07	1.97E-06
U-235	2.00E-03	UF ₆ , UO ₂ F ₂ , UO ₂ (NO ₃) ₂	2.84E-09	5.37E-09	2.76E-04	7.15E-08	1.05E-06	4.11E-09	1.02E-07	3.22E-05
U-238	5.00E-02	UO ₂ , U ₃ O ₈	2.23E-08	2.38E-08	2.80E-07	6.58E-07	9.78E-06	2.22E-08	8.22E-07	6.62E-07
U-238	5.00E-02	UO ₃ , UF ₄ , UCl ₄	6.71E-09	7.33E-09	1.42E-05	1.98E-07	2.94E-06	6.71E-09	2.54E-07	1.90E-06
U-238	2.00E-03	UF ₆ , UO ₂ F ₂ , UO ₂ (NO ₃) ₂	2.42E-09	5.37E-09	2.66E-04	6.88E-08	1.01E-06	2.73E-09	9.61E-08	3.20E-05
Pu-238 (W)	1.00E-03	All other compounds	2.80E-05	1.00E-09	1.84E-05	1.52E-04	1.90E-03	9.62E-10	7.02E-05	1.06E-04
Pu-238 (Y)	1.00E-05	Oxides	1.04E-05	4.40E-10	3.20E-04	5.80E-05	7.25E-04	3.86E-10	2.74E-05	7.79E-05
Pu-239 (W)	1.00E-03	All other compounds	3.18E-05	9.22E-10	1.72E-05	1.69E-04	2.11E-03	9.03E-10	7.56E-05	1.16E-04
Pu-239 (Y)	1.00E-05	Oxides	1.20E-05	3.99E-10	3.23E-04	6.57E-05	8.21E-04	3.75E-10	3.02E-05	8.33E-05

Table 3B. Dose Conversion Factors and Other Dose Calculation Parameters for SRS ORWBG

limiting DCF's are in **bold**

Radionuclide	f1	Ingestion Class	CEDE Ingestion Sv/Bq							Effective
			Gonad	Breast	Lung	R Marrow	B Surface	Thyroid	Remainder	
H-3	1.00E+00	Water Vapor	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11
C-14	1.00E+00	organic forms	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10
										1.73E-11
Cl-36	1.00E+00	all compounds	7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	8.61E-10	
Co-60	5.00E-02	oxides, hydroxides, halides, nitrates	3.19E-09	1.10E-09	8.77E-10	1.32E-09	9.39E-10	7.88E-10	4.97E-09	2.77E-09
Co-60	3.00E-01	Organics and complex organics	7.23E-09	5.08E-09	4.96E-09	5.49E-09	4.81E-09	4.68E-09	1.06E-08	7.28E-09
Sr-90	3.00E-01	soluble salts	1.51E-09	1.51E-09	1.51E-09	1.94E-07	4.19E-07	1.51E-09	6.14E-09	3.85E-08
Sr-90	1.00E-02	SrTiO ₃	5.04E-11	5.04E-11	5.04E-11	6.45E-09	1.39E-08	5.04E-11	6.70E-09	3.23E-09
Tc-99	8.00E-01	all compounds	6.04E-11	6.04E-11	6.04E-11	6.04E-11	6.04E-11	6.04E-11	1.02E-09	3.95E-10
I-129	1.00E+00	all compounds	1.38E-10	3.31E-10	1.65E-10	2.21E-10	2.17E-10	2.48E-06	1.99E-10	7.46E-08
Cs-137	1.00E+00	all compounds	1.71E-11	1.56E-12	2.12E-13	5.23E-12	1.43E-12	8.87E-15	7.55E-11	2.79E-11
Np-237	1.00E-03	all compounds	2.46E-07	1.45E-10	1.53E-10	2.18E-06	2.72E-05	1.10E-10	2.10E-07	1.20E-06

Table 3B. Dose Conversion Factors and Other Dose Calculation Parameters for SRS ORWBG (cont'd)

limiting DCF's are in **bold**

Radionuclide	f1	Ingestion Class	CEDE Ingestion Sv/Bq							Remainder	Effective
			Gonad	Breast	Lung	R Marrow	B Surface	Thyroid			
U-235	5.00E-02	Hexavalent forms	2.67E-09	2.49E-09	2.46E-09	6.81E-08	1.05E-06	2.45E-09	1.03E-07	7.19E-08	
U-235	2.00E-03	Insoluble forms	3.34E-10	1.21E-10	1.01E-10	2.78E-09	4.20E-08	9.82E-11	1.84E-08	7.22E-09	
U-238	5.00E-02	Hexavalent forms	2.31E-09	2.31E-09	2.30E-09	6.80E-08	1.01E-06	2.30E-09	9.69E-08	6.88E-08	
U-238	2.00E-03	Insoluble forms	1.02E-10	9.33E-11	9.22E-11	2.72E-09	4.04E-08	9.20E-11	1.16E-08	6.42E-09	
Pu-238	1.00E-03	Others	2.33E-07	8.41E-12	8.49E-12	1.27E-06	1.58E-05	7.99E-12	6.00E-07	8.65E-07	
Pu-238	1.00E-04	Nitrates	2.33E-08	9.28E-13	8.50E-13	1.27E-07	1.58E-06	7.99E-13	7.44E-08	9.08E-08	
Pu-238	1.00E-05	Oxides	2.33E-09	1.80E-13	8.64E-14	1.27E-08	1.58E-07	7.99E-14	2.18E-08	1.34E-08	
Pu-239	1.00E-03	Others	2.64E-07	7.69E-12	7.74E-12	1.41E-06	1.76E-05	7.49E-12	6.43E-07	9.56E-07	
Pu-239	1.00E-04	Nitrates	2.64E-08	8.09E-13	7.75E-13	1.41E-07	1.76E-06	7.49E-13	7.77E-08	9.96E-08	
Pu-239	1.00E-05	Oxides	2.64E-09	1.21E-13	7.89E-08	1.41E-08	1.76E-07	7.50E-14	2.12E-08	1.40E-08	

US EPA Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion. (EPAA-520/1-88-020), September 1988, Office of Radiation Programs, Federal Guidance Report No. 11.

Table 4.
TRITIUM DOSE RATES FOR YEAR 2000
AT VARIOUS LOCATIONS IN FMB AND THE SAVANNAH RIVER

Location	Dose s /year	mrem/year
Seep line (FMB)	5.10×10^{-4}	51.0
Road C (FMB)	1.20×10^{-4}	12.0
FM-6 (FMB)	0.34×10^{-4}	3.4
Highway 301 Bridge (SR)	1.06×10^{-7}	0.01
RM-60.9 (SR)*	9.3×10^{-8}	0.009

*RM-60.9 (SR) is a measuring point 20-30 miles upstream from Beaufort-Jasper.

Note: Concentration of any isotope in FMB was calculated with a flow rate at FMB of 7.8×10^6 m³/year. To obtain the concentration at any other location, one must multiply the calculated concentration

$$C_{\text{location x}} = \text{Calculated Concentration} \times \frac{7.8 \times 10^6 \frac{\text{m}^3}{\text{yr}}}{\text{flowrate at location x}}$$

Flow rates for all locations are given in the Appendix.

Table 5.
MAXIMUM COI DOSE RATES AT VARIOUS LOCATIONS IN FMB AND THE SAVANNAH RIVER

Location	Pu ²³⁹ (1) (mrem/yr)	Np ²³⁷ (2) (mrem/yr)	I ¹²⁹ (3) (mrem/yr)	Tc ⁹⁹ (4) (mrem/yr)	C ¹⁴ (5) (mrem/yr)	U ²³⁸ (6) (mrem/yr)	U ²³⁵ (6) (mrem/yr)
Seep line (FMB)	3.12	6.18	9.41	0.22	4.96	0.38	0.017
Road C (FMB)	0.73	1.46	2.22	0.052	1.17	0.09	0.004
FM-6 (FMB)	0.21	0.42	0.64	0.015	0.34	0.003	0.001
Highway 301 Bridge (SR)	6.47 x 10 ⁻⁴	1.28 x 10 ⁻³	1.95 x 10 ⁻³	4.58 x 10 ⁻³	1.03 x 10 ⁻³	7.9 x 10 ⁻⁵	3.4 x 10 ⁻⁶
RM-60.9 (SR)	5.72 x 10 ⁻⁴	1.13 x 10 ⁻³	1.73 x 10 ⁻³	4.04 x 10 ⁻³	9.10 x 10 ⁻⁴	7.0 x 10 ⁻⁵	3.1 x 10 ⁻⁶

Other COIs such as Cs¹³⁷, Pu²³⁸, Sr⁹⁰, and Co⁶⁰ never make it to FMB and the Savannah River from ORWBG.

- (1). Maximum dose rate occurs 80,000 years after 1952.
- (2). Maximum dose rate occurs 800 years after 1952.
- (3). Maximum dose rate occurs 200 years after 1952.
- (4). Maximum dose rate occurs 51 years after 1952.
- (5). Maximum dose rate occurs 800 years after 1952.
- (6). Maximum dose rate occurs 6,000 years after 1952.

Discussion

The dose that a person receives in one year from natural background radiation is, on the average, 300 mrem (6). The risk of fatality from this common and unavoidable background dose of 300 mrem is 1.5×10^{-4} (6). The dose rate due to tritium from ORWBG in the year 2000 that a person would receive from drinking one's entire need of water (2.2 liters/day) for a whole year at the seepline is 51 mrem. This dose rate drops to 3.4 mrem at FM-6 and to 0.01 mrem at Highway 301 bridge just below the site boundary in the Savannah River. Furthermore, this dose rate at the seepline in year 2007 drops to approximately 1 mrem/year.

The drinking water pathway is not the only route through which a person may receive dose. Other pathways include fish consumption, swimming, boating, and shoreline activities. The dose rate due to fish consumption, which could be as high as that of drinking water, is more than 99% caused by Cs¹³⁷ and Sr⁹⁰ in the fish (see Savannah River Site, Environmental Data for 1998, p. 134). Since the Cs¹³⁷ and Sr⁹⁰ in the ORWBG never make it to FMB, it cannot contribute to the dose rate from fish. The contributions from swimming, boating, and shoreline activities to dose rate is less than 0.2% (see Savannah River Site, Environmental Data for 1998, p. 134).

Conclusions and Recommendations

This work showed that it is possible to develop a simplified model for the estimation of surface water contamination. This report provides one such model which has been calibrated using existing data from one source, tritium.

In addition to validation of the developed model for tritium, other calibration of the model for all the COI's should be undertaken immediately.

The first step in the process of continuing the calibration for other isotopes is to obtain accurate and consistent concentrations of each isotope measured at specific locations with known flow rates. The measured concentration must be attributable to known origin. More detailed modeling of landfill performance, leachate generation, and solute transport may be used to confirm the level of conservativeness of the existing model. Additionally, model sensitivity to parameter uncertainty should be evaluated and documented. Other potential exposure pathways may also be considered.

In Table 3 the calculated peak concentrations of Cd, Hg, and Pb are 0.33 g/L, 1.4 g/L, and 0.63 g/L respectively. It is believed that these calculations are conservative in that the predicted values are higher than one would expect to measure. However, the only way we can verify the accuracy of the model used would be to calibrate for each element and each isotope. Based on the results we obtained thus far however, there appears to be no environmental problems animating from the transport of Cd, Hg, and Pb from the ORWBG to FMB and the Savannah River.

Also peak concentration of VOCs released to FMB is 93 g/L and this occurs in the year 2003. EPA limit on VOCs is 100 g/L. This is too close for comfort. What is needed again is measured values of VOCs to help us calibrate the model and thus gain confidence in our projection.

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Appendix

**10-Year Average Flow Rates
 At Various Sampling Points Along FMB And The Savannah River**

Station	10-Year Ave. Flow Rate (m ³ /year)
FM-2	6.47 x 10 ⁶
F-08	2.33 x 10 ⁶
F-3A	2.38 x 10 ⁶
FM-6	3.26 x 10 ⁷
RM-120	1.06 x 10 ¹⁰
RM-60.9	1.2 x 10 ¹⁰
Road C	9.34 x 10 ⁶

RM-120 corresponds to Highway 301 Bridge.
 RM-60.9 corresponds to approximately 20-30 miles upstream from Beaufort-Jasper.
 The other stations are located on the map in the Appendix.

Data provided by Peter Fledderman. According to Dr. Fledderman the seep line flow rate (2.22 x 10⁶ m³/yr) is derived from flow rates at FM3A, FM3, F12, and F13. Flow rate seep line = FM3A - FM3 - F12 - F13. Flow rates at FM3, F12 and F13 are for three-year averages (1997, 1998, 1999):

- FM3 = 2.1 x 10⁶ m³/year
- FM12 = 1.0 x 10⁵ m³/year
- FM13 = 3.2 x 10⁴ m³/year

Measured Tritium Flux to FMB (in Ci/year)			
Year	Measured Flux	Year	Measured Flux
1968	83	1984	4481
1969	165	1985	4687
1970	73	1986	5210
1971	2007	1987	6150
1972	506	1988	3670
1973	1115	1989	3600
1974	1385	1990	4280
1975	2521	1991	6420
1976	1729	1992	4090
1977	433	1993	5330
1978	219	1994	3090
1979	2851	1995	4010
1980	3652	1996	3200
1981	2070	1997	2960
1982	3281	1998	3490
1983	4018		
Data taken from reference (1).			

Map of Study Area

Computer Output For All COI Calculations