Model implementation to evaluate the collective future radionuclide releases from multiple facilities at the Savannah River Site

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ABSTRACT

A comprehensive Composite Analysis (CA) has been performed considering 152 different sources of residual radioactive material at the Savannah River Site (SRS). As part of the CA, a model was developed to perform deterministic base case calculations using the commercial GoldSim software. The model treated transport and decay of radionuclides as they are released at the source location and transported through the source region, vadose zone and aquifer to stream outcrops and from there to the Savannah River. A dose to the public was calculated assuming recreational use of stream water and residential use of river water. Specific results from the modeling evaluation indicate that the collective maximum dose from all 152 anticipated sources indicate that maximum exposures expected to occur to any offsite member of the public (MOP) will not approach the 300 uSv/yr (30 mrem/yr) dose constraint, and in fact are currently estimated to be only 10% of this. For each of the points of assessment (POA's) evaluated, the highest cumulative dose is realized at the Lower Three Runs POA and is calculated to be 29.7 uSv/yr (2.97 mrem/yr). The major dose contributing radionuclide for all of the POA's, with the exception of Upper Three Runs, was Cs-137 in the contaminated streambed sediments. In Upper Three Runs Np-237 from the H-Area Canyon Building was the major dose contributing radionuclide.

INTRODUCTION

Composite Analyses (CA's) are required at all Department of Energy (DOE) sites per DOE Order 435.1, and require an accounting of all sources of DOE man-made radionuclides and DOE enhanced natural radionuclides that are projected to remain on the site after site operations have ceased. In evaluating the impact of these residual radionuclides, a 1000 uSv/yr (100 mrem/yr) primary dose limit to a hypothetical off-site member of the public has been established as the CA performance measure. As a practical matter however, a dose constraint (i.e., administrative dose limit) of 300 uSv/yr (30 mrem/yr) has also been established by DOE to prevent the potential dose from exceeding a significant fraction of the primary dose limit. The results of a CA are an estimated dose to the hypothetical member of the public at points of assessment, which are selected based upon the site's land use plans, over a minimum 1,000 year period after disposal facility and tank closure and/or all DOE site operations have ceased. This paper summarizes the main components of a CA recently performed at the DOE's Savannah River Site (SRS), emphasizing the development and implementation of models utilized to perform that evaluation. Finally, although still considered to be preliminary, the results of the assessment are presented.

MAIN COMPONENTS OF COMPOSITE ANALYSIS

The initial elements of the CA involved a compilation of data and information that was sufficiently detailed to support the development of the CA conceptual model [1]. Several screening analyses were conducted. One of these investigations focused on determining the appropriate radionuclides to evaluate in more detail. Initially, 849 radionuclides were considered and as a result of the analysis, the list of radionuclides that merited more thorough evaluation was reduced to 49 [2]. Screening was also conducted to determine the potential pathways for public exposure at the POA's to those radionuclides released from sources of residual radioactivity from SRS and to eliminate some potential pathways from further consideration. Two exposure pathways for further evaluation at the POA's were identified, the residential pathway and recreational pathway [3].

In parallel with this, the CA conceptual model was developed, defining the both the strategy for simulating the release of residual radionuclides and the relevant features of the system to incorporate within the model framework [4]. This analysis defined the points of assessment (POAs), assessment period (AP) of interest, release pathways, pathway properties and characteristics and many more features. This conceptual model formed the basis for developing the CA Base Case deterministic model that is described in this paper. Next, an intensive effort was undertaken to establish a radionuclide inventory for all anticipated residual sources anticipated to remain at the SRS End State. This effort involved consultation with SRS custodial organizations for SRS facilities, waste tanks and waste disposal sites in order to identify those having a process history associated with radionuclides to insure that no facilities were inadvertently omitted and to establish the radionuclide inventory for all identified sources. Eventually, the radionuclide inventory identified 126 separate sources of residual radionuclides, including land surface based sources, Integrator Operable Units (IOU's, or stream corridors corresponding to each of the main SRS streams) and several tritium plumes [5]. One of the major components of the CA involved the development of a Base Case deterministic model that could be utilized to evaluate the impact of the release of residual radionuclides during the 1000-year period following the SRS anticipated End State. Development and use of this model to analyze future releases constitutes the major emphasis of this paper [6]. As part of the CA, a sensitivity and uncertainty analysis was also performed [7] which required the use of the Base Case model with some adaptations.

CA MODLE DEVELOPMENT AND IMPLEMENTATION

The modeling efforts followed the approach outlined in the CA Conceptual Model report [4]. A conceptual diagram utilized to evaluate the base case calculations is shown below in Figure 1. This diagram indicates that radionuclide fluxes are released from surface based source through the vadose zone and aquifer to the stream mouth and Savannah River where a dose to a member of the public is calculated. Of the 126 sources identified in the inventory report [5], 15 were subsurface sources consisting of groundwater plumes (GOUs) and radionuclides in stream-bed sediments (IOUs). These sources are also integrated into the conceptual diagram shown in Figure 1.

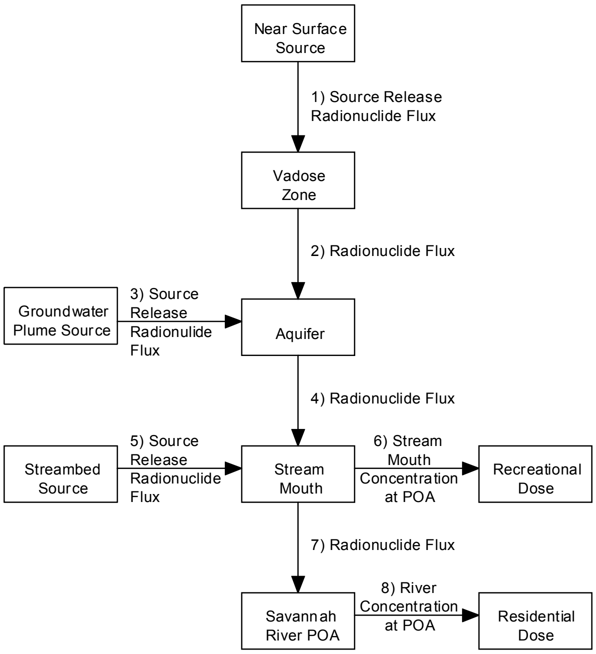

Figure 1. Conceptual diagram for base case deterministic model development

Because concentrations for CA dose modeling are needed only within surface water sources at the SRS boundary (i.e. stream mouths or Savannah River) for the base case, groundwater concentrations were not required. Radionuclides fluxes from the source through the vadose and aquifer zones to the streams/river were computed to generate surface water concentrations at the POA's. Transport modeling was performed for the 49 parent radionclides, and their daughters with half-lives more than 3 years, identified in the radionuclide screening report [2]. Progeny with half-lives less than 3 years were assumed to be in secular equilibrium with parent isotopes.

Model Structure and Features

The base case modeling effort employed the use of the GoldSim™ code to create a one-dimensional model of radionuclide transport from a source location through above ground structures (representing the waste material and engineered barriers), the vadose zone, and the saturated aquifer into a designated stream and the Savannah River. Recreational dose calculations were performed using the stream concentrations of radionuclides and residential doses are calculated using radionuclide concentrations in the river. Doses were automatically computed within a dose module imbedded within the GoldSim model.

The CA inventory identified 111 surface sources of radionuclides and 15 subsurface sources for which SRS End State radionuclide inventories were calculated. Of the original 111 surface sources certain ones were sub-divided based on different criteria, including the presence of diverging aquifer flow paths, multiple release mechanisms from the same facility or because of the presence of different types of waste tanks with different associated degradation and radionuclide release rates. After subdividing the original 111 sources, a total of 137 separate sources were identified.

Modeling was performed in two steps for surface based radionuclide sources, first a generic simulation was performed on the 137 sources assuming the residual radionuclide source was simply released to the surface soil, directly. If the total dose for a surface source from this analysis was less than 1 uSv/yr (0.1 mrem/yr) for all time from the release date to 10,000 years beyond the assumed site end-state date of 2025, the “generic” dose was accepted as a conservative estimate of the actual dose and no further analysis was performed for that surface source. If the maximum dose calculated by the “generic” release scenario exceeded 1 uSv/yr (0.1 mrem/yr) or 0.1% of the 1000 uSv/yr dose limit), additional analysis was performed to account for the presence of engineered barriers that would inhibit radionuclide transport or to include a more realistic treatment of the mechanism for radionuclide release. Out of the 137 surface sources analyzed using the “generic” release scenario, the maximum dose from 24 sources exceeded the 1 uSv/yr (0.1 mrem/yr) criterion. The specific release mechanisms considered in the CA are listed in Table 1, which also presents a brief description of how each mechanism was implemented within the model.

Table I. Source release mechanisms considered in CA and implementation description

Release Mechanism	Description
Solubility controlled	Source inventory is released into the waste cells, Kds are set to zero within the waste zone and the radionuclide concentration in the water phase within the waste cells is determined by solubility.
Kd controlled	Source inventory is released into the waste cells, waste Kds are set by input distributions and water solubility is assumed to be infinite.
Fixed release rate	Source inventory is released into the waste cells at a constant rate specified through model input, Kds are set to zero within the waste zone and solubility is assumed to be infinite.
Diffusion controlled	Source inventory is released into the top cell of the vadose zone through diffusion.
Surface release (“generic” release scenario)	Source inventory is released into the top cell of the vadose zone. Transport through the unsaturated and saturated zones is Kd controlled.
Streambed sediment source	Source inventory is released into the sediment cell connected to the stream.
Groundwater plume source	Source inventory is released uniformly into the aquifer cells.

The contaminant transport model was designed to run a single source at a time. Automation methods were developed to sequentially run a series of CA source simulations without the need for user intervention. The basic model structure is indicated in Figure 2 and consists of a Waste Zone, Barrier, Vadose Zone, Aquifer Zone and Stream and River segments, all of which correspond to the basic conceptual model. Cell sizes in the model varied between different sources, as they were simulated, but the number of cells and general model structure did not. Values for parameters such as source inventory, source release mechanism, infiltration, transport path length, transport velocity, materials, and event timing are all entered into the model through the input.

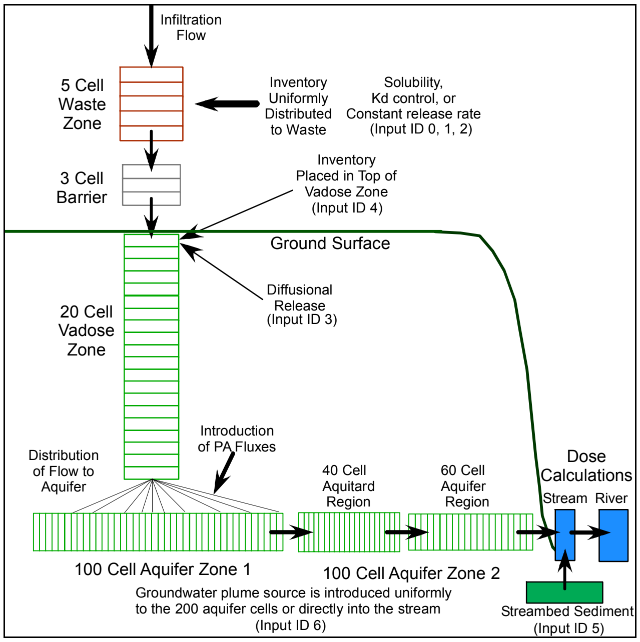

Figure 2. Schematic representation of entire GoldSim contaminant transport model [6]

The waste layer was simulated as a one-dimensional string of 5 mixing cells, for which the capacity to designate the appropriate release mechanism for the specific source was developed. The rate of flow through this segment was controlled by the infiltration rate. The cell composition is calculated as a mixture of sandy soil and clayey soil properties where the clay fraction is specified through model input. Three mixing cells were placed between the waste zone and the unsaturated soil (vadose zone) to simulate the presence of a concrete base that the waste may have been placed on. Material properties in these cells are specified as a mixture of concrete and clayey soil properties.

The vadose zone layer consists of 20 mixing cells connected in a one-dimensional flow path with material properties in these cells specified as a mixture of clayey soil and sandy soil properties. This feature was used, if needed, to model some number of cells at the top of the vadose zone as clayey soil and the lower cells as sandy soil depending on site-specific field conditions. These characteristics, as well as the total length of the vadose zone, were specified through model input for each source as it was simulated.

A shown in Figure 2, the aquifer zone is a one-dimensional aquifer region divided into two 100-cell segments, the first of which is directly beneath the footprint of the surface disposal facility and the second of which extends from the perimeter of the footprint to the aquifer discharge location at a site stream. The latter segment is divided into a 40 cell segment in which multiple cells can be designated as consisting of clay material, as needed. The latter 60 mixing cells are assumed to be saturated sandy soil. As is the case in the vadose zone, aquifer cells can be designated as different in size for one source locality to another. This is accomplished by source specific input designations for all key parameters, including aquifer flow rates, derived from existing 3D aquifer models.

Flow from the aquifer empties into a mixing cell representing a site stream into which groundwater discharges for a given surface unit. This is the first cell where the contaminant concentration is calculated. The flux of the contaminant exiting the aquifer (Ci/yr) is divided by the stream flow (m^3/yr) to obtain a contaminant concentration (Ci/m^3) that is then passed to the dose module where the recreational dose is calculated. For the deterministic base-case calculations, mean stream and river flow rates were used. The stream cell is also connected to a sediment cell from which releases from contaminated stream sediments are computed.

Flow from the stream cell passes to the river cell where another concentration is calculated based on the specified Savannah River flow rate. The river concentration is also passed to the dose module for calculation of the residential dose.

Acquisition of aquifer information

A significant portion of the model input was that associated with the aquifer segment. A separate analysis was conducted to acquire the necessary aquifer parameters needed in the modeling of 1D aquifer transport from potential CA Unit sources to their ultimate discharge point(s) [7]. The GoldSim-based 1D aquifer model, described above, requires the following list of parameters for each CA unit (source) of interest:

- The Point of Assessment (POA) for each CA unit's discharge location.
- The overall aquifer flow path length.
- The flow path arc length for Aquifer Zone 1
- The flow path arc length for the next 40-cell segment of Aquifer Zone 2.
- The number of cells in the front end of this segment that contains clayey material.
- The pore velocity to be used for all sandy sections of the 1D aquifer flow path.
- The pore velocity to be used for all clayey sections of the 1D aquifer flow path.
- The inventory fractions for the 100 cells defined in Aquifer Zone 1.

Various algorithms and programs were employed to extract the relevant information from the four different regional 3D groundwater models that previously have been developed at SRS, each drawing upon an extensive database of hydrogeologic data. The extent of model domains associated with each of these models is shown in Figure 3, along with a typical cross-section extracted from one of the models indicating the grid mesh, element sizes and color coded to indicate aquifer and aquitard zones.

The approach to estimating the required 1D aquifer modeling parameters was to utilize the appropriate regional groundwater model to track a large number of 3D stream traces emanating from the footprint of each CA Unit (i.e., ~ 1000 uniformly distributed particles over its aerial footprint) to their appropriate discharge points. During this tracking process, stream trace dependent values for variables such as travel distance, travel time, and Sandy/Clayey pore velocities were obtained. From this information average 1D aquifer parameters were computed for each CA Unit of interest, as well as probability distributions of these variables [8].

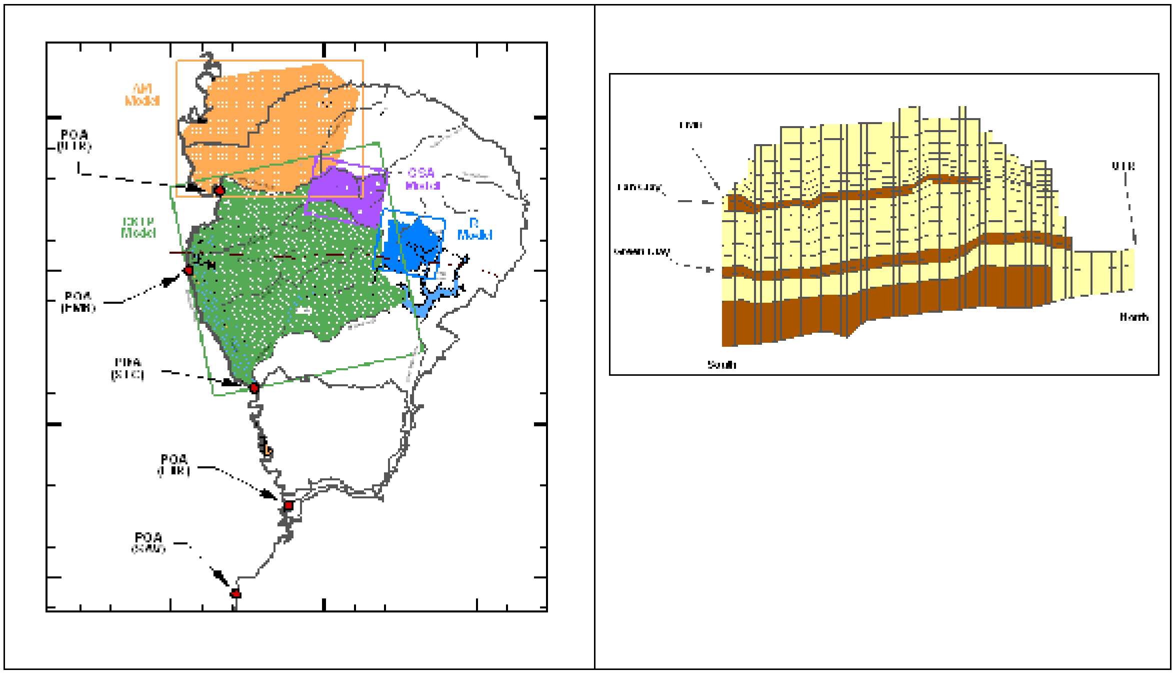

Figure 3. Location of SRS regional model domains and a typical cross-section [7]

BASE CASE RESULTS

The results of the base case deterministic evaluation are presented in this section and must be regarded as preliminary, as the internal DOE review of the SRS CA has not yet been completed. These results are summarized and presented according to the POA's, which correspond to the major SRS streams and the Savannah River. These results are summarized below in Table 2. A more extensive reporting of the results is recorded in [6].

Specific results reported for each POA include the Maximum Cumulative Dose, Major contributing source, Major contributing radionuclide and the Major Exposure Scenario (or pathway). The highest of the Maximum Cumulative Doses is realized at the Lower Three Runs POA and is calculated to be 29.7 uSv/yr (2.97 mrem/yr). The major contributing radionuclide source for all of the POA's, with the exception of Upper Three Runs, was Cs-137 in the contaminated streambed sediments. In Upper Three Runs Np-237 from the H-Area Canyon Building was the major dose contributing radionuclide. The major exposure pathway for the SRS streams (where the Recreational Scenario was evaluated) was by the ingestion of fish. In the Savannah River, where the Residential Scenario was evaluated, ingestion of vegetation was determined to be the dominant exposure pathway.

Highest doses realized by way of the Recreational pathway, which was evaluated using radionuclide concentrations in the stream water at the mouth of each stream just prior to its discharging into the Savannah River.

Table II. Deterministic base case results [6]

Point of Assessment	**Max. Cum. Dose (uSv/yr)**	**Major Contributing Source**	**Major Contributing Radionuclide**	**Major Exposure Scenario/Pathway**
Upper Three Runs	10.6	H-Canyon Building	Np-237	Recreational (Fish Ingestion)
Fourmile Branch	21.6	FMB IOU	Cs-137	Recreational (Fish Ingestion)
Steel Creek/Pen Branch	4.2	SC IOU	Cs-137	Recreational (Fish Ingestion)
Lower Three Runs	29.7	LTR IOU	Cs-137	Recreational (Fish Ingestion)
Savannah River	1.7	LTR IOU	Cs-137	Residential (Veg. Ingestion)

SENSITIVITY AND UNCERTAINTY

As a part of the CA investigation, eight major categories of sensitivity were performed, several of which required additional simulations using the base case deterministic GoldSim model. The sensitivity cases were chosen to address the requirements in the LFRG Manual [9] to consider factors such as release rates, radionuclide inventories, alternative points of assessment, groundwater divides, stream flow variation, and alternative disposal actions in sensitivity and uncertainty analysis [7]. Specifically, the cases considered included the following:

- Low Flow conditions in SRS streams and SR (7Q10 rate assumed to persist)
- Alternative POA's reflecting a reduced site area
- Source Unit inventory adjustments
- GSA groundwater divide position changes
- Alternative point in time for SRS End State
- C-14 Bioaccumulation factor
- Impact of removing Clay from Aquifer along groundwater pathway
- Longer-term peak doses – 16 have a peak > 1,000 years, highest is 3.6uSv/yr

Most of these scenarios did not require additional model simulations since varying the parameter/scenario had a demonstrable linear effect on the result, hence spreadsheet calculations sufficed. Additional model simulations were performed to evaluate certain source unit inventory adjustments and scenarios involving different assumed positions of the groundwater divide in the GSA.

Uncertainty was addressed using the GoldSim model in its probabilistic (Monte Carlo) mode and as described in [7]. Modifications were made to the base case model to allow it to simulate up to 5 sources simultaneously. In addition, probability distributions were built into the model for material properties, water flow rates, concrete degradation rate variables and dose calculation parameters. In addition to these, distributions associated with K_d values associated with different elements were also incorporated [10]. Uncertainty was addressed for a reduced number of cases, focusing on the 17 most significant sources (each contributed > 0.5 uSv/yr) as determined in the base case analysis [6], and results reported for each of the POAs. To summarize the findings, doses at the 95th Percentile ranged from 115 uSv/yr (11.5 mrem/yr) to 1.0 uSv/yr (0.1 mrem/yr) at the LTR and Savannah River POAs, respectively. [7]

CONCLUSIONS

This CA represents a significant step forward over previous CA investigations at SRS in that the scope of the investigation was expanded from a relatively small area surrounding the GSA to include the entire ~800 km^2 of the SRS, so as to encompass all potential sources of residual radioactivity that might remain at the projected SRS End State. As a result, the model developed as a part of this investigation is Site-wide in scope and has the capability of simulating transport of residual radionuclides from closure facilities located anywhere across the SRS to points of assessment at the SRS site boundary.

The specific results from the GoldSim modeling evaluation conducted as part of the SRS CA indicate that the collective maximum dose resulting from the release of radionuclides from all 152 anticipated SRS End State sources of residual radionuclides demonstrate that maximum exposures expected to occur to any offsite MOP will not approach the 300 uSv/yr (30 mrem/yr) dose constraint, and in fact are currently estimated to be only 10% of this. For each of the POA's evaluated, the highest Maximum Cumulative Dose is realized at the Lower Three Runs POA and is calculated to be 29.7 uSv/yr (2.97 mrem/yr). The major contributing radionuclide for all of the POA's, with the exception of Upper Three Runs, was Cs-137 in the contaminated streambed sediments. In Upper Three Runs Np-237 from the H-Area Canyon Building was the major dose contributing radionuclide. The major exposure Scenario/pathway for the SRS streams (where the Recreational Scenario was evaluated) the dominant exposure pathway was by the ingestion of fish. In the Savannah River, where the Residential Scenario was evaluated, ingestion of vegetation was the dominant exposure pathway. The uncertainty evaluation lends added assurance to the conclusion that the 300 uSv/yr (30 mrem/yr) dose constraint will not be exceeded in that even at the 95'th Percentile, that performance measure is not expected to be exceeded.

This investigation represents an analysis that is expected to be built upon in coming years through a maintenance program. At some point, when sufficient new and improved information becomes available, the SRS CA will be updated. In the near-term, a major area of improvement is expected to be in the development of more accurate estimates of the residual radionuclide inventories associated with abandoned facilities as they undergo decontamination and decommissioning (D&D). This type of information will be easily incorporated in the existing model such that informed management decisions might be made in a timely fashion.

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