4 OVERVIEW OF APPROACH

4.1 Statement of Goals and Constraints

The goal of this phase of the Savannah River Site (SRS) Dose Reconstruction Project is to estimate the doses and cancer risks to hypothetical receptors from SRS releases of radioactive materials to the air and water over 39 years of operation. In addition, the uncertainties in these dose and risk estimates are provided. This is an intermediate phase dose reconstruction that provides more detail and precision than a screening analysis, but it lacks the detail and precision of a full dose reconstruction that is based on the behavior of real people.

As described in Chapter 3, the hypothetical scenarios guided the analysis. These scenarios, once completed and accepted, were considered to be fixed. The activities, behaviors, and conditions ascribed to each scenario were meant to represent a range of activities that might have occurred in the area of the SRS over the time period studied. Some of the attributes specified in the scenarios are expected to bound realistic attributes in a way that increases the dose estimates. Factors associated with the receptors were considered to be fixed even though these factors might vary for real receptors. For example, the consumption rates of various types of foodstuffs by the hypothetical receptors were fixed at high values (if the scenario so specified) or nominal values (if the scenario was silent).

Numerous additional variables related to the migration of radionuclides in the biosphere and their uptake by plants and animals were used in the analysis. As described in Section 4.2.3, the analysis proceeded in two steps: 1) a deterministic step in which point estimates of dose and risk were obtained by using nominal values of the variables and 2) a probabilistic step in which a distribution of dose and risk values was obtained by fixing many variables at their nominal value but allowing key variables to be uncertain. In general the values and distributions used to represent these variables were chosen to be representative and neutral, tending neither to increase or decrease the dose and risk estimates.

Although the overall goal for this dose reconstruction is simply stated, it was necessary for the analysis to address the particular characteristics of the area surrounding the SRS and the level of detail sought for this phase of the dose reconstruction. The following considerations shaped the choice of approach:

- Radionuclide releases:
  - -- Vary substantially with time.
  - -- Several radionuclides.
  - -- Releases to air and water.
  - -- Multiple locations for releases.
  - -- Base release estimates and their uncertainties on Phase II.
- Working group scenarios:
  - -- Seven scenarios with four receptors each.
  - -- Age of receptors is an important factor to explore.
  - -- Scenarios incomplete as work commenced.
  - -- Many different types of activities for each receptor.
  - -- One home location for each scenario; additional locations for several receptors.
- End points of analysis:
  - -- Dose.
  - -- Risk.
  - -- Organ doses as needed.
  - -- Evaluate uncertainty in dose.

- -- Use generic environmental models.
- -- Estimate dose and risk by radionuclide, year, receptor, pathway, etc.

- Comprehensive approach:
  - -- Use site-specific data or, if unavailable, appropriate generic data.
  - -- Model dose-significant aspects of the scenarios.
  - -- Model all important transport and exposure processes.
  - -- Use representative variable values not intended to overestimate or underestimate dose.

The approach described in this chapter responds to these particular aspects as well as to the overall goal of the study. These aspects were addressed by the choice of: an overall approach, the models used, and the implementation of the models, the data input to the calculation, the data obtained from the calculation, and the software used to automate the calculations.

4.2 Analytical Framework

The analytical framework may be described in terms of the assessment process, the modeling process, and the analysis steps. Although these aspects are related, they address different facets of the overall analytical framework.

4.2.1 Assessment Process

A dose reconstruction is a special type of retrospective dose assessment or radiological assessment based on past releases of radioactive material to the environment. The essence of a radiological assessment has been succinctly summarized (1) as:

> "The ultimate goal of radiological assessment is to show the relationship between the 'source term,' or quantity and types of released radionuclides, and the potential effect on human health. The assessment process must proceed in a logical fashion, following the radioactive pollutant of interest from its point of origin along various exit pathways to the environment, then considering its transport in air, water, soil, or food sources to man. Once transport and intake are determined, the dose from radiation and resulting risk to health can be calculated."

In other words, the dose reconstruction starts with the release of radionuclides from SRS; continues with the transport by air, water, and the food chain; models the exposure of the hypothetical receptors to contaminated media (air, water, soil, and food); and results in an estimation of doses and risks.

Figure 4-1 shows the risk assessment approach (2), and Section 4-3 discusses the approach in more detail. The INPUT is the set of site information including the releases compiled in Phase II (3) and the specification of the hypothetical scenarios. The OUTPUT is the health risk to each individual receptor estimated by the radiological assessment. Note that the output of any step of the overall assessment is the input to the next step of the assessment.

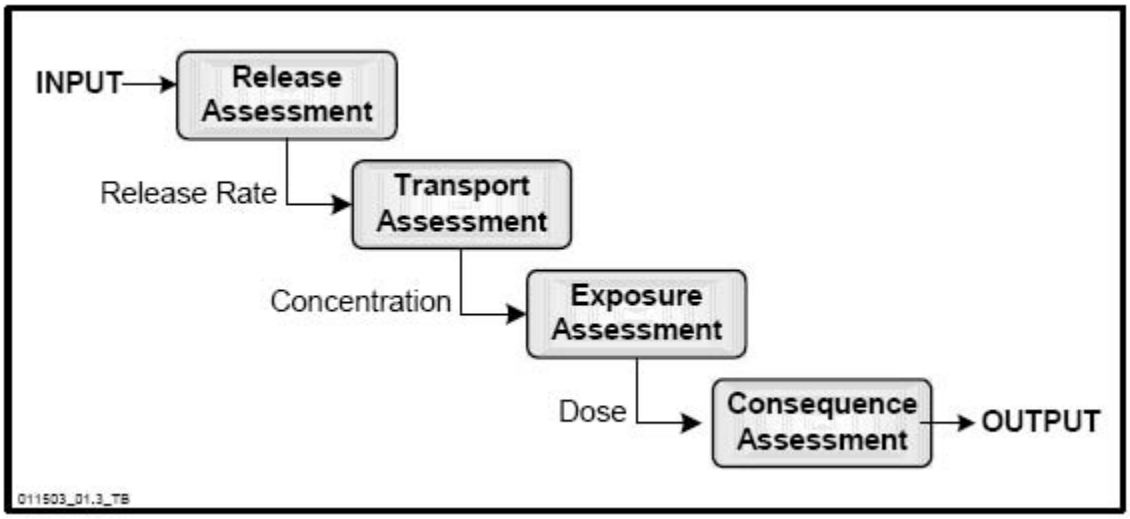

Figure 4-1 Risk Assessment Approach (2)

This dose reconstruction process can be viewed as four linked assessments (2). In the case of a radiological assessment, these linked assessments provide the following data:

- The Release Assessment provides the rate of release of radionuclides as a function of time and location of the source.
- The Transport Assessment provides the concentration of radionuclides in the environment (i.e., concentrations in air, water, soil, and foodstuffs as a function of time and location around the SRS).
- The Exposure Assessment provides the dose to a particular receptor based on their contact with contaminated media (air, water, soil, or foodstuffs).
- The Consequence Assessment provides the risk of cancer incidence and mortality.

The assessment process is described in a greater level of detail in Figure 4-2 for air releases and Figure 4-3 for liquid releases. Figure 4-2 for air releases shows how the transport assessment links concentrations in different media: air, soil, plants, and animals. These contaminated media lead to exposure of receptors by different pathways (4 of the 13 pathways for air releases are shown explicitly; “plant ingestion” represents 5 distinct pathways; “animal ingestion” represents 4 distinct pathways). Receptors are exposed through three exposure routes: inhalation and ingestion of radionuclides and exposure to direct radiation (external dose). Doses and risks are estimated using standard dose conversion factors. Figure 4-3 for liquid releases shows how the transport assessment links concentration in the water to concentration in fish. These contaminated media lead to exposure of receptors by different pathways (all of the 5 pathways for water releases are shown). Each of the four major parts of the assessment is primarily supported by different sources of information, as shown at the bottom of the figures. The Release Assessment is based primarily on the Phase II Report; the Transport Assessment is based primarily on the Phase II Report and Site Data; the Exposure Assessment is largely based on the scenarios specified by the CDC; and the Risk Assessment is based on federal radiation guidance, contained in Federal Guidance Reports 11, 12, and 13 (4), (5), (6).

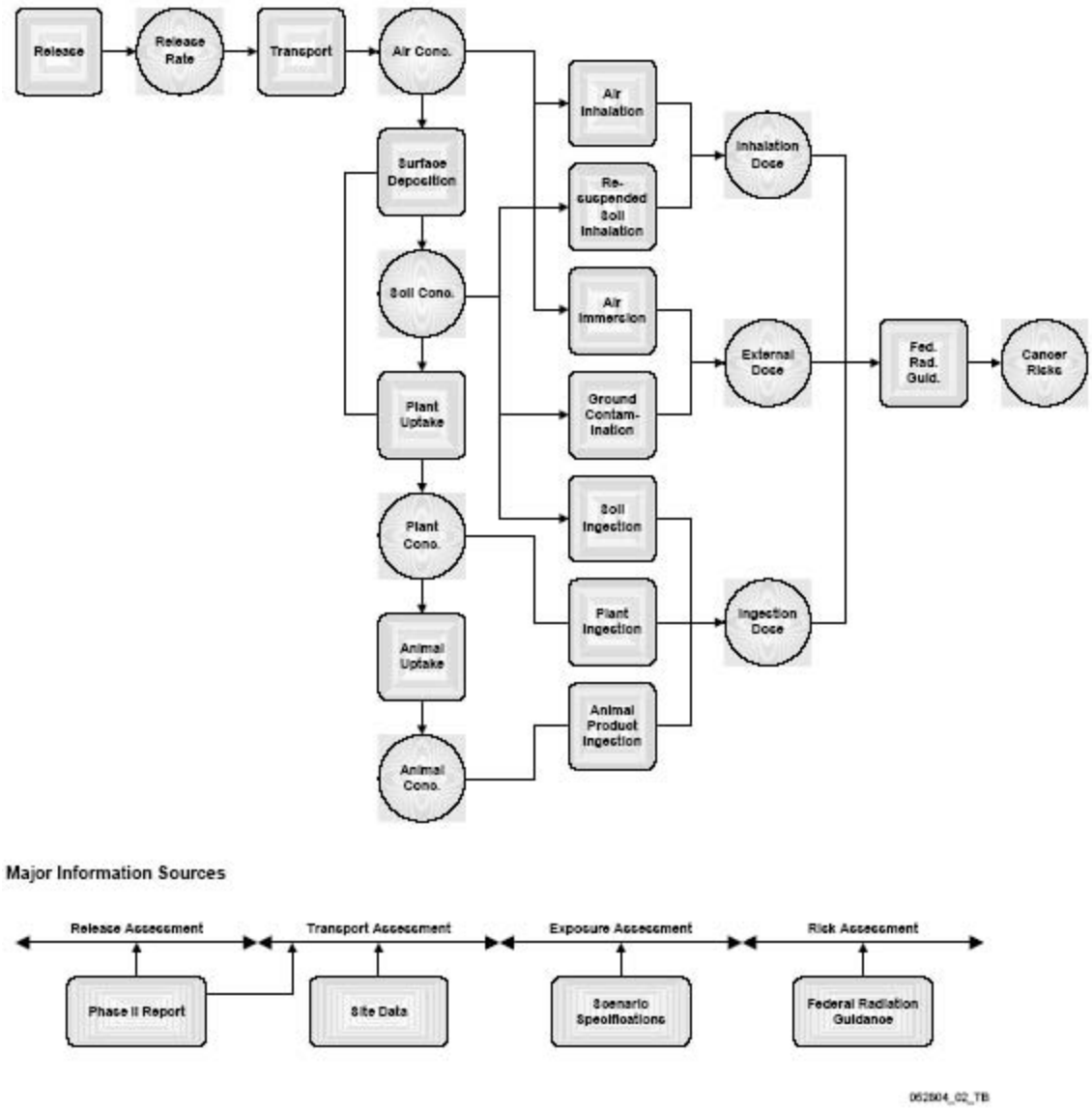

Figure 4-2 Overall Modeling Approach for Air Releases

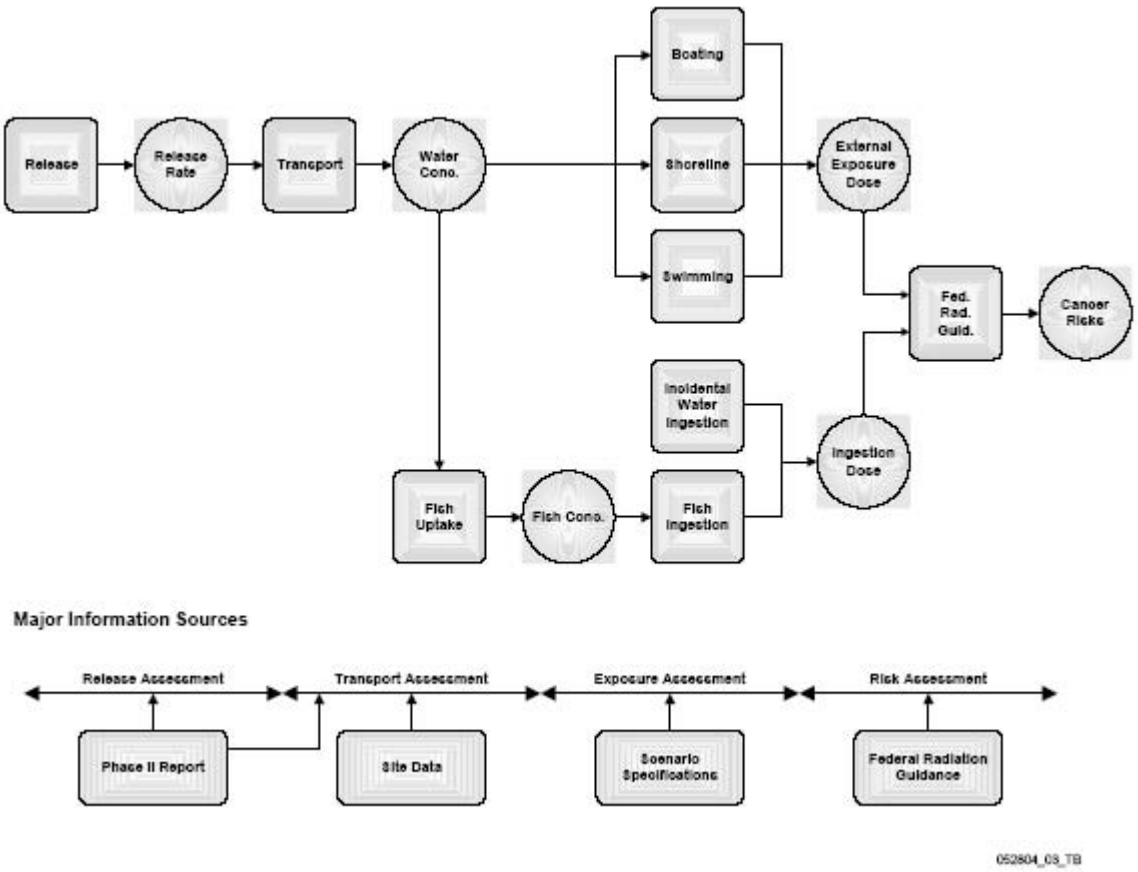

Figure 4-3 Overall Modeling Approach for Liquid Releases

4.2.2 Modeling Process

These steps, described above in the text and Figure 4-1, provide a general procedure used to conduct this dose reconstruction; however, there are several other dimensions to the study. One important dimension is the modeling sequence followed in this and most environmental studies. The modeling sequence, shown schematically in Figure 4-4, consists of three components: 1) conceptual model, 2) mathematical model, and 3) numerical model.

The conceptual model is developed first and is a qualitative or semi-quantitative representation of the processes, conditions, features, and behaviors involved in the release and transport of radionuclides, the exposure of receptors to contaminated media, and the risks incurred in each receptor from these exposures. Section 4.3 presents many of the aspects of the conceptual model. For example, this dose reconstruction requires consideration of a time-varying release of radionuclides, the release of multiple radionuclides together, releases of radionuclides into air and water, releases of radionuclides from multiple locations, and receptors engaged in varied activities at several locations. If any of these aspects were different, the entire modeling approach would be different. For example, if we were studying pollution from the morning rush hour in a large urban area, the pollution would be released over a relatively short time (not years) and it would be released relatively uniformly over a large area (not released at a point).

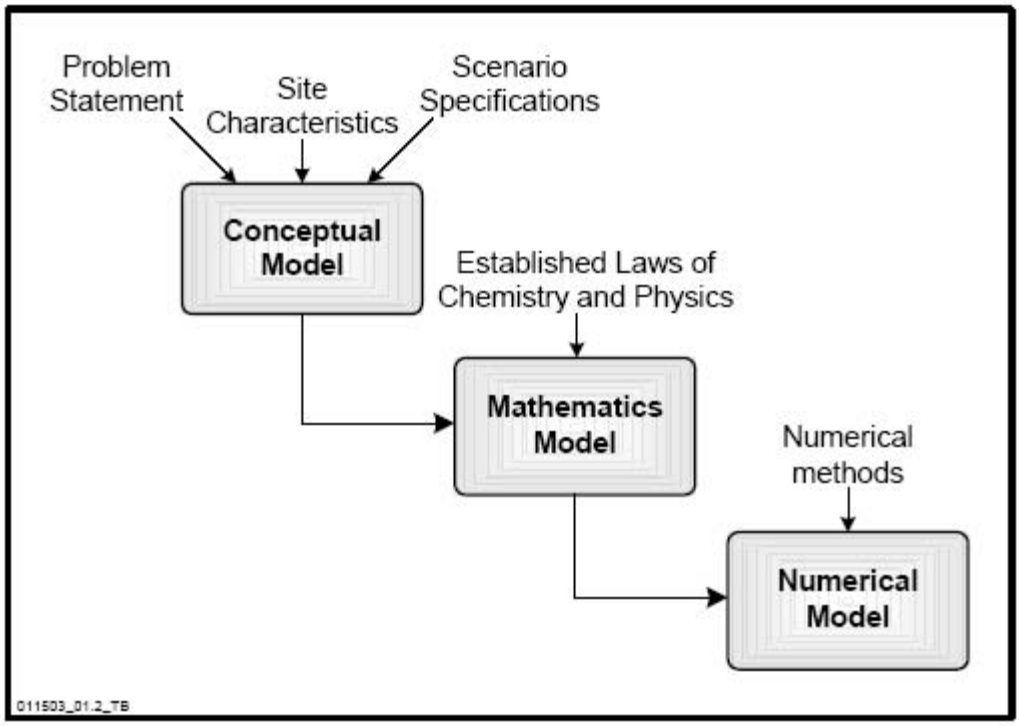

Figure 4-4 Schematic of Modeling Process

The mathematical model is derived from the conceptual model. It represents all the aspects of the conceptual model as a set of mathematical equations that usually involve a number of variables (quantities that may change with location, time, events, releases, receptors, or particular activities). These equations use well-established laws of physics, chemistry, and biology to represent the four dose reconstruction assessments

In turn, the numerical model is derived from the mathematical model. The numerical model is essential because it provides the quantitative estimate of dose to each receptor that is the study end goal. The numerical model may be little more than a bookkeeping method or a very complex numerical procedure; for this study, the numerical model included both ends of this spectrum. To obtain the quantitative estimate, values for all the variables employed in the mathematical model must be supplied. For this study, a very large number of variables needed to be carefully specified because the variable specification must represent the characteristics of the site and the surrounding area and the behavior of the receptors.

As described in more detail in Section 4.4, the numerical model used for this dose reconstruction is encoded in the GENII computer code. Although this generic dose assessment computer code has already encoded a large variety of mathematical models, a major and crucial task of this project was to configure the GENII code to represent the conceptual model for this dose reconstruction. This configuration was achieved in two main ways:

1. The GENII code is comprised of many modules, and each module represents a particular process in the overall approach presented in Figure 4-1 (e.g., the uptake of radionuclides by a plant from the soil in which it grows). Incremental doses to a receptor are estimated by linking together a sequence of these modules. For example, a particular sequence might include: 1) transport of some of the release by air dispersion to a specified location, 2) deposition onto the soil, 3) incorporation into the soil, 4)

uptake by a plant, 5) ingestion of the edible portion by the receptor, 6) dose to the receptor, and 7) resulting risk to the receptor. A fundamental decision was determining which modules to use and how they should be interconnected. Some modules, although available in GENII, were deliberately omitted (e.g., contamination of soil by irrigation with contaminated water was not used because agricultural practices in the SRS vicinity did not include irrigation by river water.) Each complete set of modules leading to a receptor dose has been termed "an exposure pathway" as described in Chapters 9 and 11. A total of 18 different exposure pathways were used in this study: 13 for air releases and 5 for water releases.

2. Providing the number and location of places where radionuclides were released and receptors were exposed was essential in representing the site. Chapter 3 describes the choice of the exposure locations based on the CDC/SRS Health Effects Subcommittee (SRSHES) scenarios. Chapter 6 describes the choice of locations for the release of radionuclides to air; four virtual sources were used to represent time-varying releases from multiple facilities. Chapter 7 describes how concentrations of radionuclides in water were estimated at two locations based on releases from multiple facilities.

An essential aspect of the analytical framework is the central importance of the conceptual model. Very simple environmental and radiological analyses may be performed by choosing a computer code, supplying a set of input data, and directly obtaining the answer. However, all but the simplest environmental analyses require careful development of the conceptual model. For this study it was necessary to consider: 1) the complex geometrical configuration of sources and receptors, 2) the time-varying characteristics of the releases and receptors, 3) the complex processes governing transport of radionuclides in air and water, and 4) the uncertainties in release data and other information. For this dose reconstruction, determination of the conceptual model required careful research and in some cases extensive analyses. These enabling analyses are incorporated in this report; several were supplied to the CDC and SRSHES as independent white papers for review and comment as the work was in progress.

4.2.3 Analysis Steps

The analysis was conducted in two steps: 1) a deterministic step resulting in a point-estimate of dose for each receptor and 2) a probabilistic step resulting in many estimates of dose (a dose distribution) for each receptor. Although the two steps had different scopes, goals, and results, they yield complementary information that provides a more comprehensive understanding of how the SRS releases induced doses in the hypothetical receptors. Table 4-1 summarizes some important differences between the two analysis steps.

Step 1 established a point-estimate value of dose and risks for each receptor. This was accomplished by assigning a single representative value for each variable used in the dose assessment; for this study hundreds of variables were specified after research and evaluation. These representative values were chosen to be realistic and neutral (i.e., not intentionally overestimating or underestimating the doses). Perhaps more important than establishing a point-estimate of dose, these modeling results were used to understand the relative importance of radionuclides, transport pathways, exposure pathways, and other factors. This information, presented in Chapter 11, was used as input for conducting the second step.

Although a single representative value was used for each input variable in Step 1, every variable is uncertain to one degree or another. Two major types of uncertainty are variability and lack of knowledge. Variability comes from parameter values that change in time or over the geographical region modeled. For example, consumption rates by receptors for various foodstuffs changed with nutritional habits over time, but were assumed constant, because these data were not available on a site-specific basis. Because there is not a single value, there is uncertainty as to which one to choose. An example of lack of knowledge is a parameter value not measured for the SRS, but measured elsewhere. There may be a value, but it cannot be applied without uncertainty. Both types of uncertainty were encountered in this

study. This uncertainty in input variables is usually represented by a probability distribution that describes the likelihood that a variable will have a particular value.

Table 4-1 Comparison of Steps 1 and 2

Attribute	Step 1	Step 2
Analysis Type	Deterministic.	Probabilistic.
Variables	All have a fixed value.	Most have a fixed value; 14 uncertain.
End Point	Dose and risks.	Dose.
Subcategories of Dose and Risk	All (organs, radionuclides, exposure pathways, release mode).	Only total dose.
Radionuclides	All (result of Level 1 screening in Phase II).	Minor contributors to dose screened out.
Exposure Pathways	All (all potential contributors).	Minor contributors to dose screened out.
Primary Goal	Understand how doses arise; screening for Step 2.	Establish confidence intervals around mean estimated dose.
Result	Single estimate of dose for each receptor.	Multiple estimates of dose for each receptor.

Step 2 of the analysis evaluated the effect of input variable uncertainty on dose estimates. This probabilistic analysis was simplified by 1) eliminating radionuclides and exposure pathways that were clearly minor contributors to dose and 2) eliminating from the set of uncertain input variables those variables estimated to be minor contributors to the uncertainty in dose. These simplifications helped to focus the analysis and eliminated some extensive computations likely to yield little benefit. By considering input variables with a strong influence on the uncertainty in dose as uncertain, Step 2 provided average values (mean and median) of the dose for each receptor as well as confidence intervals around those values. Although the probability distributions describing the input variables were anchored by the point estimate values for those variables, the mean and median doses calculated in Step 2 were generally higher than the point-estimates of dose calculated in Step 1. In addition, Step 2 included some sensitivity and uncertainty analyses. These analyses developed quantitative measures that indicated which input variables had the largest effect on dose and which variables contributed most to the uncertainty in dose.

4.3 Assessment of Radionuclide Release, Transport, Exposure, and Consequence

The modeling process for this study has four major components:

1. Release of radionuclides into the air and to surface water.
2. Transport of radionuclides through the air, surface water, and food chain (soil, plants, and animals) to exposure locations.
3. Exposure of receptors to contaminated media (air, water, soil, foodstuffs).
4. Dose and risk assessment.

Each of these components is described more fully below. Note that, because calculation of dose is performed in the fourth, rather than the third component, this is a slightly different breakdown than is shown in Figure 4-1. This change, which is explained more fully in Section 4.3.3, is made for convenience and has no substantive effect.

4.3.1 Release of Radionuclides

Chapters 5, 6, and 7 discuss the release and transport of radionuclides into the air and surface water. Because it was difficult to cleanly separate the analysis of release and transport, Chapters 6 and 7, although nominally treating transport, also treat certain aspects of the release. The goal of the release assessment was to develop a time history of radionuclide releases on a yearly basis. Although some information was available for some facilities and some radionuclides on a much shorter time interval, annual average releases were considered suitable for this intermediate-phase dose reconstruction. Furthermore, the Phase II report, which provided the source term for Phase III, defined the source terms as annual releases.

Using information from the Phase II study and from other sources, a compilation of data was created that listed the quantities of radionuclides released for each year into the air and water by each major SRS facility. Data were compiled for 15 individual facilities, including 5 reactors, 2 separations facilities, 1 tritium recovery and purification facility, 2 waste treatment facilities, 2 seepage basins, and 3 other areas were radioactive materials were handled and stored. These data were used as input to the transport assessments performed for this study. For example, facility-specific atmospheric releases were coalesced into four groups that were then represented in the transport calculation by four virtual sources.

In compiling these data, careful checking and evaluation was performed to ensure that the detailed source terms compiled for this phase were consistent with the summary releases stated in the Phase II report. Because the summary releases incorporated certain correction factors that could depend on a particular radionuclide, facility, and year, ensuring consistency required significant care and effort. For the probabilistic analysis, the same single factor was applied to all radionuclides, from all facilities, for all years; this factor raised or lowered all releases to account for the uncertainty in knowing precisely the quantities that were released.

4.3.2 Air, Water, and Food Chain Transport Assessment

Radionuclides migrate from the point of release through the environment and end up in one of five environmental compartments or media: air, water, soil, plants, or animals. The transport assessments estimate the concentrations of radionuclides in these various media. As described in Section 4.3.3, a receptor may come into contact with these contaminated media in a variety of ways that can result in a dose to the receptor. For convenience, this report has partitioned the discussion of transport into three parts: Chapter 6, Transport of Radionuclides through the Air to an Exposure Location; Chapter 7, Release of Radionuclides to Water and Transport to an Exposure Location; and Chapter 8, Food Chain Transport.

As discussed in Chapter 6 and Appendix D, the transport of radionuclides released to the air from onsite facilities to exposure locations is estimated by an extension of the Gaussian plume model. This extended model, the sector-averaged model, sums up contributions over a range of wind speeds and stability classes characteristic of the site. The result of this calculation is an annual concentration of each radionuclide in air at the specified exposure location, which depends only on the release for that year.

In the absence of detailed information about meteorological conditions during the early years of the SRS operation, meteorological data, the Joint Frequency Distribution data, averaged over 20 years of SRS operation (specifically, four five-year averages were averaged) was applied to each of the 39 years

considered in the study. Modeling the changes in annual average meteorology did not seem appropriate at this phase because other, more significant uncertainties would not have been addressed. For example, acute releases occurring over a few hours or days contributed substantially to the release quantities in early years. These releases, if modeled more precisely as acute events with known weather conditions specific to the release time, may have produced substantially different dose estimates. For example, if a large acute release occurred with the wind blowing in an infrequent direction (say toward the south), the actual dose could have been higher for receptors located to the south than doses computed using annual averages, while the dose to receptors in other locations might be slightly overestimated by the averaging approach. Considering weather conditions on an annual basis can not address these uncertainties. During transport of radionuclides from the release point to the exposure location, the model considered loss of radioactive material resulting from radioactive decay and deposition. Release and exposure locations were modeled as points. Transport of radionuclides from 4 virtual sources to 10 exposure locations was analyzed. For the uncertainty analysis, the Joint Frequency Distribution data obtained for the SRS were considered to be fixed. However, parameter variable distributions for certain other parameters related to air transport, such as the radii of radioactive particles, were considered uncertain.

The water transport was addressed by estimating the concentration of radionuclides in water at two exposure locations: 1) a point near the town of Martin on Lower Three Runs Creek and 2) a point on the Savannah River just below its confluence with Lower Three Runs Creek. The exposure location on the Savannah River was used to represent potential exposure locations elsewhere on the river because there was no strong basis for the estimation elsewhere and, at this point, all the liquid releases from the site were diluted by the smallest quantity of river water containing the entire release.

The simplest approach to modeling water concentrations is to divide the annual quantity of radionuclides released by the annual flow. This simple model was unsuccessful because 1) the concentrations estimated this way did not match the measured concentrations for key radionuclides and 2) significant processes for storage and release of radionuclides by sediment and biota on the SRS were not addressed. Tables 7-3 and 7-4 present the estimated versus actual concentrations for key radionuclides.

Two different modeling approaches were used to calculate concentrations in the Savannah River and Lower Three Runs Creek. For concentrations in the Savannah River, a model used in Chapter 5 of the Phase II report for three radionuclides was adapted and extended to additional radionuclides included in this study. This model had taken into account the storage and release of radionuclides in bodies of water on the SRS site. For Lower Three Runs Creek, actual measured concentrations at Martin were used whenever possible; however, only data for ^{137}Cs, ^{90}Sr, and tritium concentrations were available. For early years, when concentrations were likely high, direct measurements were not available; however, concentrations were estimated based on annual releases and flow rates by extrapolating from years with concentration data. Chapter 7 describes more fully these models and extrapolation methods. For the uncertainty analysis, liquid transport variables were considered to be fixed; however, the radionuclide concentrations were varied by the adjustment factor described for releases.

This study did not consider increases in radionuclide concentrations of in water bodies, such as streams, rivers, ponds and reservoirs, from the air release of radionuclides. Such a pathway was not suggested by the scenarios evaluated. An analysis of such an environmental pathway is not necessarily straightforward, since the concentrations in such surface water bodies depend, not only on direct deposition into the water, but also mobilization and migration of radionuclides deposited on the ground surface and vegetation in the watershed supplying the pond or reservoir. It should be noted that the Phase II analysis and the NCRP screening method on which it is based do not consider this pathway. For water bodies receiving liquid releases (the Savannah River and Lower Three Runs Creek), the liquid releases clearly dominate the concentration levels. Since those releases produced small doses, the doses from this additional pathway are anticipated to be extremely small. Section 13.3.3 recommends that this pathway be studied.

Soil concentration was determined by considering deposition from the air, mixing in the soil layer, and removal by radioactive decay, leaching, and weathering. Many of the variables in this model (e.g., particle diameter and weathering rates) were considered candidates for treatment in the probabilistic analysis. The process of deposition at exposure locations was the same as those used to assess depletion of the plume during transport of radionuclides from the release point to the exposure location. Similar models are used to estimate deposition on plant surfaces. A simpler model was used to estimate deposition of radionuclides from water into sediments on the side of streams. Chapter 8 describes these models and variables in more detail.

A standard but complex model was used to estimate the concentration of radionuclides in plants. The model considers uptake from deposition on leaves, uptake by roots from contaminated soil, migration to edible parts by the plant, and removal by weathering and other processes. Numerous plant-specific and radionuclide-specific uptake factors were researched for inclusion in this study (e.g., the growing period and standing biomass for forage was researched). Many of these food-chain input variables were considered as candidates for treatment in the probabilistic analysis. Chapter 8 describes these plant food-chain models and variables in more detail.

A relatively simple, standard model was used to estimate the concentration of radionuclides in animals. This model considers the daily ingestion rate of the radionuclide and the fraction of the amount ingested that is retained in a particular tissue such as meat (muscle), milk, or eggs. These variables (i.e., the consumption rates for particular animals and uptake rates for particular radionuclides and animals) were researched. Many of these variables were considered candidates for treatment in the probabilistic analysis. Chapter 8 describes these animal food-chain models and variables in more detail.

4.3.3 Exposure Assessment

To produce a dose estimate, an exposure assessment usually combines information about radionuclide concentrations in contaminated media with information about how receptors come in contact with the contamination. However, as explained in Section 4.3.4, it is more convenient to combine the dose and risk considerations together. The exposure assessment then calculates intake for radionuclides inhaled or ingested, or calculates exposure for external radiation. These outputs of the exposure assessment are readily converted to dose (and risks) by multiplying an appropriate dose conversion factor that is age dependent.

Dose to a receptor is produced when contaminated media contact the body through one of three exposure routes: external exposure, ingestion, or inhalation. A fourth exposure route, dermal contact, is not considered important in this study[1]. Eighteen different exposure pathways were selected as appropriate to characterize the doses produced at the SRS through these three exposure routes. The following exposure pathways are associated with each exposure route:

- External radiation:
  - Immersion in a plume of air.

[1] Doses from absorption of contaminants through the skin are generally considered to be small for most environmental exposure to radioactive contaminants because doses from ingestion and inhalation tend to dominate. For example, the screening methodology used in Phase II to determine important radionuclides and pathways does not include dermal exposure. Most radioactive contaminants considered in this study, with the exception of tritium and chemically organic radioiodine, are likely to be in an inorganic chemical form, which generally has a relatively low dermal absorption (absorption fraction 0.01 or less). One source (7) suggests that dermal absorption from exposure to soil may be more important than soil ingestion if the absorption fraction is greater than 0.1. Since ingestion of soil contributed very low doses, doses from dermal absorption are generally expected to be even smaller.

- -- Exposure to contaminated soil.
- -- Exposure to a contaminated shoreline.
- -- Exposure to contaminated water while swimming.
- -- Exposure to contaminated water while boating.

- Ingestion:
  - -- Leafy vegetable consumption.
  - -- Root vegetable consumption.
  - -- Fruit consumption.
  - -- Grain consumption.
  - -- Beef consumption.
  - -- Poultry consumption.
  - -- Milk consumption.
  - -- Egg consumption.
  - -- Inadvertent soil consumption.
  - -- Fish consumption.
  - -- Inadvertent ingestion of water while swimming.

- Inhalation:
  - -- Inhalation of contamination in the air.
  - -- Inhalation of contamination resuspended from soil.

The models used for each of these exposure pathways are similar and involve multiplication of the following factors:

- Medium concentration.
- Intake/contact rate.
- Exposure duration.
- Daily activity factor.
- Annual activity factor.

An example of an intake rate is the quantity of beef consumed per year. A contact rate could be the amount of air breathed per day. Exposure duration measures the amount of time a subject is in contact with contaminated media. The daily exposure factor could be the number of hours spent swimming or boating for each occurrence of such a recreational event. The annual activity factor could be how many days a year was spent swimming or boating. The result of these 18 exposure models are either the amount of radionuclide taken into the body (intake) or the amount of exposure to external radiation. Although the form of each model is the same, the variable values used in each are selected to represent the characteristics of the receptor as delineated in the scenarios. Appendix E presents the rationales for variable values associated with receptor behavior such as food consumption rates and breathing rates. Generally, U.S. average values (e.g., from U.S. Environmental Protection Agency [EPA] or U.S. Nuclear Regulatory Commission [NRC] guidance) were used. Variable values associated with receptor behavior were not treated as uncertain variables because they described hypothetical scenarios. In addition, overlaying an additional treatment of uncertainty seemed redundant because the specification of these hypothetical scenarios was intended to bracket a wide range of behaviors. Furthermore, other variables associated with the scenarios, such as the location and the age of family members, were fixed by the scenario specifications.

Appendix F addresses variables that are independent of receptor actions but depend on site-specific environmental conditions. Where information was available, values specific to the SRS or the surrounding region were used. Some variables depended on local practices that varied over time.

However, SRS-specific data frequently were not available. In those cases, generic data were obtained from other sources, such as the International Atomic Energy Agency's handbook of parameter values (8), if the variable values were available and were appropriate. As a last resort, default variable values associated with the GENII code were used (9).

4.3.4 Dose and Risk Assessment

This assessment calculates dose, cancer incidence, and cancer risk for each receptor. These doses and risks are calculated from the intakes and exposures that are the output of the exposure assessment. The calculation is accomplished by multiplying the intake or exposure by a dose conversion factor or a risk conversion factor. These conversion factors have been developed through over 50 years of scientific research and modeling and are approved by international and national radiation protection organizations. The U.S. Environmental Protection Agency (EPA) issued tables of these coefficients in its April 2002 update to Federal Guidance Report (FGR) No. 13 (10). External exposure doses for all pathways except water immersion were calculated using adult dose coefficients issued by EPA in FGR No.13 (6). Dose coefficients for external exposure from water immersion were those issued by EPA in its FGR No. 12 (5). Similarly, cancer risks (both incidence and fatality) were calculated by using risk coefficients issued by EPA in its April 2002 update to FGR No. 13 (10). External exposure risks for all pathways except water immersion were calculated using adult dose coefficients issued by EPA in FGR No.13 (6). Risk coefficients for external exposure from water were assumed to be 0.05 per sievert for cancer fatality and 0.06 per sievert for cancer incidence.

For this study, all risk and dose coefficients (conversion constant from radiation exposure to probability of cancer and radiation dose from exposure) were applied to the analysis as point-estimates. Uncertainty in the dose and risk coefficients in the uncertainty analysis was not analyzed. Appendix D of FGR No.13 (6) outlines an approach to derive uncertainty intervals for these dose and risk coefficients. This approach, however, is complex and lengthy and requires multiple expert elicitations. This was judged to be beyond the scope of this phase, which focused on variables with far more uncertainty which focused on the characteristics of the site and the surrounding population.

4.4 Computational Framework – Computer Analysis

To automate the computational process, a combination of existing and custom-designed software was used. The assessments of radionuclide transport, human exposure, dose, and risk were performed using state-of-the-art environmental analysis and risk assessment software (i.e., Version 2 of GENII). The GENII code was linked to a pre-processor and post-processor. The pre-processor was developed to efficiently compile and prepare input data for use by the GENII code. The post-processor was developed to efficiently determine doses and cancer risks for both the point-estimate and probabilistic analyses. For the latter, a generally available computer program, Latin Hypercube Sampling (LHS), was used to provide multiple samples of the input variable values (realizations) to the core computer code (11).

4.4.1 Selection of Environmental Analysis and Risk Assessment Software

At the early stages of the project, it was recognized that the assessments to be performed were computationally demanding. There were three main reasons for this:

1. As explained in Section 4.2, the dose assessment requires the linking of several sub-assessments or calculation modules. Given the 18 different exposure pathways considered and the number of times each chain of modules is activated, the calculation must be automated for the calculation to be feasible. Furthermore, each module requires input variable values, which it may share with other modules. The consistent and accurate transfer of these variable values between modules also must be automated.

2. The dose was calculated by adding up incremental doses from each year, radionuclide, exposure pathway, medium of release, etc. This calculation was done for each of the 28 receptors. Doses and risks were also disaggregated by organ (i.e., a huge amount of data needed to be stored, transferred, and processed).
3. Some variables changed as a function of time. The quantities released of each radionuclide changed annually. The sensitivity of the receptors to radiation dose was modeled as changing with the age of the children in each scenario. Some behavioral characteristics (e.g., the amount of beef consumed) also changed in time. These temporal changes were required to be synchronized.

Three approaches were considered to automate the dose reconstruction calculations: 1) use an existing code, 2) custom-develop a code, and 3) use an existing code but augment it with additional custom software to facilitate the analysis. Approaches 1) or 3) were preferred, assuming an existing computer code could be found that met the analytical requirements of the study.

As addressed in Appendix H, the analytical requirements were compared to the capabilities of existing computer codes. Among these requirements were the ability to simulate the models in each of the four linked assessments described in Section 4.2, the ability to allow desired inputs and provide desired outputs, and the flexibility to adapt to conditions near the SRS. Sixty-six codes were identified based on their general classification as tools for environmental transport, exposure, dose, and risk modeling. After screening these codes, 17 candidate codes were evaluated for their suitability. This evaluation eliminated codes that only addressed a limited number of pathways and exposure scenarios. From this evaluation, two suitable codes emerged: Hanford Environmental Dosimetry System, Generation II, Version 2 (GENII); and Multimedia Environmental Pollutant Assessment System (MEPAS). Additional relevant information about the two codes was collected by obtaining and reviewing available literature and copies of these codes, and discussing various code characteristics with representatives who were responsible for developing and validating the codes. These codes were then critically compared for each analytical requirement. This evaluation chose Version 2 of GENII.

The GENII computer code was developed at Pacific Northwest National Laboratory (PNNL) to support radiological exposure and risk assessment for EPA's Office of Indoor Air and Radiation. The GENII code was developed to provide a state-of-the-art, technically peer-reviewed, documented set of programs for calculating radiation doses from radionuclides released to the environment. Radionuclide transport via air, water, or biological activity may be considered. Details of the GENII code may be found in its software design document (9).

4.4.2 Linkage of GENII Code with Pre- and Post-Processors

To efficiently address the large amount of data that was used for the analysis and the voluminous nature of the calculated results, a pre-processor and post-processor were linked to the GENII code. Figure 4-5 shows the schematic of information flow. Appendix G presents a detailed discussion of the computational process. Note that the preprocessor automated the preparation of a modified GID (Global Input Data) file, an input file for the GENII code; this avoided the potentially error-prone process of manually entering a large amount of data into GENII through the FRAMES interface.

The pre-processor warehouses input data (e.g., the quantities of radionuclides annually released into the air and water and the specifications of the seven hypothetical family exposure scenarios) and prepares this data for use by the dose program. After receiving this input data, GENII performs the transport and exposure pathway computations that estimate the dose and risk. These calculations are based on unit values (1 Becquerel (Bq) released, 1 kilogram of beef ingested per year, 1 hour spent at an exposure location). The post-processor then accepts the output from GENII and performs additional calculations to adjust the output from GENII to reflect receptor behaviors and characteristics representative of the

assumed age of the receptor (e.g., the annual quantities of a specified food consumed by a teenager). Adjustments are also made for the age-dependent radiation sensitivity of the receptor. The result is radiation doses and cancer risks for each receptor that are appropriate for the age and assumed lifestyle of that receptor. The post-processor is also used to create files for input to the sensitivity and uncertainty analysis.

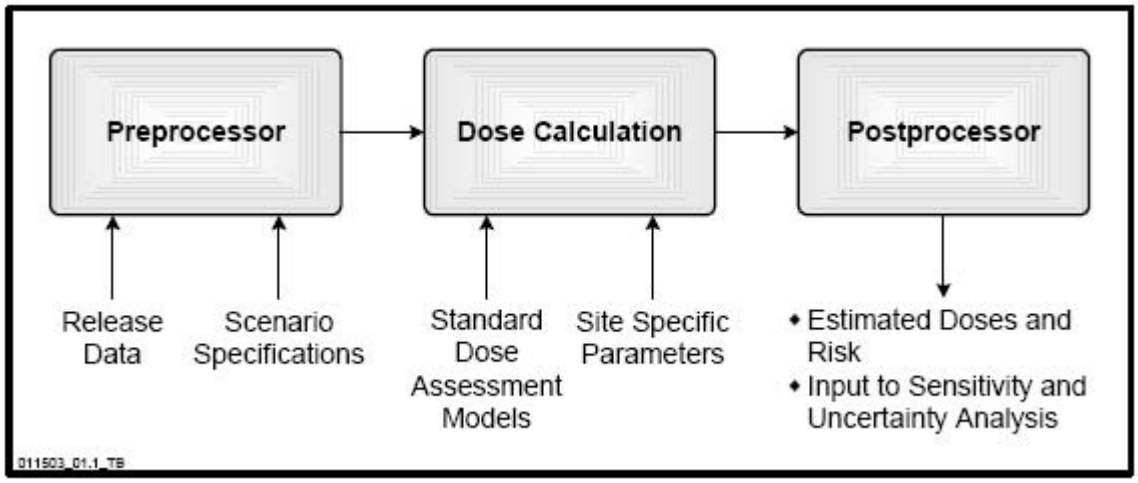

Figure 4-5 Schematic of Information Flow for the Dose Reconstruction Effort

4.4.3 Probabilistic Calculations

The same basic computational approach was used to perform the probabilistic analysis. However, multiple sets of input variable values (realizations) were generated by the generally available LHS computer code (11). The LHS code takes as input the probability distributions describing the uncertainty in selected input variables and provides a set of realizations of those variables. The statistical method encoded in LHS permits efficient estimation of statistics for the dose. Thus, the dose calculation was performed for each realization. The pre-processor was used to sequence through the 40 realizations of uncertain input variables.

4.5 Quality Assurance and Quality Control Procedures

The Quality Assurance Program for this study was designed to provide oversight of all activities and actions performed in support of the development of the point-estimates and the uncertainty analysis. In the initial stages of this study, it was determined that errors could be introduced through calculations and adjustments to existing information and data, through inputting data into electronic spreadsheets and files, through programming of modeling software, and through the interpretation of the modeling results. To address these potential sources of error, Standard Operating Procedures (SOPs) were developed which delineate the protocols for reviewing data management activities, data input, software development, and technical and editorial review of the study report.

The SOPs developed for use on this study include:

- Work Process Controls for the Savannah River Dose Assessment.
- Quality Assurance Training.

- Technical Review and Approval of Task Products for the Savannah River Dose Assessment.
- Records Management for the Savannah River Dose Assessment.
- Quality Assurance Review of Scanned Documents.
- Production of Electronic Records from Hardcopy Documents.
- Computer Software Design for the Savannah River Dose Assessment.
- Quality Assurance of Computer Codes Used for the Savannah River Dose Assessment.
- Quality Assurance (QA) for Testing and Accessing Computer Codes Used for the Savannah River Dose Assessment.
- Information Control.

These SOPS were prepared by the Project Quality Assurance Manager, approved by the Project Director, and the project staff was trained to the requirements of the SOPs.

The basic requirements of the Quality Assurance program for this study as delineated in the SOPs include:

- All project staff must be knowledgeable of the requirements of the applicable SOPs.
- All work products developed in support of this study must be technically or editorially reviewed by a qualified independent reviewer for calculational or input errors and approved for use on the study by the Project Director. A qualified independent reviewer is someone who has the appropriate background through education or experience and was not responsible for the development of the work product.
- All calculations or modifications to data must be reviewed to determine 1) if the calculation was appropriate, i.e. was the right mathematical formula used for the calculation, and 2) was the calculation executed correctly.
- All software developed for this study must be supported by an approved design document and the software must be verified and validated as correct. The software verification and validation process is described in Appendix P – Quality Assurance/Quality Control.
- All documentation relating to the development and review of work products, such as technical review forms, drafts of report sections, decision documents, project staff communications, and original data sources, are considered Quality Assurance Records and must be maintained in accordance with the Records Management and Information Control SOPs.

4.6 References

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