NUREG/CP-0163

Proceedings of the Workshop on Review of Dose Modeling Methods for Demonstration of Compliance With the Radiological Criteria for License Termination

Held at
NRC Headquarters Auditorium
Rockville, Maryland, USA

November 13-14, 1997

Edited by
T.J. Nicholson, USNRC/RES
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ABSTRACT

The public "Workshop on Review of Dose Modeling Methods for Demonstration of Compliance with the Radiological Criteria for License Termination" was held at the NRC Headquarters Auditorium, Rockville, Maryland, on November 13-14, 1997. The workshop was one in a series to support NRC staff development of guidance for implementing the final rule on "Radiological Criteria for License Termination." The workshop topics included discussion of: dose models used for decommissioning reviews; identification of criteria for evaluating the acceptability of dose models; and selection of parameter values for demonstrating compliance with the final rule. The 2-day public workshop was jointly organized by RES and NMSS staff responsible for reviewing dose modeling methods used in decommissioning reviews. The workshop was noticed in the Federal Register (62 FR 51706). The workshop presenters included: NMSS and RES staff, who discussed both dose modeling needs for licensing reviews, and development of guidance related to dose modeling and parameter selection needs; DOE national laboratory scientists, who provided responses to earlier NRC staff-developed questions and discussed their various Federally-sponsored dose models (i.e., DandD, RESRAD, and MEPAS codes); and an EPA scientist, who presented details on the EPA dose assessment model (i.e., PRESTO code). The workshop was formatted to provide opportunities for the attendees to observe computer demonstrations of the dose codes presented. More than 120 workshop attendees from NRC Headquarters and the Regions, Agreement States; as well as industry representatives and consultants; scientists from EPA, DOD, DNFSB, DOE, and the national laboratories; and interested members of the public participated. A complete transcript of the workshop, including viewgraphs and attendance lists, is available in the NRC Public Document Room. This NUREG/CP documents the formal presentations made during the workshop, and provides a preface outlining the workshop's focus, objectives, background, topics and questions provided to the invited speakers, and those raised during the panel discussion. NUREG/CP-0163 also provides technical bases supporting the development of decommissioning guidance.

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PREFACE

A public workshop, noticed in the Federal Register (62 FR 51706), was held at the U.S. Nuclear Regulatory Commission (NRC) Headquarters Auditorium, Rockville, Maryland. The workshop objectives were to: (1) provide the NRC staff and the public with an overview of currently available Federally-sponsored dose models appropriate for decommissioning dose assessments; and (2) discuss NRC staff-developed questions related to model and parameter selection criteria for evaluating the acceptability of the models and parameters for demonstrating compliance with the final rule on "Radiological Criteria for License Termination" (62 FR 39058). This workshop was one in a series designed to support NRC staff efforts in developing guidance for implementing the final rule on "Radiological Criteria for License Termination." The guidance will identify criteria for evaluating the acceptability of dose models and parameter values to demonstrate compliance with the final rule.

In support of this effort, NRC staff from the Offices of Nuclear Regulatory Research (RES) and Nuclear Material Safety and Safeguards (NMSS) jointly organized the 2-day public workshop on review of dose modeling methods. The workshop presenters (see "Agenda") included: NMSS and RES staff who discussed both dose modeling needs for licensing reviews, and development of guidance related to dose modeling and parameter selection needs; U.S. Department of Energy (DOE) national laboratory scientists who developed the Federally-sponsored dose models, and provided responses to earlier NRC staff-developed questions through presentations and discussions of their dose code (i.e., DandD, RESRAD, and MEPAS codes); and a U.S. Environmental Protection Agency (EPA) scientist who presented details on their dose assessment model (i.e., PRESTO code).

During the lunch hour and afternoon break on the first day of the workshop, computer demonstrations of the dose codes were provided to the attendees. More than 120 workshop attendees from NRC Headquarters and the Regions, Agreement States; as well as, industry representatives and consultants; scientists from EPA, U.S. Department of Defense (DOD), Defense Nuclear Facilities Safety Board (DNFSB), DOE and national laboratory; and interested members of the public participated. An official transcript of the workshop, including a listing of attendees, was placed in the NRC Public Document Room.

This NUREG/CP reports on the workshop proceedings in a more formal manner than the official transcripts by providing documentation of the technical papers presented. The technical papers, prepared by the invited speakers and their colleagues, after the meeting, address, in part, questions raised during their presentations, and in the panel discussions at the conclusion of the workshop. The NUREG/CP is also designed to provide technical bases and discussions to support development of the decommissioning guidance.

The NRC staff considered a range of dose models that may be appropriate for use in site-specific dose assessments for specific pathways. The goal of the workshop was to provide an overview of the dose models currently available for NRC staff to consider, when developing regulatory guidance for selecting dose models to be used in demonstrating compliance with the final rule on

"Radiological Criteria for License Termination." Additionally, the workshop provided an open forum to discuss: the capabilities, experiences and appropriateness of each dose model presented; information and methods available for selecting site-specific parameter values; and ideas for developing a minimum list of technical issues that need to be addressed and satisfied in an NRC licensee's request to use a site-specific screening and/or site-specific modeling dose code which go beyond the default screening model (i.e., DandD code). The workshop was not meant to discuss comparisons between the dose codes, nor to critically compare the dose models, but rather to simply allow the developer of each Federally-sponsored code to respond to NRC staff questions.

A series of questions were developed by a team of RES and NMSS staff to explore how appropriate the identified Federally-sponsored dose models are NRC staff needs. These questions were reviewed by NRC management and sent to the invited speakers. The speakers were requested to address the following questions in their presentations (and later in their technical papers, which are published in this NUREG/CP):

1. Please describe the history of the analytical method's development (e.g., Who developed it? For what purpose was it developed? Who were the sponsors? Is there documentation on the code such as a "users' manual?").

2. What transport mechanisms, scenarios, and exposure pathways are considered?

3. How are parameter values determined for input?
(Can uncertainties be incorporated into the parameter distributions and the subsequent dose calculations?)

4. What radionuclides and chemicals that can affect radionuclide transport are considered?
(Is decay and in-growth considered? to what extent?)

5. What are the time and spatial geometry limitations inherent in the analytical method?

6. To what extent can alternative remedial actions be assessed and compared (e.g., comparison of concentrations, doses, and costs)?

7. To what extent has the dose model been tested and included in bench-marking studies?

8. To what extent can the analytical method handle complex:
(a) source term characterization; (b) multiple source terms; (c) hydrologic and hydrogeologic conditions; (d) exposure pathway combinations; (e) remedial methods linked to cost and monitoring programs; and (f) ALARA considerations?

9. Does the dose model include software graphical output for portraying dose versus time for various exposure pathways and specified radionuclides and total effective dose equivalents (TEDE), including uncertainties?

10. Can the analytical method consider various restrictions on land use and site boundaries in calculating concentrations and/or doses, and in determining monitoring strategies?

The workshop followed the following agenda:

AGENDA

November 13

1:00 p.m.	Welcome and Introductions - Joseph Murphy, *Director, Division of Regulatory Applications, Office of Nuclear Regulatory Research (RES)/NRC*
1:15	Meeting Objectives and Review of Agenda - Cheryl Trottier, *Chief, Radiation Protection and Health Effects Branch, RES/NRC*
1:30	Dose Modeling Needs for Licensing Reviews - David Fauver, *Office of Nuclear Material Safety and Safeguards (NMSS)/NRC*
2:00	Development of Guidance Related to Dose Modeling and Parameter Selection Needs - Chris Daily, *RES/NRC*
2:45	BREAK
3:00	D&D Code - Theresa Brown, *Sandia National Laboratories (SNL)*
4:00	RESRAD Code - Drs. Charlie Yu and Ernesto Faillace, *Argonne National Laboratory (ANL), &* Andrew Wallo, *DOE*
5:00	ADJOURN

November 14

9:00 a.m.	Review Agenda and Announcements - Thomas Nicholson, *RES/NRC*
9:15	MEPAS Code - Drs. John Buck & Gene Whelan, *Pacific Northwest National Laboratory (PNNL)*
10:15	BREAK
10:30	PRESTO Code - Dr. Cheng Hung, *U.S. Environmental Protection Agency (EPA)*
11:30	LUNCH
1:00 p.m.	Panel Discussion on the Strategy for Moving from the NRC Baseline Screening Model - Jack Parrott, NMSS/NRC, Panel Moderator
	Panel: Theresa Brown, *SNL* — Charlie Yu, *ANL*
	John Buck, *PNNL* — Gene Whelan, *PNNL*
	Cheng Hung, *EPA* — Chris Daily, *RES/NRC*
	David Fauver, *NMSS/NRC* — Mark Thaggard, *NMSS/NRC*
2:30	BREAK
2:45	Resume Panel Discussion
4:45	Closing Remarks - John W.N. Hickey, *Chief, Low-Level Waste and Decommissioning Projects Branch, NMSS/NRC*
5:00	ADJOURN

An important component of the workshop was a panel discussion. The panel was comprised of the invited speakers plus NMSS staff working on decommissioning reviews (see panel members listed above, in the "Agenda"). The panel discussion objective was to provide NRC staff with technical information to consider during the development of guidance on site-specific modeling. The panel discussion, moderated by Jack Parrott, NMSS, was structured to: (1) provide both a review of the previous NRC staff presentations on the baseline screening model, and a summary of NRC staff licensing needs; (2) engage the panelists in a second series of questions prepared by the NRC staff and transmitted to them prior to the workshop (see below); and (3) open the discussion, on development of dose modeling guidance, to all workshop attendees.

Technical considerations provided to the panelists prior to the workshop included the following information and questions:

> "The guidance being developed by the NRC will recommend the critical modeling components that should be evaluated when moving from the DandD screening model, and default parameters, to site-specific modeling and parameters. The goal of the guidance is to ensure that NRC licensing decisions involving site-specific modeling are consistent, and to allow for a seamless transition from screening to site-specific modeling. This would include the underlying assumptions and justification required to support the site-specific analysis. The NRC is seeking recommendations for criteria which can be used for the acceptability of codes proposed for demonstrating compliance with the license termination rule on a site-specific basis.
>
> Questions to the panel:
>
> 1. What would be the strategy for moving from the NRC baseline screening model to your model, using site-specific information?
> In responding, please describe what suggestions you would give to the users of your code that would help them justify moving from the NRC baseline screening model to:
>   - alternative parameter values,
>   - alternative mathematical formulations,
>   - alternative conceptual models (i.e. changing, adding, or deleting pathways).
>
> Please also describe how the user of your code could maintain the concept of the critical group when moving to your code.
>
> 2. What information can you provide to the potential users of your software so that it meets basic software QA requirements, and so that modifications to the software are controlled?
>
> 3. With regard to software QA procedures, what information can you provide to potential users so that your code can be used with confidence to demonstrate compliance with regulatory requirements?"

Specific answers to these questions and others posed during the panel discussion are provided in the official workshop transcripts (available in the NRC Public Document Room). The panelists responses were also incorporated into each speaker's technical paper. These technical papers are presented in this NUREG/CP.

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FOREWORD

This technical proceedings report, NUREG/CP-0163, was prepared by the NRC staff, using formal technical papers prepared by the invited workshop speakers. The workshop objectives were to both provide the NRC staff and the public with an overview of currently available Federally-sponsored dose models appropriate for decommissioning assessments, and to discuss NRC staff-developed questions related to model and parameter selection criteria, for evaluating the acceptability of the models and parameters for demonstrating compliance with the final rule on "Radiological Criteria for License Termination" (62 FR 39058). This NUREG/CP reports on the public workshop proceedings in a more formal manner than do the official transcripts, which are available in the NRC Public Document Room, by providing documentation of the technical papers presented. The technical papers were prepared by the invited speakers and their colleagues after the workshop. These papers address, in part, questions raised during both; the invited speakers' presentations, and the panel discussion held at the conclusion of the workshop. NUREG/CP-0163 also provides technical bases supporting the development of decommissioning guidance.

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DOSE MODELING FOR THE LICENSE TERMINATION RULE

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INTRODUCTION

The U.S. Nuclear Regulatory Commission's new rule on radiological criteria for license termination consists of dose-based decommissioning limits, prudently conservative screening criteria, and a flexible approach to site-specific dose modeling. The staff is continuing to develop guidance for the use of dose modeling to demonstrate compliance with this new rule. A description of the dose modeling aspects of the new rule and an update on the development of guidance to implement the dose modeling will be presented here.

DECOMMISSIONING OPTIONS IN THE LICENSE TERMINATION RULE

The new rule allows a licensee to select which decommissioning option is best for its site, through the implementation of an unrestricted- or a restricted-use requirement. The basic terms of the new rule are that: (1) The unrestricted-use dose limit is 25 mrem/yr; (2) The restricted-use dose limits are 25 mrem/yr, with restrictions in place, and 100 mrem/yr assuming failure of restrictions; (3) There is a second restricted-use option, with dose limits of 25 mrem/yr, with restrictions in place, and 500 mrem/yr, assuming failure of restrictions, that contains more demanding requirements for implementing and maintaining the site restrictions.

THE LICENSE TERMINATION PROCESS

From a licensing perspective, the license termination process starts with comparison of site-

specific measurements with screening criteria. Screening criteria are essentially preapproved decommissioning limits, analogous to what are referenced now in the Site Decommissioning Management Plan action plan. The screening criteria will be radionuclide concentration limits in soil or activity per unit area limits on building surfaces. Essentially, the screening criteria will be an unrestricted use limit that is prudently conservative. Most NRC licensees, including sealed source users, radiographers, and users of short-lived isotopes, should be able to meet the limits in the screening criteria without further analysis to satisfy decommissioning requirements. More complex sites containing uranium or thorium, or significant levels of loose byproduct material contamination, will probably not meet the screening criteria.

One goal of the guidance for the license termination rule is to develop screening criteria that are conservative but not overly conservative, or bounding. The parameters being put into the screening criteria model are being reviewed closely. It is not intended that the screening criteria model will be applied to the maximally exposed individual, but, rather, to the critical group, as defined in the new rule.

If the site-specific measurements are above the screening criteria, the staff anticipates that licensees will perform site-specific dose assessments. Although site-specific dose assessments may not be necessary for most NRC licensees, the majority of the people attending this workshop are associated with complex sites that will require site-specific dose assessments.

FLEXIBLE SITE-SPECIFIC DOSE MODELING

The default parameters and scenarios that staff is establishing in the guidance will be used as baseline screening values, to begin the dose assessment process. However, the licensee may want to do site-specific modeling because, for example, the assumption of the presence of an onsite pond for fish consumption in the baseline scenario may not be appropriate because the site is in the desert. Or some other site-specific situation may exist where the licensee believes that it is justified to modify some of the defaults in the baseline scenario or parameters. The staff

believes that the most efficient way to get through the dose assessment process is to start with the assumptions in the screening scenario and then to reassess, if appropriate, and explain the reasons for the deviations from the baseline screening scenario. This is as opposed to starting the process from the site-specific situation by developing a set of parameters and scenarios from scratch, without considering the baseline situation.

The development of site-specific parameters and pathways that are not related to the baseline scenarios and parameters will raise many questions during the review, such as why the licensee is making certain assumptions in the model or why certain pathways are not included. Therefore, the staff believes that the dose assessment process needs to start with the baseline screening scenario and parameters and then, if needed, to justify changes to the pathways, to deal with the site-specific situations.

Site-specific modeling applies to both unrestricted and restricted use. After the preliminary evaluations, the licensee may find that, regardless of how much site-specific information is gathered, unrestricted use is not going to be a viable option because of the radionuclide concentrations present and the cost to remediate to an unrestricted-use level. In that case, a licensee may want to go to a restricted-use release.

There are two aspects of site-specific modeling to consider in a restricted-use situation. First, the licensee models the site with the assumption that the restrictions are in place. For example, if a licensee were to opt for onsite disposal, with 4 feet of cover, there would be a site-specific assessment for that configuration. That assumes that institutional controls will be maintained such that there will not be intrusion into the disposal. In that case certain pathways, such as a resident farmer consuming food grown onsite and breathing soil resuspended from the surface, may not be significant pathways whereas groundwater may be an important pathway. There is also the second requirement of a 100 mrem/year (or 500 mrem/yr) limit on dose for unrestricted use. This scenario would assume that there is intrusion into the disposal after a failure of institutional controls. In that case, the licensee will have to do site-specific dose assessment for

the unrestricted-use situation.

One could envision a situation where some other land use besides the baseline resident farmer scenario could be justified without restriction. However, staff has not fully developed which scenarios other than the resident farmer would be appropriate for the unrestricted-use situation. That is an issue that the staff will be working on over the next several months.

GUIDANCE DEVELOPMENT CHALLENGES

From a licensing perspective, reasonableness and efficiency need to be considered in the development of the dose modeling guidance. This will help the licensees comply with the regulation and, of course, help the staff do its job reviewing the dose modeling submittals. One of the challenges for staff is to develop, in a guidance document, NRC review criteria, for dose modeling, that will reasonably accept some site-specific parameters and site-specific situations, while also assuring the public that, over a 1000-year period, doses to the critical group will not likely exceed a certain level. If the guidance is developed correctly by the staff and followed closely by the licensees, there will be an efficiency in the dose modeling and review process. Therefore, NRC is being very careful in the process of developing this guidance, so that a reasonable review process will result.

There are other challenges with the development of this guidance. There is a optimization dynamic between the flexibility of the guidance and the level of effort (and therefore cost) of review for the regulator. The staff is aware of this dynamic and is trying to balance these two competing goals.

That's a brief overview of how dose modeling fits into the process of determining compliance with the dose criteria in the rule and staff's development of the guidance for the dose modeling. Staff is looking forward to this workshop and will use the information and comments presented here to help us refine and develop an efficient licensing process.

DEVELOPMENT OF GUIDANCE RELATED TO DOSE MODELING AND PARAMETER SELECTION NEEDS[1]

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Abstract

NRC staff and contractors are developing guidance on dose modeling and parameter selection needs to support implementation of the decommissioning rule. An overview is provided on the decision methodology and imbedded decision framework being developed by the NRC staff and contractors for implementing the decommissioning rule. Information is provided on how dose models may be used in the context of the proposed methodology for decommissioning assessments. Information and methods being developed for selecting default parameters or replacing default parameters in the DandD code are also presented.

Introduction

NRC staff and contractors are developing guidance related to decommissioning assessments including a decision methodology and framework for selecting and using dose models to demonstrate compliance with the final rule on "Radiological Criteria for License Termination" (62 FR 39058)(USNRC, 1997b). Additional background information on the license termination rule and its technical aspects are provided in the Generic Environmental Impact Statement (USNRC, 1997a). This paper provides information on the decision methodology, decision framework, modeling hierarchy, and parameter analysis process being developed as specific regulatory guidance documents in support of the license termination rule.

Work in Progress and Completed

Specific products being developed or completed for providing guidance on implementing the decommissioning rule include:

1. An outline of the decision methodology for selecting and using dose models in the process of decommissioning sites including information on screening approaches which

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[1]The information presented in this paper represents proposed draft guidance as of November, 1997. It is intended as a discussion of information under development and does not represent the final staff position on guidance for license termination.

will be presented in draft NUREG-1549;
2. The DandD software developed by Sandia National Laboratory (see Gallegos and others, 1998 in this NUREG/CP) which is being further refined and tested;
3. A method for selecting default parameters to use within DandD in screening;
4. A method for replacing default parameters in DandD which is also included in draft NUREG-1549;
5. Detailed documentation of scenarios, calculations, parameter distributions, and default parameter selection as presented in Volume 1 of NUREG/CR-5512 (Kennedy and others, 1992);
6. User's manual for the DandD software (NUREG/CR-5512, Volume 2) including information about the differences between the calculations listed in NUREG/CR-5512, Volume 1 and those in the updated DandD software; and
7. Documentation of parameter distributions that are used for developing default parameter values and the integrated process used for selecting the default values.

Since no model can work for all situations, the NRC staff also needs:

1. A method for evaluating dose assessments developed using other models (e.g., RESRAD and MEPAS);
2. Quality assurance and documentation criteria for evaluating dose assessments; and
3. Minimum criteria for parameter value selection for other models.

Decision Methodology

Figure 1 provides a simplified logic chart of the decision methodology being developed by the NRC staff and contractors. The diagram outlines the iterative approach for decision making, and provides a framework for progressing through the decommissioning process. For simple situations, licensees would progress from box 1 to box 7. This approach would be appropriate for using the DandD code with all of the default values, where a calculated dose of less than 25 mrem can be demonstrated. For such simple cases where the 25 mrem criteria is met, the process is relatively straightforward.

For more complicated cases where the initial pass through the decision methodology does not result in a calculated dose less than 25 mrem, the licensee would better define their situation by proceeding with an evaluation of decommissioning options such as additional site characterization, remediation, and/or restricted use (see box 8 in Figure 1). The process is designed to direct the analyst to consider options prior to making a decision as to restricted versus unrestricted release, and to utilize the most efficient path to decommissioning the site.

The decision methodology (to be presented in draft NUREG-1549) is an iterative process grounded in the real world. The methodology is not a simple pass/fail initial test in that if a licensee cannot demonstrate that the dose is below 25 mrem on the first pass, it does not mean they have failed the process, rather, it means that they are early in the process, and more analysis

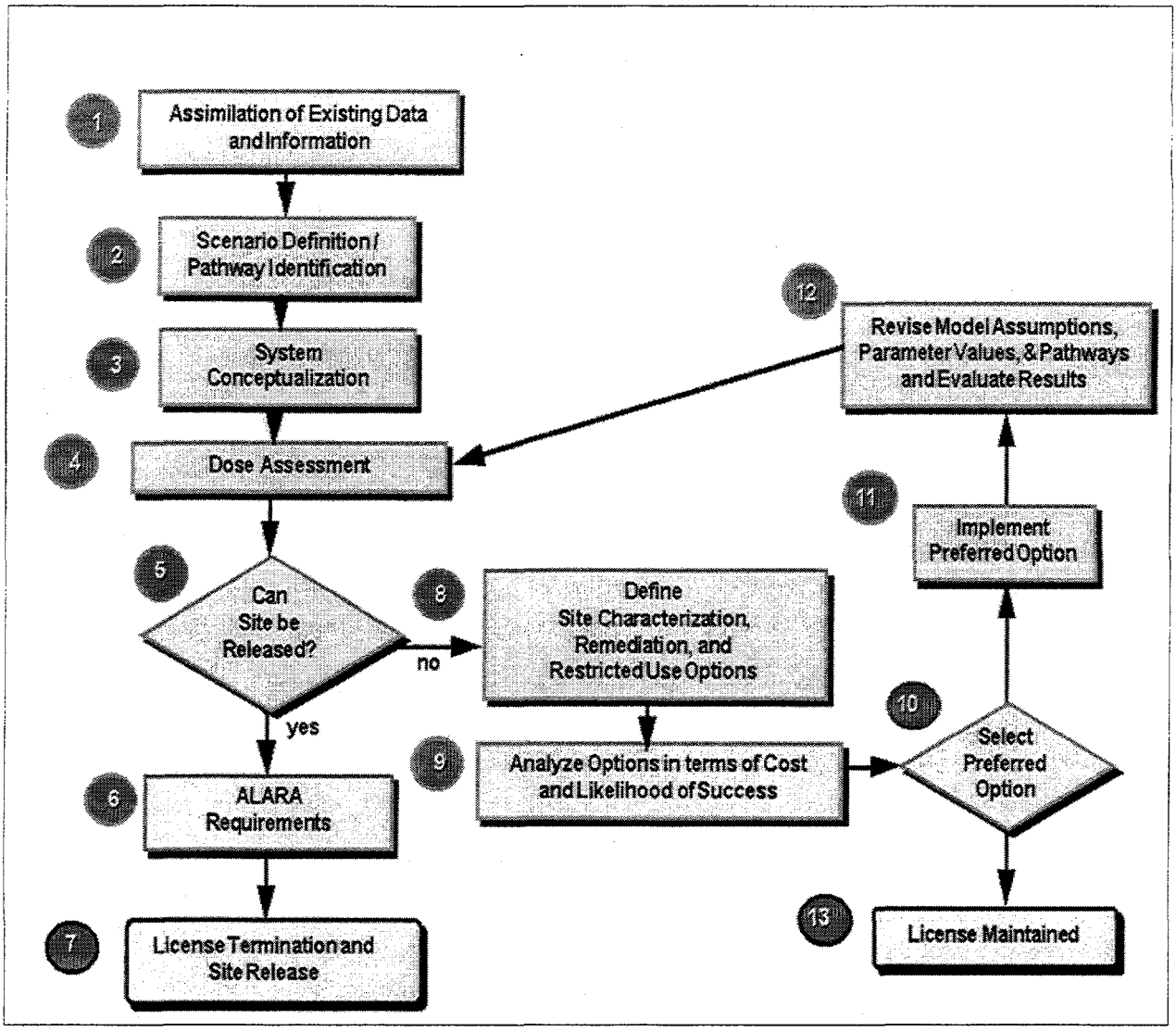

Figure 1. Logic diagram for the Decision Methodology.

needs to be performed. An underlying concept in this decision process is that as more site information is gathered, the uncertainty in the dose assessment is reduced, and the calculated dose should also decrease. The assumption is that initially in the screening process licensees do not have much detail on the site, and therefore the assessment should be relatively conservative. As application of the methodology progresses to utilize more site-specific information, the dose assessment becomes more realistic, and the calculated dose should decrease. Developing such a methodology allows for better optimization of decommissioning activities, balancing of costs and actions, and an efficient framework for moving through the decommissioning process.

The decision methodology provides a simple path for those sites which do not warrant a great

deal of analytical complexity. In addition, the methodology allows for the introduction of needed information in a gradual and more efficient manner. Being an interactive process, the methodology facilitates constructive dialogue among the regulators, stakeholders and licensees at appropriate points and in a realistic manner. The methodology provides a transparent and open approach for conducting and evaluating dose assessments for decommissioning reviews.

Purpose of the Screening Model Approach

The purpose of having a screening model is to have a baseline to begin the evaluation process. The first component is default screening using generic models. These default screening models are generic in nature so that the vast majority of sites will be covered. This simplified initial screening approach is warranted because it is easy to use and is cost effective since generic default parameters are used rather than site-specific data. It is also efficient for both the licensee and NRC staff reviewers since sites that pass the screening criteria do not need to collect and submit a lot of site-specific information. If this screening approach with generic defaults is used, there is a high assurance that the site actually meets the criteria and release of the license is appropriate.

The next phase is screening with site-specific data. The generic parameters and pathways are adjusted to be more site-specific. These adjustments may include modifications to, or elimination of whole pathways, and modification of specific parameters depending upon the site-specific information. The licensee can use inexpensive techniques to gather additional data. For example, additional information can come from low cost access to regional data such as soil types, depth to ground water, and parameter distributions from the U.S. Geological Survey or Agricultural Research Service. This relatively inexpensive regional data can help to reduce uncertainties in the parameters used in the model. The approach is based on prioritizing data collection, so that the most useful and inexpensive site-specific data is obtained first. For the first iterations though the decision methodology, any revised parameters should fall within the specific ranges associated with the generic default parameter distributions, otherwise additional uncertainty analysis may be required.

Modeling Hierarchy

A modeling hierarchy is embedded within the decision methodology. The hierarchy involves a range of modeling, from simple generic analysis to complex site-specific models.

1. Default Screening

The first level of analysis is default screening using generic models in which the NUREG/CR-5512 approach applies. NUREG/CR-5512 and accompanying information provides default scenarios, parameters and pathways to be considered. The only information needed is the site-specific source term.

2. Site-Specific Screening

The next level of analysis is site-specific screening using generic models in which pathways have been varied or eliminated, and certain default parameters may be replaced with site-specific values. Again, the NUREG/CR-5512 approach applies, but a range of site-specific information may be incorporated.

3. Site-Specific Modeling

The final and most complex level of analysis is site-specific modeling. This modeling approach allows for site-specific models, alternative scenarios, and any of the pathways or parameters that may be appropriate to the site and the site-specific source term. While it is expected that the NUREG/CR-5512 approach may not be appropriate for all sites and pathways, portions of the approach may be useful for specific locations and/or pathways for sites that use more complex modeling. In developing a site-specific model, one approach may be to use the relevant aspects of the NUREG/CR-5512 model, and replace only those pathways and parameters where more realistic analysis is needed to demonstrate compliance with the dose criterion. For example, only the ground-water pathway may need to be modeled in greater detail while the remaining pathways are modeled using the methodology as described in NUREG/CR-5512. For site-specific modeling, the licensee must propose a calculational approach for NRC approval. This approach should include an evaluation of uncertainty. NRC staff is in the process of developing additional information for site-specific modeling, including guidance on what kind of information would need to be provided and how it is to be organized. This methodology and guidance will be provided in the final NUREG-1549 and Regulatory Guide DG-4006 (USNRC, 1998).

Technical Basis Documents

The NRC staff and contractors are developing the technical bases and their documentation to support the decision methodology including models, scenario identification, parameter distributions, and default parameter selection. The following documents have either been issued, or are under development:

1. NUREG-1549 contains decision methods for dose assessment;

2. NUREG/CR-5512 Volume 1 documents the scenarios and calculations;

3. NUREG/CR-5512 Volume 2 will provide a user guide for the DandD software, and information on modifications made to the models and parameters outlined in Volume 1;

4. NUREG/CR-5512 Volume 3 will provide details on the parameter distributions, the selection methodology for developing default parameters, and the generic uncertainty analysis that is the technical basis for the selection of those default parameters.

Parameter Analysis

The parameter analysis process is designed to evaluate how the model and parameters work together for estimating the dose from residual radioactivity at the site. The underlying basis of the approach is that as the licensee proceeds from screening using default parameter values to site-specific modeling, the estimated dose should decrease. Uncertainty should be reduced by using site-specific information and data. It is assumed that the licensee can obtain a better (more realistic) estimate of the dose using site-specific models and data, and such an estimate will generally be lower than that calculated using generic models and parameters in the default screening approach. The additional resources required to obtain the more realistic dose estimate need only be expended if necessary to demonstrate compliance with the dose criterion or to support a more detailed evaluation of decommissioning options.

The parameter analysis process was developed to determine if the combination of assumptions and input data lead to results that are consistent with the intended use of the code. When moving from defaults to site-specific data, or modifying pathways, new information should generally not result in an increase in the calculated dose. The technical approach identifies default parameter sets that limit the probability that the site-specific maximum total effective dose equivalent (TEDE) would exceed the default analysis maximum TEDE. For example, if all defaults are used, the calculated dose should be higher than the dose that would be calculated if any or all of the parameters were changed or pathways were modified. The process should provide assurance that even if the maximum TEDE calculated in the site-specific model exceeds the maximum TEDE determined by the default analysis, the difference would be small.

One objective in conducting this parameter analysis is to support a finding that the final default parameters are prudently, but not excessively, conservative. The analysis is also attempting to quantify what prudently conservative means. For example, in assessing residential and building scenarios, the NRC staff is determining the range and distribution for default parameters, and is performing analyses for all radionuclides and all pathways. The parameter analysis will assist in defining the default parameter values, valid parameter ranges, and combinations for replacement parameters. The analysis will also assist in determining when uncertainty assessments are needed.

Another important question to be addressed in the parameter analysis is: Given multiple valid sets of default parameter values, how can the default parameter set be chosen? One approach being pursued is to choose a parameter set where parameter values are least extreme within the criteria of selecting prudent, rather than maximum conservative values, and where all parameters within the set are as equally conservative as possible and meet an objective, reproducible criterion.

Method for Replacing Default Parameters for DandD

The proposed method for replacing default parameter values with site-specific information and/or

data for the DandD code will be documented in Volume 3 of NUREG/CR-5512 and NUREG-1549. The technical basis for identifying the default parameters presently used will be discussed in Volume 3 of NUREG/CR-5512. The process for modifying parameters, eliminating pathways, and eventually moving to other models will be discussed in NUREG-1549. The proposed method will support the decision framework approach of reducing uncertainty by applying additional data. The initial approach will allow limited substitutions, and modifications within certain limits. The licensee can proceed up to full site-specific uncertainty analysis.

References:

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USNRC, "Demonstrating Compliance with Radiological Criteria for License Termination," Regulatory Guide DG-4006, U.S. Nuclear Regulatory Commission, Washington, DC, February 1998 (available in electronic form only at http://techconf.llnl.gov/radcri/java.html).

Use of DandD for Dose Assessment Under NRC's Radiological Criteria for License Termination Rule

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ABSTRACT:

The Decontamination and Decommissioning (DandD) software package has been developed by Sandia National Laboratories for the Nuclear Regulatory Commission (NRC) specifically for the purpose of providing a user-friendly analytical tool to address the dose criteria contained in NRC's Radiological Criteria for License Termination rule (10 CFR Part 20 Subpart E; NRC, 1997). Specifically, DandD embodies the NRC's screening methodology to allow licensees to convert residual radioactivity contamination levels at their site to annual dose, in a manner consistent with both 10 CFR Part 20 and the corresponding implementation guidance developed by NRC. The screening methodology employs reasonably conservative scenarios, fate and transport models, and default parameter values that have been developed to allow the NRC to quantitatively estimate the risk of releasing a site given only information about the level of contamination. Therefore, a licensee has the option of specifying only the level of contamination and running the code with the default parameter values, or in the case where site specific information is available to alter the appropriate parameter values and then calculate dose. DandD can evaluate dose for four different scenarios: residential, building occupancy, building renovation, or drinking water. The screening methodology and DandD are part of a larger decision framework that allows and encourages licensees to optimize decisions on choice of alternative actions at their site, including collection of additional data and information. This decision framework is integrated into and documented in NRC's technical guidance for decommissioning.

1 INTRODUCTION

DandD is intended to be implemented within the structure of NRC's decommissioning decision framework (to be documented in NUREG-1549[1]). This framework is described in Section 2 of this document. This framework allows for NRC control of the risk of releasing sites erroneously,

[1] " Methods for Dose Assessment to Comply With Radiological Criteria for License Termination," NUREG-1549, U.S. Nuclear Regulatory Commission, Washington, DC (in preparation).

while at the same time not being overly restrictive in their requirements for site remediation. Licensees would be allowed to define the most cost-effective decommissioning and license termination strategy by evaluating alternative actions at their site, including possible reductions in uncertainty that would reduce overall remediation costs. Because of the nature of the DandD models and default parameter values, the NRC would not expect licensees to define concentration clean-up levels based on preliminary DandD dose calculations that fail to meet 10 CFR Part 20 dose criteria; instead, licensees would be encouraged to evaluate the cost of added information and the value it adds in better defining remedial actions.

In general, the objective of the software, Decontamination and Decommissioning (DandD), is to provide a user-friendly and somewhat automated interface to the Nuclear Regulatory Commission's (NRC) dose assessment and screening methodology for site assessment against the Radiological Criteria for License Termination Rule in 10 CFR Part 20 Subpart E [NRC, 1997]. DandD assists NRC licensees who have requested termination of their license and who, in some cases, must decontaminate lands and structures as part of the decommissioning process. The software does this by providing a tool that allows licensees to translate residual radioactive contamination levels at their site into total effective dose equivalent (TEDE) by analyzing and modeling the set of NRC-prescribed scenarios of future land-use. DandD contains models of the transport and exposure pathways associated with each of the scenarios, requiring only information on source concentration from the user. The user may, if they choose, supply site-specific information on other parameters (e.g., physical properties of the site) if available and defensible.

Specifically, DandD is the software implementation of NRC's screening methodology transport and exposure models for assessing human health and safety against the dose requirements set forth in 10 CFR Part 20 Subpart E [NRC, 1997]. For this discussion, screening refers to the release of a site where little or no site-specific information is known or used, other than level of contamination. To provide useful and defensible screening level calculations, the NRC has developed reasonably conservative scenarios, pathway models, and parameter values, and has implemented these in DandD. "Reasonably conservative" implies that the calculated doses are more likely to be overestimates of the actual dose rather than accurate estimates or underestimates, but at the same time are not necessarily worst case estimates. As a result, the scenarios and models implemented in DandD are relatively simple. To perform these screening calculations, the DandD software automates the scenarios, models, mathematical formulations, and assumptions documented in NUREG/CR-5512, Volume 1 [Kennedy and Strenge, 1992] and Volume 2[2]. The generic modeling approach defines radiation exposure scenarios to address residual radioactive contamination inside buildings, in soils and in ground water. For buildings, two scenarios are presented. The scenarios relate either volume or surface contamination levels to estimates of the annual TEDE received during each year of exposure with the conditions defined in the scenarios.

For the simplest level of analysis (previously referred to as Level 1 screening), the user is required to provide a minimum amount of site-specific information. In general, only information about source concentration is required for their site for this level of analysis. This level of analysis has

[2] Residual Radioactive Contamination From Decommissioning, User's Manual, NUREG/CR-5512, Volume 2, U.S. Nuclear Regulatory Commission, Washington, DC (in preparation)

effectively been automated in DandD, and therefore provides certain licensees with a simple and cost-effective method to demonstrate compliance. This level of analysis uses deterministic values for all model parameters. At the final release of DandD Version 1.0, the default parameter values will have been defined through a systematic process of assessing the variability of each parameter and then defining default values that produce generic dose estimates that are unlikely to be exceeded at any real site. The derivation and final values of the default parameter values for DandD Version 1.0 will be discussed in NUREG/CR-5512, Volume 3[3] (i.e., default parameter values in NUREG/CR-5512, Volume 1 will not be used).

If a licensee has site-specific information for certain parameters, they may choose to replace the default parameter values with alternative values, and employ the default transport and exposure models. This level of analysis, which can easily be conducted with DandD, was previously referred to as Level 2 screening. Licensees are not required to conduct the "Level 1" screening calculations prior to proposing changes to parameter values.

As discussed above, the default parameter values for the NUREG/CR-5512 modeling (which are implemented in DandD) are based on probability distributions representing the variability across the country for physical parameters, and within the screening group for behavioral and metabolic parameters. As a consequence, the licensee would likely need little supporting information to defend significant changes to the parameter values. This approach of moving away from the "reasonably conservative" values used in the NUREG/CR-5512 modeling could be used by all sites until the point that further reduction in simulated dose would require model changes. This would necessarily require the licensee to step away from using DandD. For example, those models might be multi-dimensional flow, transport or exposure models. At that point, new model parameter values would have to be developed and supported by the licensee.

DandD produces reports in NRC-defined and accepted text and graphics formats that will allow the NRC to efficiently assess compliance with the 10 CFR Part 20 dose criteria and to determine if more detailed modeling should be required.

2 USE OF DandD WITHIN THE NRC D&D DECISION FRAMEWORK

A logical, consistent decision process is viewed as a useful tool that will support licensee planning of decommissioning activities and NRC review of license termination requests. To support this process, a decision methodology has been developed to support implementation of the dose assessment requirements in 10 CFR Part 20 Subpart E (see Figure 1). The decision process encourages an assessment of the entire range of dose modeling options from which a licensee may choose, from changing a single parameter to changing multiple parameters and modifying pathways or models.

[3] Residual Radioactive Contamination From Decommissioning, Parameter Analysis, NUREG/CR-5512, Volume 3, U.S. Nuclear Regulatory Commission, Washington, DC (in preparation)

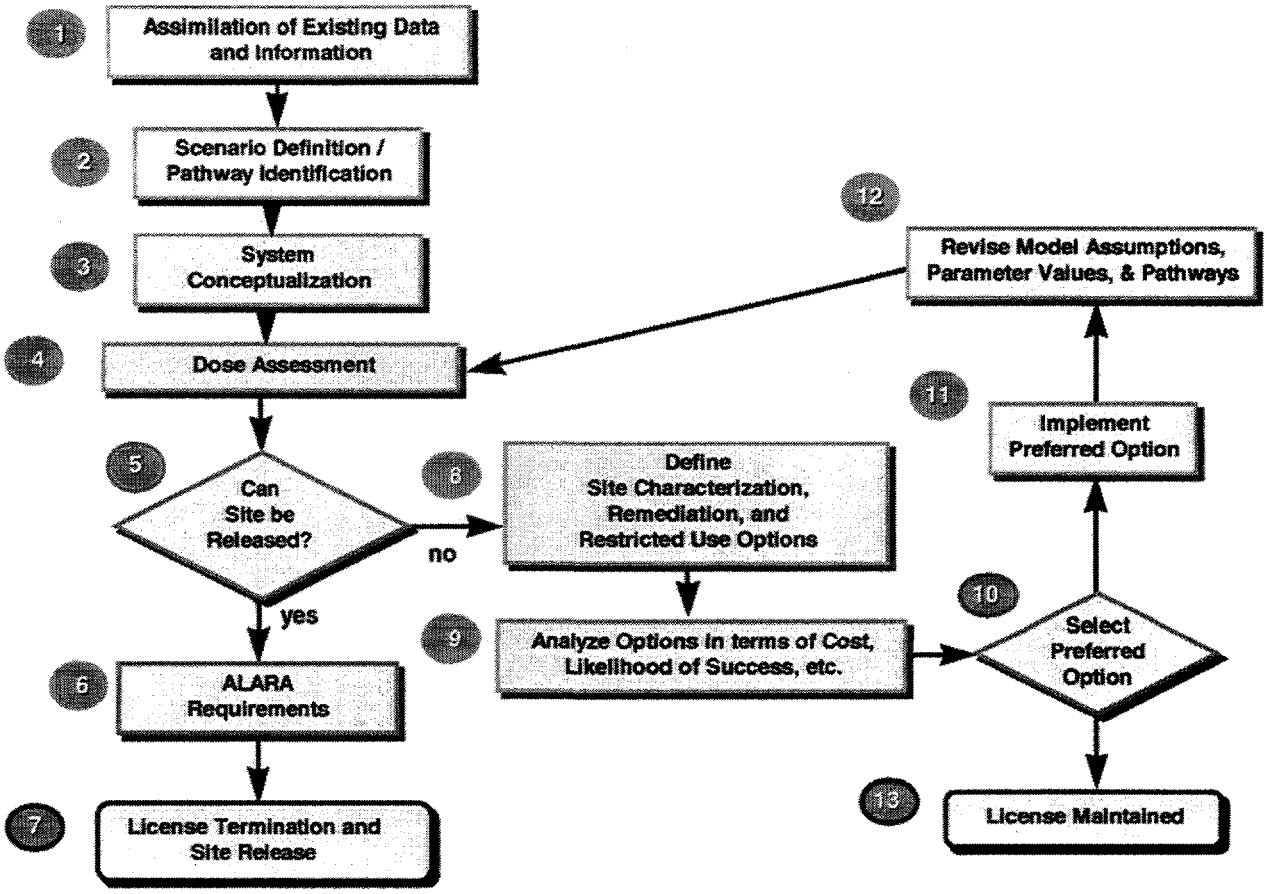

Figure 1 - NRC decommissioning decision framework

As discussed above, generic exposure scenarios and pathways have been defined based on the NUREG/CR-5512 methodology [Kennedy and Strenge, 1992] and can be used by licensees who are applying the default scenarios and parameters using the DandD software. The default screening scenarios and pathways provide the licensee with a simple method of demonstrating compliance using little site-specific information. The generic models and default parameters are intended to estimate a reasonably conservative value of the dose that the average member of the critical group could receive. The default parameters were developed probabilistically to control the risk associated with releasing a site based on source term data alone. Figure 2 illustrates where portions of the framework have been predefined for the "Level 1" screening analyses. Figure 2 also illustrates where DandD can be used to execute certain steps in the process. These will be discussed under each step below.

For licensees with more complex decommissioning situations, the decision process supports the modification of model parameters to allow site specific factors to be taken into account while still using the default models. This allows a licensee to use site-specific values in place of some or all of the default parameters. Thus, the new dose estimates will have a high likelihood of being lower than the previous estimates, but should still have a high likelihood of being lower than the actual

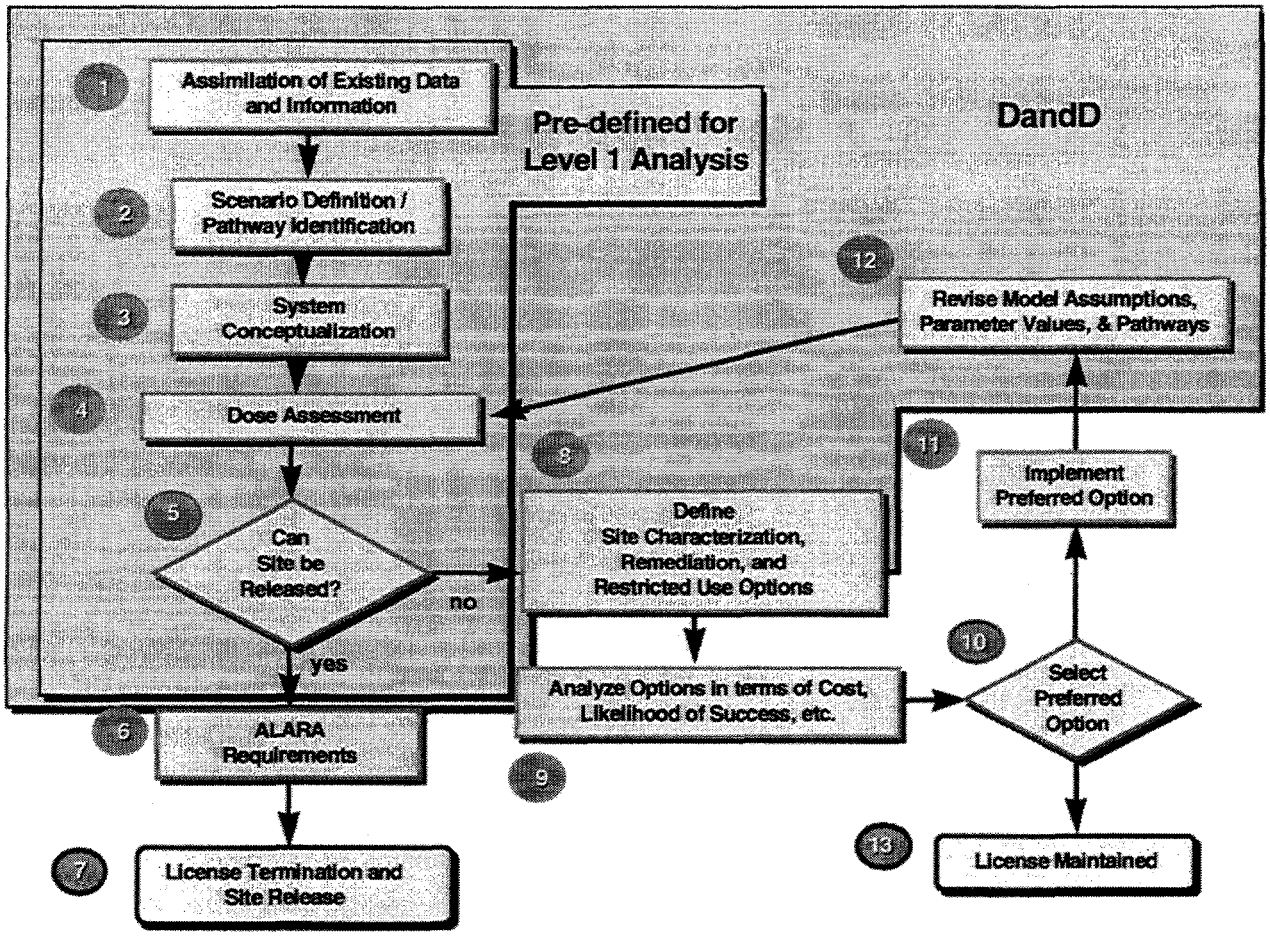

Figure 2 - Implementation of DandD and Level 1 screening in decision framework

dose for a particular site based on the use of the default models. The site specific data are used to support modifying or eliminating a particular scenario or pathway, or to demonstrate that a parameter or group of parameters can be better represented by site specific values. Alternative exposure scenarios may be appropriate based on site-specific factors that affect the likelihood and extent of potential future exposure to residual radioactivity.

Step 1: The first step of the decision process involves gathering and evaluating existing data and information. Licensees must provide information regarding the types and amounts of radioactive material they possessed on their site. The licensee may start the process with other defensible site-specific information (e.g., physical properties of the site), and can input this information into the DandD code, either through modifications to default parameter values or through elimination of pathways.

Step 2: The second step in the decision process involves defining the scenarios and pathways that are important for the site dose assessment. For a generic application, this step has already been completed by the NRC, based on the generic scenarios and pathways for screening that have been

defined and described in NUREG/CR-5512, Volume 1 [Kennedy and Strenge, 1992].

These generic scenarios and pathways have been implemented in the DandD code. The four exposure scenarios are:

- residential,
- building occupancy,
- building renovation, and
- drinking water.

In the NUREG/CR-5512 methodology, and in DandD, the exposure pathways for the building scenarios are external exposure, inhalation exposure, and secondary ingestion. The residential scenario considers external exposure, inhalation, and the following ingestion pathways: drinking water, food grown from irrigation water, land-based food, soil, and fish. The types of land-based food considered for the residential scenario are leafy vegetables, other vegetables, fruit, grain, beef, poultry, milk, and eggs. Three types of animal feeds are considered: forage, stored grain, and stored hay. The drinking water and residential scenarios use a simple three-box water-use model to account for radionuclide decay, progeny ingrowth, and environmental transport. The three boxes (or layers) in the water-use model are the surface soil, unsaturated soil, and the aquifer.

Step 3: This step involves system conceptualization, which includes conceptual and mathematical model development and assessment of parameter uncertainty. For a generic application, this step has already been completed by NRC (i.e., the models described in NUREG/CR-5512, Volume 1). In addition, these models and the default parameter values have been automated and implemented in the DandD software. For more complex sites, licensees may use site-specific conceptual and mathematical models.

Step 4: This step involves the dose assessment for the site, which means running the DandD or other appropriate models with the applicable site-specific source term.

The framework is designed such that the level of complexity and rigor of analysis conducted for a given site should be commensurate with the level of risk that the site poses. Although all sites are expected to step through Steps 1 through 7, the amount of work that goes into each of these steps should be based on the expected levels of contamination and the health risks they pose. For example, a site with a sealed source would obviously not be expected to conduct calculations (if any) that are the same complexity as a site with extensive soil and groundwater contamination.

Step 5: The fifth step is the first major decision point in the methodology, and involves answering the question of whether the dose assessment results are less than the dose criterion of 25 mrem/yr in 10 CFR Part 20, Subpart E. DandD provides graphical and text output of TEDE to evaluate the results of the analysis. In addition, the user can view the dose history for any radionuclide, for all radionuclides, and for any path within a given scenario.

IF THE RESULT IN STEP 5 IS THAT THE CALCULATED DOSE IS LESS THAN OR EQUAL TO 25 mrem/y, THEN:

Step 6: If the result in Step 5 is that the 25 mrem/y criterion has been met, the licensee can proceed to satisfy any remaining ALARA requirements. Conducting ALARA analyses and evaluating if the doses are ALARA are beyond the scope of the DandD software.

Step 7: In this step the final documentation is completed, including documenting any survey results used to calculate the source term and the results of the dose calculations. DandD provides a written report in a format that is acceptable for NRC's review and evaluation of the site's ability to meet the dose criteria in 10 CFR Part 20.

IF THE RESULT IN STEP 5 IS THAT THE CALCULATED DOSE IS GREATER THAN 25 mrem/y, THEN:

Step 8: The purpose of this step is to define options for proceeding with the license termination process. Note that the framework would not recommend that a licensee define concentration clean up goals after the initial iteration of simple dose calculations until other options have been evaluated that could reduce the calculated doses and the cost of remediation, if it is necessary at all. There are basically three options that the licensee could apply either alone or in combination: Option 1 - Activities that reduce uncertainty (information/data collection), Option 2 - Activities that reduce contamination (remediation), and Option 3 - Activities that reduce exposure (land-use restrictions).

Only a limited number of sites will need to perform complex dose assessment and options analyses, with most sites performing an options analysis that is relatively simple and straightforward. For example, a site with a small, contained source of contamination that is obviously simple to remove would not perform extensive analyses on large suites of alternative data collection and remediation options. The same may be true for certain complex sites, where the configuration of the contamination, site conditions, or regulatory requirements cause the options for proceeding forward to be relatively limited and straightforward. The sites which will benefit the most from this options analysis are those with complex contamination situations where this process can be used to analyze a variety of simple and complex options and define the most effective and cost-efficient decontamination and decommissioning strategy.

The first option, activities that reduce uncertainty, begins by looking at the default parameter values in the NUREG/CR-5512 model and what they represent. The default parameter values for the NUREG/CR-5512 modeling (that have been implemented in DandD) are being developed based on probability distributions representing the expected variability across the country. A probabilistic parameter analysis is being performed to select a set of default parameters that meet the NRC's requirements to control the risk associated with releasing a site based only on source term information. The risk is controlled by NRC selecting screening parameters that, as a set and within the context of the specified model, provide a specified level of confidence that the dose estimate will go down as more site specific information is used in modeling. In addition, the parameters are selected in a manner that controls the amount by which the dose could exceed the

screening dose. The parameter analysis also provided information regarding the valid ranges for site specific parameter changes that a license could propose without an additional uncertainty analysis. As a consequence, the licensee needs less supporting information to defend changes to the parameter values that are within the limits specified in the parameter analysis. This is important in evaluating the relative worth of collecting additional data on these parameters under Step 9.

The second option listed above is based on actual reduction of the quantity of residual radioactivity remaining on the site. Information that may be useful for evaluating this option is contained in the final environmental impact statement for 10 CFR Part 20, Subpart E (NUREG-1496) and DG-4006. If the third option, reduction of exposure, is pursued, the licensee is required by 10 CFR Part 20, Subpart E, to demonstrate that unrestricted release is not ALARA. This is discussed in Regulatory Guide DG-4006.

DandD can be used to a certain extent under Step 8 to identify certain options by evaluating the consequences of possible reductions in uncertainty or possible reductions in contamination.

Step 9: This step involves the analysis of options, primarily in terms of cost and the likelihood of success. To evaluate the likelihood of success, an analysis of the potential outcome (consequence analysis) will need to be performed for each of the options identified in Step 8. The consequence analysis should be no more complex than necessary to support a reasonable and cost-effective evaluation of the options. The cost and time required to complete each option must be estimated, and the analysis should also address the uncertainty associated with each potential outcome. The desired endpoint is a determination of the likelihood or probability that carrying out a given option will result in meeting the criteria of 10 CFR Part 20, Subpart E.

The result of the activities performed under Step 9 is a logically organized list of options, and the corresponding cost, likelihood of site release (probability of success), and other important considerations given that the option is pursued. In some cases, the decision regarding the preferred option will be obvious; for example, a low cost of success and failure, high probability of success option will generally be selected over a high cost, low probability of success option, assuming the regulatory requirements are equal. However, the preferred option will not always be obvious, and additional analysis may be required for sites attempting to balance complex issues. At this point in the decision process, the idea is not to permanently eliminate options from further consideration, but rather to select the optimum approach under the current state of knowledge.

This step in the decision framework should support an evaluation of the cost and time impacts of both success and failure. Generally, low cost / high likelihood of success options, or combinations of options, are preferred. This step should also include ALARA considerations (see DG-4006), in terms of cost/benefit calculations as well as qualitative considerations. With regard to costs, the licensee should consider that if the option(s) selected are successful, the license will be released and further costs will be minimized. However, if the selected option(s) are unsuccessful, it may be necessary to perform additional characterization or remediation, or there may need to be an evaluation of restricted use (with its associated costs).

Generally, Step 9 is outside the scope of DandD.

Step 10: Once the various options have been evaluated, the preferred option can be selected. This step is outside the scope of DandD.

[**Step 13**: For those rare situations where the licensee is unable to meet the criteria of 10 CFR Part 20, Subpart E, it may be necessary to maintain the license. Consequently, this step does not represent a permanent resolution, but an interim action until the problem can be resolved.]

Step 11: Under this step, the preferred option is implemented. For example, if additional site characterization was the selected option, this is the step where the data collection would be performed. This Step is outside the scope of DandD.

Step 12: Once the preferred option has been implemented, the model assumptions, parameter values, and pathways (as appropriate) are revised. Within DandD, this may mean a change in a deterministic parameter value (default or otherwise), or an elimination of a pathway through the appropriate parameter changes. If a specific scenario can be defensibly ruled out, then it is simply not analyzed in DandD. To support a future request for license termination, any site survey results, parameter data, or laboratory tests should be carefully documented.

Step 4: The revised source term and parameter values are used in the next iteration of the dose assessment. Depending on the application, the licensee can leave the original default model assumptions and pathways unchanged, and continue to use the DandD software. Note that in other more complicated situations a licensee might seek to modify these assumptions and pathways or apply different models (and hence different codes/software).

Step 5: The revised dose assessment is performed to determine if the calculated dose meets the requirements in 10 CFR Part 20, Subpart E.

IF THE CALCULATED DOSE IS STILL GREATER THAN 25 mrem/y, THE LICENSEE PROCEEDS ONCE AGAIN TO STEP 8.

If the calculated dose is less than or equal to 25 mrem/y, the licensee can proceed with license termination as described in DG-4004.

3 WORKSHOP QUESTIONS

This section addresses the specific questions posed prior to and during the "Workshop on Review of Dose Modeling Methods for Demonstration of Compliance with the Radiological Criteria for License Termination."

3.1 Question 1

Please describe the history of the analytical method's development (e.g., who developed it)? For what purpose was it developed? Who were the sponsors? Is there documentation on the code such as a "Users' Manual"?)

The Decontamination and Decommissioning (DandD) software package has been developed by Sandia National Laboratories for the Nuclear Regulatory Commission (NRC) specifically for the purpose of providing a user-friendly analytical tool to address the technical dose criteria contained in NRC's Radiological Criteria for License Termination rule (10 CFR Part 20 Subpart E; NRC, 1997). Specifically, DandD embodies the NRC's screening methodology to allow licensees to convert residual radioactivity contamination levels at their site to annual dose, in a way consistent with both 10 CFR Part 20 and the corresponding implementation guidance developed by NRC. The computational and analytical portion of DandD implements the scenarios and models found in NUREG/CR-5512, Volume 1 [Kennedy and Strenge, 1992]. The final Users' Manual for DandD is in preparation and should be completed in 1998[2].

3.2 Question 2

What transport mechanisms, scenarios, and exposure pathways are considered?

Within DandD, the transport mechanisms, scenarios, and exposure pathways have been defined by the NRC, based on the generic scenarios and pathways for screening that have been developed and described in NUREG/CR-5512, Volume 1 [Kennedy and Strenge, 1992].

The four generic exposure scenarios implemented in DandD are:

- residential,
- building occupancy,
- building renovation, and
- drinking water.

In the NUREG/CR-5512 methodology, and in DandD, the exposure pathways for the building scenarios are external exposure, inhalation exposure, and secondary ingestion. The residential scenario considers external exposure, inhalation, and the following ingestion pathways: drinking water, food grown from irrigation water, land-based food, soil, and fish. The types of land-based food considered for the residential scenario are leafy vegetables, other vegetables, fruit, grain, beef, poultry, milk, and eggs. Three types of animal feeds are considered: forage, stored grain, and stored hay. The drinking water and residential scenarios use a simple three-box water-use model to account for radionuclide decay, progeny ingrowth, and environmental transport. The three boxes (or layers) in the water-use model are the surface soil, unsaturated soil, and the aquifer.

Because of concerns about potential ground-water contamination from residual radioactive contamination in soil, a generic water-use model was developed to permit evaluation of the annual TEDE for drinking water from wells (drinking water scenario). The generic water-use model was

also used in the evaluation of multiple pathways associated with contaminated soil. The generic treatment of potentially complex ground-water systems provides a conservative analysis that may only suggest when additional site data and more sophisticated modeling are warranted.

3.3 Question 3

How are parameter values determined for input? (Can uncertainties be incorporated into the parameter distributions and the subsequent dose calculations?)

The default parameter values for the NUREG/CR-5512 modeling (implemented in DandD) are being developed based on a probabilistic analysis using input parameter distributions representing the expected variability across the country. A probabilistic parameter analysis was performed to select a set of default parameters that meet the NRC's requirements to control the risk associated with releasing a site based only on source term information. Risk is defined as the risk that a site will be released when it exceeds the dose criterion. The risk is controlled by selecting screening parameters that, as a set and within the context of the specified model, provide a specified level of confidence in the dose estimate and control the amount by which the dose could exceed the criterion. The parameter analysis also provided information regarding the valid ranges for site specific parameter changes that a license could propose without an additional uncertainty analysis.

For the screening calculations that use the default parameter values, it is important to note that uncertainty has implicitly and quantitatively been incorporated in the analysis because of the nature of the process used to define the defaults. For user supplied changes to the default parameter values, DandD restricts the range of possible values that can be input. The NRC and SNL are presently conducting analyses to evaluate the uncertainty in output when alternative parameter values are used. In addition, the NRC will provide guidance for altering parameter values and accounting for uncertainty.

3.4 Question 4

What radionuclides and chemicals which can affect radionuclide transport are considered? (Is decay and in-growth considered? To what extent?)

DandD includes all 224 NRC-listed radionuclides and automatically models chain decay and ingrowth of daughters. The code gives the user options on how to report doses from progeny including reporting implicit progeny doses separate from the parent or reporting implicit progeny doses as part of the parent doses. The code does not model the fate and transport of hazardous chemicals.

3.5 Question 5

What are the time and spatial geometry limitations inherent in the analytical method?

Certain analytical practical limits have been incorporated in the DandD code to constrain the evaluation period. For the residential scenario, although the regulatory time period is 10^3 years,

the maximum analysis time is 10^6 years. For the building occupancy scenario, although the typical analysis period is 1 to 70 years, the analytical maximum in the code is again 10^6 years.

In terms of spatial considerations, the system geometry is defined by NUREG/CR-5512 transport process models [see Kennedy and Strenge, 1992]. In general, the user cannot modify system geometry in DandD, although pathways may be eliminated through modifications in parameter values. In addition, for the residential scenario, the user may specify the number of different layers in the unsaturated zone. Spatial geometry is not considered in many cases due to the nature of the models.

3.6 Question 6

To what extent can alternative remedial actions be assessed and compared (e.g., comparison of concentrations, doses, and costs)?

Multiple executions of DandD can be used to compare alternative parameter values and the corresponding concentration levels to provide the necessary resulting doses that would result in compliance with 10 CFR Part 20. These analyses are contingent upon the model assumptions inherent in DandD. Based on these resulting proposed cleanup levels, estimates can be developed outside of DandD for the cost to collect the necessary data and the costs of remediation. However, because of the nature of the DandD models and default parameter values, the NRC would not expect concentration clean-up levels to be defined based on preliminary DandD dose calculations that fail to meet 10 CFR Part 20 dose criteria; rather, the cost of added information and the value it adds in better defining remedial actions should be provided.

DandD is intended to be implemented within the structure of NRC's decommissioning decision framework (documented in NUREG-1549[1]). This framework is described in Section 2.0. This process has been defined to allow the NRC to control the risk of releasing sites erroneously, while at the same time not being overly restrictive in the requirements for site remediation. This would allow licensees to define the most cost-effective decommissioning and license termination strategy by evaluating alternative actions at their site, including possible reductions in uncertainty that would reduce overall remediation costs.

3.7 Question 7

To what extent has the dose model been tested and included in bench marking studies?

Final functional testing of the DandD software is currently in process. Testing and documentation are expected to be completed by March, 1998. Extensive testing of baseline models was completed in 1994. A beta test of the software was conducted and completed in 1996. Documentation of the results of this beta test is expected to be published in early 1998. Extensive testing of the user interface has been completed and will be documented in the final test report. A model comparison is planned for 1998, where the DandD model assumptions will be compared against other dose code model assumptions. DandD has not been included in any formal bench marking studies.

3.8 Question 8

*To what extent can the analytical method handle **complex**: (a) source term characterization; (b) multiple source terms; (c) hydrologic and hydrogeologic conditions; (d) exposure pathway combinations; (e) remedial methods linked to cost and monitoring programs; and (f) ALARA considerations.*

3.8.1 Source Term Characterization

The source term in DandD is treated through deterministic input of radionuclide source concentrations (activity/area or activity/volume). It is expected that the licensee would conduct an evaluation of the source outside of DandD to define the deterministic input value for input into the code. DandD then assumes a homogeneous source concentration across the entire area or volume of the appropriate scenario. The NRC has developed guidance (DG-4006) for licensees to define source concentrations for use in DandD.

3.8.2 Multiple Source Terms

Multiple source terms would be handled in DandD in one of two ways. In the first, different sources may be superimposed and equivalent source concentrations defined. DandD would then evaluate the composite effect of all the sources. In the second approach, different sources could be evaluated within DandD independently. Total dose may be derived from the sum of the independent analyses or this information may be used to guide options identification for data collection or remediation. Because of the nature of the transport and exposure models in DandD, multiple sources cannot be treated as spatially distributed.

3.8.3 Hydrologic and Hydrogeologic Conditions

The site hydrologic and hydrogeologic conditions in DandD are based on the transport models in NUREG/CR-5512, Volume 1. Certain hydrogeologic conditions may be altered by changes in parameter values; however, alternative models are not possible in DandD, except through elimination of scenarios, pathways, and assumptions by changes in parameter values. Increased complexity in hydrologic and hydrogeologic conditions is expected to be handled by following the D&D Decision framework and identifying where increased complexity is supportable with site-specific information and where it is necessary and appropriate.

As an alternative, DandD does allow the user to import concentrations in the groundwater that have been derived from another model. In this case, the user would conduct flow and transport calculations outside of DandD, and derive from these calculations, a representative groundwater concentration that is then read into DandD. The pathway transport calculations in DandD then proceed as before.

3.8.4 Exposure Pathway Combinations

Multiple simultaneous pathways are automatically handled in DandD (see Sections 2 and 3.8.2). The source is partitioned among the different pathways based on the process models and parameter values. DandD reports doses from all pathways and radionuclides combined, dose from each radionuclide, and dose from each pathway. Pathways may be eliminated in DandD by defining appropriate parameter values.

3.8.5 Remedial Methods Linked to Cost and Monitoring Programs

Remedial methods linked to cost and monitoring programs are outside the scope of DandD; however, it is expected that these would be treated through implementation of the NRC Decision Framework

3.8.6 ALARA

Based on the ALARA analysis requirements described in DG-4006, DandD is capable of conducting the individual dose portion of the analysis. Cost modeling would be conducted outside of DandD.

3.9 Question 9

Does the dose model include software graphical output for portraying dose versus time for various exposure pathways and specified radionuclides and total effective dose equivalents including uncertainties?

DandD provides the following output, in both graphical and text formats:

- TEDE vs. time for each isotope
- TEDE vs. time for each pathway
- calculation of time and magnitude of maximum TEDE
- simultaneous display of all or any TEDE vs. time curves

The software allows the user to alter the graphical output if desired. There is no explicit treatment or display of uncertainty within DandD, except in the process that has been used to derive default parameter values, where uncertainty has been explicitly treated.

3.10 Question 10

Can the analytical method consider various restrictions on land use and site boundaries in calculating concentrations and/or doses, and in determining monitoring strategies?

DandD can be used to conduct dose calculations during the period when site land-use restrictions fail, in which the compliance assessment would be against restricted release dose criteria defined in 10 CFR Part 20.1403. In this case, the user would likely be assuming that the NRC default scenarios were operable. DandD can also be used to conduct dose calculation during the period

when restrictions are in place by eliminating or altering pathways appropriately. As with any other code, this would be acceptable if the model assumptions in DandD are appropriate and defensible. In the case of determining monitoring strategies, the DandD output can be used to quickly define important pathways and nuclides that contribute most to dose.

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NRC (U.S. Nuclear Regulatory Commission) (1997a), Radiological Criteria for License Termination; Final Rule, Federal Register: July 21, 1997, Volume 62, Number 139, pp. 39057-39092.

U.S. NUCLEAR REGULATORY COMMISSION DOSE MODELING WORKSHOP, NOV. 13–14, 1997, RESRAD MODEL PRESENTATION

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ABSTRACT:

RESRAD was one of the multimedia models selected by the U.S. Nuclear Regulatory Commission (NRC) to include in its workshop on radiation dose modeling and demonstration of compliance with the radiological criteria for license termination. This paper is a summary of the presentation made at the workshop and focuses on the 10 questions the NRC distributed to all participants prior to the workshop. The code selection criteria, which were solicited by the NRC, for demonstrating compliance with the license termination rule are also included. Among the RESRAD family of codes, RESRAD and RESRAD-BUILD are designed for evaluating radiological contamination in soils and in buildings. Many documents have been published to support the use of these codes. This paper focuses on these two codes. The pathways considered, the databases and parameters used, quality control and quality assurance, benchmarking, verification and validation of these codes, and capabilities as well as limitations of these codes are discussed in detail.

1 INTRODUCTION

On November 13–14, 1997, the U.S. Nuclear Regulatory Commission (NRC) conducted a workshop on radiation dose modeling and demonstration of compliance with the radiological criteria for license termination. The RESRAD model, developed at Argonne National Laboratory (ANL) for the U.S. Department of Energy (DOE), was one of the models the NRC selected to include in the workshop. The RESRAD model and code are used to derive site-specific guidelines for allowable residual concentrations of radionuclides in soil and to calculate doses, risks, and guideline values (Yu et al. 1993b). Argonne's presentation focused on the 10 questions the NRC distributed to all participants prior to the workshop. The NRC also asked participants to suggest criteria for selecting code for demonstrating compliance with the license termination rule. On the basis of its experience in developing and using computer models for decontamination and decommissioning, Argonne recommended the following criteria for selecting computer code for demonstrating compliance with the license termination rule:

- Code should have a users' manual and other supporting materials documenting its methodology and databases/parameters.

- Code should be benchmarked, verified, and undergo quality assurance (QA) and quality control (QC) procedures.

- Code should be easy to use and the results reproducible.

- Code should have a state-of-science dose conversion factors (DCFs) database and transfer factors database.

- Code should be able to evaluate both soil and building contamination.

- Code should address both volume and surface contamination with varying thicknesses and areas, with or without cover.

- Code should address time-dependent processes such as ingrowth and decay, in both the source and during transport in the environment.

- Code should address radionuclide-dependent processes such as leaching, transfer, and migration (retardation).

- Code should support estimations of both individual dose and average collective dose and risk.

- Code should include, or allow users to construct, all potential exposure scenarios.

- Code should have the capability to accommodate modification of parameters as well as selection/suppression of pathways.

- Code should be able to perform sensitivity analysis and probabilistic uncertainty analysis.

- Code should have specific models for special radionuclides (e.g., tritium, carbon-14, and radon-222 and radon-220) that behave differently in the environment and in buildings.

- Code should have a sufficient radionuclide database, and it should be easy to add radionuclides if needed (under QA/QC conditions).

2 ARGONNE'S RESPONSES TO NRC QUESTIONS

The following sections present the questions asked by the NRC regarding the RESRAD code and Argonne's responses.

2.1 Question One

1. *Please describe the history of the analytical method's development (e.g., who developed it? For what purpose was it developed? Who were the sponsors? Is there documentation on the code such as a "users' manual"?).*

Development of the RESRAD model and code was initiated in the early 1980s. The code has evolved into its present form as a result of extensive reviews, application experience, and scientific development. The model and code were developed as integral parts of DOE guidelines for control of residual radioactive material issued as interim guidance in 1984–85; incorporated into the DOE public and environmental radiation protection directive, Order DOE 5400.5 in 1990; and proposed as part of Title 10, Part 834 of the *Code of Federal Regulations* (10 CFR 834) in 1993.

During 1983 and 1984, DOE conducted workshops to support the development of its guidelines for controlling residual radioactive material. The workshops were attended by representatives from DOE (Offices of the Secretary, Nuclear Energy, Defense Programs, Energy Research, General Counsel and Environment and Policy and DOE field offices); the national laboratories (Argonne, Los Alamos, Oak Ridge, and Pacific Northwest); industry (The Aerospace Corp.; Bechtel National, Inc.; Bendix Field Engineering; EG&G; Jacobs Engineering; and UNC Nuclear Industries); the U.S. Environmental Protection Agency (EPA); and the NRC. These workshops resulted in the development of draft interim guidelines issued for review and comment in 1984. The interim guidelines contained generic soil concentration criteria (based on models that were predecessors of RESRAD) that were to be the maximum concentration levels that could not be exceeded and that would be subjected to the ALARA (as low as reasonably achievable) process to determine how far below the criteria authorized limits for a cleanup should be set. The generic soil concentration criteria approach was generally found to be unacceptable because of its inflexibility and because it was difficult to address ALARA requirements without specifically estimating like doses to populations associated with alternative cleanup limits. Current DOE requirements and the RESRAD model and code were developed on the basis of experience associated with early effects.

DOE used input from field and program elements attempting to apply the interim guidelines to determine that a standardized dose/ALARA-based approach would be the most flexible and cost-effective way to establish protective authorized limits for the release of DOE real property. Initially, DOE guidelines simply required that authorized limits for the release of property be developed to be as low as is reasonably achievable below the 100 mrem per year

primary dose limit. Later guidance recommended the use of a dose constraint of about one quarter of the primary dose limit as the cap for the ALARA analysis to ensure that multiple sources would not result in public exposures exceeding the "all sources" primary dose limit.

The RESRAD code was developed for use in conducting dose assessments and supporting ALARA process analyses necessary to meet DOE requirements. The initial criteria used by DOE to develop the RESRAD model and code were as follows:

- The model
  - must be sufficiently flexible to handle multiple radionuclides, all significant pathways, numerous land uses, and various spatial configurations and other site-specific considerations.
  - should be based on the best peer-reviewed science available.
  - should be able to handle special radionuclides such as tritium, carbon-14, and radon.
- The code implementing the model should
  - run on computer systems readily available to DOE and DOE contractors.
  - be user friendly.
  - be validated and verified.
  - be fully documented.
  - permit sensitivity analyses for various parameters.
  - output dose estimates or soil guidelines.
  - provide graphical output as a function of time, pathway, and radionuclide.
  - default parameters should be selected so as not to underestimate potential doses should they be used for screening assessments in lieu of site-specific factors; *guidance, however, should encourage site-specific analysis and discourage the use of default parameters.*

Subsequently, the following criteria for code were added, on the basis of user input and DOE needs.

- should estimate both risks and doses.

- should be capable of uncertainty analyses, graphical output dose distributions, and deterministic values.

- should be capable of evaluating indoor building contamination in addition to outdoor soil contamination.

Several national laboratories and DOE program offices were involved in the initial development of the code. Argonne spearheaded the development effort, and DOE was the sole sponsor of the project.

RESRAD is designed for evaluating sites that contain residual radioactive material. It can be used to derive contaminated site cleanup criteria and for site screening and pre- and postremediation dose/risk assessment. It is designed with user-friendliness and flexibility in mind. Initially, the RESRAD code was developed on the IBM main frame computer and was later converted to a PC code. After several years of testing and evaluation, the first version of the RESRAD PC code was published in June 1989, along with a users' manual (Gilbert et al., 1989) that documents the methodology used in the code and the DOE guidelines for residual radioactive material. These guidelines were revised, and in 1990, they were issued as part of DOE Order 5400.5. On the basis of input from DOE and non-DOE users, including the NRC and the EPA, the code and model were updated and several supporting documents were prepared to aid in the use of the RESRAD code. These include the *RESRAD Data Collection Handbook* (Yu et al., 1993a), *Compilation of Radionuclide Transfer Factors* (Wang et al., 1993), *RESRAD Sensitivity Analysis* (Cheng et al., 1991), *RESRAD Benchmarking Against Six Radiation Exposure Pathway Models* (Faillace et al., 1994), and *Verification of RESRAD* (Halliburton, 1994). The RESRAD code is continually maintained and updated under control of a DOE-approved QA plan. An updated users' manual (Yu et al., 1993b) was published in September 1993; a new update of the manual is planned for 1998.

RESRAD is designed for evaluating soil contamination. Another code, RESRAD-BUILD is designed for evaluating indoor building contamination. The RESRAD-BUILD code was also developed by Argonne for DOE. A users' manual (Yu et al., 1994) was published in November 1994, and a draft RESRAD-BUILD Data Collection Handbook is under development.

In addition to the RESRAD and RESRAD-BUILD codes, ANL developed several codes in the RESRAD series for DOE. These codes are shown in Figure 1. RESRAD-CHEM includes special models for volatile compounds and dermal absorption pathways. RESRAD-BASELINE was developed to perform baseline risk assessments in accordance with EPA human health risk

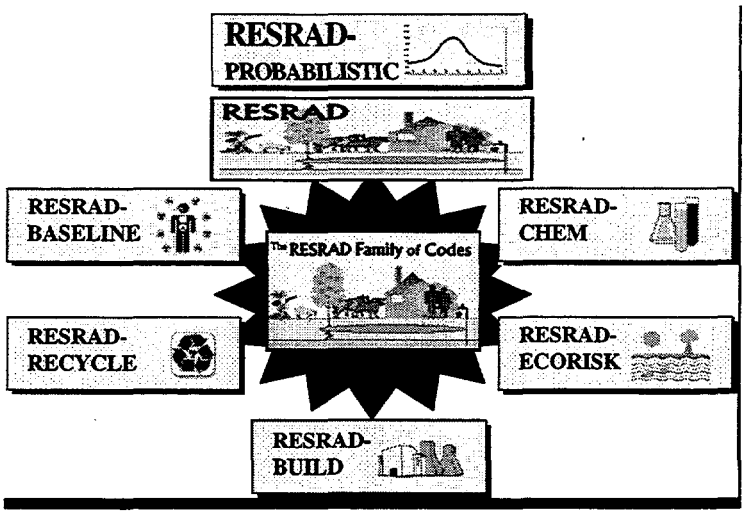

Figure 1. The RESRAD Family of Codes

assessment guidelines. The RESRAD-BASELINE database contains both radionuclides and chemicals. RESRAD-RECYCLE estimates radiation doses to various receptors resulting from the recycle and/or reuse of radioactively contaminated materials/equipment. RESRAD-ECORISK estimates the risk to ecological receptors from contaminant exposure. The RESRAD-Probabilistic code was developed to quantify uncertainties associated with predicted doses and risks. The probabilistic code has been incorporated into the RESRAD, RESRAD-BUILD, and RESRAD-RECYCLE codes.

2.2 Question 2

2. What transport mechanisms, scenarios, and exposure pathways are considered?

2.2.1 RESRAD

In the RESRAD code, the initial source of contamination is assumed to be radionuclides in soil; however, measured concentrations of radionuclides in a downgradient well or pond can also be entered. The code will calculate (predict) contaminant concentrations in various media and pathways.

Up to nine exposure pathways can be modeled in RESRAD: direct exposure to external radiation from contaminated soil material; internal dose from inhalation of airborne radionuclides, including radon progeny; and internal dose from ingestion of plant foods grown in the contaminated soil and irrigated with contaminated water, meat and milk from livestock fed with contaminated fodder and water, drinking water from a contaminated well or pond, fish (and other aquatic organisms) from a contaminated pond, and contaminated soil. These pathways and

the transport among environmental media are shown in Figure 2. The transport mechanisms considered in the RESRAD code are listed in Table 1.

The code may be used to analyze doses to on-site individuals under current or plausible future land uses of the site. The default land use scenario in RESRAD assumes an on-site subsistence farmer with all exposure pathways active. By suppressing selected pathways and modifying applicable intake or occupancy parameter values, the user may simulate any number of potential scenarios such as (but not limited to) recreational, industrial, and residential. Two scenarios that may be modeled in RESRAD are shown in Figures 3 and 4. Doses to off-site individuals may be modeled by following the recommendations in the users' manual. These models are being incorporated in a version of the code that will calculate off-site doses and risks directly.

In most cases, the code should be applied to chronic exposure scenarios with durations of one year or more, particularly for those scenarios with food pathways. However, the code may also be used to assess short-term exposures from external gamma, inhalation, soil, and water ingestion pathways.

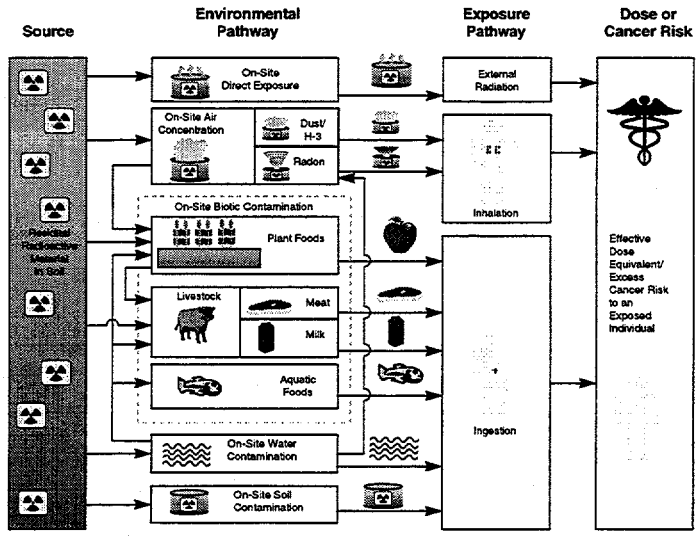

Figure 2. Graphical Representation of Pathways Considered in RESRAD

Table 1. Transport Mechanisms Considered in RESRAD

Transport Mechanism	Media	Affected Exposure Pathways
Leaching	Soil→water	All pathways
Advection	Water	Water-dependent pathways
Mixing with uncontaminated soil	Soil	Water-independent pathways
Erosion (source loss only)	Soil→water/air	All pathways
Resuspension	Soil→air	Inhalation of particulates; ingestion of plant, meat, and milk
Diffusion	Soil→air	Inhalation of radon
Off-gassing	Soil→air	C-14 pathways
Evapotranspiration	Soil→air	Tritium pathway
Bioaccumulation	Water→aquatic organisms	Ingestion of aquatic organisms
Root uptake	Soil→plant	Ingestion of plant, meat, milk
Foliar deposition	Air→plant	Ingestion of plant, meat, milk
Irrigation	Water→plant	Ingestion of plant, meat, milk
Photosynthesis	Air→plant	C-14 pathways
Electromagnetic (gamma, x-ray) and charged particle (beta) transport	Soil→human	External
inhalation	Air→human	Inhalation of particulates, radon, $^{14}CO_2$, HTO
Ingestion	Soil→livestock	Meat, Milk
	Water→livestock	Meat, Milk
	Plant→livestock water→ human	Meat, milk
	Soil→human	Water
	Plant→human	Soil
	Meat→human	Plant
	Milk→human	Meat
	Aquatic organisms →human	Aquatic organisms
Dermal Absorption	Air→human	Tritium pathway

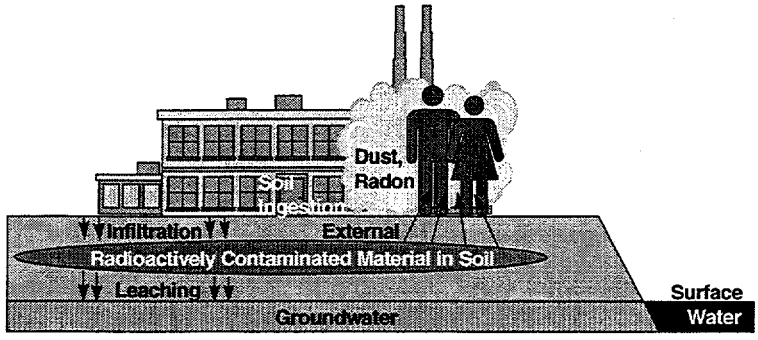

Figure 3. Schematic Representation of Exposure Pathways in a Typical Industrial Use Scenario

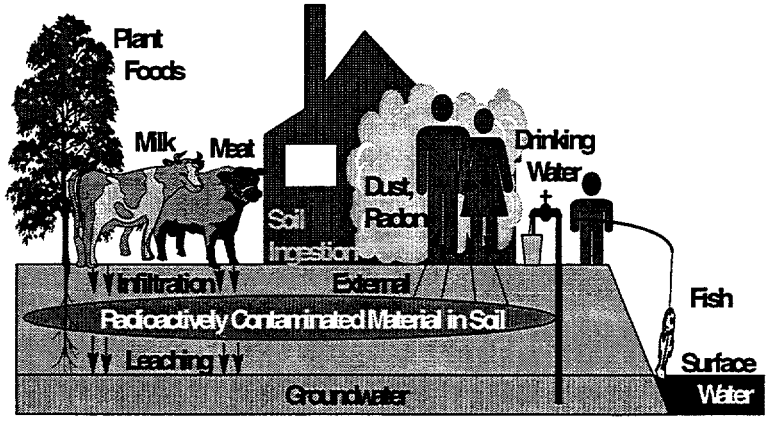

Figure 4. Schematic Representation of Exposure Pathways in a Typical Subsistence Farming Scenario

2.2.2 RESRAD-BUILD

In RESRAD-BUILD, an individual may be exposed to a source through up to seven exposure pathways, as shown in Figure 5 and listed below:

- External exposure directly from the source,
- External exposure due to air submersion,
- External exposure to materials deposited on the floor,
- Inhalation of airborne radioactive particulates,
- Inhalation of aerosol indoor radon progeny (in the case of radon predecessors),

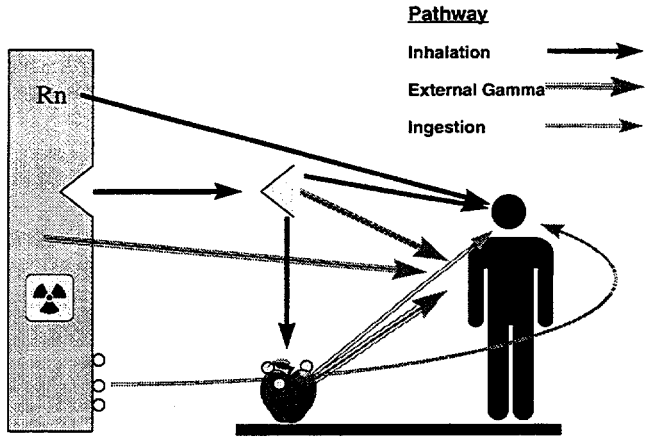

Figure 5. Graphical Representation of Pathways Considered in RESRAD-BUILD

- Inadvertent ingestion of radioactive material directly from the source, and

- Inadvertent ingestion of radioactive materials deposited on the surfaces of the building compartments.

Contaminants may move from the source to the receptor by the various transport mechanisms outlined in Table 2.

RESRAD-BUILD may be used to assess a number of different exposure scenarios related to building activities. The code may be used as a scoping tool in preparation for decontamination activities and estimates both individual and collective doses to cleanup workers. It can be used to derive cleanup criteria under occupancy or renovation scenarios. Finally, it can be used as a tool for ALARA, by assessing the dose impact of the no-action alternative versus different remedial activities.

2.3 Question 3

3. *How are parameter values determined for input? (Can uncertainties be incorporated into parameter distributions and the subsequent dose calculations?)*

Table 2. Transport Mechanisms Considered in RESRAD-BUILD

Transport Mechanism	Media	Affected Exposure Pathways
Erosion/air release fraction (volume source only)	Source→air	All pathways
Removable fraction/ lifetime/air release fraction (all other source types)	Source→air	All pathways
Diffusion (volume source only)	Source→air	Inhalation of radon, tritium
Radon release fraction (all other source types)	Source→air	Inhalation of radon
Plate-out	Free state →surfaces	Inhalation of radon
Attachment	Free state→particulates	Inhalation of radon
Decay with recoil	Surfaces→free state Particulates→free state	Inhalation of radon
Electromagnetic (gamma, x-ray) and charged particle (beta) transport	Source→human Surface→human	External External
Ventilation	Air	All air-dependent pathways
Deposition	Air→surfaces	All air-dependent pathways
Resuspension	Surfaces→air	All air-dependent pathways
Inhalation	Air→human	Inhalation of particulates, tritiated water vapor, and radon
Ingestion	Source→human Surfaces→human	Direct ingestion Indirect ingestion
Dermal absorption	Air→human	Tritium

2.3.1 RESRAD

The database included in the RESRAD code consists of two categories of parameters: contaminant-specific and site- or scenario-specific.

The first category includes parameters that are not modified frequently, but may be changed and saved in a user-specific data file. These data include decay and ingrowth functions, DCFs, cancer risk slope factors, and biological transfer factors (plant/soil, meat/fodder, milk/fodder, fish/water, other aquatic organisms/water). The defaults for these parameters are conservative and are derived from federal guidance reports (Eckerman, et. al., 1988; Eckerman and Ryman, 1993; EPA, 1994) or literature searches (Wang et al., 1993). Figure 6 shows a typical RESRAD screen for these parameters. Data are available for 84 radionuclides with half-lives greater than or equal to one month.[1] Some radionuclides were added at the request of the NRC.

[1] The user may select from two sets of radionuclide databases based on a half-life cutoff. The default database is for 67 radionuclides with half-lives greater than six months.

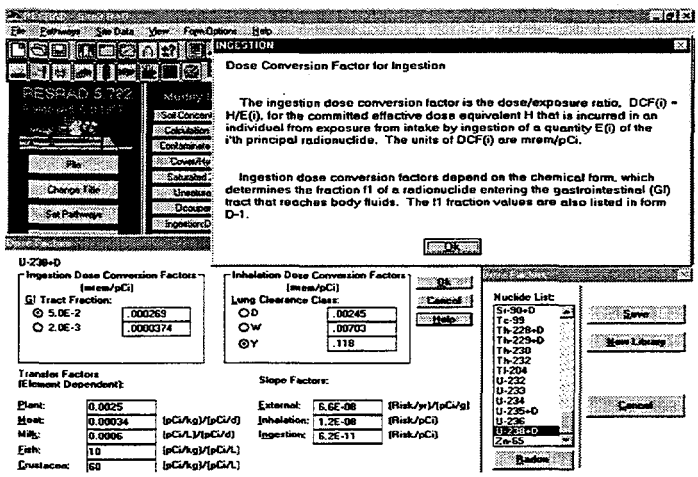

Figure 6. Typical RESRAD Dose Factor Library Screen

For those radionuclides with short-lived decay products, the latter are assumed to be in secular equilibrium with their parent and are accounted for implicitly in the dose or slope factors of the parent.

For the second category of parameters, RESRAD provides a default set of more than 150 parameters representative of national averages or reasonable maximum values for a subsistence farming scenario. Any of these parameters may be modified to reflect site-specific conditions and are grouped as follows (examples are shown in parentheses):

- Physical parameters (size, depth, density, porosity, diffusion coefficient)
- Hydrological parameters (hydraulic conductivity, gradient, soil b parameter, water table depth)
- Geochemical parameters (distribution coefficient, leach rate, solubility)
- Meteorological parameters (precipitation, evapotranspiration, erosion, runoff, mass loading)
- Usage and consumption parameters (inhalation, irrigation, ingestion, occupancy)

The *Data Collection Handbook* (Yu et al., 1993a) and the *Compilation of Parameter Distribution* (Yu et al., 1997) provide guidance on selecting site- and scenario-specific input values. RESRAD reduces the amount of parameter data input required from the user by only allowing access to those parameters used to calculate doses from a particular pathway. For

example, if the food ingestion pathways are suppressed, the consumption rates for plants, meat, milk, or fish are rendered inaccessible (see Figure 7).

Two tools are provided to account for variability and uncertainty in parameter values. Both the sensitivity analysis and uncertainty analysis tools may be used by the licensee to establish priorities for gathering input data; they may also be used by the regulator to determine the parameters that should receive attention.

RESRAD uses graphic output to illustrate the effects of variability in a single parameter on the response (e.g., dose as a function of time). The sensitivity analysis feature allows the user to enter a factor that will be used to multiply and divide the base parameter value (Figure 8). Sensitivity analysis can be performed on almost all input parameters, with up to five parameters per run. The code then graphically calculates the sensitivity of the result due to the variation of each parameter's values and holds all other parameters at their base value (Figure 9).

The uncertainty analysis feature (Figure 10) allows the user to assign one of five distribution types (normal, lognormal, uniform, loguniform, and triangular), along with the associated statistical parameters for the distribution (e.g., mean, standard deviation, minimum, maximum), to two or more parameters. The user may also correlate two or more dependent parameters. The code then samples these distributions and performs a user-selected number of runs. The results (dose/risk as a function of time) are presented both statistically (minimum, maximum, average, standard deviations) and graphically in Figures 11 and 12.

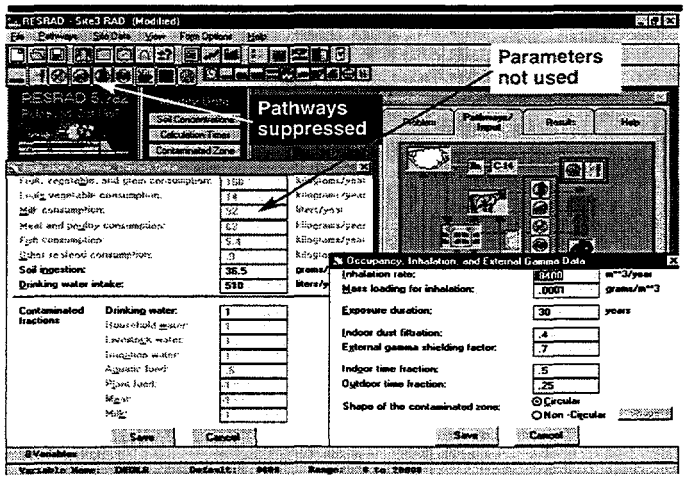

Figure 7. Typical RESRAD Site-Specific Parameter Input Screen

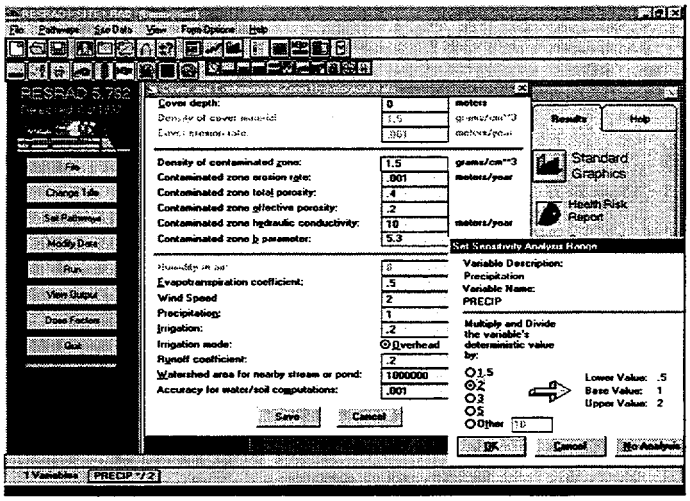

Figure 8. Typical RESRAD Sensitivity Analysis Input Screen

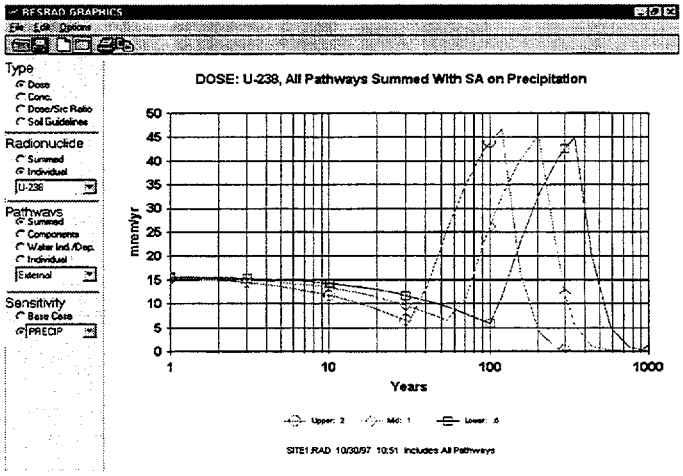

Figure 9. Typical RESRAD Sensitivity Analysis Graphical Output Screen

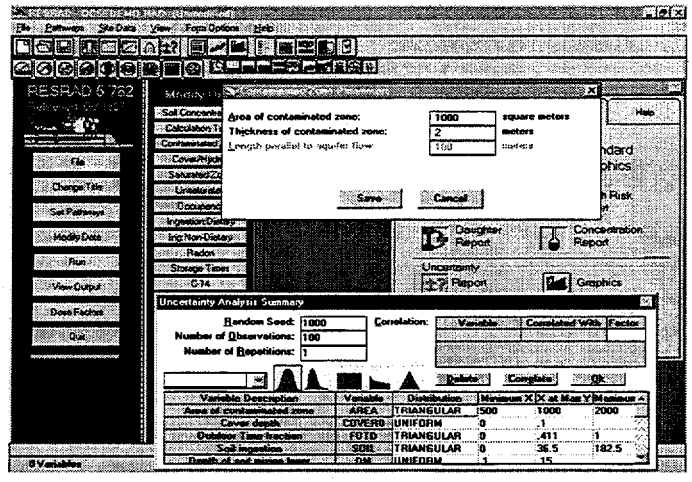

Figure 10. Typical RESRAD Uncertainty Analysis Input Screen

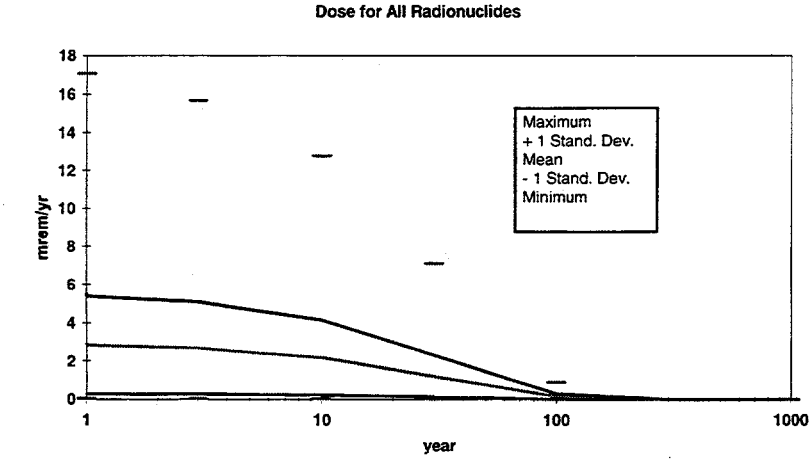

Figure 11. Typical RESRAD Uncertainty Analysis Graphical Output Screen — Statistical Distribution of Results

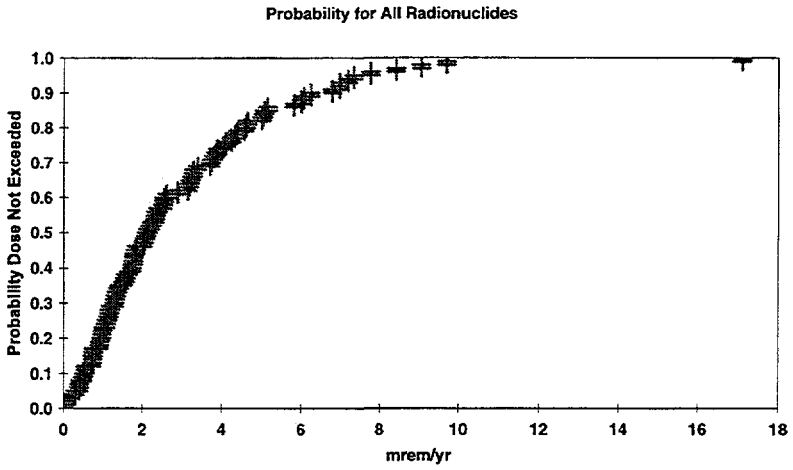

Figure 12. Typical RESRAD Uncertainty Analysis Graphical Output Screen — Cumulative Probability Distribution of Results

2.3.2 RESRAD-BUILD

The contaminant-specific database for RESRAD-BUILD is consistent with the RESRAD database, with the exception of the transfer factor library, which is not required in performing dose assessments for building scenarios.

Over 40 site- and scenario-specific parameters are used in RESRAD-BUILD. These can be grouped as follows (with examples in parentheses):

- Temporal parameters (total time, indoor fraction, receptor time fraction),
- Spatial parameters (source and receptor coordinates, number of rooms),
- Air flow parameters (air exchange rates, room dimensions, deposition velocity, resuspension rate),
- Shielding parameters (thickness, density, material, orientation),
- Source characteristics (radionuclide concentration, source type, dimensions, direction, removal rate, air release fraction, radon parameters, and tritium parameters), and
- Receptor characteristics (inhalation and ingestion rates).

The defaults included in RESRAD-BUILD are based on a generic occupancy scenario. Because of high variability in building properties, sources, receptors, and scenarios that can be modeled, most default values should be replaced with site- and scenario-specific values. A data collection handbook is being prepared to assist users in gathering the required input data. RESRAD-BUILD does not have a sensitivity analysis feature; it does, however, have the same uncertainty analysis feature as the RESRAD code.

Figure 13 shows a typical parameter input screen from the RESRAD-BUILD code.

2.4 Question 4

4. What radionuclides and chemicals which can affect radionuclide transport are considered? (Is decay and in-growth considered? To what extent?)

2.4.1 RESRAD

The RESRAD database includes 84 principal radionuclides and 52 associated radionuclides in the decay chains (i.e., a total of 136 radionuclides). RESRAD does not perform dose or risk calculations for hazardous chemicals. This task is performed by other codes in the RESRAD family, that is the RESRAD-CHEM and RESRAD-BASELINE codes. The RESRAD-CHEM code performs transport and exposure calculations consistent with those performed by the RESRAD code (see response to Question 1). A total of 151 inorganic and organic compounds are included in the RESRAD-CHEM and RESRAD-BASELINE codes.

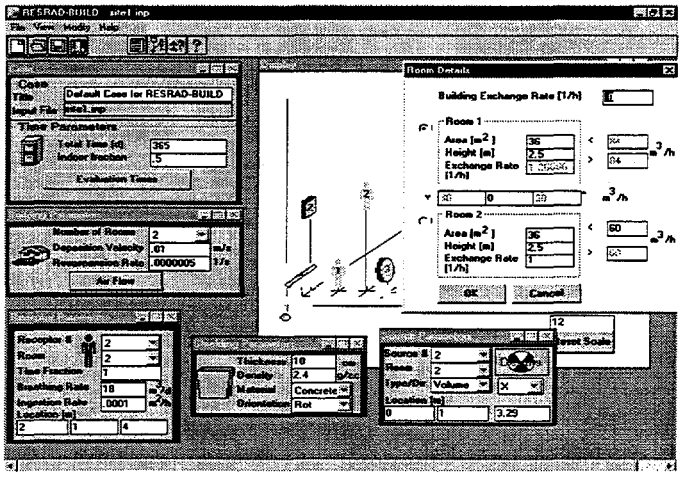

Figure 13. Typical RESRAD-BUILD Site-Specific Parameter Input Screen

The chemical form of the radionuclide is considered in the DCFs for radionuclides taken up internally. For ingestion, the user may select the DCF for one or more gastrointestinal (GI) tract fractions; for inhalation; the user may select the DCF for one or more inhalation classes. RESRAD defaults are for the most conservative DCFs, where more than one GI fraction or inhalation class is available. Short-lived radionuclides (i.e., those with half-lives less than one month or six months, depending on the user-selected cutoff) are considered to be in secular equilibrium with their parents. Thus, their DCFs and slope factors are added to the DCF and slope factor of the parent. An exception to this are radon isotopes and their short-lived progeny, for which ingrowth is tracked explicitly.

Special methodologies have been developed that take into account the different chemical forms and transport of tritium (as tritiated water and water vapor) and carbon-14 (as organic carbon and carbon dioxide) in the environment (Figure 14).

Longer-lived progeny for all radionuclides are tracked separately from their parents. This is particularly important in groundwater transport where different distribution coefficients may be assigned to the decay products. This allows the user to account for the different chemistries of the decay products during transport from the contaminated zone through the unsaturated zone and into the saturated zone. The distribution coefficient (K_d) for each long-lived radionuclide within each zone may be different and will depend on the chemical form of the radionuclide and the soil properties. These K_ds may be entered directly by the user, or the code may be used to estimate these values using four separate methodologies (Figure 15): (1) input of radionuclide concentrations in a downgradient well and time since material placement, (2) direct input of the leach rate from the contaminated zone, (3) input of a solubility limit, and (4) correlation with the soil/plant transfer factor. It is quite possible, with the above methodology, to simulate the more rapid transport of a soluble decay product, which may arrive at the exposure point ahead of its slower moving insoluble parent.

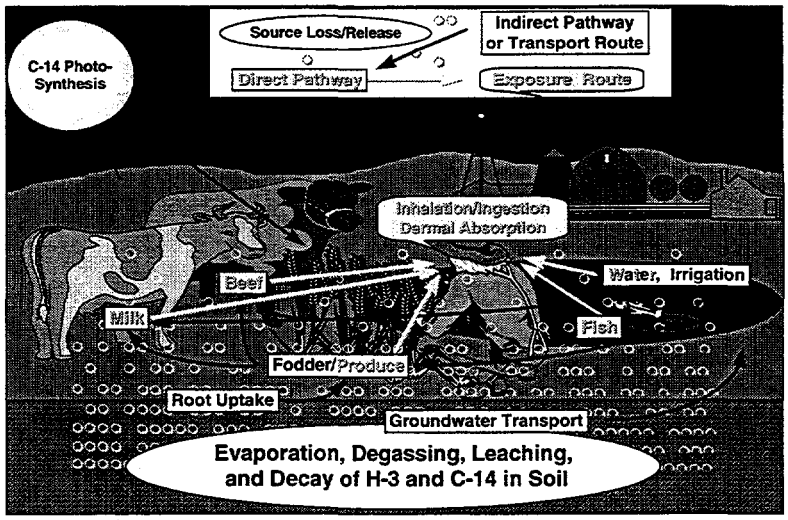

Figure 14. Special Models for Tritium and Carbon-14 in RESRAD

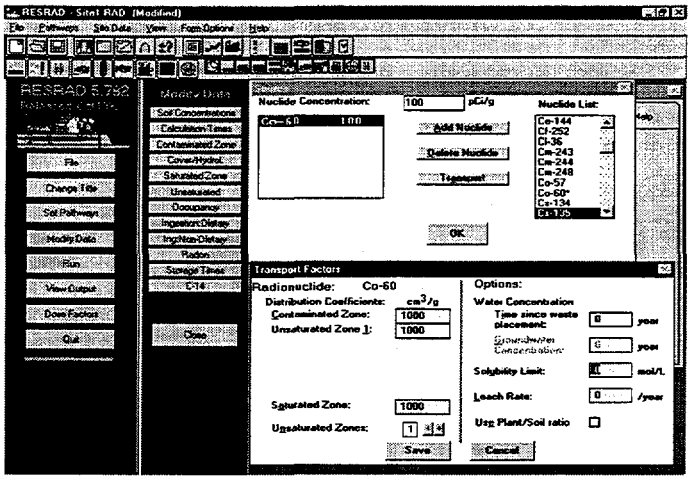

Figure 15. Typical RESRAD Distribution Coefficient Parameter Input Screen

The user may also account for the chemical form of the radionuclides by adjusting the biological transfer factors. These factors are used to estimate the transport of radionuclides from soil to plants, fodder to meat or milk, and water to aquatic organisms.

2.4.2 RESRAD-BUILD

As with RESRAD, RESRAD-BUILD applies only to radionuclide and not chemical contaminants. There is no biological transport of radionuclides. The chemical form of the radionuclide is accounted for implicitly in the DCFs used, as well by using special models for the diffusion of radon and tritium. Radionuclide decay is considered for all radionuclides, and ingrowth is accounted for explicitly when decay products have half-lives greater than the cutoff.

2.5 Question 5

5. *What are the time and spatial geometry limitations inherent in the analytical method?*

2.5.1 RESRAD

RESRAD calculates annual doses, soil guidelines, radionuclide concentrations, and lifetimes risks as a function of time. The user may enter up to nine times (time zero is always calculated). Any time horizon up to 100,000 years may be selected (the default is 1,000 years), but the uncertainty in the results will increase with increasing time. The code will also estimate

the time at which the peak dose occurs for each radionuclide and for all radionuclides summed. With few exceptions, RESRAD should be applied to chronic exposure scenarios (i.e., over one or more years of exposure) rather than short-term exposure conditions. For exposure durations greater than one year, RESRAD performs a time-integration of excess cancer risks that takes into account changes in the radionuclide concentrations in all media as a function of time.

RESRAD has few spatial constraints. The methodology requires the input of homogeneous layers (one optional cover layer, one contaminated zone, one to five optional unsaturated zones, and one optional saturated zone). The code provides graphical feedback on the thickness of the layers entered by the user (Figure 16). Nonhomogeneous (or multiple) contaminated layers may be simulated in separate runs, each with a distinct homogeneous contaminated layer, and the resulting doses may be summed. The code can also be used to perform hot spot analysis to assess doses from small subareas of contamination. No constraints are placed on the area or thickness of any layer.

In most cases, the receptor is assumed to be on-site (outdoors and/or indoors, one meter above the soil surface) and may obtain water from a well or pond located in the middle of the site (mass-balance model) or at the downgradient edge of the site (nondispersion model). For the external gamma pathway, the default source area is conservatively assumed to be circular, with the individual located above the center. However, the user may select a noncircular area, with the receptor located anywhere, including off-site locations (Figure 17). The manual contains the methodology, implemented in a version of the code currently undergoing testing and evaluation, to estimate doses to off-site receptors from airborne and groundwater transport.

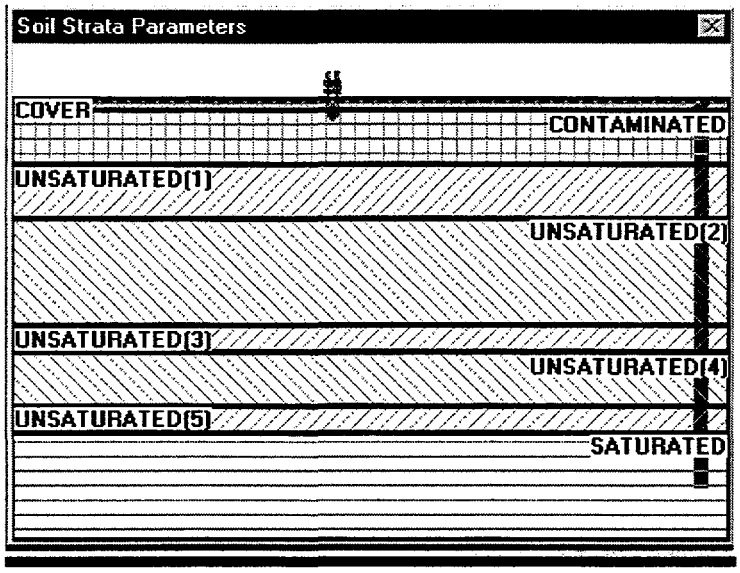

Figure 16. Typical RESRAD Soil Strata Parameter Screen

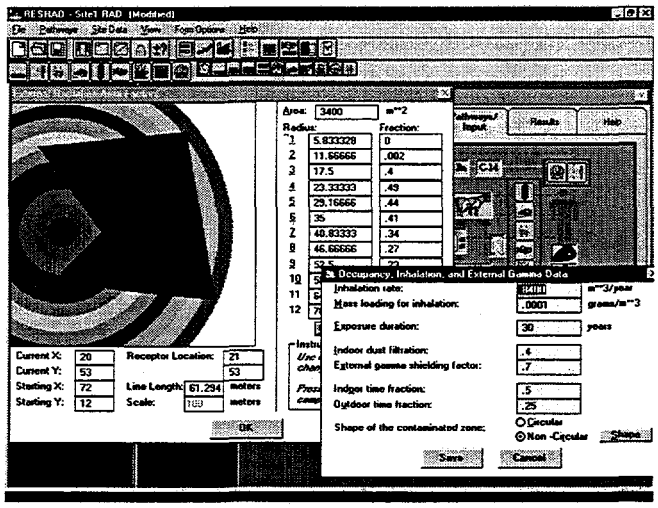

Figure 17. Typical RESRAD Shape Factor Parameter Input Screen

2.5.2 RESRAD-BUILD

Similar to RESRAD, RESRAD-BUILD calculates doses as a function of time; the user can input up to nine times. There is no limitation on the maximum time, but as a practical matter, the user should limit the calculations to the anticipated maximum lifetime of the building. By allowing future times to be investigated, it is possible to investigate the effects of source removal processes coupled with radionuclide decay and ingrowth.

The RESRAD-BUILD code is very flexible regarding spatial definitions of problems. By entering source and receptor locations in a Cartesian coordinate system, the user may place up to 10 sources and 10 receptors at any point within this coordinate system. However, receptors may not be co-located with sources or placed at locations that intersect source planes or axes. For the external gamma model, a shield of varying thickness, density, and material type may be specified for each source-receptor location pair (up to 100 shields). For the air pathways, one, two, or up to three rooms may be defined, each with unique dimensions and air exchange properties (Figure 18). Rooms must be adjacent to one another. Air is allowed to flow between adjacent rooms and may be exchanged with outside air; direct air flow between nonadjacent rooms, however, is not allowed. In a two- or three-room scenario, rooms may be configured horizontally or vertically (or mixed), with or without a basement. Receptors and sources may be placed anywhere within a room, or even outside the building, if only the external gamma pathway is of concern.

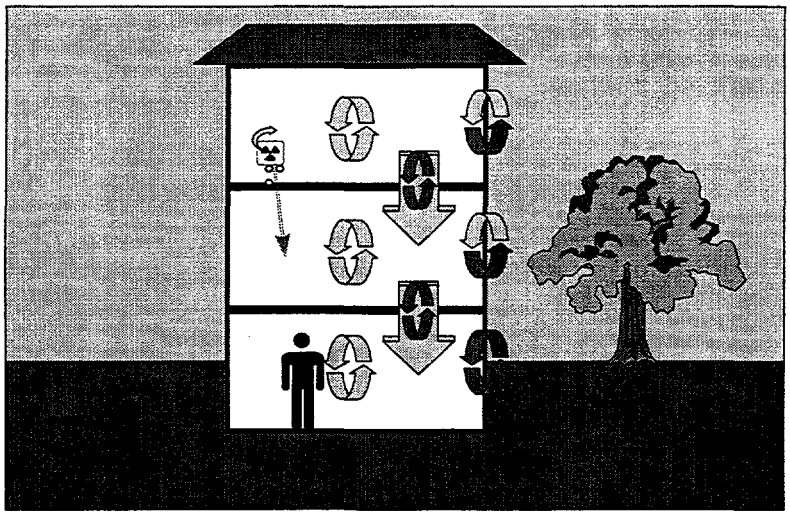

Figure 18. Schematic Representation of the RESRAD-BUILD Three-Room Model

Four source types may be specified, each with their own spatial definitions (Figure 19). A point source is simply defined by its coordinate location. A line source is defined by its length, its coordinate location at the center of the line, and a direction parallel to one of the three coordinate axes. A surface source is modeled as a disk and is defined by its area, its coordinate location at the center of the area, and a direction that is normal to the surface and parallel to one of the three coordinate axes. A volume source is modeled as a cylinder with up to five layers, one of which contains the contamination. Each layer can be defined with a unique thickness, density, erosion rate, porosity, and radon transport properties. The other dimensional definitions are the same as for a surface source. Two or more sources may be co-located. For example, a wall that is both volumetrically and superficially contaminated may be simulated by placing a volume source and a surface source at the same location; a hot spot may be simulated by placing a point source anywhere along the surface or inside the volume.

Receptors may be defined as points that represent the location at which the dose rate is measured. By entering different locations and time fractions at each location, a scenario may be set up to calculate collective doses to more than one individual, the total dose to a single individual at multiple locations, or any combination. Two receptor-source orientations, rotational and anterior-posterior, may be simulated. The latter is used when the receptor faces the source and results in slightly higher direct gamma doses than the former.

2.6 Question 6

6. *To what extent can alternative remedial actions be assessed and compared (e.g., comparison of concentrations, doses, and costs)?*

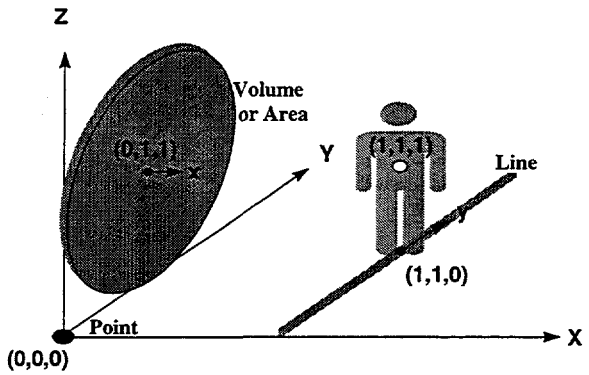

Figure 19. RESRAD-BUILD Source Types and Geometry Definitions

2.6.1 RESRAD

The RESRAD code provides output in the form of doses, risks, cleanup guidelines, and contaminant concentrations. Multiple runs of the code, as well as the sensitivity and uncertainty analysis tools discussed in the response to Question 3 may be used to assess the effects of alternative remedial actions. An example may be a sensitivity analysis performed to assess the effect on the dose of adding covers of varying thickness (Figure 20). The results are displayed both in text reports or graphically and may be used as input to cost-benefit analysis models. Sensitivity and uncertainty analyses can also be applied to assess the effects on time-dependent concentrations in various media. The results may then be used in performing ALARA analyses, as discussed in the response to Question 8, or in developing monitoring strategies, as discussed in the response to Question 10.

2.6.2 RESRAD-BUILD

With the exception of the sensitivity analysis feature and graphical output (not currently available in RESRAD-BUILD), the same applies to RESRAD-BUILD.

2.7 Question 7

7. *To what extent has the dose model been tested and included in benchmarking studies?*

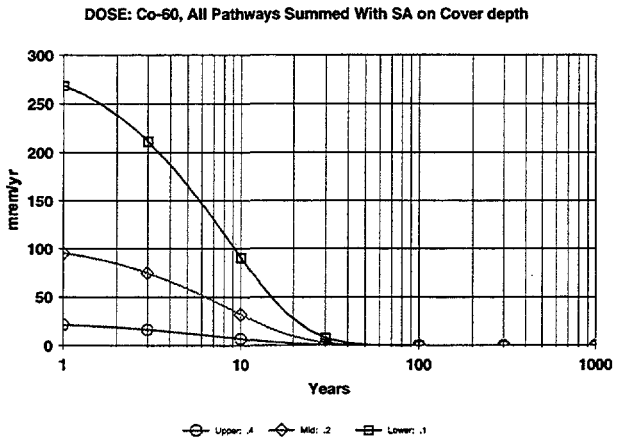

Figure 20. Example Sensitivity Analysis Graphical Output — Dose vs. Cover Thickness

2.7.1 RESRAD

The RESRAD code is subject to strict configuration control under ANL's RESRAD Software QA Plan. Under this plan, changes to RESRAD must be approved by the Project Leader and Program Manager. A modification must be reviewed by:

- An independent scientist or programmer,
- the Project Systems Analyst,
- the Project Leader, and
- the Program Manager.

All modifications are reviewed prior to a new code release by all programmers to ensure that there are no internal conflicts. Modifications to the code are made to maintain a state-of-the-art methodology, as well as implement suggestions made by users and sponsoring agencies.

The code has been verified and validated since 1989. An independent verification was performed by a competitively selected contractor who was entirely independent of the development of RESRAD in June 1994 (Halliburton NUS, 1994). RESRAD has been included in international code validation studies, including the Biospheric Model Validation Study: Phase II (BIOMOVS II) (Gnanapragasam and Yu, 1997a) and the Validation of Model Predictions (VAMP) study (Yu and Gnanapragasam, 1995; Gnanapragasam and Yu, 1997b) sponsored by the International Atomic Energy Agency (IAEA, 1996). These studies used actual monitoring data obtained in Europe from the Chernobyl accident and actual uranium mill tailing data. In

these "blind" studies, real-world data were provided to the participants who used their models to evaluate the data and provide an estimate of radiation dose. RESRAD has provided results that compare favorably with the "official" answers, which are only furnished after the estimates of each code developer are submitted.

RESRAD has been benchmarked against a number of other pathway analysis codes and methodologies, including GENII, GENII-S, DECOM, PRESTO, PATRHRAE, NUREG/CR-5512 (Faillace et al., 1994) and MEPAS and MMSOILS (Cheng et al., 1995; Mills et al., 1997). The latter was sponsored by the EPA (Laniak et al., 1997). These benchmarking studies have provided valuable information on how each code addresses a similar set of input parameters and exposure scenarios. These comparisons are useful in assessing the limitations of each code. In some cases, this has led to uncovering errors or initiating modification in a few of the codes that were benchmarked. RESRAD has performed satisfactorily in both benchmarking studies.

Independent of Argonne and DOE, the NRC has evaluated RESRAD prior to approving it for use by its staff and licensees. Technical suggestions furnished by the NRC staff were incorporated into the code and additional radionuclides were added. Similarly, the EPA's Science Advisory Board reviewed RESRAD as part of its review of the development of generally applicable standards for residual radiation at sites after cleanup (Wolbarst et al., 1996).

RESRAD also has benefited from more than a decade of field applications at over 300 sites in the United States and overseas. It is used as a teaching tool at a dozen universities, including Oregon State University, Ohio State University, Rensselaer Polytechnic Institute, and the University of Tennessee.

More than 60 RESRAD training workshops have been conducted at various locations in the United States upon request of several federal (including DOE, NRC, and EPA) and state environmental, health, and safety agencies (e.g., New York, Louisiana, Connecticut, among others). Over 1,000 people have been trained at these workshops.

A computerized user database is maintained to inform users when a major revision of the code has been issued. Users may also visit the RESRAD Family of Codes web page at "www.ead.anl.gov/resrad.html" for code status and updates, an on-line version of the *Data Collection Handbook*, upcoming training workshops, and other information. Surveys and questionnaires are issued periodically to obtain feedback. Users may also contact ANL directly through e-mail at "RESRAD@anl.gov" or by phone to obtain technical assistance. Feedback obtained from users through technical assistance, training workshops, and surveys is incorporated into code revisions.

2.7.2 RESRAD-BUILD

RESRAD-BUILD is under the same software QA plan as RESRAD. Code modification and verification have been documented since 1994. The external gamma calculations performed by the code have been successfully benchmarked against MICROSHIELD (a point-kernel code) and MCNP (a Monte Carlo code). Over 10 RESRAD-BUILD training workshops have been conducted since 1996; approximately 200 people have been trained at these workshops.

2.8 Question 8

8. To what extent can the analytical method handle complex: (a) source term characterization; (b) multiple source terms; (c) hydrologic and hydrogeological conditions; (d) exposure pathway combinations; (e) remedial methods linked to cost and monitoring programs; and (f) ALARA considerations?

2.8.1 RESRAD

(a) The RESRAD source term is entered as average soil concentrations of initially present radionuclides. The user may also enter groundwater concentrations to estimate the radionuclide K_ds. Short-lived radionuclides are assumed to be in secular equilibrium with their parents. Ingrowth, decay, leaching, off-gassing (C-14), and evapotranspiration (tritium) are all used to estimate the change in source concentrations as a function of time; the erosion rate is used to estimate changes in the cover and/or source thickness as a function of time (Figure 21).

(b) Multiple source terms, as well as hot spots, may be modeled by adding the results from separate runs. Features in the text and graphic output reports allow users to export data to spreadsheet programs for ease of analysis.

(c) Precipitation, irrigation, runoff, and evapotranspiration are all considered in estimating the infiltration rate. The RESRAD model assumes homogeneous hydrogeological soil properties within each horizontal layer. Up to five unsaturated layers, each with unique properties, may be modeled. These soil layers are illustrated in Figure 16. Two one-dimensional groundwater models, the mass-balance model and the nondispersion model (shown in Figure 22), may be selected for the calculations of on-site doses. For off-site groundwater transport, a three-dimensional dispersion/one-dimensional advection model is being tested and evaluated. Potentially contaminated water for drinking, household uses, livestock, and irrigation may be modeled as originating from a well and/or pond.

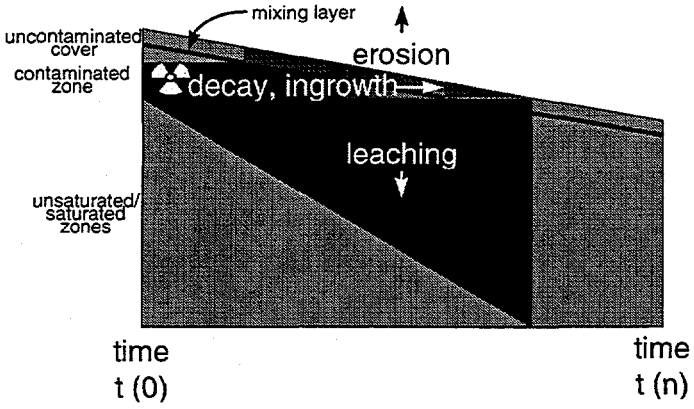

Figure 21. RESRAD Time-Dependent Source Evolution

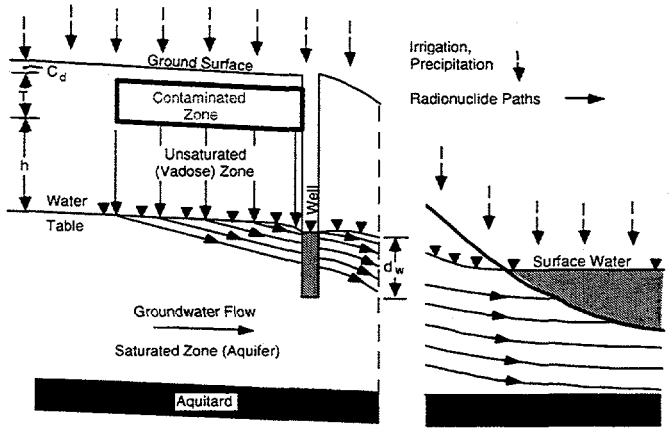

Figure 22. RESRAD Non-Dispersion Groundwater Model

(d) One or more pathway combinations, up to a total of all nine exposure pathways, may be simulated in a single run (the radon pathway can only be evaluated when a radon precursor is part of a source). It is easy to turn pathways on or off in RESRAD. Once a pathway is turned off, parameters that are unique to the pathways are suppressed, and users do not need to provide data for those parameters.

(e) RESRAD may be used as a tool to evaluate various remedial methods. The scenarios and input parameters can be easily modified, and multiple runs can be performed for each alternative. Also, the sensitivity and uncertainty analysis features of the code discussed in the responses to questions 3 and 6 may be applied to parameters related to alternative remedial methods (e.g., cover thickness or thickness of the contaminated zone) to assess their impact when the resulting doses or concentrations are entered in a cost-benefit model or are used to establish monitoring programs.

(f) Sensitivity and uncertainty analysis features, as well as multiple runs, may also be applied as a modeling tool when conducting the ALARA analysis. The output provided by RESRAD for a number of different scenarios or parameter variations can be used as input in a cost-benefit model. RESRAD has been used as an ALARA tool at a number of DOE sites, including Hanford and Fernald. The DOE draft ALARA standard (DOE 1997) provides additional information on using RESRAD for ALARA analysis and includes case studies for sites (Colonie, Elza Gate, Maywood, Ventron, and Weldon Springs) where RESRAD has been used as an ALARA tool.

2.8.2 RESRAD-BUILD

RESRAD-BUILD can be used to simulate four types of sources and up to 10 sources per run. For more details on parts (a) and (b) of this question, see the response to Question 5. Because the RESRAD-BUILD code does not assess the dose from groundwater contamination, part (c) of this question does not apply. In response to part (d), the user may assess doses from any combination of the seven pathways available (the radon pathway can only be evaluated when a radon precursor is part of a source). The response to parts (e) and (f) for RESRAD also applies to RESRAD-BUILD.

2.9 Question 9

9. *Does the dose model include software graphical output for portraying dose vs. time for various exposure pathways and specified radionuclides and total effective dose equivalents, including uncertainties?*

2.9.1 RESRAD

The graphical software package allows the user to view not just dose versus time, but also soil guidelines and concentrations as a function of time. The user may view the total effective dose equivalents or the contribution of individual radionuclides (including decay products) (see the example in Figure 23), as well as the dose from all pathways or the contribution of individual pathways (see the example in Figure 24). The user may also view the sensitivity of dose/guidelines as a function of time for each parameter selected for sensitivity (see Figures 9 and 20). A separate graphics package included with the uncertainty analysis allows the user to view the results of multiple iterations of the code; the cumulative distribution of total dose; and statistical plots showing minimum, maximum, average, and standard deviations of the total dose as a function of time (see Figures 11 and 12). Different plotting options (logarithmic vs. linear plots, color vs. black and white, solid lines vs. dashed lines) are available to the user. The data from the plots may be exported to a spreadsheet or copied to the clipboard for incorporation into documents.

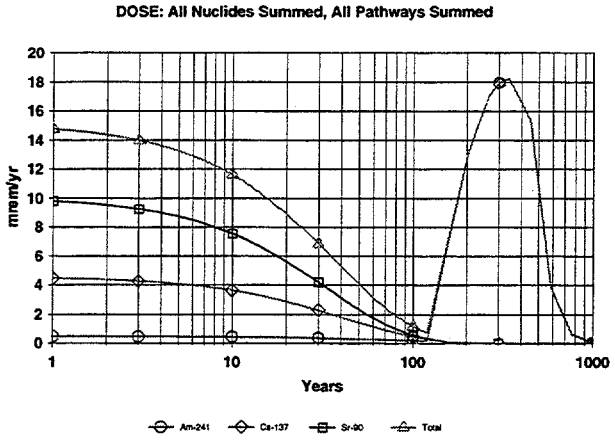

Figure 23. RESRAD Graphical Output — Dose Contributions by Radionuclide

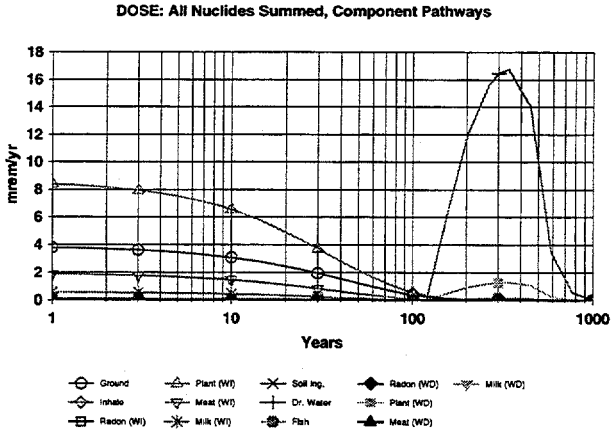

Figure 24. RESRAD Graphical Output — Dose Contributions by Pathway

2.9.2 RESRAD-BUILD

The current version of RESRAD-BUILD does not have a graphical output package. However, RESRAD-BUILD provides graphical visual feedback of the source types/direction, number of sources and receptors, and their locations relative to each other.

2.10 Question 10

10. Can the analytical method consider various restrictions on land use and site boundaries in calculating concentrations and/or doses and in determining monitoring strategies?

2.10.1 RESRAD

The RESRAD model can be used to assess most land uses, whether restricted or unrestricted, by simply altering the scenarios as indicated in the response to question 2. In addition, the cleanup criteria can be formulated to take into account a period of institutional control prior to the unrestricted release of the property. Soil cleanup criteria are calculated automatically by the code for each radionuclide entered, on the basis of a user-specified annual dose limit. By estimating the times at which the peak doses from water-independent pathways and water-dependent pathways occur (Figure 25), the code can be used to prioritize the

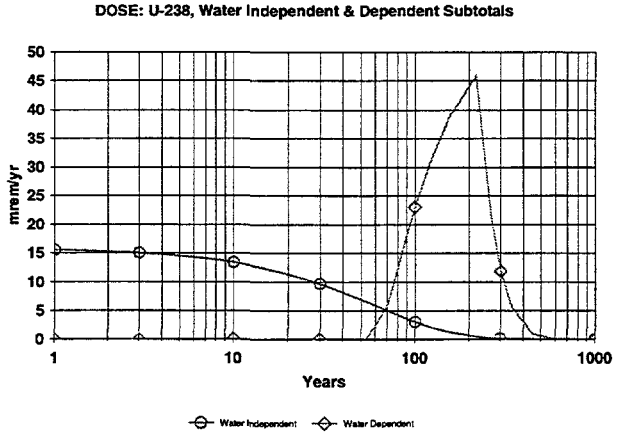

Figure 25. RESRAD Graphical Output — Water Independent and Dependent Subtotals

monitoring strategies for various media such as soil, air, water, and food products. The code also predicts time-dependent radionuclide concentrations in various media (see the example in Figure 26), which can be used to determine monitoring strategies and data quality objectives. The off-site receptor airborne dispersion and groundwater transport methodology described in the users' manual can be used to evaluate conditions at or beyond the site boundary.

2.10.2 RESRAD-BUILD

As indicated in the response to Question 5, RESRAD-BUILD does not have significant spatial limitations and can be used to assess very site-specific building contamination problems. However, with the exception of the external gamma pathway, assessments are limited to locations inside a building. The code can assess the dose to single or multiple receptors from contamination in a number of sources in single or multiple rooms of a building. The effect of building-use restrictions may be easily assessed by modifying the parameter values (typically receptor locations, occupancy factors, consumption rates, and/or release factors) to accommodate the desired usage scenario. The results can also be used as input for monitoring strategies, particularly for external gamma dose rates and airborne contaminant levels. The code is particularly useful in estimating changes in concentrations over time as a function of decay, ingrowth, or physical removal rates.

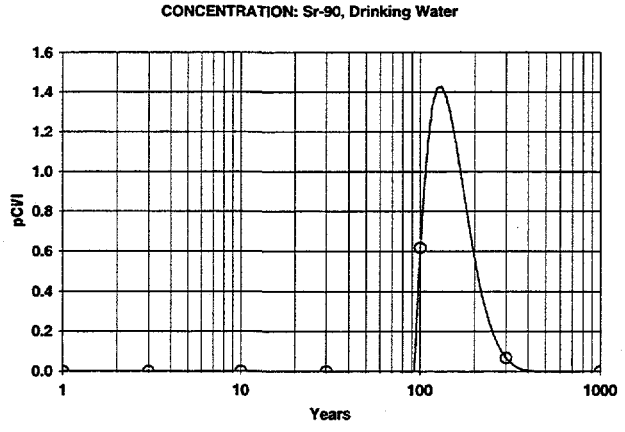

Figure 26. RESRAD Graphical Output — Radionuclide Concentration in Drinking Water

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Response to Nuclear Regulatory Commission's Ten Questions Pertaining to Site-Specific Models for Use in the License Termination Rule: Multimedia Environmental Pollutant Assessment System (MEPAS)

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Introduction

This paper is in response to the US Nuclear Regulatory Commission (NRC) ten questions posed at the Modeling Workshop held November 13 and 14, 1997. The ten questions were developed in advance of the workshop to allow model developers to prepare a presentation at the Workshop. This paper is an expanded version of the Multimedia Environmental Pollutant Assessment System (MEPAS) presentation given at the Modeling Workshop by Pacific Northwest National Laboratory (PNNL) staff.

This paper is organized by the ten questions asked by the NRC, each sections devoted to a single question. The current version of methodology is MEPAS 3.2 (NRC 1997) and the discussion in this paper will pertain to that version. In some cases, MEPAS 4.0, which is currently being developed under the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES) (Whelan et al 1997), will be referenced to inform the reader of potential capabilities in the near future. A separate paper is included in the document that discusses the FRAMES concept.

Brief Description of the MEPAS software

The Multimedia Environmental Pollutant Assessment System (MEPAS) software utilizes sophisticated modeling codes to quickly and easily assess risks from activities that could impact human health, such as remediating hazardous waste sites (Whelan et al 1987, Whelan et al 1992, Buck et al 1995). This innovative computer program for PC and UNIX systems helps answer such questions as "How risky is this hazardous waste site?" and "What is the low-risk cleanup solution?" The software integrates models and quickly provides an overall evaluation of risk for a site or an incident. This capability supports key decisions on priorities and low-risk solutions to waste cleanup. The MEPAS software provides physics-based modeling codes for environmental risk assessment. It quickly integrates results from separate models of contaminant behavior in various media (air, soil, ground water, surface water) and for different scenarios, turning a task that could take weeks (or might never be attempted) into a few hours' work.

MEPAS integrates and evaluates transport and exposure pathways for chemical and radioactive releases according to their potential human health impacts (multimedia in this context refers to multiple environmental transport media). MEPAS takes the nontraditional approach of combining all major exposure pathways into a multimedia computational tool for public health impact. MEPAS is a physics-based approach that couples contaminant release, migration and fate for environmental media (groundwater, surface water, air) with exposure routes (inhalation, ingestion, dermal contact, external dose) and risk/health consequences for radiological and non-radiological carcinogens and non-carcinogens.

This integration of models to provide an overall assessment is the key benefit of using MEPAS. Assessing risks involves examining pathways for contaminants to reach humans. Whereas past systems often looked at one pathway at a time, MEPAS looks at all pathways and computes total risk to humans from a particular site. The software prompts the user to supply the necessary information, integrates population exposure routes into the analysis, and computes the subsequent risks for the site. Investigators can easily locate site data and files and modify them to assess the risks of various cleanup options or scenarios. The system ranks environmental problems according to potential for human health impacts--helping to assign priorities to cleanup efforts.

For further information on MEPAS please refer to MEPAS web site address: http://mepas.pnl.gov:2080, MEPAS Email: mepas@pnl.gov, or call Gariann Gelston at 509 376-8308

Question 1: Describe the history of the analytical method's development?

The MEPAS software package was first conceived by PNNL staff and submitted to the US Department of Energy (DOE) in 1984. The initial mathematical formulations for the MEPAS was developed and published for external review in 1987. Based on review comments for DOE, other government agencies, and private companies, these formulations were modified and converted into computer software. The MEPAS software was initially developed for the DOE's Environmental Survey Project that evaluated and ranked waste sites from 36 DOE installations across the country. The first version of MEPAS was completed in 1989 and applied to 16 DOE installations (DOE 1988). MEPAS 2.0 was completed and applied to the 36 DOE installations in 1991. This completed the initial application of the MEPAS software and worked out many of the appli-

cation bugs and user issues associated with the software package.

Version 3.0 of MEPAS was completed in 1994 with funding from DOE and internal funds at Battelle to make the software more tailored to site-specific analyses and assessments. The user interface was upgraded to allow users to input site-specific data and to conduct calibration analyses for the source, transport, and exposure components of MEPAS. Version 3.1 of MEPAS was completed in 1995 and included some refinements in the user interface and the output of the exposure/risk module. Version 3.2 of MEPAS was co-funded by DOE and NRC (NRC 1997) to allow for annual dose and risk information and to include a new Source-Term Release Module. This Source-Term Release Module allowed for mass balance of contaminants from the different source terms and to ensure mass partitioning between the different transport media. Version 4.0 of MEPAS is currently in development and is expected to be available by summer of 1998. This version will include a Windows-based user interface and will allow for linking of MEPAS modules with other environmental models developed independent of MEPAS.

The MEPAS software has gone through extensive internal and external scientific review to ensure that its algorithms are defensible and appropriate to assessment applications. Table 1 gives a brief summary of some of the key external reviews of MEPAS. Table 2 provides a summary of the major applications that have used MEPAS for assessing contaminant release, transport, exposure and impacts. Extensive application of MEPAS has ensured that the software is operating correctly and is flexible to the needs of the users and clients.

Question 2: What transport mechanisms, scenarios, and exposure pathways are considered?

The current version of MEPAS (version 3.2) has four main sets of modules associated with its structure. These are source, transport, exposure and impact modules. Figure 1 provides a diagram of the overall structure of MEPAS 3.2. The Source-Term Release Module (STRM) (Streile et al 1996) ensure mass balance and partitioning to the appropriate transport media via the following release mechanisms: volatilization, wind and mechanical suspension of particles, infiltration in to the subsoil, overland runoff and flow, and decay/degradation at the source through radioactive decay and reducing processes such as hydrolysis, photolysis, and chemical transformations. External mass sources and sinks can be defined by the user to simulation additional activities at the source. There are four main source types handled by the MEPAS STRM; surface/subsurface soil, surface impoundments, saturated soils (aquifers), and active sites (known emissions from stacks, vents, pipes). For each time step, the depletion and addition of mass is balanced with the initial source mass and partitioned to the appropriate transport media. The key result from the STRM are time varying contaminant emissions from the different release mechanisms and the remaining mass at the source. Figure 2 shows a schematic of the STRM and its release mechanisms.

The transport modules consist of an atmospheric, surface water, surface/subsurface soil (vadose zone), and groundwater (saturated zone) modules. These transport modules interact with each other to allow for complex transport scenarios. An example of a complicated transport scenario that MEPAS can simulate is: three vadose zones of different soil characteristics leaching to a saturated zone that discharges into a river (surface water). The atmospheric transport module (Droppo and Buck 1996) provides long term time-varying air and soil (from dry and wet deposition) concentrations to the area surrounding the source. The atmospheric transport module uses site-specific or regional climatology data (frequency of occurrence by wind speed, wind direction, and atmospheric stability) averaged over a minimum of several years. These air and soil concentrations are sector averaged over 16 directions and 10 distances (from 100m to 80,000m) centered on the source.

The surface/subsurface soil module (vadose zone) simulates the aqueous contaminant transport though the partially saturated soil layers. The vadose zone module (Whelan et al 1996) uses a one-dimensional advective, one-dimensional dispersive equation to simulate water and contaminant flow though the partially saturated soil. Several vadose zone modules can be link together to simulate a complicated soil horizon at a site. Each vadose zone is model separately with the time-varying contaminant fluxes output from the previous zone as input to the next vadose zone. This ensures mass balance though the system and allows for modeling of sites with complex geohydrology. The contaminant fluxes from the vadose zone(s) can be diverted to several saturated zones by assigning percentage of fluxes to the different saturated zones (main aquifer and perched aquifers). Figure 3 is a diagram of how the vadose and saturated zones can be linked in MEPAS.

The groundwater or saturated zone module (Whelan et al 1996) uses a one-dimensional advective, three-dimensional dispersive equation to simulate water and contaminant flow though the saturated soil. A saturated zone can be a source or transport module in the MEPAS structure. Up to 10 different groundwater and groundwater to surface water receptors can be simulated in a given run. The surface water module includes river and wetlands. This surface water module (Whelan and McDonald 1996) is a steady state one-dimensional advective, two-dimensional dispersive equation for solute transport. It is for nontidal rivers with unidirectional flow in definable channels. This module can be linked to the groundwater and source term (overland or

direct discharge) modules. Different surface water receptors can be simulated with varying discharge rates.

The exposure module (Strenge and Chamberlain 1995) simulates four exposure routes: ingestion, inhalation, dermal contact, and external exposure. There are 25 different exposure pathways associated with these exposure pathways. Figures 4 –8 show these exposure pathways in MEPAS exposure module by environmental media. The exposure module inputs environmental concentrations from contaminated soil, water, and air and produces time-varying doses as output. The time scale of these doses can be varied based on user needs. The risk module inputs time-varying doses from the exposure module and computes carcinogenic impacts from radionuclides and chemicals and noncarcinogenic impacts from hazardous chemicals. These impacts can be in the form of cancer incidence or fatalities for radionuclides, cancer incidence for carcinogenic chemicals, or hazard quotient for noncarcinogenic chemicals.

Question 3: How are parameter values determined for input? Can uncertainties be incorporated into the parameter distributions and dose calculations?

Though the development and implementation of the MEPAS software a hierarchy of data to be used for a parameter has been developed. If at all possible, site-specific parameter values should be used. In most cases MEPAS allows users to input site-specific information into the modules where appropriate. If site-specific data is not available, MEPAS documentation (Buck et al 1995) suggests were regional data can be obtained for parameter values. These kind of data are generally climatological, meteorological, and geohydrology type data. If regional data is not available for the assessment, representative parameter values are provided by the different modules to allow the user to complete the assessment. These representative parameter values are based on studies and characteristics of the site. Examples of such data are bulk density, porosity, field capacity and distribution coefficients. All these parameter values are referencable. MEPAS does not supply default values at are considered conservative for all situations because different application goals and site situations can affect results such that conservatism can not be guaranteed.

MEPAS has a sensitivity and uncertainty module (Doctor et al 1990) that allows the user to input and determine distributions for most of the parameters required for MEPAS runs. A Latin hypercube sampling system (modified Monte Carlo) is used to sample the different parameters selected by the user for the evaluation. A suite of distribution types is available to the user. This module allows the user to determine which parameters are the most sensitive for the given models and site characteristics. Once the sensitive parameters have been determined, uncertainty analysis can be conducted to understand how conservative and uncertain the results from the evaluation are. These analyses can be conducted on the contaminant doses as well as fluxes, concentrations, and impacts. The results are graphical output of the cumulative and probability density function for the endpoint selected. The partial R^2 can be obtained for each parameter analyzed.

Question 4: What radionuclides, and chemicals which can affect transport, are considered? Is decay and in-growth considered? To what extent?

MEPAS has an extensive set of radionuclides and chemicals that can be evaluated by the software. The Multimedia Modeling Environmental Database and Editor (MMEDE) module (Warren and Strenge 1994) contains 197 radionuclides and 408 organic/inorganic chemicals with all the required physical, chemical and health related parameters (Strenge and Peterson 1989). Constituents can be easily added to MEPAS through a constituent database editor. MEPAS constituent database contains all the long-lived radionuclides (1/2 life greater that a day) that the DandD software does. This was confirmed with Sandia National Laboratory in 1996. MEPAS has a few special constituents that are handled different from the other constituents. These are H3, C14, I129, and Rn222.

MEPAS does consider radioactive decay in all the source, transport and exposure pathways. MEPAS uses the DandD code decay sequences. The waterborne transport component of MEPAS 3.2 requires that the progeny have the same transport properties as their parent consistent. This issue will be resolved in the MEPAS 4.0 version, where progeny will have transport properties independent of their parent constituents. The dosimetry calculations used in MEPAS are from Federal Guidance Reports 11 and 12.

Question 5: What are the time and spatial geometry limitations inherent in the analytical methods?

MEPAS has been used on site-specific, area-specific, installation-specific, regional-specific and nationwide assessments. There are no real bounds on the spatial and temporal geometry in the MEPAS methodology. MEPAS methodology can easily be handle site to national scale assessments. The normal bounds of MEPAS transport is 80 km for the atmospheric transport pathway but this can be expanded to much great distances very easily. The Waterborne transport

pathway general has no limits of distance. It uses what ever the assessment requires. The normal time dimensions of MEPAS varies from 1 year to 10,000 years but models are not limited to these dimensions. MEPAS has been used for analysis of less than a year and more than 1,000,000 years and the user can easily define this assessment-specific issues. The spatial and temporal geometry flexibility is associated with source, transport, exposure and impacts. MEPAS output has been linked to Graphical Information Systems (GIS) to provide useful displays of spatial and temporal information. Figure 9 provides an example of an installation-wide display of risk information.

Question 6: To what extent can alternative remedial action be addressed and compared? Comparison of concentrations? Dose and costs?

The MEPAS methodology was developed to assess human health impacts from radioactive and hazardous waste sites. The results of this methodology can be used to determine if further action is required for the waste sites. A logical extension of the MEPAS methodology is to take its outputs and assess the type of alternative remedial actions required for site and the cost of such actions. That is why DOE funded PNNL to development the Remedial Action Assessment System (RAAS) (technologies (Hartz and Whelan. 1988). MEPAS and RAAS have been integrated to allow users to assess the human health impacts from waste sites and the type of alternative remedial actions applicable for each waste site. Figure 10 shows the integration between MEPAS and RAAS software.

The RAAS software (windows-based) contains over 100 remedial technologies (Hartz and Whelan. 1988, Bagaasen et al 1993) that can operation separately or in technology trains to implement risk reduction at waste sites. A list of the RAAS technologies is provided in Figure 11. The integration of the MEPAS and RAAS software allows the user to assess pre-, during and post-remediation human health impacts for a single or a set of waste sites. Results from RAAS can be used by decision makers to support environmental decisions by providing a comprehensive conceptual site mode, baseline human health impacts (via MEPAS methodology), applicable technologies, remediation alternatives, contaminant concentrations, residual impact estimates, secondary waste streams, completion time estimates, preliminary cost estimates, and worker impact estimates.

Question 7: To what extent has the dose model been tested and included in benchmarking studies?

The dose model associated with the MEPAS methodology has been in use by PNNL and DOE for over 10 years. These ten years of application along with the model's full QA/QC documentation in accordance with DOE orders and PNNL standards ensure appropriate testing of the software. Some of these applications have resulted in model comparisons (Moskowitz et al 1996, Morris and Meinhold 1988, EPA 1988, Health and Welfare Canada 1992, Holmes et al 1994). Recently the MEPAS methodology was benchmarked with other multimedia environmental model. The RESRAD, MMSOILS, and MEPAS methodologies were benchmarked through a co-funded DOE and EPA effort. The resulting EPA/DOE document (EPA/DOE 1995) provides comparisons of the three modeling methodologies based on evaluations of several selected sites. In general, the three methodologies gave similar results for the dose calculations. There were some significant differences between the methods on the source and transport calculations. MEPAS exposure and risk models have also been compared with the GENII model developed for DOE by PNNL to compute radioactive dose values for residual contamination. The MEPAS models compared very well with this separate model.

Question 8: To what extent can the analytical method handle complex source term characterizations? Multiple source terms? Hydrologic and hydrogeologic conditions? Exposure pathway combinations? Remedial methods linked to cost and monitoring programs? ALARA considerations?

MEPAS has a Source Term Release Module (STRM) that can handle several complex source types and configurations. The STRM can evaluate soil (surface and subsurface), surface impoundments, aquifers, and active sites (i.e., stacks, vents, and direct discharges). The STRM also allows for the user to input know contaminant emission rates for all or some of the contaminants. The STRM can also evaluate remediated sites that have caps and waste form that are cement or glass.

The STRM conducts mass balance from the source for all contaminates over the simulation time period. This is accomplished by evaluating mass changes for each contaminant for each time set for each release mechanism (soil suspension, volatilization, infiltration, overland runoff, decay/degradation at the source, and known inflow/outflow). These mass losses are than partitioned to the appropriate

environmental media for transport. MEPAS 3.2 can evaluate multiple and secondary sources through a two-step process. MEPAS 4.0 (due in summer of 1998) will be able to evaluate multiple and secondary as a single step.

Sites with complex geology and hydrology can be assessed using MEPAS vadose and aquifer modules. The vadose and aquifer modules use the advective-dispersive equation to evaluate water and contaminant movement in the soil column and groundwater. This allows for variations of concentrations with time and depth. The vadose module assumes homogeneous soil properties but several vadose zones can be model in secession to simulate different soil layers with depth. In the MEPAS 4.0 version, multiple aquifers can be linked together to simulate transport through heterogeneous groundwater.

The MEPAS exposure module allows the user to develop complex combinations of exposure pathways. The exposure module allows for four exposure routes (ingestion, inhalation, dermal contact, and external exposure). These routes link to 25 different exposure pathways that can be evaluated in MEPAS. Complex food chains can be developed such as irrigation of crops to cows to milk to humans using bioaccumulation factors. Figure 12 shows an example of a typical food chain pathway used in MEPAS.

As mentioned in Question 6, MEPAS is linked to the RAAS software that allows for evaluation and comparison of different alternative remedial actions. MEPAS have been used to develop and refine monitoring programs at the Hanford Site. Based on modeling into the future, new monitoring efforts were developed and refined to adjust for the movement contaminants with time.

Question 9: Does the analytical method include software graphical output for portraying dose verses time for various exposure pathways and specified radionuclides and total effective dose equivalents including uncertainties?

The MEPAS 3.2 version does not produce graphical output of the different results. Results from MEPAS 3.2 can easily be imported (use of comma delimited file format) into MS EXCEL or other graphical system to product the required plots. An example of such a MS EXCEL plot is shown in Figure 13. The sensitivity/uncertainty module does product graphical results of the cumulative and density functions as a function of the results.

MEPAS 4.0 will have graphical viewers for all the main results of the MEPAS (contaminant emissions, contaminant concentrations, doses, and impacts). These graphical will be easy in import into any work processor software for inclusion in reports because this version of MEPAS will be Windows-based.

Question 10: Can the analytical method consider various restrictions on land use and site boundaries in calculating concentrations and/or doses, and in determining monitoring strategies?

MEPAS was developed to deal with different kinds of DOE and EPA waste sites. This means that land use (agricultural, industrial, recreational, and residential) is a critical issue that MEPAS addresses in the exposure module. MEPAS can compute individual and population impacts for on-site and off-site receptors. Figure 14 provides a summary of the different types of receptors applicable to MEPAS. The results from MEPAS can be provided by contaminant, environmental media, exposure scenario, and receptor. This flexibility allows the user to review and report their results in many different ways to understand the assessment in many dimensions. Results can be summed up to provide summary and cumulative information.

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TABLE 1. List of major external reviews of MEPAS software

US EPA Review of HRS and other models (1988)
NAS Hanford Single Shell Tanks Panel (1989)
External Review of DOE Priority System (1991)
US EPA review (November 1991)
NAS Review of DPM and other models (1991)
Health and Welfare Canada Review (1992)
External Review for Programmatic Environmental Impact Statement (1993)
NAS Risk Prioritization Report (1994)
National and International Multimedia Model Benchmarking (1995)

TABLE 2. List of major applications conducted using MEPAS software

Hanford Single Shell Tanks (1989)
DOE Survey uses MEPAS (1990)
Hanford Grout Study
INEL Risk-Based Ranking
State of Washington (1990)
Hanford 100-Area Study (1992)
U.S. Air Force Base Applications
DOE's Programmatic Environmental Impact Statement (PEIS)
Hanford Remedial Action-Environmental Impact Statement (1994)
Baseline Environmental Management Report (1995)
Waste Isolation Pilot Plant (1996)
Hanford Integrated Risk Assessment Project (1993-1996)

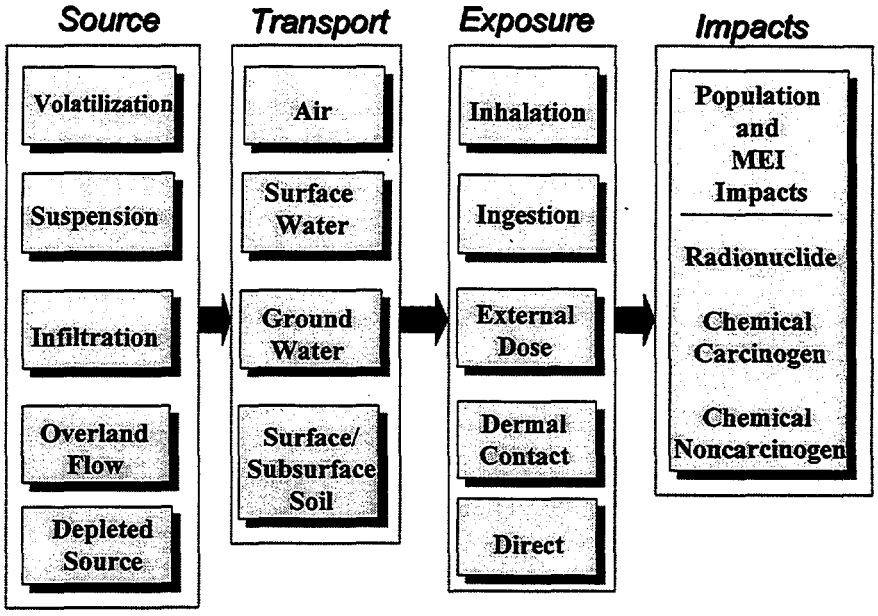


Figure 1. Diagram of MEPAS Overall Structure

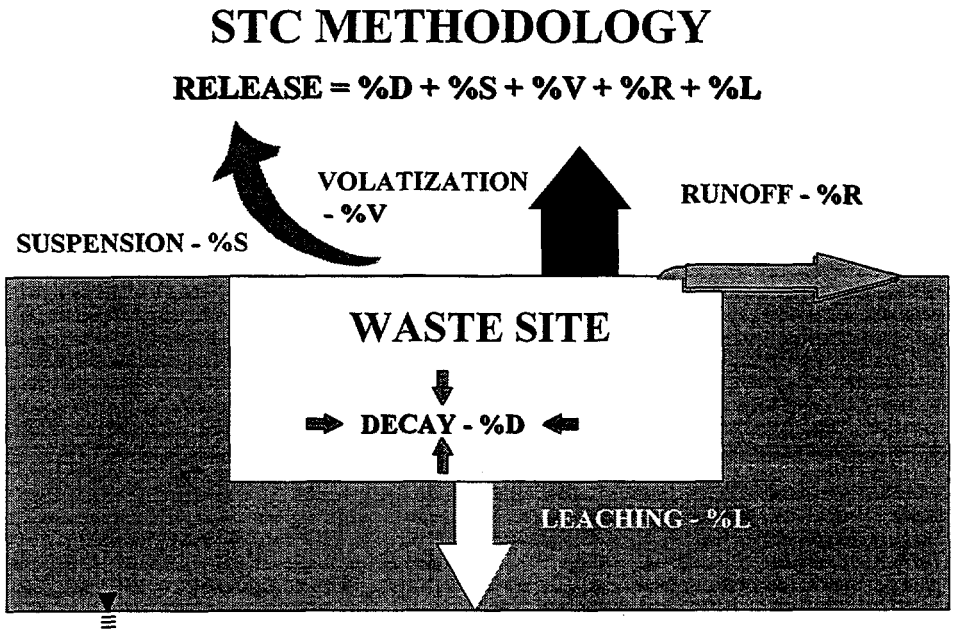


Figure 2. Diagram of Source Term Release Modules

Diagram of Modeled Zones

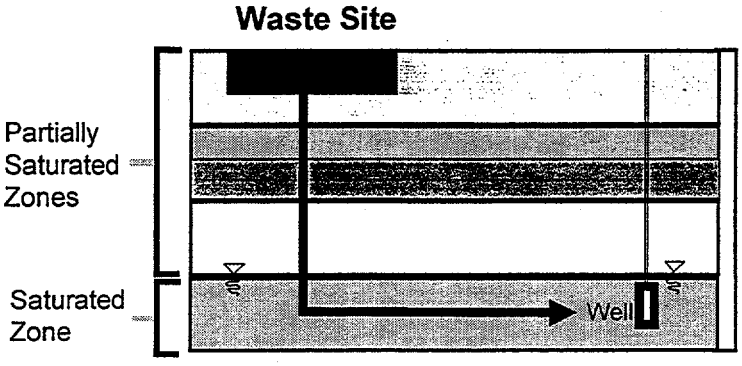
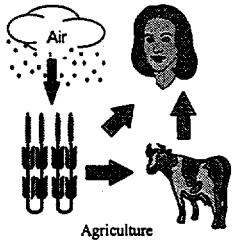


Figure 3. Example of the Linkage between Vadose and Saturated Zones

Air Exposure Routes

- Ingestion
  - Leafy Vegetables
  - Other Vegetables
  - Meat
  - Milk
  - Soil
- Dermal
  - Soil
- Inhalation
  - Air



- Resuspension
  - Soil
- External
  - Soil
  - Air

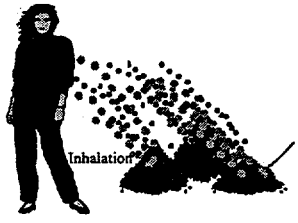


Figure 4. Exposure Routes and Pathways for the Atmospheric Medium

Groundwater Exposure Routes

- Ingestion
  - Drinking Water
  - Showering
  - Leafy Vegetables
  - Other Vegetables
  - Meat
  - Milk
- Dermal
  - Showering
- Inhalation
  - Showering

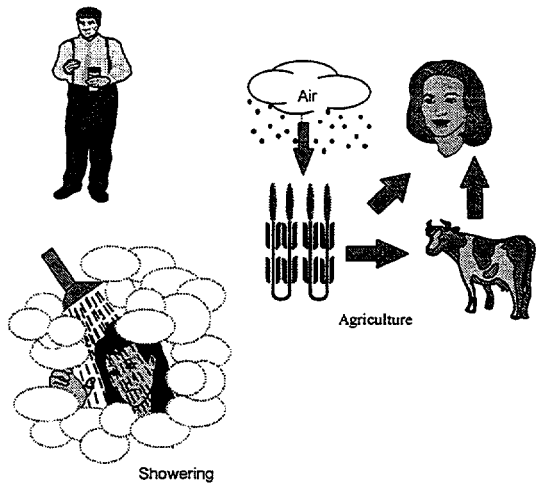


Figure 5. Exposure Routes and Pathways for the Groundwater Medium

Surface Water Exposure Routes

- Ingestion
  - Drinking Water
  - Showering
  - Leafy Vegetables
  - Other Vegetables
  - Meat
  - Milk

- **FinFish**
- **Shell Fish**
- **Swimming**
- **Shoreline**

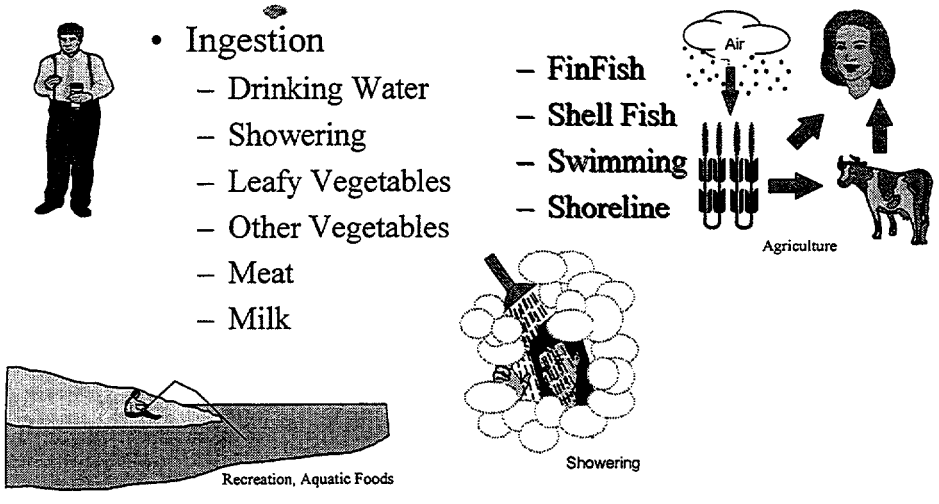


Figure 6. Exposure Routes and Pathways for the Surface Water Medium

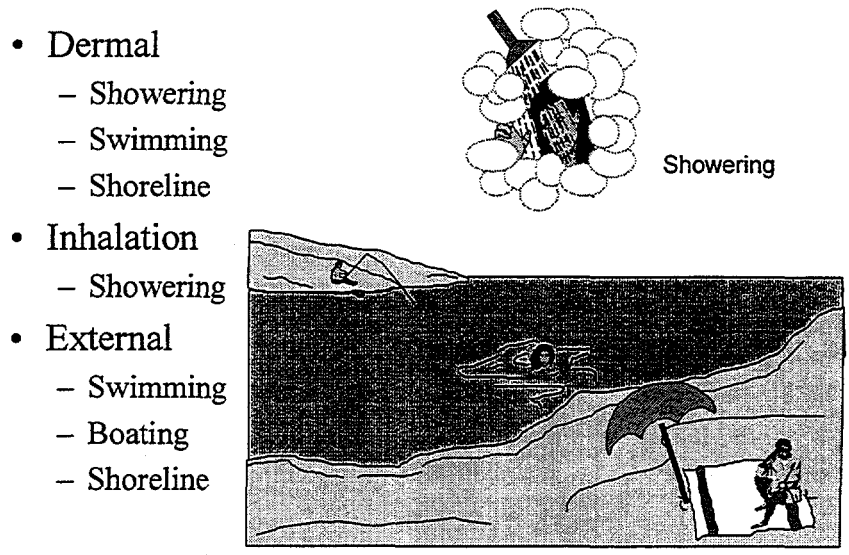


Figure 7. Exposure Routes and Pathways for the Surface Water Medium (Cont)

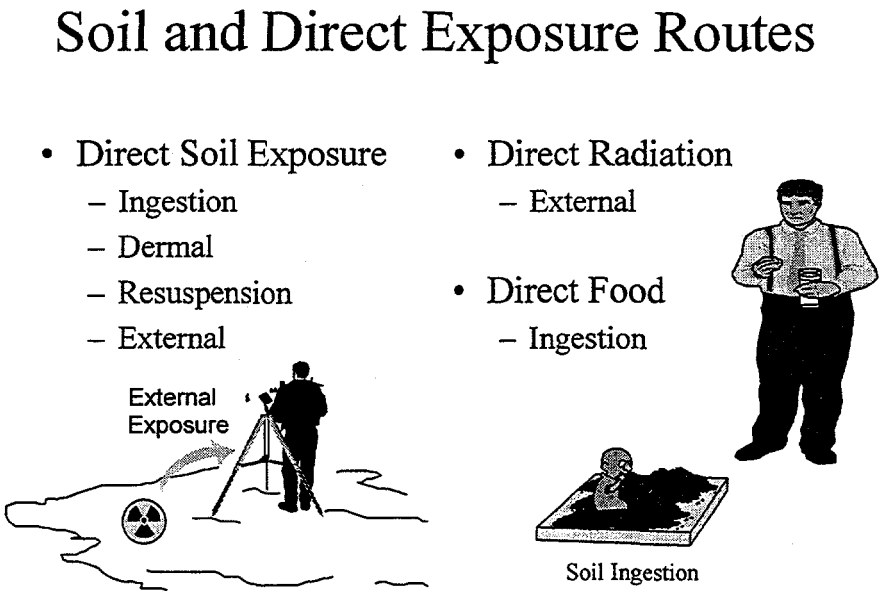


Figure 8. Exposure Routes and Pathways for the Soil and Direct Medium

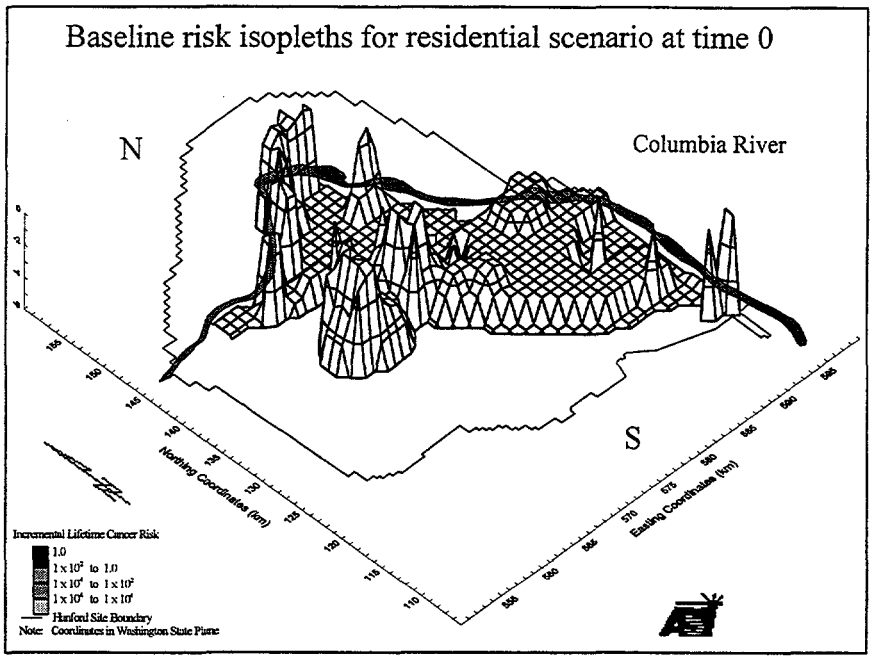


Figure 9. Illustration of Spatial and Temporal Dimensions of MEPAS Results

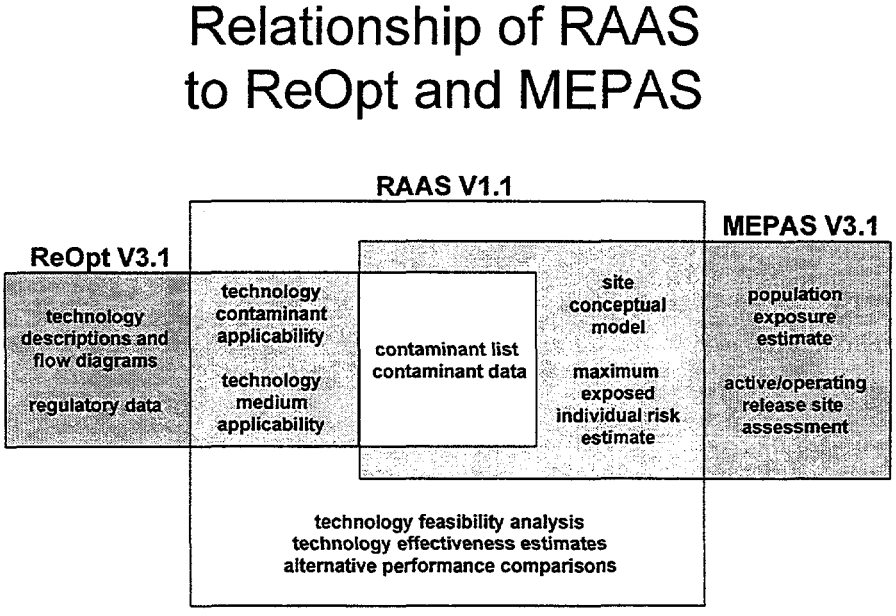


Figure 10. Diagram of the integration of MEPAS and RAAS Software Capabilities

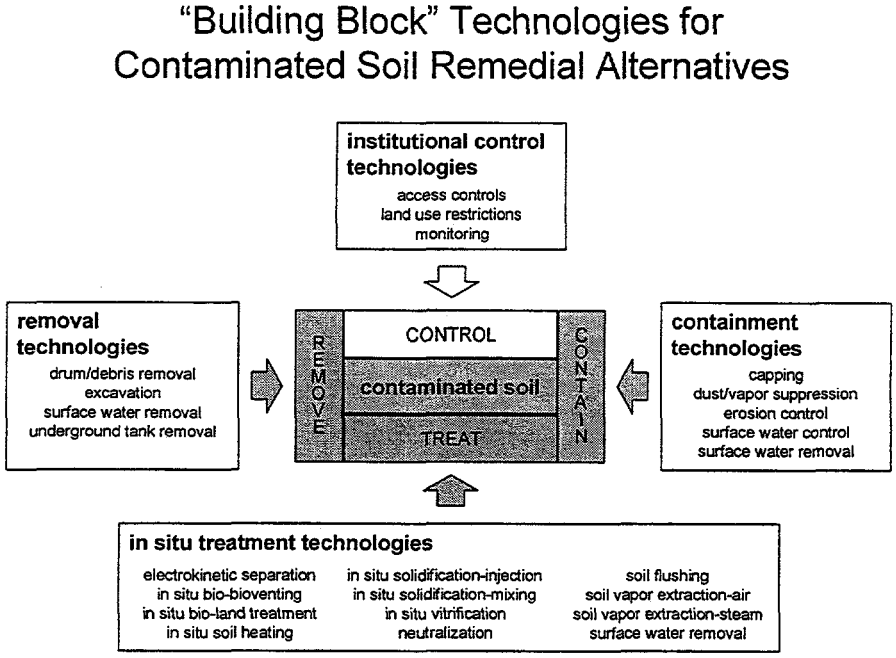


Figure 11. Diagram of the Different Technologies Available in RAAS Software

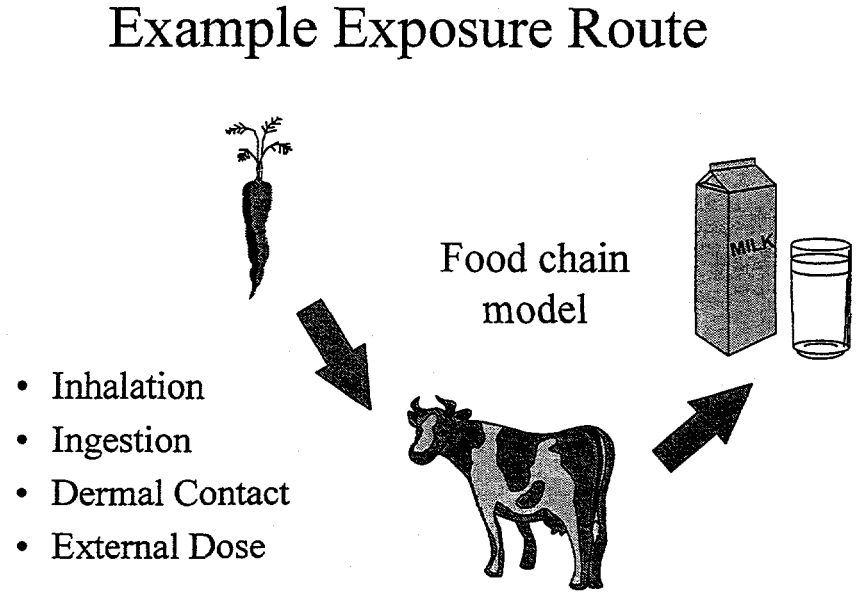


Figure 12. Example of Food Chain Pathway in MEPAS

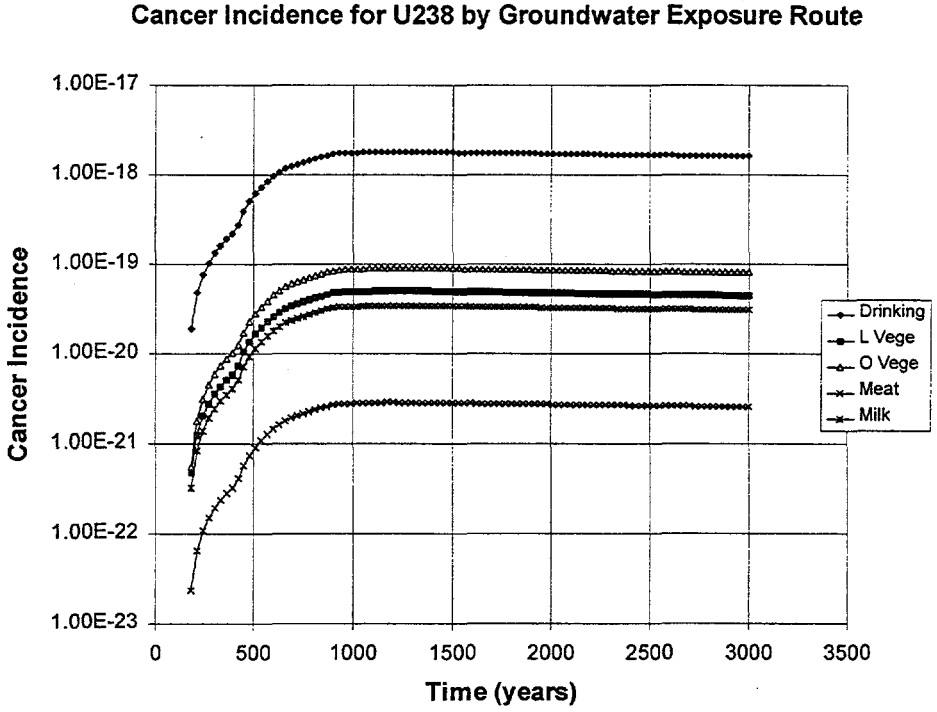


Figure 13. Example of Graphical Output of MEPAS Results via MS EXCEL

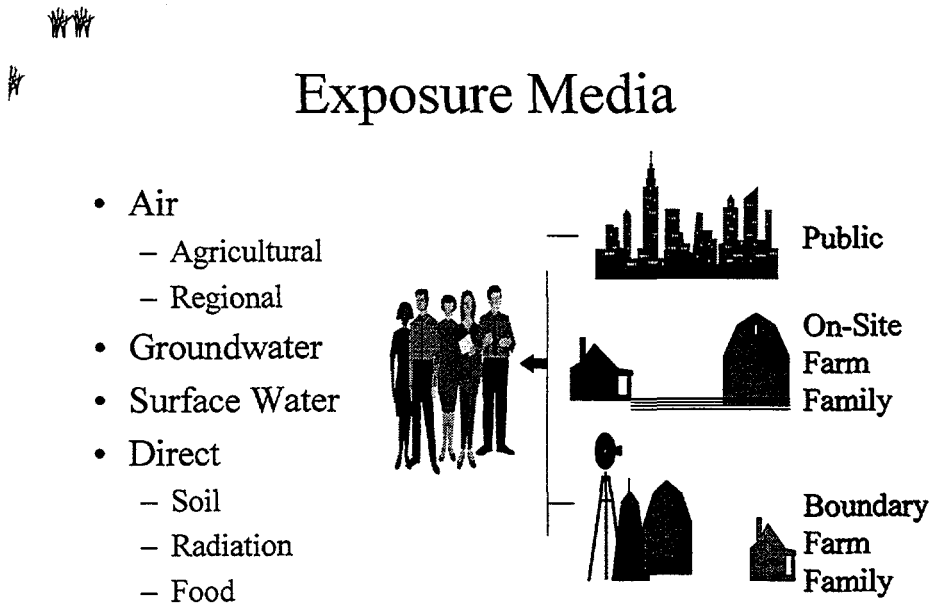


Figure 14. Diagram of Different Receptor Typses Available in MEPAS Methodology

Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES)

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Introduction

The objectives of the Nuclear Regulatory Commission (NRC) Workshop on the Review of Dose Modeling Methods for Demonstration of Compliance with the Radiological Criteria for License Termination are to 1) provide the NRC staff and the public with an overview of currently available Federally-Sponsored dose models appropriate for decommissioning assessments and 2) discuss NRC staff-developed questions related to model selection criteria with the final rule on "Radiological Criteria for License Termination" (62 FR 39058). The NRC has been working on regulatory guidance for residual radioactive contamination from decommissioning. Detailed documentation of the scenarios and calculations are presented in NUREG-5512, Volume 1 (Kennedy and Strenge 1992). The NRC with the support of Sandia National Laboratory (SNL) has been developing a decision methodology (i.e., NUREG-1549) that can implement NUREG-5512 as part of the decommissioning of sites.

This Decontamination and Decommissioning (DandD) methodology was developed to specifically address the dose-based criteria for license termination and utilizes a series of box models that have been connected to represent scenarios that address the release of contaminants from a source into the environment, contaminant movement through various environmental media, and exposure/dose to humans through various exposure routes. DandD incorporates all of the information necessary for a Level 1 screening assessment (e.g., NRC 1994), where the necessary scenarios and pathways have been "hard-wired" into the model, including building scenario, residential occupancy, groundwater transport to drinking water, and building renovation. A Level 1 assessment "embodies a procedure for screening candidate hazardous waste sites," and a Level 2 assessment estimates site-specific "environmental risks and remediation costs" (NRC 1994).

DandD is based on an extensive default parameter library and attempts to provide a conservative assessment with non-site-specific parameter values. As a cost-effective and quick-assessment analysis, this approach meets Level 1 screening guidelines. The NRC is looking to move the DandD methodology to more site-specific analyses, hence, a Level 2 assessment. The intent is not necessarily to choose another model to replace DandD but to formulate a strategy to smoothly transition from a screening level analysis to a more site-specific assessment. This strategy may be represented by 1) updating the default parameter database with more site-specific information, 2) updating the modules of the DandD code to represent more site-specific phenomena, or 3) linking DandD to modules of other Level 2 models, where appropriate. Regardless of the chosen approach, it is imperative that some sort of commonality exists between the Level 1 and Level 2 versions of "DandD," which results in a smooth transition. Consistency between the Level 1 and 2 versions should be a very important from a regulatory perspective. In effect, an approach may be required to allow linkages between components of different models to help in the smooth transition from a Level 1 to a Level 2 assessment.

As part of the NRC Workshop on the Review of Dose Modeling Methods for Demonstration of Compliance with the Radiological Criteria for License Termination, NRC has identified ten questions to help in the evaluation process of including approaches other than DandD and its default-data set (NRC 1997). Because the NRC staff envisions that the screening calculations will be performed using DandD, a platform or framework for linking modules with DandD may be beneficial to help meet the needs of NRC for moving DandD from a Level 1 analysis to a Level 2 assessment. Discussion of such a framework would, in effect, link the ten NRC questions.

History of Framework Development

For over 40 years, medium specific models have been and will continue to be developed in an effort to understand and predict environmental phenomena, including fluid-flow patterns (e.g., groundwater, surface water, and air), contaminant migration and fate, human or wildlife exposures, impacts from specific toxicants to specific species and their organs, cost-benefit analyses, impacts from remediation alternatives, etc. For nearly 40 years, medium-specific models have been combined for either sequential or concurrent assessments (Whelan et al. 1986). The evolution of multiple-media assessment tools has followed a logic progression, as illustrated by Figure 1:

- In 1959, the Stanford Watershed Model (SWM) was developed and represented one of the first "integrated" models, as it linked multiple processes by simulating the land-phase of the hydrologic cycle for an entire watershed (Crawford and Linsley 1966).
- In 1969, Oak Ridge National Laboratory presented the Unified Transport Approach (UTA) and more refined versions like the Unified Transport Model (UTM-TOX; Patterson et al. 1984), which coupled (i.e., "hard-wired") detailed numerical models, describing individual environmental media (e.g., groundwater, air, surface water,

and soil). Although these models have been funded by the U.S. Environmental Protection Agency (EPA; Patterson 1986), the UTA did not progress into general use possibly because 1) the models tended to be difficult to understand, operate, modify, and maintain; 2) data to operate the models were generally unavailable; and most importantly 3) computer power to drive the system was lacking at the time.

- In 1978, mixing-tank models, which represent compartments with uniformly mixed contents, began a large resurgence in the assessment arena. Mackay and Paterson (1986) noted that Baughman and Lassiter (1978) suggested using evaluative models, which suppressed the phenomenological detail usually associated with the more mechanistically-based models. As a result, numerous mixing tank models with varying degrees of sophistication have been developed (Burns et al. 1982; Mackay 1979; McCall et al. 1983; McKone and Kastenberg 1986); Renner 1995).
- In 1984, development of the first semianalytically based, fully coupled, sequential multimedia model, which accounted for temporally and spacially varying contamination (chemicals and radionuclides) within designated media (i.e., compartments) began (Whelan et al. 1987). Each medium-specific model was "hard-wired" into the system, so replacing medium-specific components was not built into the system. Since 1984, a number of semianalytical multimedia models have been introduced (Whelan et al. 1992; Yu 1993; Hung 1996; Moskowitz et al. 1996; Laniak et al. 1997; Mills et al. 1997). These multimedia models were made possible with the introduction of desktop computing.
- In 1987, the development of large multipurpose frameworks began, which "hard-wired" a suite of codes together and investigated, not just the distribution of contaminants in the environment, but relationships between a suite of issues deemed valuable (e.g., regulatory criteria, data quality objectives, CERCLA and RCRA processes, etc.) (Hartz and Whelan 1987). Some of these multipurpose frameworks include the Remedial Action Assessment System (RAAS; Whelan et al. 1990) and Sandia Environmental Decision-Support System (SEDSS).

In all of these approaches, individual components (or models) are "hard-wired" into the systems, and to a certain degree, the legacy of the original model that has to be forced into the system is compromised. Any changes to the components will invariable result in changes to the system, because these systems were not designed to accommodate change.

If significant modifications are required in these existing systems, the changes tend to be cumbersome, as illustrated by Figures 2 and 3. Figure 2 illustrates the interrelationships and connections between components composing an existing system. In multiple-component systems, models, modules, attributes, or subroutines are usually linked to each other in the typical "spider-web" arrangement. Each time a new attribute is added to the system, connections (e.g., data processor or mathematical algorithm) are arranged between new features and existing ones. In many instances, modifications to the actual programs themselves must be initiated, thereby changing the legacy of the model. Experience has clearly demonstrated that modifications within the "spider-web" construct many times results in unnecessary and unexpected changes in other components. Although changes can be made, the process tends to be time- and resource-consuming.

A "cleaner" approach for incorporating new models, modules, attributes, or subroutines is to reduce the number of variations in the connections so that existing and new attributes maintain their original legacy, realizing that some relatively minor modifications may be necessary. If the interaction and connection of components is focused at the interface between the components, then adding new components or modifying existing ones would not impact the system as a whole, as illustrated by Figure 3. Changes in the assessment do occur over the life of the project, and a system should be able to adjust (within reason). By specifying interface specifications, models, modules, databases, and other frameworks can now effectively communicate, as each one will know a priori the connection requirements (e.g., "telephone numbers") for communication.

Significant changes also occur with the computational power of computers, programing languages, new and innovative concepts and approaches, more enhanced databases, and access to new and improved databases, etc. Also, different organizations and people require different relationships between models and assessments to meet needs. To allow a suite of users the flexibility and versatility to construct, combine, and couple attributes that meet their specific needs without unnecessarily burdening the user with extraneous capabilities, the development of a computer-based methodology to implement a Risk Analysis in Multimedia Environmental Systems (FRAMES) was begun in 1994. FRAMES represents a platform which links elements together and yet does not represent the models that are linked to or within it; therefore, changes to elements that are linked to or within FRAMES do not change the framework.

Structure

Over the past 10 years, researchers have focused on developing fully integrated, physics-based, intermedia models that allow for a more transparent connection between individual medium-specific modules. These models take a holistic approach to environmental assessment of potential contaminant impacts as they simulate 1) the release of contaminants into the environment, 2) migration and fate

through various environmental media (i.e., groundwater, surface water, air, and overland surfaces), and 3) resultant exposures and impacts. The overall scope of these models includes evaluation of on- and off-site impacts from active and inactive sites involving both chemical and radioactive wastes. Although differing in their individual scope, these multimedia models tend to be "analytical" in nature (e.g., mainly compartmental, analytical, semianalytical, and/or empirical algorithms). Just because numerical and structured-value (e.g., Hazard Ranking System) models are traditionally not associated with the physics-based multimedia models, this should not preclude their use within this holistic approach or from access as an outside model. In addition, there is no reason why a framework cannot be established that accounts for both the level of detail (i.e., resolution) of the models (e.g., structured-value, analytical, and numerical) and the scale of the assessment (e.g., medium-specific, watershed, regional, and global).

A number of government agencies and private companies have used single and multimedia models for federal regulatory and compliance activities associated with NEPA, CERCLA, and RCRA as well as for state regulatory and compliance activities. The advantage is in consolidating these single-medium and multimedia models into one standard tool. Consolidating the best aspects of these models could highlight their strengths and minimize their shortcomings. In addition, EPA and DOE have developed many other useful models that would benefit from access to this new framework (e.g., IEM, EPACMTP, EXAMS, WASP, TOXIWASP, HELP, PRZM, GENII, AT123D, etc.), thereby providing users with greater access to these models. As technology advances, a next-generation framework would eventually be needed to address regulatory, compliance, oversight, and site-specific applications, and would be linked to a GIS to facilitate data transfer and analysis and presentations. This expanded system could also link human-health/ecological impacts with remedial technology assessment, cost analyses, and risk reduction. The new framework (e.g., FRAMES) could service various agency's needs in defining soil cleanup levels and waste-site exit concentration criteria, evaluating risk reduction by remediation technologies, generating end-point cost drivers, meeting regulatory applications, conducting programmatic studies, and assessing site-specific applications. The result could be a compositely constructed system, that greatly enhances versatility and flexibility to allow more focused and cost-effective multimedia modeling assessments.

Data Linkages and Information Transfer

Within the modeling-based FRAMES resides a collection of computer algorithms that simulate elements of a transport, exposure, and risk-assessment system, including contaminant source and release to environment (including surface hydrology); overland, vadose zone, saturated zone, atmospheric, surface water, food-supply (including animals and plants to humans); intake computation, and health impacts. Each of these elements, and many that are not listed, will be represented by separate modules. Each of these modules should:

- be object oriented. An object-oriented module represents a component that is independent of other components. Each component is viewed as an entity, where interactions and linkages occur at interfacing junctions and where a transfer of information can occur. Object-oriented design currently represents the state-of-the-art in design.
- import the data required for execution. The data may be imported from result files contained in FRAMES or directly from the user. It is a requirement of each module to read all data items correctly from the appropriated files in FRAMES.
- execute the model correctly, given the data gathered in the import process.
- correctly export data to FRAMES data files.
- not have data redundancy, as when data are accessible, visible, and transferable to all components. The data-overlap concept is contrary to object-oriented design and results in a less efficient system. Object-Oriented designs do not usually require data to be visible to all components.

There are three software considerations with respect to data-transfer linkages: data redundancy, dynamically linked modules, and a framework user interface.

Data redundancy:

Data redundancy occurs when the same information is stored more than once. Within a given element classification (e.g., vadose zone), certain data requirements exist. For example, moisture content is a traditional characteristic of the vadose zone. Specifying the exact form of the data in each element could limit access by new modules that may be added to the system, and any data storage and retrieval system should not be developed that may limit access. For example, even though two vadose-zone modules require moisture content as a characteristic of the element, one module may require the information as a dry-mass fraction and the other may require the same information as a volumetric fraction. Mandating the exact form of the characteristics describing the element would mandate wholesale changes to the data input requirements of each module. In addition, this approach would limit flexibility and versatility by not allowing FRAMES to address future new and innovative trends contained in potentially new models trying to gain access to the framework. Therefore, a new system must easily allow for change without constraining access to future developments. The burden to absorb change should

never be on the framework; if so designed, FRAMES would become obsolete in a short period of time.

To meet these needs and constraints, FRAMES structures its data linkages to allow for the following types of data files:

- Primary Data Communication Files (PDCF): PDCFs are the data files that are used to transfer information between modules. These files embody the concept of object-oriented design by specifically identifying and segregating data associated with the linkages at the boundaries of the modules.
- Global Input Data Files (GIFs): The GIF files will be stored where all user input is stored. Each module is responsible for deciding what data are included for itself. The GIF files contain Modular User Interface Sections (MUISs). The MUISs represent the user-supplied information that is transferred through the Modular User Interface (MUI). These sections allow for updates to each module, new data requirements for each module, and changes without constraining access to future developments.
- Other Data Files: Under the design, FRAMES has unlimited access to data and databases. Other data files could include, but are not limited to:
- Imported Data Files: Data files that contain information needed for models. (i.e., laboratory results of soil, air, and water samples, which are typically in spreadsheet form).
- Exported Data Files: Data files that serve as input to larger assessments [e.g., results of a site assessment are reformatted for efficiency in the Modular Risk Approach (MRA; Whelan et al. 1994)].
- Maintained Databases: Databases that are maintained by other individuals (e.g., IRIS for toxicological data, GEMS for population data. etc.).

Dynamically Linked Modules

The modules must be linked as the direct result of user selection. This requires strict protocols to determine the validity of various linkages and resolve all data-transfer needs. Linkage concerns include the following:

- A system should be constructed such that 1) data, specific and unique to each module but not produced by other modules, can be user-supplied and 2) data, specific and unique to each module but produced by other modules, can be supplied by other modules.
- Individual modules must be linked in such a manner as to facilitate data transfer at the interface between modules.

File specifications describe how all information is to be stored within the framework and passed between modules. These file specifications are not associated with information storage or transfer within each module, only with the transfer of information to the framework or another module. The input and/or output data files used for transferring information have the following attributes:

- The files should be easily used by the most common modeling languages and software. Typical languages include FORTRAN, C, C++, Pascal, and Visual Basic; typical software includes Excel and Lotus.
- Where appropriate, the files should include both the numerical values and their corresponding units.
- The files should be self-descriptive. When a user with no knowledge of the file or its specifications views the file, the user should be able to correctly interpret the data stored therein.
- As much as possible, the files need to be computer platform independent. Platform independence will allow part of an assessment to be completed on more powerful computers.
- Separate input and output data files should be developed. The input data refer to those required for a successful completion of a module's application. All input data will be stored in the GIF file, which is required to successfully operate the module. User input data are isolated from all calculated results to ensure that the sensitivity/uncertainty analysis runs efficiently and aids in the ability to reproduce results. Output data refer to calculated results.

Framework User Interface

A Framework User Interface (FUI) must be designed and implemented that will 1) allow for relatively easy inclusion of additional modules and models, 2) promote access to national databases; 3) minimize data-exchange requirements within FRAMES, 4) allow for unlimited access to data, and 5) address linkage concerns. The responsibilities for the FUI need to be established so each module can function within the system without added restrictions but still allow the responsibilities to be defined. The FUI is responsible for the following

- Ensuring that the modules are connected properly and appropriately.
- Ensuring that the module has access to an unlimited supply of data, where appropriate.
- Allowing for unique forms of data entry (i.e., selecting soil properties from a map of the United States or from the Soil Conservation Service soil triangle, or retrieving data directly from sources on the Internet).
- Establishing protocols for implementing components of the FUI. For example, the FUI will not allow a module to be run until input data requirements through the MUI are complete and data required from other modules are available.

- Ensuring that if a module behaves inappropriately, then the data for the other modules are protected from the errant module, and inform the user of errant behavior of modules.
- Managing storage of user data and results.
- Managing information to inform the user of which modules are available in FRAMES.

Object-Oriented Design

A structure should be developed so that the type of model employed within the framework is (more or less) unimportant. In effect, the structure should view all of its components as real-world objects, uninterested in the inner workings of the objects. For example, FRAMES should not discriminate between an analytical or numerical model. If time-varying concentrations at a location are required, FRAMES should not be concerned with the model that produced them. If the objects represent real-world components, the user will be able to conceptualize the problem and construct modules that address the conceptualization.

To develop an "object-oriented" framework, specifications for structuring FRAMES must be identified: 1) the form of the boundary conditions between modules, 2) units, 3) storage protocol for input and output data, 4) user-interface requirements, 5) scale (physical size and attributes of the assessment), 6) mesh resolution (i.e., level of detail associated with the boundary conditions between modules), etc. FRAMES should allow the user to choose models to use. FRAMES should allow the user the option to 1) incorporate these models into the framework as a working module or access the model from outside FRAMES, 2) access outside data, 3) pick and choose and match modules, 4) obtain help/guidance, and 5) interact with other frameworks. FRAMES should represent a constant among the ever-changing models and modules that are replaced over time. By developing an approach that uses an object-oriented framework, a system can be developed that provides a mechanism for using models that have been previously developed, as well as models that will be developed be developed in the future.

Figure 4: 1) represents a framework that encompasses, interacts with, and connects modules that are typically associated with current physics-based multimedia assessments (e.g., MMSOILS, MEPAS, RESRAD, PRESTO, etc.); 2) illustrates how FRAMES surrounds and interacts with medium- or attribute-specific modules; and 3) presents the interrelationships between a FUI and the modules housed within the FUI. Typical modules include those identified in the figure, where modules can be added or deleted depending on the assessment. For example, if ecological or GIS modules are required, they can simply be added, as long as they meet framework specifications. Likewise, a probabilistic module can be added when Monte Carlo assessments are required. The FUI helps the user define the problem, which establishes protocol to 1) select the appropriate modules needed to address the problem, 2) controls the flow of information to and from the modules chosen for the problem, and 3) segregates input from output data by placing the data into special input and output data files [i.e., Global Input and Output Data Files (GIFs and GOFs)].

Figure 5 presents a more detailed illustration of the actual implementation of a module within FRAMES. As illustrated in Figure 4, each module is contained within the FUI. The user initially interacts with the FUI, identifying the constituents of interest, developing the Conceptual Site Model (CSM), and initiating the sequence of selected modules from within FRAMES and models from outside FRAMES. The FUI input and output data are stored in the GIFs and GOFs, respectively. The first module, which is chosen by the user with the help of the FUI, is then initiated as part of the CSM. The first MUI is then activated, and the user inputs the appropriate information for that module. Additional information could also be supplied to the MUI from previous modules. The GIFs and GOFs interact with the MUI through a data-processing program (i.e., circles in Figure 5). The output from the MUI is converted to the appropriate units and stored in the GIF using a data-processing program. Other parameters calculated from input data (e.g., retardation factors, which are calculated from moisture content, distribution coefficient, and bulk density) are likewise stored in the appropriate GOF for use by succeeding modules (including GIS or sensitivity/uncertainty modules) from within FRAMES or other, outside frameworks.

As Figure 5 shows, the MUI interacts directly with the GIFs and GOFs through data processing programs. The FUI actually initiates each module's application (i.e., runs the module). A data-processing program reads input from a GIF, which originated from the MUI. The boundary conditions for the module are read from a GOF. These boundary conditions may originate from the FUI, MUI, or a model outside of FRAMES. The outside model's output would be stored in a GOF in FRAMES by way of a data processing program (see Figure 5). All data from the GIFs and GOFs are processed into the appropriate units and formats by data-processing programs, which in effect reformat the information so the individual module does not have to be modified. After the module is implemented, it writes its information to its normal files and processes selected data output for a GOF by way of a data-processing program. Therefore, multiple data-processing programs may be required for each module. These programs basically convert the information to the correct units and store data within the proper time and space scales, where appropriate. Technical specifications for these data-processing programs should contain as few constraints as possible. Because all input data are stored in a GIF, sensitivity/uncertainty analyses are easy to implement. All output is stored in GOFs, allowing for easy access and analysis, including plotting, statistical analyses, QA/QC, report writing, summations, etc. As Figure 5 shows, if

more than one module was selected by the user, the FUI would call up the next module's UI, and the process would be repeated.

Because the analysis is dependent on the constraints of the problem to be solved, different problems may require different models or features. Any framework should be structured to take advantage of the appropriate models required for the analysis. As opposed to trying to convert all needed models or programs to meet its constructs, FRAMES should provide an access port for these models. Under FRAMES, these models would have access to GOFs though a data-processing program. The specifications for this program would identify the format for easy access without unduly burdening the preexisting model or program. Figure 5 illustrates the means by which these outside programs could access and interact with FRAMES.

Framework User Interface (FUI)

The user or an automated-access program (also referred to as a "user") interacts through the FRAMES FUI. The FUI is the interface that accesses the contaminant database and subroutines for setting up the problem and establishing the CSM. The current chemical database contains between 500 and 800 chemicals and radionuclides. Information includes physical and chemical characteristics of each constituent, environmental partitioning data, transfer and uptake rates, and exposure and risk data. Databases traditionally used by EPA, DOE, and NRC are included, where appropriate, so the user can meet specific needs dictated by the problem at hand. The CSM includes the construction of the problem that the user needs solved. With the help of the FUI, the user describes the problem and chooses the appropriate modules and models to address it. All modules under FRAMES would be available for selection from a pop-down menu. The user sequentially selects the appropriate source-term modules, transport pathways, and exposure routes that specifically address the problem. The FUI organizes the selection process to ensure that only appropriate selections are available. All input data to the system resides in GIFs. Input data are segregated from other data so sensitivity/uncertainty analyses can be easily performed within FRAMES. Any input data modified within the FUI would be stored in designated GOFs. Access to both GIFs and GOFs would be made available to all modules that reside within FRAMES. Both GIFs and GOFs would also be available for access by outside frameworks, models, or control programs (see Figure 4). Following selection of the appropriate modules and models, the FUI would automatically call up each individual MUI of the selected modules in the correct order. When the user has interacted with each MUI and addressed all inquiries sequentially, the FUI would implement all analyses in the appropriate order. Therefore, all MUIs would be sequentially accessed and implemented prior to running each of the modules in their appropriate order.

Real-world, object-oriented design represents the foundation of FRAMES. By structuring FRAMES so the objects represent real entities (e.g., 3-m thick, sandy-loam, vadose-zone layer), the FUI is able to visually capture the essence of the CSM for the user. In effect, the FUI offers a tool for "laying out the plumbing" to perform waste site assessments. From 50 to 80% of the learning that is generated occurs during the CSM-development phase (i.e., prior to model simulation). Learning results from asking and answering basic questions such as,

'What is connected to what?'

'How does the process really work?'

'What is consumed when this and that are produced?'.

Once the "plumbing" has been arrayed, the software shifts to serve as a vehicle for tracing the dynamics that are implied by the "plumbing."

Figures 6 and 7 present very simple illustrative examples of how the user visually constructs the CSM using the FUI. Icons are available that describe the modules housed within the FUI (e.g., source, vadose zone, saturated zone, river, air, receptors, food chain, etc.). The user chooses and connects icons that recreate the actual or potential path of the contaminants as they move from the source to the receptor.

Figure 6 (i.e., Site 1) illustrates the emission of a contaminant from a source, as it partitions to the air (e.g., volatilization or suspension) and to a saturated zone (e.g., leaching or direct discharge). Two receptor locations are identified. Both receptors are breathing air and drinking water contaminated by the source, and risk calculations are being computed for each receptor location. The lines connecting the source to the receptor via the air and saturated zone visually show the path that the contaminant follows.

Figure 7 (i.e., Site 2) illustrates the emission of a contaminant from a source, as it partitions to 1) the air (e.g., volatilization or suspension), 2) the first of two vadose zones (e.g., leaching or direct discharge), and 3) a river (e.g., direct discharge). Three receptor locations are identified. The first receptor 1) is directly in the path of the atmospheric plume, emanating from the source, and 2) breathes the contaminated air. The second receptor eats contaminated crops that were irrigated from water taken from the river, which was contaminated by the source. The third receptor is directly exposed to contaminated drinking water from contamination that migrated through two vadose zones and a saturated zone to a drinking-water well. Three sets of risk calculations are performed, but only two icons are defined because the assumptions forming the basis of the risk calculations are the same for two of the receptors.

Figure 8 presents a detailed illustrative example of what the current FUI looks like and illustrates the release of contaminants from a source (i.e., Hanford Tanks), as it partitions to the air (Hanford Air) and the first of two vadose zones (Zone 1 and Zone 2). Vadose-Zone contamination eventually migrates and contaminates the saturated zone (Hanford Aqu), which discharges to two different rivers (Columbia and Yakima). Two receptors are identified (Native American and Adult Pop) and are exposed to air and water contamination that has made its way through three different food chain locations and routes (Richland, Kennewick, and Pasco). The Native American and Adult Pop live in all three locations but have different life styles and breathe air and consume food and water differently. Separate risk calculations are, therefore, computed for each receptor (Native Risk and Adult Pop Risk).

Each icon in Figure 8 contains three circles (see left side of each icon in Figure 8) of which only one circle is visible. If the topmost circle (red light on the actual screen) is visible, this denotes that a model has been chosen to represent the icon; this condition is not illustrated in Figure 8. If the center circle is visible, as illustrated in all but one of the icons (yellow light on the actual screen), then this denotes that the module's database has been populated. Finally, if the lowermost circle is viable, as illustrated with the "Contaminants" icon, then the module has been run. This street-light approach provides the user with an instantaneous visualization of the status of the assessment. As one can imagine, the pictures in Figures 6 through 8 can quickly become very messy and appear to be fairly complex. If the pictures do become too detailed, it conveys to the user that a very complex problem is being assessed.

In addition to presenting a flow diagram of the CSM, the FUI it is also responsible for coordinating icon names and three-dimensional locations, which are relative to a reference point for the geographic location. For example, nearly all the sites at the Hanford installation in Richland, Washington, are given coordinates related to the most northwest corner of the installation. The third dimension is the elevation of the icon. A unique name is required for each icon, and the same name for two icons implies that the icons are the same icon. By allowing multiple icons with the same name, the FUI can account for different activities impacting the same icon.

Even though the pull-down-icon approach is flexible and versatile, certain protocol are enforced. For example,

- One icon can represent and encompass a rather detailed and complex model type. For example, a source-term release module may include many different types of sources (e.g., elevated and heated stacks, landfills, ponds, etc.), although the source is only represented by one icon.
- Every problem must begin somewhere. In FRAMES, the source represents the beginning, and the user designates what the source is. For example, the source could be designated by groundwater concentrations at a drinking-water well, where no transport calculations are required. The water concentrations would be directly used in any dose/risk computations.
- The FUI does not allow cyclic dependencies. Contamination from a source will not be allowed to cycle through several modules and return to its point of origin, as illustrated by Figure 9. In Figure 9, there is an emission from the source to the air, which then deposits contamination back on the original source. Because the results from one module sequentially interact with the next module, concurrent and simultaneous analyses with feedback loops between modules are not addressed.

Scale and Resolution Considerations

The world is an extremely complex place. Any attempt to develop a framework that is all-encompassing will result in an extremely cumbersome tool that is difficult to use or contains an undue amount of constraints. The most efficient frameworks are developed to address specific problems. By developing an approach that solves too many broad questions, unnecessary constraints are placed on the system.

If a global assessment is required, then this framework should not have to also meet requirements to address site-specific analyses. This is not to say that a site-specific analysis may not be important, but the site-specific analysis should represent a boundary condition to the global assessment. The temporal, spacial, and data requirements for a global assessment are different from those associated with a site specific assessment. Frameworks should be developed separately for these differences in scale and resolution, but the different frameworks should be structured so they can communicate with each other. In this manner, the site-specific release at Chornobyl, for example, can be included as a boundary condition to an ensuing regional assessment. Any tool that is developed to solve ALL problems is a tool that usually is too cumbersome to use for most problems. Dividing the problem into manageable components allows for an efficient and effective analysis.

When frameworks are developed to integrate the effects of multiple components, scale must be considered in the development process. Scale is defined as the physical size and attributes of the problem that is being addressed. Four basic scales could be defined as follows: medium-specific, watershed, regional, and global. Medium specific refers to those models and assessments that address specific media during the analysis, such as, waste site, vadose zone, saturated zone, river, air, estuary, overland runoff, even geochemical modules. In other words, a specific code has been developed to address a particular aspect of the environment. The

information is generally site-specific, although regional and national data may be incorporated into the model. Examples of a multimedia framework composed of medium-specific modules include PRESTO, RESRAD, HRS, SSL, MEPAS, MMSOILS, MULTIMED, GEOTOX, SMCM, and DPM. Watershed scale refers to watershed analyses and the aspects of dealing with watersheds as an entity; typical models include DHSVM, ARM, HSPF, CREAMS, and NPS. Similar comments could be made about assessments and tools used on regional and global scales. It should be noted that a model of any level of detail could be associated with each of these scales. For example, analytical and numerical models can be used in a medium-specific assessment; likewise, global assessments are not necessarily limited to numerically based models.

Resolution refers to the temporal- and spacial-mesh resolution associated with the assessment (i.e., requirements associated with the transfer of data). Although the mesh resolution could be defined a number of different ways, it is defined herein based on the types of assessments that are typically performed. Three mesh sizes have been identified: low, medium, and high. A typical low-resolution approach would be represented by a structured-value approach or an approach that lends itself to being self-contained, even if simple quantitative calculations are involved. With this approach, these models would most likely not be subdivided into components but be used as a single entity; examples include HRS, DPM, and SSL. A low-resolution approach could be associated with any of the four scales identified earlier (e.g., medium-specific, watershed, regional, or global).

A typical medium-resolution approach is physics-based (e.g., compartmental, analytical, empirical, or numerical) and lends itself to "uniform or average conditions" over an area or plane. The assessment is not unduly burdened with detailed temporal and spacial discretizations. Although the type of model may inherently influence the level of resolution (e.g., structured-value for low resolution and analytical for medium resolution), specifications of the boundary conditions between models will tend to dictate the mesh resolution. For example, spacially uniform flow conditions are traditionally associated with a medium-resolution-based problem. Spacially uniform flow conditions could be supplied by an analytically or numerically based model. The boundary conditions dictate the mesh resolution (i.e., medium), not the model that is employed in the assessment.

A typical high-resolution approach is traditionally physics-based, where finer resolution is required both temporally and spacially. For example, the high-resolution framework may require the ability to track three-dimensional variations in time with concurrent interactions at all locations. These types of requirements are typical of numerical models. Although numerical models are traditionally used in these situations, analytical models can also be used, if desired. FRAMES should be flexible enough to allow a less complex model to be used, where appropriate; therefore, the level of detail associated with the model does not dictate the resolution associated with FRAMES; the boundary conditions between modules dictate the resolution.

A matrix correlating mesh resolution with scaling dependency is presented in Table 1. Because no methodology or framework can efficiently and effectively address every level dealing with scale and resolution, the shaded areas in the table represent the resolution and scale envisioned for the first framework silo. Additional silos would be developed for other scale and resolution combinations. The scale and resolution categories are important for comparing the different modeling systems with FRAMES. The different categories of scale are, but are not limited to, site-specific, field/facility, regional, watershed/airshed, and global. The different resolution categories will include, but not be limited to, screening, analytical, and numerical. It is important to match the scale and resolution requirements of an assessment to the appropriate modeling system. FRAMES is initially being designed to meet the needs of a single waste site, multiple waste site, and multiple waste site/multiple geographical area assessments. Although FRAMES is being designed for these types of assessments, its design allows for linkages with modeling systems of different scale and resolution for special analysis.

Figures 10 and 11 illustrate the interrelationships and interactions between frameworks representing different scales. By housing approaches as they differ by scale and resolution, efficient frameworks can be developed. Because the frameworks have similar constructs, and because GIFs and GOFs form the basis of each framework, multiple frameworks can communicate. Because units, types and forms of data and formats are known for each framework, data-processing programs can be developed to access the GIFs and GOFs of other frameworks. Therefore, if a medium-specific analysis is required as a boundary condition to a regional analysis, the regional analysis would have access to this assessment, and a data-processing program would transfer the information from the medium-specific framework to the regional framework. Outside access to another model or framework would be similar.

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TABLE 1. Matrix Correlating Mesh Resolution with Scaling Dependency[a]

	SCALE			
RESOLUTION	MEDIUM SPECIFIC	WATERSHED	REGIONAL	GLOBAL
LOW				
MEDIUM				
HIGH				

a. Shaded areas represent resolution and scale envisioned for the first framework silo. Additional silos would be developed for other scale and resolution combinations.

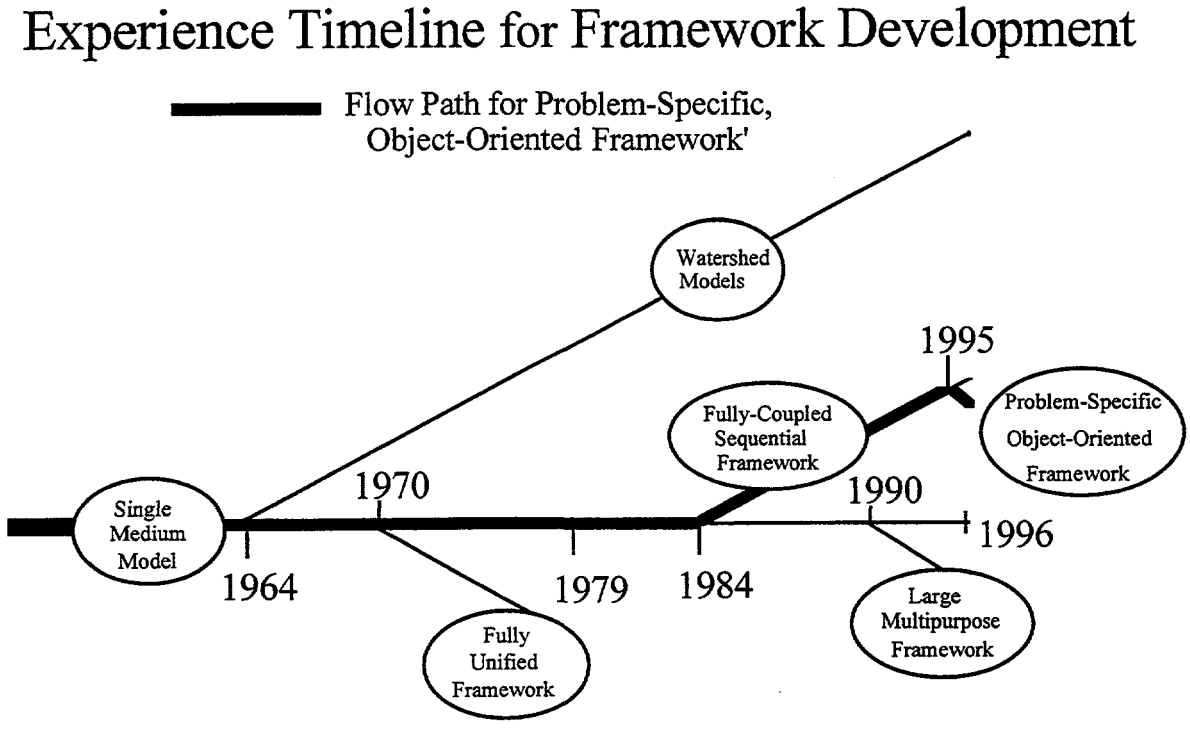

Figure 1. Time Line for Multimedia Model Development

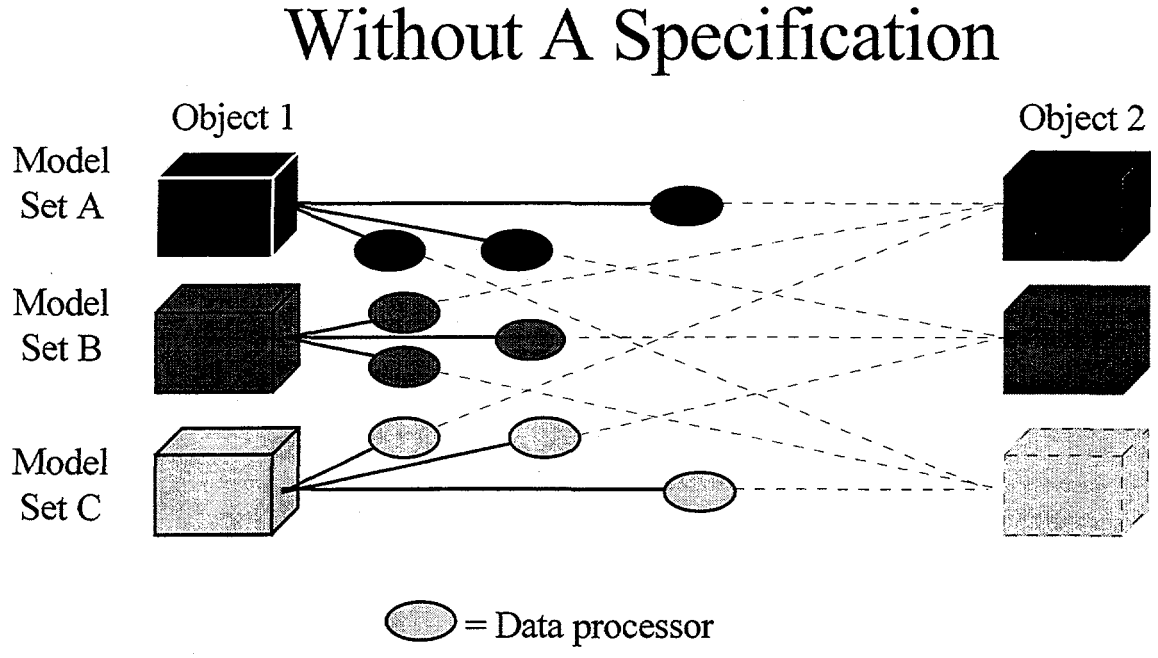

Figure 2. Illustration of the Interrelationships and Connections Between Components Comprising a Typical Existing System

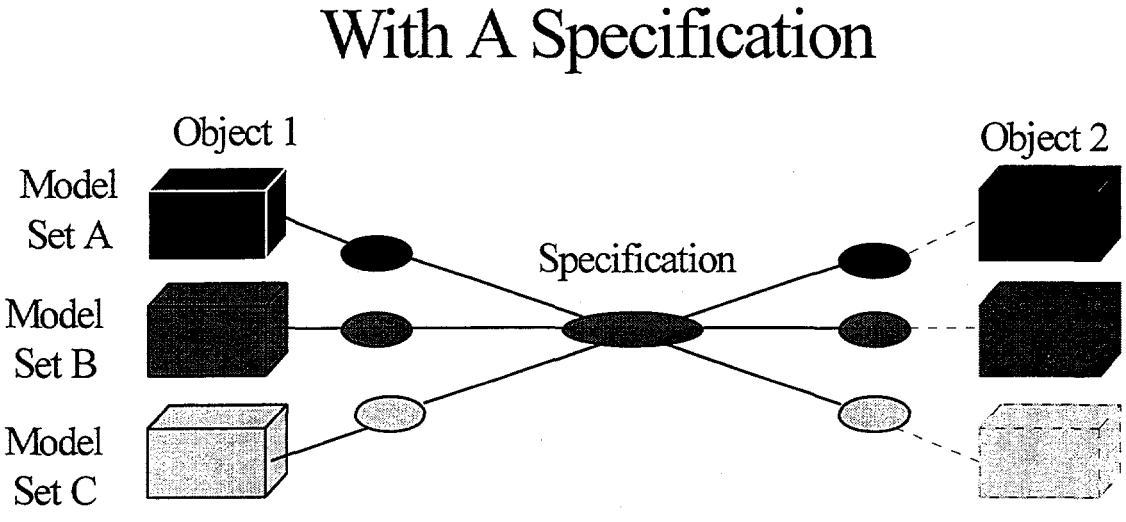

Figure 3. Illustration of the Connection Between Components with Interface Specifications

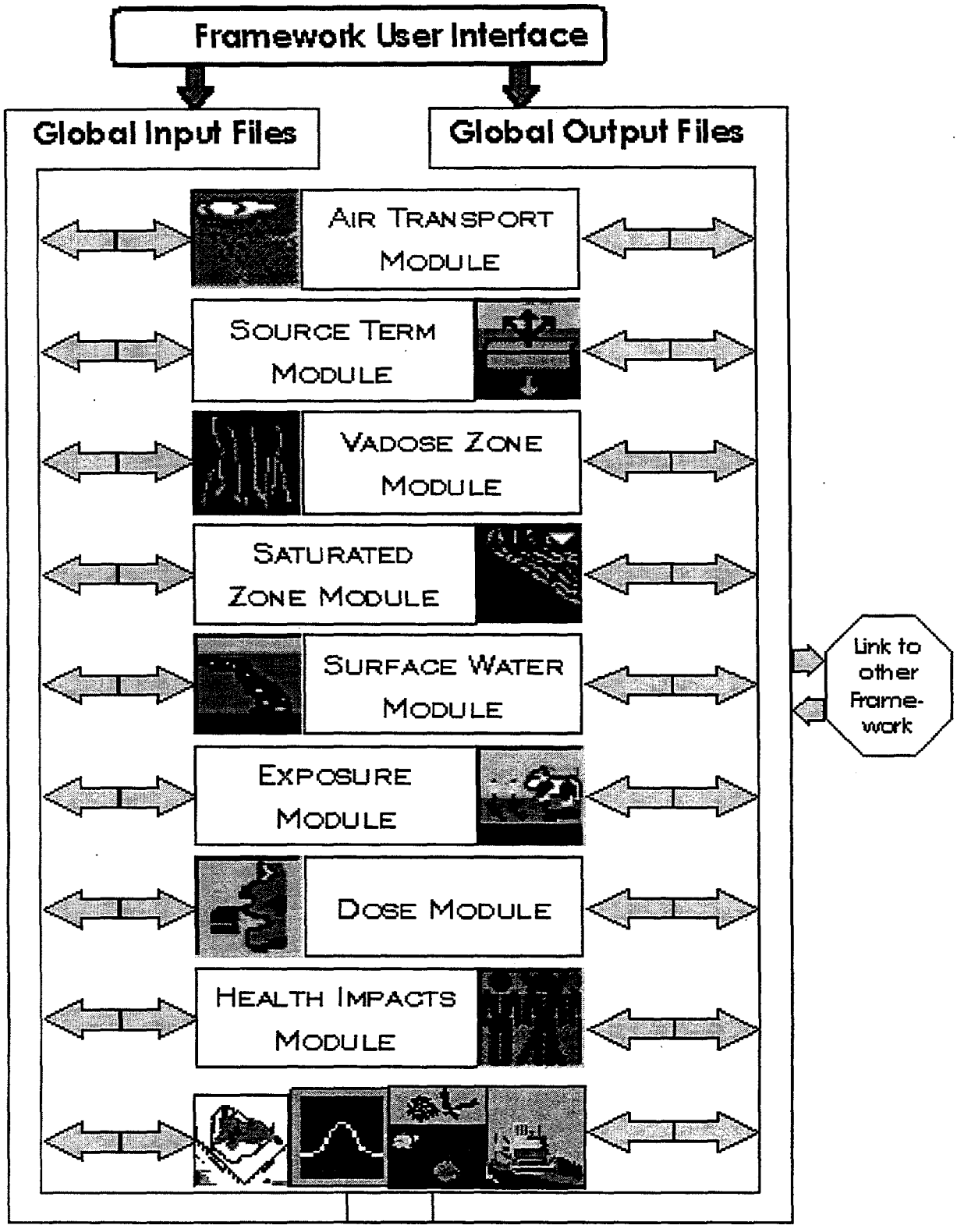

Figure 4. Structure of FRAMES User Interface and Global Input & Output Data Files, which House Medium-Specific Modules

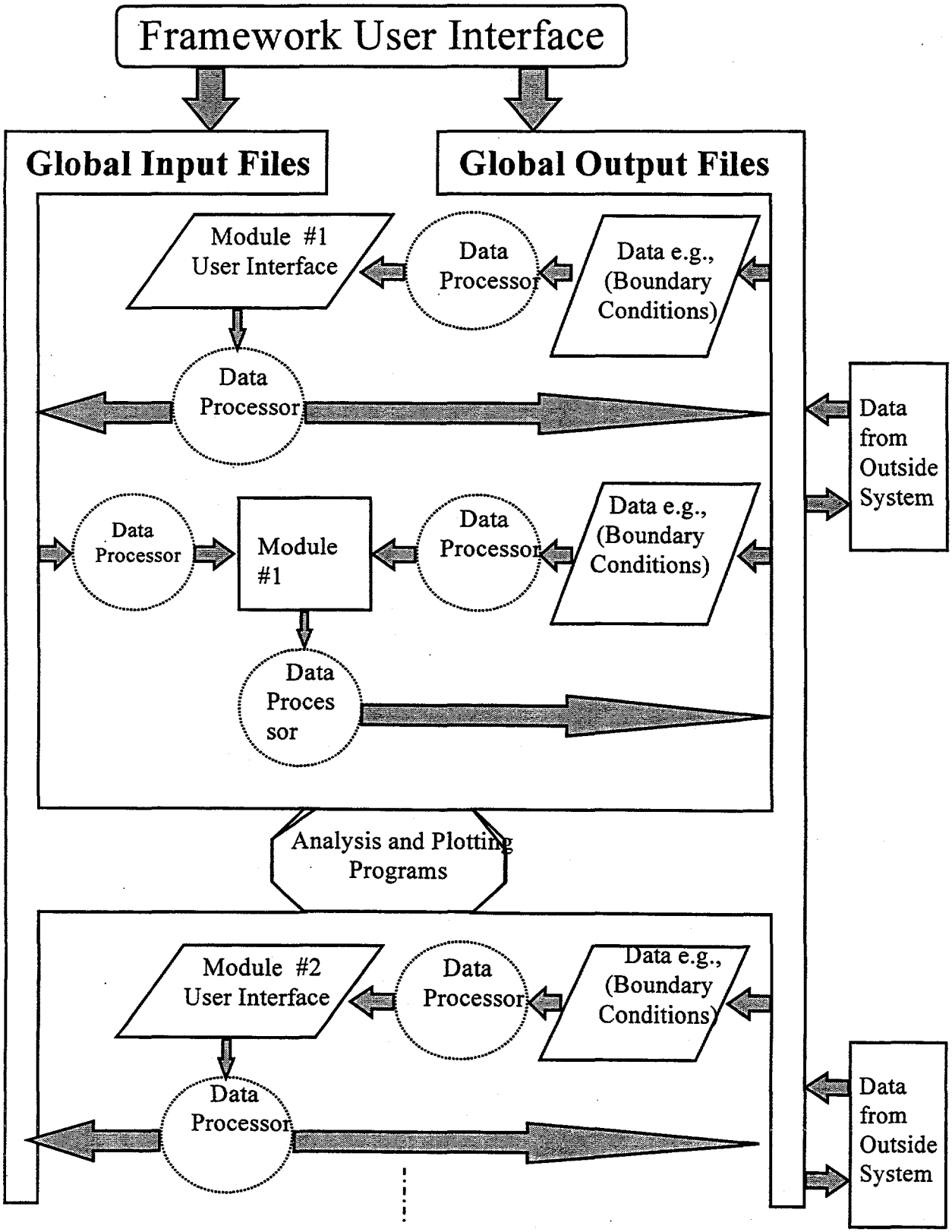

Figure 5. Detailed Illustration of the Implementation of a Module within FRAMES

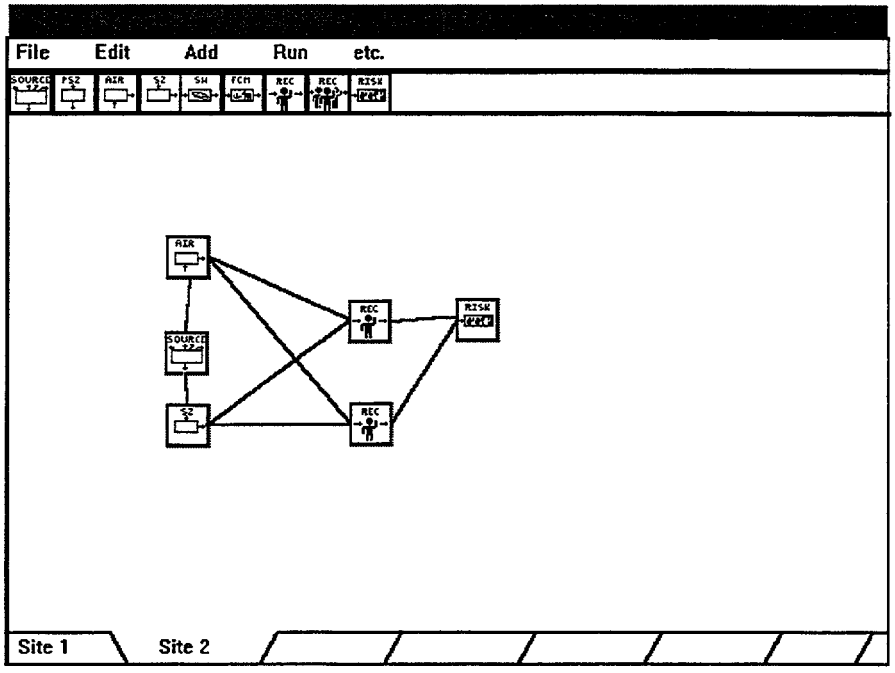

Figure 6. Simple FUI Example Illustrating Contaminant Emissions to the Air and Saturated Zone with Two Receptor Locations

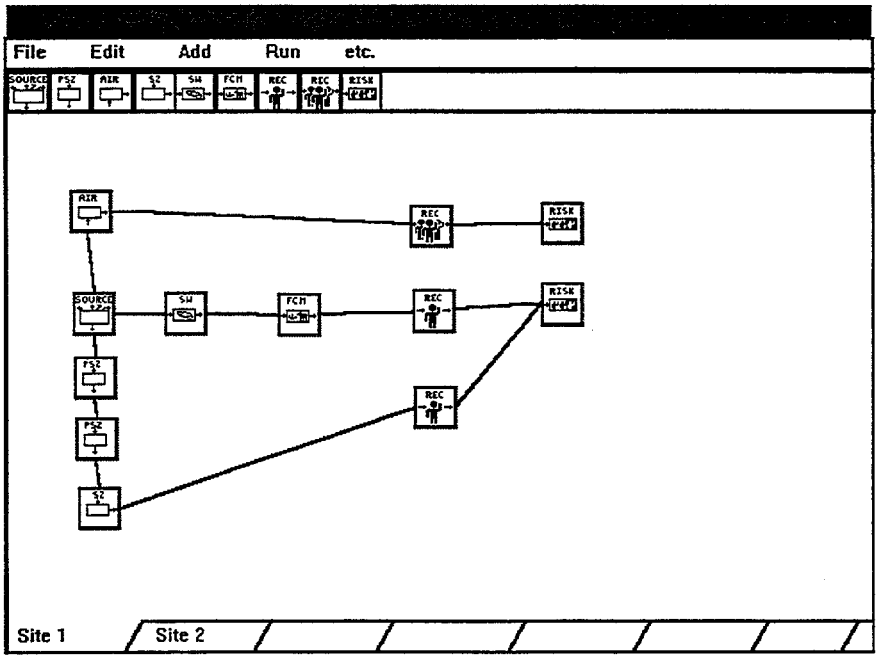

Figure 7. Simple Framework User Interface Example Illustrating Contaminant Emissions to the Air, tow Vadose Zones, and a River with Three Receptor Locations

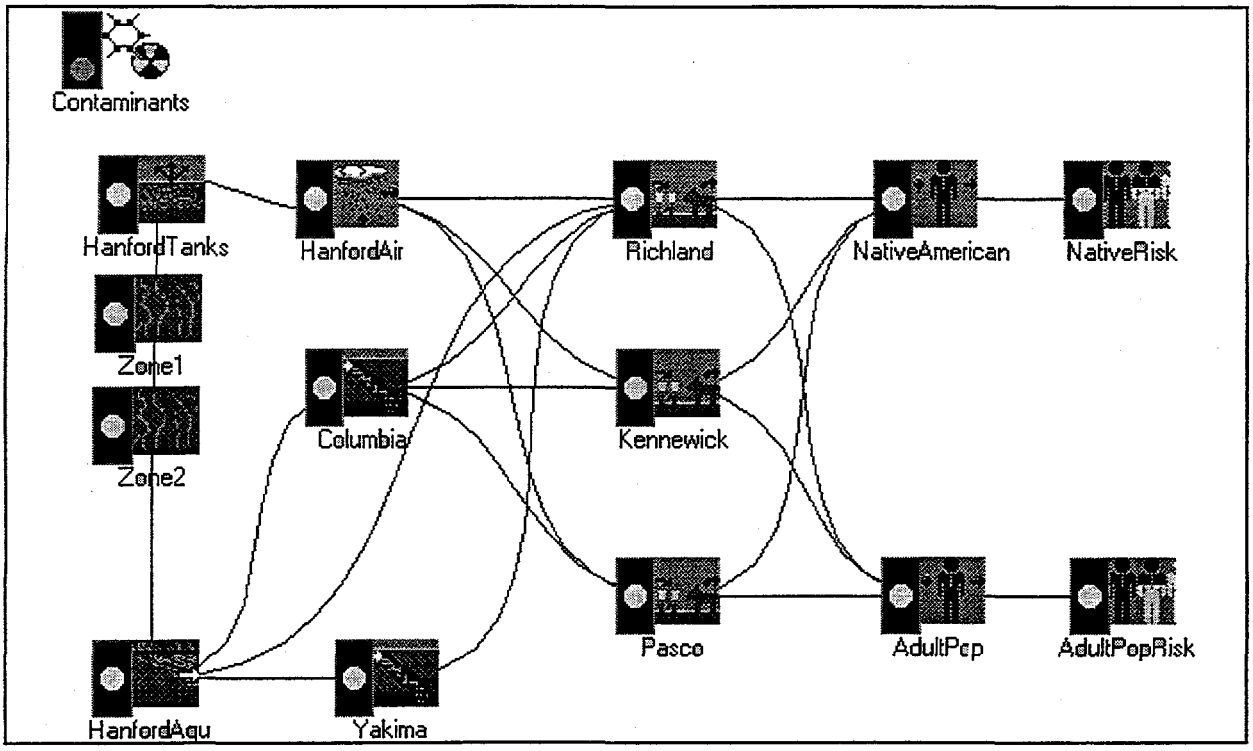

Figure 8. Illustrative Example of the Framework User Interface Describing the Conceptual Site Modeling Scenario

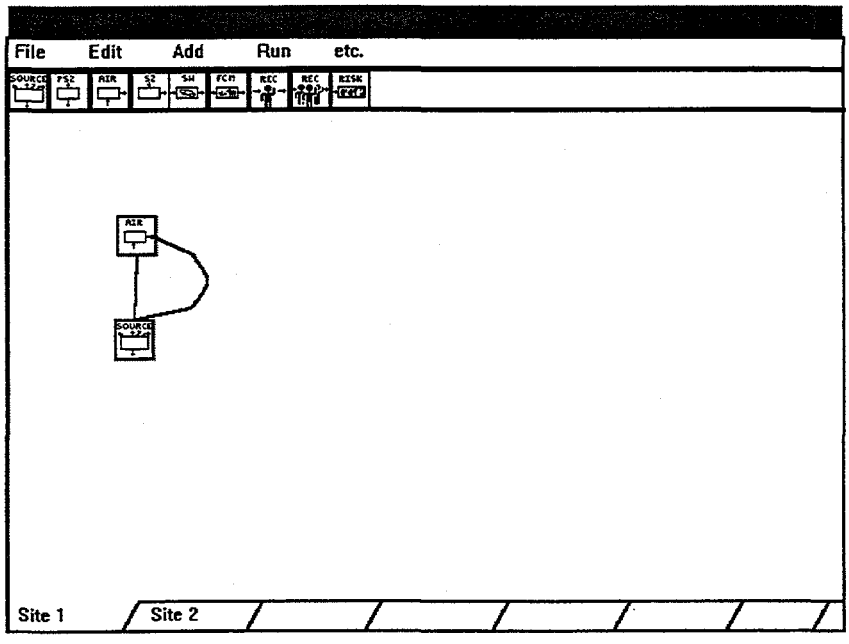

Figure 9. Illustrative Example of a Feedback Loop

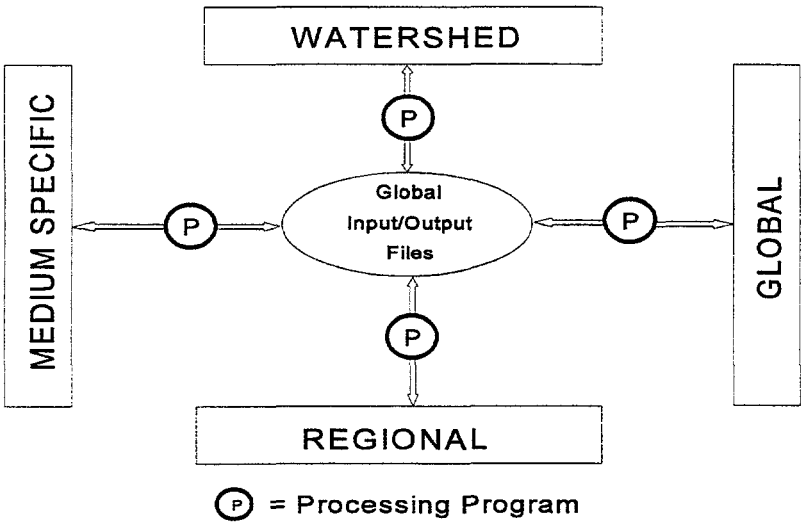

Figure 10. Interactions Between Frameworks Representing Different Scales

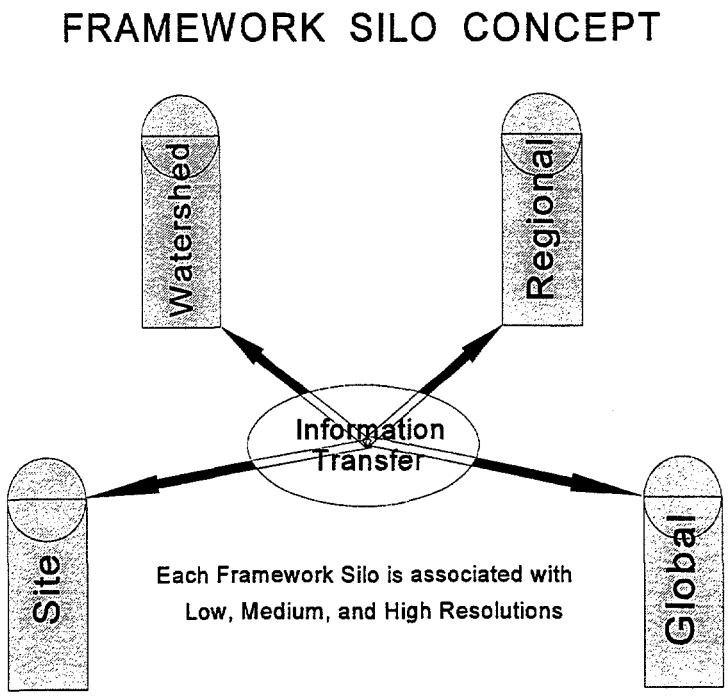

Figure 11. Illustration of the Interaction of Between Different Framework Silos

OVERVIEW OF PRESTO MODEL

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ABSTRACT: This paper presents an overview of the PRESTO model characteristics to facilitate selecting and applying models for dose assessments. The model was designed by the US EPA to assess the health impacts for regulatory analysis of a radioactive waste disposal site or of a soil cleanup site. The model was designed to provide the effective dose, cancer incident risk, and mortality risk to the maximum exposed individual and the cumulative fatal cancer death and genetic health effects to the general population for cost-benefit, marginal cost, and ALARA analyses for the implementation of a regulation or an environmental standard. In order to provide meaningful, convincing, and accurate cost-benefit and ALARA analysis results, special attention was given to design accurate transport submodels related to the groundwater pathway. In addition, special attention was also given to simplify the model to save computer processing time and to reduce the required time in preparing the data matrix for the regulatory analysis decision model.

1 INTRODUCTION

The intent of this paper is to present an overview of the development and capabilities of PRESTO in support of an NRC effort to develop a methodology for selecting a site specific model for regulatory and compliance applications. The U.S. Nuclear Regulatory Commission is developing a regulatory guide on "Demonstrating Compliance with the Radiological Criteria for License Termination." As a supporting tool to demonstrate compliance, NRC is in the process of developing a methodology for site-specific modeling. This methodology is to be used for supplementing the currently available screening model, DandD.

A workshop was held November 13-14 at Nuclear Regulatory Commission Headquarters as one of a series of interactions with Agreement States, licensees, and the public to gather suggestions and ideas for developing this guide. Developers of currently available dose models were invited to the workshop to present an overview of their models. Presentations of MEPAS, RESRAD, PRESTO and DandD models were included. The purpose of the presentations was to provide an overview of each model for NRC staff's consideration in developing regulatory guidance for selecting a dose model to be used in demonstrating compliance with the final rule on "Regulatory Criteria for License Termination." To assess the applicability of each model, ten questions were compiled by the NRC modeling committee for the speakers to use as guideline for their presentation.

The subjects concerning the ten questions that NRC modeling committee compiled were:

1. History of the model development,
2. Transport mechanisms, scenarios, and exposure pathways considered,
3. Determination of input parameter values,
4. Radionuclide transport effects considered,
5. Time and spatial geometry limitations inherent in the analytical method,
6. Assessment of alternative remedial action,
7. Extent of model testing,
8. Handling of source term, hydrologic and geohydrologic conditions, exposure pathway combinations, cost and monitoring programs, and ALARA,
9. Graphical capability of plotting time distribution and probability density distribution,
10. Adaptability of land-use scenario and flexibility of output format.

This paper summarizes the overview of PRESTO presented in the workshop. The primary focus is to address these ten questions and to discuss the model's accuracy.

2. CHARACTERISTICS OF PRESTO MODEL

2.1 History of PRESTO Model Development

The design of the PRESTO model (Prediction of Radiological Effects due to Shallow Trench Operation) was conducted by staff members of the Office of Radiation and Indoor Air (ORIA), Environmental Protection Agency (EPA) in 1979, for the purpose of supporting the development of EPA's Environmental Standards for Management and Disposal of Radioactive Waste. The design, including model structure and mathematical formulations, was coded into a computer model at Oak Ridge National Laboratory in 1980 under EPA's extramural contract. The integrated PRESTO model included three parts: (1) atmospheric transport inherited from existing AIRDOS-EPA model, (2) newly coded transport models based on EPA's design specifications, and (3) an infiltration model coded by an ORIA staff member.

To support EPA's Low Level Waste rule, a regulatory decision model was developed using operation research techniques. The regulatory decision model compared various viable alternatives to optimize the disposal cost using the environmental standard as a constraint. To support the decision model, PRESTO was designed to calculate: (1) cumulative population health effects, (2) cumulative genetic effects, and (3) maximum committed effective dose. The number of years of premature death was not included in the output because the monetary value of human life could not be included in the decision model.

Although a screening model would have been sufficient for the regulatory analysis, PRESTO was designed to be a simple, yet accurate, site-specific model. A dynamic simulation of the radionuclide transport in the multimedia was used because this is the only way to maintain reasonable accuracy. Because the groundwater pathway is the major pathway of human exposure, extra attention was given to developing the groundwater related submodels, including

infiltration, leaching, release, and groundwater transport.

A one-dimensional groundwater transport model was selected even though this simplification may theoretically introduce significant error. This selection was inevitable because employing a two- or three-dimensional model would considerably increase the complexity and the numerical calculation instability of the model. In addition, code stability would become more difficult when the daughter nuclide ingrowth effects are integrated into the transport system. Fortunately, after careful investigation, the potential error was found to be small for normal applications. A detailed discussion of the error is presented in Chapter 3.

The first version of PRESTO was completed in 1982 and was reviewed by ORIA staff members. The model was modified in 1984 by Rogers and Associates, Engineering Co. (RAECO) to accommodate disposal alternatives being considered by EPA to support the Low Level Waste rule. A year long third party extramural review was conducted in 1983, and an extensive International Experts Review was conducted in February 1984. The model underwent EPA Science Advisory Board review before being released to the public in 1987.

The version of PRESTO released in 1987 included executable computer codes and a user manual containing model methodology. PRESTO was divided into two models, PRESTO-EPA-CPG and PRESTO-EPA-POP (Refs. 1 and 2). The CPG model calculates the maximum individual committed effective dose, while the POP model calculates cumulative health and genetic effects. PRESTO was subsequently improved and interface software added to facilitate operation. Updated versions of PRESTO-EPA-CPG and PRESTO-EPA-POP were published in 1992 and 1996, respectively.

PRESTO has been expanded to cover the scenarios normally encountered in soil cleanup, including restricted, partially restricted and unrestricted land-use and various soil treatments. The expanded versions were coded and tested by the model developers (planned and designed by ORIA staff and coded by RAECO) and underwent third party independent quality assurance. These new versions are designated as PRESTO-EPA-CLNCPG and PRESTO-EPA-CLNPOP. Their documentation and user's manuals are being prepared and are scheduled to be published in 1998.

2.2 Transport Mechanism, Scenarios, and Exposure Pathways Considered

PRESTO is designed to handle scenarios having waste disposal in shallow trenches or contaminated soil with or without a clean soil cover. The waste can be either solidified or remain in as is form, and can also be modeled with or without containerization. Humid or arid meteorological conditions can be analyzed for the case of a frozen ground, which retards infiltration.

The contaminated soil scenario option includes clean soil cover, chemical treatment, or mechanical treatment. The land-use scenario options include unrestricted land-use (urban and suburban usage), restricted land-use (fenced with surveillance), and partially restricted (limited land-use, such as a recreational or industrial park).

To calculate the transport of radionuclides from the source to the environmental receptors, PRESTO considers three major environmental transport pathways, atmospheric, surface water, and groundwater. Infiltration rate and overland flow, which are the driving forces for the transport of radionuclides in the groundwater and surface water pathways, are calculated using dynamic equations of the overland flow, subsurface flow, and atmospheric diffusion systems. Simplified system of equations are used for the complex infiltration analysis which enables the calculation to be integrated into PRESTO. This infiltration submodel was verified using results obtained from field investigations conducted by the USGS and the NRC (Ref. 5). The results obtained from PRESTO agreed well with the results obtained from field investigators.

A multi-phase dispersion concept leaching model was used to calculate the leaching rate of radionuclides out of the waste/contaminated soil. The results obtained from this model agreed with the field data better than those obtained from a steady uniform leaching model.

As stated in Section 2.1, a one-dimensional model is used for the groundwater transport reaches, even though a one-dimensional model may, in principle, induce significant theoretical error into the calculation of the rate of radionuclide transport. Fortunately, the error could potentially be induced was proven to be small for a maximum individual dose calculation (no theoretical error can be induced in cumulative cancer deaths and genetic effects calculations). A detailed discussion of this error is presented in Chapter 3.

The radionuclide concentration in a well calculated by PRESTO-EPA-CPG, depends heavily on the depth that the well penetrates into the aquifer and the treatment of the well mechanics. The model requires the depth of effective mixing as an input to calculate radionuclide concentrations in the well. The effective mixing depth is calculated based on the well mechanics and the depth that the well penetrates into the aquifer. It is recommended that a plausible scenario be used to determine the depth of penetration. Under this scenario, the depth of well penetrating into the aquifer is determined based on current state regulations (see Section 3.5 for further detail). The effective mixing depth of the dilution water stream is calculated based on the pumping rate and the aquifer characteristics; the pumping rate is calculated from the sum of drinking water, cattle feed, and crop irrigation for a family of four members.

A plug flow model, with no dispersion and benthos load effects, is used for the surface water transport model. This model, although simple, is considered sufficient for PRESTO applications. This is because an annual average transport rate is required for the dose calculation, and the complex retardation effects that exist in surface water transport will not affect the annual average transport.

A conventional Gaussian plume atmospheric transport model is used to calculate the transport of resuspended radionuclides from the source area to downstream environmental receptor(s). The depletion of the plume due to fallout and electrochemical deposition is calculated based on the methodology adapted from the AIRDOS-EPA model (Ref. 6).

Health impacts are calculated for three human receptors (an on-site resident, an off-site resident, and the general population), and the concentration for three environmental receptors

(groundwater, surface water, and air). The model considers all significant pathways that result in exposure to human receptors. These exposure pathways vary with the human receptors being considered. The exposure pathways for the off-site resident include: ingestion of drinking water, crops, milk, livestock, fish, and soil; inhalation from air; direct exposure from the ground and air; and immersion in the air. Exposure pathways for an onsite resident include inhalation of indoor and outdoor radon and the direct exposure in a basement, in addition to all pathways to an off-site resident. Finally, the general population is exposed to all pathways that an off-site resident is exposed to except the inhalation, direct exposure, and immersion from air.

2.3 Determination of Input Parameter Values

Generally speaking, the input parameter values used in the model are divided into four groups: important site-specific data, meteorological data, national average generic data and health impact conversion factors. Because the model is designed to be a site-specific, site-specific input values are to be supplied by the user. In this context, the physical meaning of these parameters is explained thoroughly in the user's manual. The source of parameter values is expected to be from field data, generic engineering handbooks, or from educated expert judgement as a last resort. The selection of these sources depends on the sensitivity of the parameter, the availability of resources, and desired modeling accuracy.

National average generic data, such as the water consumption rate, are given in the standardized input file included in the PRESTO model package. These data may be used without modification.

The meteorological data includes hourly rainfall, daily average temperature, and daylight length. Three data sets are provided to represent the humid South (South Carolina), the humid North (New York State), and the arid West (Nevada). The user may select the meteorological data set closest to the specific site being analyzed. The hourly rainfall data given in the data set are to be used as the relative rainfall distribution. The true hourly rainfall for a specific site is calculated in the model using the user assigned average annual rainfall data and the relative hourly rainfall distribution from the selected data set.

The health impacts conversion factors include fatal cancer, cancer incidence, genetic effects, committed effective dose, mortality risk, and incidence risk. Conversion factors for the forty radionuclides normally found in low-level radioactive waste are included. These conversion factors are taken from Federal Guidance Report No 11 and 12. The users may add additional nuclides.

PRESTO includes two types of models, deterministic and probabilistic. The probabilistic model requires two types of input files to perform an uncertainty analysis. The first type includes all the input files required to run the deterministic model, while the second type includes the data to specify the probability distribution of random input parameters. The types of probability distribution for the random input parameters are limited to the uniform, log-uniform, normal (truncated), log-normal (truncated), and triangular distributions. The maximum number of realizations that the model can take is 3000.

2.4 Radionuclide Transport Effects Considered

The PRESTO model only calculates the transport of radioactive chemical species. Chemical reactions which may occur during the course of transport are not included. All together, forty radionuclides commonly found in the low-level radioactive waste are built into the model. For the groundwater transport pathway, all potential changes in the transport characteristics due to physico-chemical reactions are lumped together into a linear sorption model known as the distribution coefficient (K_d). Because of differences in the physico-chemical environment in each transport reach considered, different K_d values can be assigned to the ground surface, waste matrix, unsaturated soil, and aquifer reaches, respectively.

To accommodate complex waste forms, three options are available for calculating the rate of leaching of radionuclides from the waste or contaminated soil matrix. These options include chemical exchange (K_d), chemical exchange with solubility limits, and annual release rates. The first and second options apply to the sorption-desorption waste, and the third option applies to a solidified waste.

The physico-chemical reactions and benthos load effects are not considered in the surface water transport. This simplification is acceptable, because the celerity of the transport is so great that the time required to transport a radionuclide from the source area to the receptor of interest (hours or days) is much shorter than the duration of average value that PRESTO uses to calculate health impacts (one year).

Radioactive decay and daughter nuclide ingrowth effects are considered in all transport reaches, including groundwater, surface water, and atmospheric transport pathways. The analysis employs a moving control volume concept. The model assumes that there is no relative movement between the parent nuclide and daughter nuclides. Therefore one may consider an imaginary control volume which moves with the same speed as the parent nuclide. This assumption is theoretically acceptable in the surface water transport reach because there is no retardation effect being considered in the transport process. However, the assumption is not theoretically acceptable for the atmospheric and groundwater transport reaches because relative motion between parent and daughter nuclides is expected in a generic case.

An additional crude assumption was needed to validate the above basic assumption for atmospheric and groundwater transport reaches. This crude assumption involves assuming that the deposition velocities (atmospheric pathway) and the distribution coefficient (groundwater pathway) for the parent and daughter nuclides are identical. This assumption is theoretically not true. However, due to the fact that the travel distance is normally short (< 300 meters), the error induced from this assumption is normally small. In addition, only up to four members of daughter nuclides in the decay chain is considered to simplify the calculation.

2.5 Time and Spatial Geometry Limitations Inherent in the Analytical Method

In general, if the distance from the boundary of the contaminated source to the well receptor is relatively short compared to the length of the source area, significant errors may be

induced in the calculation of groundwater transport when the contaminated area is assumed to be a point source. Unfortunately, most of the maximum individual effective dose calculation scenarios fall into this category. In addition, this error increases rapidly as the size of the contaminated site increases. Therefore, the size of a contaminated site should be limited if a point source is assumed and a reasonable accuracy of analysis is desired. Although PRESTO assumes a point source in calculating the atmospheric transport, an area source is assumed for the calculation of the groundwater transport. Therefore, there is no limitation on the spatial geometry of a source area.

Since a dynamic integration of the radionuclide transport is involved, the duration of the simulation time is limited by the available computer storage. The current version of the model limits the real time of simulations to 10,000 years. This limitation is sufficient for most normal applications, because the committed effective doses for critical radionuclides reach peak values in hundreds of years.

From a numerical analysis viewpoint, the space and time increments control the stability of numerical calculations. PRESTO assumes a one-year increment for all transport analysis except for the calculation of the infiltration rate through the contaminated source matrix which, assumes a one-hour increment. A space integral is used in integrating the radionuclide transport to the downstream section of the contaminated source matrix (collection reach). A space increment equal to one-tenth the length of the contaminated site is used in this integration. These time and space increments are built into the model without user's interaction. Over ten years of model applications, the preset time and space increments have proven to be adequate without inducing any instability in the numerical calculations.

2.6 Assessment of Alternative Remedial Action

As mentioned in Section 2.1, PRESTO was designed to generate a data matrix required by the regulatory analysis decision model, which is used to optimize the cost of waste disposal or soil cleanup. Therefore, the model has to be designed as a site-specific application model. To achieve this goal, dynamic simulation submodels were used, to the extent practicable, for increasing the model accuracy and the comparability of viable scenarios. In addition to the ultimate outputs discussed in the previous sections, the concentrations of radionuclides in well water are also printed out for reference use. This feature enhances the flexibility of comparing remedial action scenarios.

In comparing costs and benefits, the cumulative health impacts (EPA uses the sum of cumulative fatal cancer deaths and cumulative genetic effects) should be considered. EPA's past studies showed that there is no correlation between the maximum dose and the cumulative health impacts. A simulation model calculating the cumulative health impacts is therefore essential in comparing the benefits resulting from a postulated scenario. PRESTO was designed to provide the above data. The output from PRESTO can also be used for cleanup/disposal cost estimation, allowing the results to be used for benefit and cost comparisons.

An alternative cost-benefit comparison would use the number of years of premature death. PRESTO did not include this parameter in the output because the establishment of the monetary

value for this parameter is still in a premature stage. The PRESTO model can easily incorporate this feature as soon as the above difficulty is resolved.

2.7 Extent of Model Testing

Quality assurance (QA) was considered to be the first priority in the course of model development. QA of PRESTO began right after the completion of the draft of model planning and design. The model also underwent extensive in-house and interagency technical review and test runs when the first version of the computer code was completed.

A year long third party extramural review was conducted by Inter Systems Inc. in 1983 (Ref. 7), as soon as the in-house preliminary system analysis was completed for the Low-Level Waste rule. The QA included the review of each mathematical formulation, the algorithm and accuracy of the computer coding, and test runs of the program.

An extensive International Experts Review was conducted in February 1984. The attendees included experts from national laboratories, federal agencies, industrial entities, and international experts. A two-day meeting was held to discuss the adequacy of the mathematical formulation, input data used in the analysis, and justification of the results.

Following extensive system analysis for generating the data matrix and the marginal cost of implementing the Low-Level Waste Rule, the model underwent an eight-month long EPA Science Advisory Board review. Three subcommittees were formed to review the adequacy of submodels in the area of transport, food-chain, and health effects conversion factors. The model was approved with some recommended improvements.

Recent modifications in 1997 to accommodate the soil cleanup scenario underwent QA by S. Cohen & Associates/RAECO. An in-house QA effort is currently underway to complete the PRESTO-EPA-CLNCPG and PRESTO-EPA-CLNPOP models.

2.8 Handling of Source Term, Hydrologic and Geohydrologic Conditions, Exposure Pathway Combinations, Cost and Monitoring Programs, and ALARA

As stated in Section 2.1, PRESTO is specifically designed for the purpose of regulatory analysis. Therefore, special attention was given to the handling of the source term, hydrologic and geo-hydrologic conditions, exposure pathway combinations, cost and monitoring programs, and ALARA. Detailed descriptions of each are contained in the following subsections.

2.8.1 Source Term Handling

2.8.1.1 Source Term Characterization

The source terms PRESTO can handle are divided into three categories, contaminated soil, waste, and their mixture. The contaminated soil contains mostly natural soil, and it responds

to the infiltrating water by a sorption-desorption process (K_d). The waste can be in a form of activated metal or absorbing waste. The absorbing waste can be either in an as-is or a solidified form. Furthermore, the waste can be disposed of with or without a container.

In actual modeling applications, the source terms are categorized as absorbing waste, solidified waste, and activated metal. Because of the concentration difference, the absorbing waste is further divided into absorbing waste and trash; the solidified waste is divided into solidified waste and incinerated/solidified waste. The model does not have the option to handle liquid waste form, because the current NRC 10 CFR 61 Regulations for the disposal of low-level radioactive waste do not allow the disposal of liquid waste without solidification.

The leaching characteristics of an absorbing waste are assumed to follow the linear sorption-desorption model, and the release rate is derived based on a mass-balance equation assuming a compartment type model. Detailed discussion of the multi-phase leaching model used in PRESTO is described in Section 2.8.2.2.

The conventional empirical formula, which assumes a constant fractional release rate is used to calculate the release of radionuclides from a solidified waste. The container effects are treated based on the assumption that: (1) no release could occur when the container is intact, (2) release occurs once the container breaks, and (3) the number of container failures increases linearly with time within the user assigned time period.

2.8.1.2 Multiple Source Term

PRESTO can handle multiple source terms as stated in Subsection 2.8.1.1. However, the model considers each of the source terms to be uniformly distributed over the entire waste volume. Theoretically speaking, the distribution of waste with different characteristics could affect the results of the health impacts analysis, especially when a small volume of high concentration waste is placed in an isolated spot in the disposal volume. PRESTO provides the flexibility of handling this type of case with some manipulation of the calculation scheme. The process includes two computer runs, one for the concentrated waste only, and the other for all waste excluding the concentrated waste. The results of combined dose versus time can then be obtained by adding up the results of doses for both runs obtained at the same time step. The peak of the combined dose is the maximum dose expected for the waste site.

2.8.2 Hydrologic and Geohydrologic Conditions

2.8.2.1 Infiltration Model

A dynamic model is employed for calculating the annual infiltration rate. Since infiltration water is the driving force for leaching radionuclides out of the waste matrix and is one of the most sensitive variables in a risk assessment model, the accuracy of the infiltration rate analyses directly affects the accuracy of the results of modeling.

Controlling both computation time and the stability of numerical analysis is known to be

extremely difficult in direct solution of the original system equations representing the overland flow, subsurface flow, and atmospheric diffusion. The PRESTO model employs a simplification technique (Ref. 8) to overcome these difficulties. The technique involves the transformation of the original partial differential system equations into ordinary differential system equations by dividing the soil moisture into three components, hygroscopic, pellicular, and gravity water. Hourly rainfall and daily average temperature data are used to calculate frozen soil conditions and the rate of infiltration, overland flow, and evaporation loss. The computation time and the stability of numerical analysis are controlled to an acceptable level by this technique.

2.8.2.2 Leaching Model

A multi-phase leaching model concept is used in PRESTO, which assumes that water infiltrating into the waste matrix will be concentrated into some conduits because of the heterogeneity of the waste matrix and the non uniform distribution of the water infiltrated from upstream. A linear sorption model in conjunction with the mass balance equation is used in deriving the basic equation for calculating the rate of leaching from the waste matrix. Finally, an Ad Hoc model, incorporating the multi-phase leaching concept, is used. Details of this model and its characteristics are discussed in Chapter 3.

2.8.2.3 Groundwater Transport Model

A steady uniform one-dimensional model is used for all groundwater transport reaches, including the unsaturated, collection, and aquifer reaches. The accuracy of this model will be discussed in the next chapter. The linear sorption model equation in conjunction with its mass balance equation is used to calculate the rate of radionuclides passing through a section of interest. The accuracy of using a one-dimensional model is discussed in detail in Chapter 3.

2.8.3 Exposure Pathway Combination

As stated previously, the PRESTO model is designed for preparing the data matrix for the decision model for least cost optimization required in regulatory analysis. Therefore, the main output is health impacts expressed in a form combining all pathways and all radionuclides. The components for each individual pathway and radionuclide are also printed for reference.

2.8.4 Remedial Methods Linked to Cost and Monitoring Programs

Since PRESTO is designed for cost optimization, the postulated disposal technique or remediation methods used in the analyses are reflected in the input parameters. These parameters provide inputs to remediation cost estimation and ultimately to the decision model for cost optimization.

The output generated from PRESTO for a particular remedial method can, in conjunction with input parameters, provide useful basic data for monitoring system planning and design as well as for evaluating a monitoring program.

2.8.5 ALARA

The output from PRESTO can also provide the data matrix to the decision model for maximizing the benefits of disposal or cleanup operation, known as ALARA analysis. The decision model used in ALARA analysis is similar to that used in the regulatory analysis and is an optimization model to maximize benefits using the remediation cost as a constraint. During the course of optimization, many scenarios will be generated accompanied with cost and benefit (number of cancer deaths saved). Observing the whole spectrum of the remedial options, one can select one or a series of remedial actions which maximize benefits at a reasonable cost; these scenarios are the results of ALARA analysis.

2.9 Graphical Capability of Plotting Time Distribution and Probability Density Distribution

PRESTO has the capability of plotting variations of the combined effective dose equivalent (combined effects from all pathways and all radionuclides) with time. The model also prints out the variation of effective dose equivalent for each radionuclide and pathway using the user specified time interval. The plot of the effective dose for each radionuclide and pathway can, therefore, be either plotted manually or by executing a computer run with unwanted radionuclides and pathways being disabled.

The model also has the capability to plot the probability distribution for the combined effective dose as well as for the selected random distribution input values, when a probabilistic (Monte Carlo) run is selected.

2.10 Adaptability of Land-Use Scenario and Flexibility of Output Format

As stated previously, the model can handle many land use scenarios, including restricted, unrestricted, and partially restricted scenarios. The unrestricted land use can be urban, suburban, business, or rural farm. The restricted land use option will restrict access to the general public and the area will be under surveillance. The partially restricted land use option will open the area to limited human activity such as a recreational park or an industrial park.

In addition, a variety of parameters are printed out for either follow-up analysis or a quality assurance activity. The effective dose equivalent, cumulative fatal cancer deaths, genetic health effects, and the concentration in well water are part of the main output normally used in the cost benefit analysis and in the ALARA decision model analyses. The concentration, dose equivalent, and other transport outputs resulting from a postulated land-use scenario can be used as a reference in determining monitoring strategies.

3. ACCURACY OF PRESTO MODEL

3.1 General Discussion

PRESTO calculates health impacts through a series of independent transport submodels.

Errors may incur from each submodel due to overly conservative assumptions and may accumulate to an uncontrollable level in some cases. To control the error, one should avoid overly conservative assumptions and design a submodel as accurately as possible. Furthermore, special attention should be given to the development of a submodel used in the calculation of more sensitive pathways.

The groundwater pathway is known to be the most important pathway in calculating the maximum individual dose equivalent from a waste disposal site or from a soil cleanup site. Based on our past experience, the dose to a maximum exposed individual from the groundwater pathway contributes over 90% of the total dose in nine out of ten cases. Therefore, special attention was given to groundwater related submodels, including infiltration, leaching, and groundwater transport.

No special attention is given to the atmospheric transport model because the contribution to the dose of the maximum exposed individual is negligible. The surface water pathway may contribute a significant amount to the dose of the maximum exposed individual in some cases. Therefore, the accuracy of the surface water model is also important in maintaining the accuracy of the maximum individual dose analysis. A simple plug flow model used in PRESTO, as stated in Section 2.2, is considered to be accurate enough. This is because an annual average rate of radionuclide transport is used to calculate the effective dose, and the travel time of a disturbance from one station to another (on the order of hours or days) is much shorter than the duration of the time average (a year). That is, any errors incurred in the transport analysis would compensate each other when a long-term average value is of main interest.

In addition, dynamic equations are used as much as possible in PRESTO to maintain its accuracy. The use of an empirical or a statistical model was avoided because there is, in general, not enough data being collected for developing such models. It may not be reliable to apply an empirical equation developed for other types of applications.

The accuracy of the transport models involved in calculating the groundwater pathway are discussed in the following sections.

3.2 Infiltration Model

As stated in Section 2.8.2.1, dynamic system equations are employed for the infiltration model because the infiltration water is the driving force of leaching radionuclides out of the waste matrix and is known to be one of the most sensitive variables in a dose model. Therefore, the accuracy of the infiltration rate analysis directly affects the accuracy of the dose model analysis.

The derivation and the discussion of the infiltration model characteristics are discussed in Section 2.8.2.1. As a part of model verification, the model was compared with Hillel and Van Bavel (Ref. 9) and Ripple *et al.* (Ref. 10) studies in the subsurface flow regime. The results agreed very well with those obtained from the infiltration model. The model was also validated against field studies conducted by the USGS and the NRC (Ref. 11) on a long-term groundwater recharge. The results of the USGS and the NRC studies indicated that the annual recharge in the

Barnwell site (South Carolina) was 14 to 17 in/yr and 14 in/yr, respectively. Comparing the results obtained by PRESTO model of 15.8 in/yr, one can conclude that PRESTO can provide reasonable infiltration results.

3.3 Leaching Model

A steady uniform flow model is a simple and commonly used model, which assumes that the flow of the infiltrated water is steady and uniform. Because of the simplicity in the mathematical formulation, an analytical solution has been developed and used in various dose models. However, the infiltration rate calculated from a steady uniform flow model is normally much higher than that observed in the field (Ref.12).

PRESTO employs an Ad Hoc model derived from Hung's multi-phase leaching model to calculate the rate of radionuclide leaching out of the waste matrix (Ref. 13). The multi-phase leaching model assumes that the flow of the infiltration water will not be uniform but will be concentrated in preferential conduits. This non-uniform distribution of the infiltration water is primarily caused by the heterogeneity of hydraulic conductivity of the waste matrix. Transport of radionuclides in the preferential conduit is assumed to be carried by convective flow, but the transport of radionuclides between conduits is assumed to be transported by diffusion to the nearby conduit first, and subsequently downward by convective flow.

Although the results of the analysis obtained from the multi-phase leaching model are much closer to field data, the calculation of the leaching rate is much more complex. This complexity prevents the model from being integrated into PRESTO. Therefore, an Ad Hoc model was developed using the multi-phase leaching model as a tool. The development involved the generation of an extensive data matrix and employed a dimensional analysis technique to quantify the correction factor. The results of the analysis are normally more conservative than the results obtained from the multi-phase leaching model, but closer to the field data than that obtained from a steady uniform leaching model.

The relative error between the Ad Hoc model and the steady uniform model depends on the radionuclide characteristics (decay constant and K_d value) and the geohydrologic conditions of the aquifer (lumped together in a term, "time of arrival"). The characteristics of this error have been thoroughly studied by Hung (Ref. 14). The results of Hung's study indicated that the relative error will be approximately 100% for an extremely long half-life radionuclide with a retardation factor of one, and the time of arrival of 30 years (in the collection reach).

3.4 Groundwater Model

As stated in Section 2.2, a one-dimensional model is used for all of the groundwater transport reaches, including the unsaturated soil, collection, and aquifer reaches. Since it is generally known that a one-dimensional model may induce significant theoretical error in calculating the rate of radionuclide transport, special attention has been given to the characteristics of this error.

A recent study conducted by Gnanapragasam *et al.*(Ref. 15) indicated that the relative error on the plume concentration between a one-dimensional model (PRESTO model) and a three-dimensional dispersion model (MEPAS model) varies from 0% to approximately 700% when the well receptor is moved from source (x = 0 meter) to 104,000 meters away. The results also indicated that the relative error stays in a 10% range when the location of the well receptor is limited within approximately 300 meters away from the source. Since the application of PRESTO for calculating the maximum individual dose is limited to a distance from the source of no more than 300 meters, the relative error of employing a one-dimensional model is expected to be tolerably small (less than 10%).

Moreover, a worst case radionuclide, Sr-90 (only 28.1 years of half-life), was used in the benchmarking study; the errors are expected to be suppressed to some extent for a longer half-life nuclide. In addition, the width of the source was taken to be only 8 meters. This would considerably shorten the length of the no-disturbance zone (by lateral dispersion). One should note that the relative error due to the lateral dispersion is zero in the no-disturbance zone. The length of the no-disturbance zone may be conservatively estimated as three times the source width for the purpose of this discussion. Therefore, in an actual application, with a source width of say 100 meters, the well receptor will still be near the boundary of the no-disturbance zone (the length of the no-disturbance zone is approximately 300 meters). Therefore, in an actual application, the error of employing a one-dimensional transport model is expected to be negligibly small.

3.5 Well Mechanics Treatment

As stated in Section 2.2, the results of calculating the radionuclide concentration in the well depend heavily on the depth of the pumping well penetrating into the aquifer and the treatment of the well mechanics. The results of these calculations, in some cases, may differ by as much as an order of magnitude.

As stated in Section 2.2, users of PRESTO are recommended to adopt a plausible scenario in determining the depth of penetration of the well. The scenario considers the current state regulatory practice. An important regulation commonly stated is that "a domestic well can only be drilled by a licensed well driller." Thus, once the well driller mobilized the drilling machine at a site, the well drilling cost will normally stay the same up to 200 or 300 feet because of the cost of machine mobilization. On the other hand, it is normally known that the deeper the well penetrates below the groundwater table, the better the water quality and the better the security on the water quantity. Therefore, the well will generally penetrate far below the water table. The result of using the plausible scenario is generally quite different from using the concept of maximum a probable scenario (a scenario assuming the well penetrates into a contaminated aquifer at a depth producing maximum well water concentration).

After the depth of well penetration is determined, the effective mixing depth of the dilution water stream is calculated based on the pumping rate and the aquifer characteristics. The pumping rate is calculated from the sum of drinking water, cattle feed, and crop irrigation for a family of four members. PRESTO accepts the effective mixing depth as input to calculate the

available dilution water and then calculates the radionuclide concentration in the well water.

Let us assume a plume migrating in a background groundwater flow of 10 meters/yr (Darcy) as an example. The unit width rate of transport is assumed to be 1 Ci/yr/meter when the plume reaches peak at the well. The radionuclide concentration in the well water is calculated to be 0.1 Ci/m^3 (= 1/10) if a maximum probable scenario is used (assuming the screen depth is 1 meter). However, when a plausible scenario is used, the concentration is calculated to be 0.005 Ci/m^3 (= 1/{10x20}; assuming the effective mixing depth is calculated to be 20 meters). A factor of 20 can be expected between the results obtained using a maximum probable scenario and a plausible scenario.

One can clearly see the importance of the well mechanics treatment from this example. The selection of the scenario will be, of course, up to the policy maker. In ORIA, the plausible scenario has been employed for all analyses performed with PRESTO.

4 CONCLUSIONS

1. The PRESTO model was designed by the US EPA to generate the data matrix required by regulatory analysis decision models. This includes models for assessing the marginal cost of environmental standard implementation and for ALARA analysis.
2. PRESTO outputs include the cumulative fatal cancer deaths, genetic health effects, maximum individual effective dose and radionuclide concentrations in well water.
3. PRESTO is a complete multimedia model considering all significant environmental transport pathways, including atmospheric, surface water and groundwater pathways. The food-chain pathways, include irrigation and cattle feed, and the pathway transporting radon gas into a basement and to the ground surface are also included. Three types of human receptors are considered, an onsite resident, an offsite resident and the general population. The human exposure pathways considered for these human receptors include ingestion of drinking water (from ground and surface water), crops, fish, milk, meat, and soil; inhalation of air, radon gas (outdoors and in a basement); immersion in air; and direct exposure from ground, basement, and air.
4. PRESTO considers the source to be an area source for the important groundwater pathway simulation; therefore, there is no limitation on the maximum area that the model can have without incurring unacceptable errors. However, due to the dynamic nature of the model, the health impacts to human receptors are calculated for each year. The maximum real time of simulation is, therefore, limited to 10,000 years.
5. PRESTO was designed for site-specific applications as well as for system analysis (alternative remedial action analysis). Therefore, special attention was given to the design of the mathematical formulation for those submodels relating to the ground water pathway. This was intended to maintain the required accuracy of the overall model and a meaningful system analysis.
6. The input parameters are divided into four categories: site-specific data, meteorological data, national average data, and model provided conversion factors. The site specific data requires users to pay special attention.

7. PRESTO can also perform Monte Carlo type simulations for uncertainty analysis; the distribution of the selected random input parameters can be either uniform, log-uniform, normal, log-normal or triangular; and the distribution of the input and output parameters can be displayed graphically.
8. PRESTO was designed to handle soil cleanup sites as well as radioactive waste disposal sites having waste in the form of absorbing, solidified, or activated metal, or a mixture of them. The waste can also be with or without containers.
9. PRESTO can handle various land-use scenarios, including restricted, unrestricted and partially restricted use. A clean soil cover (may contain residual radionuclides) is always required in a waste disposal scenario to cover the waste and to expel rainwater from infiltrating into the waste. However, in a soil cleanup scenario, the contaminated soil can be either covered with clean soil or exposed to the air without a soil cover. The remediation scenarios include chemical treatment and/or mechanical treatment.
10. PRESTO is fully tested, well documented, and has undergone extensive quality assurance. In addition, the model is user friendly and easy to operate.

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The public "Workshop on Review of Dose Modeling Methods for Demonstration of Compliance with the Radiological Criteria for License Termination" was held at the NRC Headquarters Auditorium, Rockville, Maryland, on November 13-14, 1997. The workshop was one in a series to support NRC staff development of guidance for implementing the final rule on "Radiological Criteria for License Termination." The workshop topics included discussion of: dose models used for decommissioning reviews; identification of criteria for evaluating the acceptability of dose models; and selection of parameter values for demonstrating compliance with the final rule. The 2-day public workshop was jointly organized by RES and NMSS staff responsible for reviewing dose modeling methods used in decommissioning reviews. The workshop was noticed in the Federal Register (62 FR 51706). The workshop presenters included: NMSS and RES staff, who discussed both dose modeling needs for licensing reviews, and development of guidance related to dose modeling and parameter selection needs; DOE national laboratory scientists, who provided responses to earlier NRC staff-developed questions and discussed their various Federally-sponsored dose models (i.e., DandD, RESRAD, and MEPAS codes); and an EPA scientist, who presented details on the EPA dose assessment model (i.e., PRESTO code). The workshop was formatted to provide opportunities for the attendees to observe computer demonstrations of the dose codes presented. More than 120 workshop attendees from NRC Headquarters and the Regions, Agreement States; as well as industry representatives and consultants; scientists from EPA, DOD, DNFSB, DOE, and the national laboratories; and interested members of the public participated. A complete transcript of the workshop, including viewgraphs and attendance lists, is available in the NRC Public Document Room. This NUREG/CP documents the formal presentations made during the workshop, and provides a preface outlining the workshop's focus, objectives, background, topics and questions provided to the invited speakers, and those raised during the panel discussion. NUREG/CP-0163 also provides technical bases supporting the development of decommissioning guidance.

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