DOC.20031014.0002

# OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

QA: QA

## ERRATA

1. TER No. TER-03-0039

DC Tracking No. 36846



| 2. Product DI: | Title: | Revision: |
|---|---|---|
| MDL-MGR-MD-000001 | Biosphere Model Report | REV 00 |

| 3. Location | 4. Clarification/Restriction |
|---|---|
| Cover Page | Add the following sentence to Block 13:<br><br>"This report addresses technical errors reported in TER-02-0053, -0054, and -0055, as they pertain to the Biosphere Model.<br><br>TER-02-0053 is addressed by the external exposure submodel discussed in Sections 6.4.7 and 6.5.5.<br><br>TER-02-0054 issues are discussed in the mathematical model for the volcanic ash scenario, in Section 6.5.2, 6.5.6, and 6.5.8.<br><br>TER-02-0055 is addressed as follows:<br>The resuspension model is part of the air submodel (Sections 6.4.2.1 and 6.5.2.1); plant uptake is addressed in the plant submodel (Sections 6.4.3 and 6.5.3); surface soil is modeled in the surface soil submodel (Sections 6.4.1 and 6.5.1); transfer of radionuclides to animals is discussed in the animal submodel (Sections 6.4.4 and 6.5.4), and the transfer of radionuclides to aquatic food is discussed in the fish submodel (Section 6.4.5)." |

| 5. QER Review: (Print Name) | Initials: | Date: |
|---|---|---|
| Kenneth O Gilterson | RLS | 09/17 2003 |
| **6. Responsible Manager: (Print Name)** | **Initials:** | **Date:** |
| MARYLA WASIOLEK | MW | 09/18/2003 |

# OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
# MODEL COVER SHEET

1. QA: QA



***Complete Only Applicable Items***

2. Type of Mathematical Model

[x] Process Model [ ] Abstraction Model [ ] System Model

Describe Intended Use of Model:
The biosphere process model is to evaluate radionuclide transport in biosphere and associated human radiation dose. It is to support the TSPA-LA.

Technical Contact/Department:
D. Wesley Wu / Biosphere

3. Title:
Biosphere Model Report

4. DI (including Rev. No. and Change No., if applicable):
MDL-MGR-MD-000001 REV 00

5. Total Attachments:
3

6. Attachment Numbers - No. of Pages in Each:
I-3 pages with a CD for electronic files, II-6 pages, III-3 pages

| | Printed Name | Signature | Date |
|---|---|---|---|
| 7. Originator | D. Wesley Wu | SIGNATURE ON FILE | 7/16/03 |
| 8. CSO | Thomas E. Rodgers | SIGNATURE ON FILE | 7-16-03 |
| 9. Checker | A.Smith, K.Rautenstrauch, J.Tappen | SIGNATURE ON FILE | 7-16-03 |
| 10. QER | Kenneth O. Gilkerson | SIGNATURE ON FILE | 7/16/03 |
| 11. Responsible Manager/ Lead | Maryla A. Wasiolek | SIGNATURE ON FILE | 7/16/03 |
| 12. Responsible Manager | for Paul R. Dixon | SIGNATURE ON FILE | 7/16/03 |

13. Remarks:

# OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
# MODEL REVISION RECORD



2. Model Title:
Biosphere Model Report

3. DI (including Rev. No. and Change No., if applicable):
MDL-MGR-MD-000001 REV 00

| 4. Revision/Change No. | 5. Description of Revision/Change |
|---|---|
| 00 / 00 | initial issue. |

**CONTENTS**

**Page**


1. PURPOSE ..... 1-1

2. QUALITY ASSURANCE ..... 2-1

3. COMPUTER SOFTWARE AND MODEL USE ..... 3-1

4. INPUTS ..... 4-1
   4.1 DATA AND PARAMETERS ..... 4-1
      4.1.1 Direct Inputs ..... 4-1
      4.1.2 Other Inputs ..... 4-1
   4.2 CRITERIA ..... 4-2
   4.3 CODES AND STANDARDS ..... 4-4

5. ASSUMPTIONS ..... 5-1
   5.1 GROUNDWATER SOURCE ..... 5-1
   5.2 CONSIDERATION OF SHORT-LIVED DECAY PRODUCTS ..... 5-1
   5.3 LONG-TERM IRRIGATION, LAND USE, AND CROP ROTATION ..... 5-2
   5.4 CROP HARVEST REMOVAL AND THE USE OF CONTAMINATED MANURE FOR FERTILIZER ..... 5-2
   5.5 RADIONUCLIDE BUILDUP IN SURFACE SOIL ..... 5-3
   5.6 CROP WEATHERING LOSS AND SURFACE SOIL GAIN ..... 5-3
   5.7 CROP ROOTS IN SURFACE SOIL ..... 5-4
   5.8 ANIMAL FEED ..... 5-4
   5.9 ANIMAL PRODUCT TYPE ..... 5-5
   5.10 DOSE COEFFICIENTS FOR EXPOSURE TO CONTAMINATED SOIL ..... 5-6
   5.11 EVAPORATIVE COOLER USE AND EXPOSURE TIME ..... 5-6
   5.12 VOLCANIC ASH SOURCE ..... 5-7
   5.13 ASH RESUSPENSION ..... 5-7
   5.14 TIME DEPENDENT MASS LOADING ..... 5-8
   5.15 RADON GAS RELEASED FROM VOLCANIC ASH ..... 5-8
   5.16 EXTERNAL EXPOSURE FROM THE GROUND SURFACE ..... 5-9

6. MODEL DISCUSSION ..... 6-1
   6.1 MODELING OBJECTIVES ..... 6-1
      6.1.1 Reference Biosphere ..... 6-2
         6.1.1.1 Geography, Geology, and Physiography ..... 6-2
         6.1.1.2 Climate ..... 6-5
         6.1.1.3 Groundwater, Human Activities, and Agriculture ..... 6-6
      6.1.2 Human Receptor ..... 6-6
      6.1.3 Exposure Scenarios and Radionuclides of Interest ..... 6-7
   6.2 BIOSPHERE FEATURES, EVENTS, AND PROCESSES ..... 6-9
   6.3 BIOSPHERE CONCEPTUAL MODEL ..... 6-15
      6.3.1 Conceptual Model for the Groundwater Exposure Scenario ..... 6-15
         6.3.1.1 Scenario Description ..... 6-16

**CONTENTS**

**Page**


6.3.1.2 Identification of Biosphere Model Components ..... 6-19
6.3.1.3 Radionuclide Transfer Interaction Matrix ..... 6-19
6.3.1.4 Submodels for the Groundwater Scenario ..... 6-20
6.3.1.5 Description of Conceptual Model for the Groundwater Scenario ..... 6-22
6.3.2 Conceptual Model for the Volcanic Ash Exposure Scenario ..... 6-29
6.3.2.1 Scenario Description ..... 6-29
6.3.2.2 Identification of Biosphere Model Components ..... 6-32
6.3.2.3 Radionuclide Transfer Interaction Matrix ..... 6-33
6.3.2.4 Submodels for the Volcanic Ash Scenario ..... 6-34
6.3.2.5 Description of Conceptual Model for the Volcanic Ash Scenario ..... 6-34
6.3.3 Alternative Conceptual Models ..... 6-38
6.3.4 FEPs Considered in the Biosphere Conceptual Model ..... 6-42
6.3.5 Radionuclide Decay and Ingrowth ..... 6-43
6.4 MATHEMATICAL MODEL FOR THE GROUNDWATER SCENARIO ..... 6-46
6.4.1 Surface Soil Submodel ..... 6-47
6.4.1.1 Primary Radionuclides in the Surface Soil ..... 6-47
6.4.1.2 Radionuclide Decay and Ingrowth in the Surface Soil ..... 6-50
6.4.1.3 Radionuclide Leaching from the Surface Soil ..... 6-53
6.4.1.4 Surface Soil Erosion ..... 6-53
6.4.2 Air Submodel ..... 6-54
6.4.2.1 Resuspended Particles from Surface Soil ..... 6-54
6.4.2.2 Aerosols from Evaporative Cooler Operation ..... 6-56
6.4.2.3 Radon Exhalation from Surface Soil ..... 6-57
6.4.3 Plant Submodel ..... 6-60
6.4.3.1 Root Uptake ..... 6-61
6.4.3.2 Uptake Following Foliar Interception of Irrigation Water ..... 6-62
6.4.3.3 Uptake by Foliar Interception of Airborne Particulates ..... 6-65
6.4.4 Animal Submodel ..... 6-66
6.4.4.1 Animal Feed ..... 6-68
6.4.4.2 Animal Drinking Water ..... 6-68
6.4.4.3 Animal Soil Ingestion ..... 6-69
6.4.5 Fish Submodel ..... 6-69
6.4.6 Carbon-14 Special Submodel ..... 6-70
6.4.6.1 Carbon-14 in Soil ..... 6-71
6.4.6.2 Carbon-14 in the Air ..... 6-72
6.4.6.3 Carbon-14 in Crops ..... 6-74
6.4.6.4 Carbon-14 in Animal Products ..... 6-75
6.4.6.5 Carbon-14 in Fish ..... 6-76
6.4.7 External Exposure Submodel ..... 6-76
6.4.7.1 Exposure to Contaminated Soil ..... 6-76
6.4.7.2 Effective Dose Coefficients for Exposure to Contaminated Soil ..... 6-79

**CONTENTS**

**Page**


6.4.8 Inhalation Exposure Submodel ..... 6-81
6.4.8.1 Inhalation of Resuspended Particles ..... 6-82
6.4.8.2 Inhalation of Aerosols from Evaporative Coolers ..... 6-83
6.4.8.3 Inhalation of Carbon-14 ..... 6-84
6.4.8.4 Inhalation of Radon Decay Products ..... 6-85
6.4.8.5 Effective Dose Conversion Factor for Inhalation ..... 6-87
6.4.9 Ingestion Exposure Submodel ..... 6-90
6.4.9.1 Ingestion of Drinking Water ..... 6-90
6.4.9.2 Ingestion of Crop Foodstuffs ..... 6-91
6.4.9.3 Ingestion of Animal Products ..... 6-91
6.4.9.4 Ingestion of Fish ..... 6-92
6.4.9.5 Inadvertent Soil Ingestion ..... 6-93
6.4.9.6 Effective Dose Conversion Factor for Ingestion ..... 6-93
6.4.10 All-pathway Dose and Biosphere Dose Conversion Factor Calculations ..... 6-96
6.4.10.1 All-pathway Doses ..... 6-96
6.4.10.2 Biosphere Dose Conversion Factors for the Groundwater Scenario ..... 6-97
6.4.10.3 Pathway Contribution to Dose ..... 6-98
6.4.10.4 Use of BDCFs in the Total System Performance Assessment Model ..... 6-99
6.5 MATHEMATICAL MODEL FOR THE VOLCANIC ASH SCENARIO ..... 6-101
6.5.1 Surface Soil Submodel ..... 6-101
6.5.1.1 Cultivated Land ..... 6-102
6.5.1.2 Non-Cultivated Land ..... 6-103
6.5.2 Air Submodel ..... 6-104
6.5.2.1 Resuspension of Volcanic Ash or a Mixture of Soil and Ash ..... 6-105
6.5.2.2 Exhalation of Radon from the Ground Surface ..... 6-107
6.5.3 Plant Submodel ..... 6-108
6.5.3.1 Root Uptake ..... 6-109
6.5.3.2 Uptake from Resuspended Soil ..... 6-110
6.5.4 Animal Submodel ..... 6-111
6.5.4.1 Animal Feed ..... 6-112
6.5.4.2 Animal Soil Ingestion ..... 6-112
6.5.5 External Exposure Submodel ..... 6-112
6.5.5.1 External Exposure to Contaminated Ground Surface ..... 6-113
6.5.5.2 Effective Dose Coefficients for Contaminated Ground Surface ..... 6-114
6.5.6 Inhalation Submodel ..... 6-117
6.5.6.1 Inhalation of Resuspended Particles ..... 6-117
6.5.6.2 Inhalation of Radon Decay Products ..... 6-118
6.5.7 Ingestion Submodel ..... 6-119
6.5.7.1 Ingestion of Crop Foodstuffs ..... 6-119

**CONTENTS**

**Page**


6.5.7.2 Ingestion of Animal Products ..... 6-120
6.5.7.3 Inadvertent Soil Ingestion ..... 6-120
6.5.8 All-pathway Dose and BDCFs Calculation ..... 6-121
6.5.8.1 All-pathway Dose ..... 6-121
6.5.8.2 Biosphere Dose Conversion Factors for the Volcanic Ash Scenario ..... 6-121
6.5.8.3 Use of BDCFs in the Total System Performance Assessment Model ..... 6-123
6.6 CONSIDERATION OF MODEL UNCERTAINTY ..... 6-124
6.6.1 Conceptual Model Uncertainty ..... 6-124
6.6.2 Mathematical Model Uncertainty ..... 6-125
6.6.3 Input Parameter Uncertainty ..... 6-128
6.6.3.1 List of Input Parameters ..... 6-129
6.6.3.2 Consideration of Parameter Uncertainty ..... 6-133
6.6.3.3 Summary of Parameter Uncertainty ..... 6-134
6.6.4 Uncertainty of Model Results ..... 6-134
6.7 BIOSPHERE MODEL ENHANCEMENT ..... 6-157
6.7.1 Disposition of FEPs within Biosphere Mathematical Model ..... 6-157
6.7.2 Comparison of Biosphere Models ..... 6-165
6.7.3 Software Selection ..... 6-168
6.8 GOLDSIM IMPLEMENTATION OF THE BIOSPHERE MODEL FOR THE GROUNDWATER SCENARIO ..... 6-169
6.8.1 Nuclide Database ..... 6-171
6.8.2 Surface Soil Submodel ..... 6-174
6.8.3 Air Submodel ..... 6-176
6.8.4 Plant Submodel ..... 6-179
6.8.5 Animal Submodel ..... 6-182
6.8.6 Fish Submodel ..... 6-185
6.8.7 External Exposure Submodel ..... 6-185
6.8.8 Inhalation Submodel ..... 6-188
6.8.9 Ingestion Submodel ..... 6-190
6.8.10 BDCF Results ..... 6-191
6.9 GOLDSIM IMPLEMENTATION OF THE BIOSPHERE MODEL FOR THE VOLCANIC ASH SCENARIO ..... 6-193
6.9.1 Nuclide Database ..... 6-195
6.9.2 Surface Soil Submodel ..... 6-197
6.9.3 Air Submodel ..... 6-198
6.9.4 Plant Submodel ..... 6-199
6.9.5 Animal Submodel ..... 6-201
6.9.6 External Exposure Submodel ..... 6-201
6.9.7 Inhalation Submodel ..... 6-203
6.9.8 Ingestion Submodel ..... 6-203
6.9.9 BDCF Results ..... 6-204

**CONTENTS**

**Page**


6.10 VERIFICATION OF THE ERMYN IMPLEMENTATION IN GOLDSIM ..... 6-205
6.10.1 Verification of the Groundwater Scenario ..... 6-206
6.10.1.1 Verification of Deterministic Calculations ..... 6-206
6.10.1.2 Verification of Stochastic Calculations ..... 6-217
6.10.2 Verification of the Volcanic Ash Scenario ..... 6-217
6.10.2.1 Verification of Deterministic Calculations ..... 6-217
6.10.2.2 Verification of Stochastic Calculations ..... 6-224

7. MODEL VALIDATION ..... 7-1
7.1 VALIDATION APPROACH ..... 7-1
7.1.1 Biosphere Model Validation Approach ..... 7-1
7.1.2 Selection of Supporting Information ..... 7-5
7.1.3 Criteria and Level of Confidence ..... 7-7
7.2 COMPARISON OF BIOSPHERE CONCEPTUAL MODELS ..... 7-8
7.2.1 Review of Biosphere Assessment Context ..... 7-8
7.2.2 Consideration of Scenarios, Submodels, and Pathways ..... 7-11
7.3 COMPARISON OF BIOSPHERE MATHEMATICAL SUBMODELS ..... 7-12
7.3.1 Comparison of Surface Soil Submodels ..... 7-14
7.3.1.1 Comparison of Surface Soil Submodels for the Groundwater Scenario ..... 7-14
7.3.1.2 Comparison of Surface Soil Submodels for the Volcanic Ash Scenario ..... 7-15
7.3.2 Validation of the Air Submodel ..... 7-22
7.3.2.1 Particle Resuspension from Surface Soil ..... 7-22
7.3.2.2 Radon from Radium-Contaminated Soil ..... 7-27
7.3.2.3 Contaminated Aerosols from the Operation of Evaporative Cooler ..... 7-29
7.3.3 Validation of the Plant Submodel ..... 7-31
7.3.3.1 Root Uptake ..... 7-31
7.3.3.2 Uptake from Irrigation Water ..... 7-35
7.3.3.3 Uptake from Resuspended Soil ..... 7-44
7.3.4 Validation of the Animal Submodel ..... 7-51
7.3.4.1 Animal Feed ..... 7-51
7.3.4.2 Drinking Water ..... 7-51
7.3.4.3 Soil Ingestion ..... 7-51
7.3.4.4 Dust Inhalation ..... 7-52
7.3.5 Validation of the Fish Submodel ..... 7-58
7.3.6 Validation of the $^{14}C$ Special Submodel ..... 7-60
7.3.7 Validation of the External Exposure Submodel ..... 7-71
7.3.8 Validation of the Inhalation Submodel ..... 7-75
7.3.9 Validation of the Ingestion Submodel ..... 7-79
7.4 NUMERICAL COMPARISON OF MODEL RESULTS ..... 7-88
7.4.1 Radionuclide Decay and Ingrowth ..... 7-88
7.4.2 Surface Soil Submodel ..... 7-92

**CONTENTS**

**Page**


7.4.2.1 Time Required for a Steady-State Condition ..... 7-92
7.4.2.2 Comparison of Radionuclide Decay Chains in the GENII-S and ERMYN Models ..... 7-94
7.4.3 Air Submodel ..... 7-96
7.4.3.1 Radon Pathway ..... 7-96
7.4.3.2 Evaporative Cooler ..... 7-98
7.4.4 Plant Uptake Submodel ..... 7-99
7.4.4.1 Direct Deposition of Irrigation Water on Crop Surfaces ..... 7-99
7.4.4.2 Crop Interception Fraction for Irrigation Water ..... 7-101
7.4.4.3 Direct Deposition of Resuspended Soil on Crop Surfaces ..... 7-101
7.4.5 Animal Submodel ..... 7-102
7.4.6 Fish Submodel ..... 7-104
7.4.7 Carbon-14 Special Submodel ..... 7-104
7.4.8 External Exposure Submodel ..... 7-106
7.4.8.1 Air Submersion ..... 7-106
7.4.8.2 Water Immersion ..... 7-110
7.4.9 Inhalation Submodel ..... 7-115
7.4.10 Ingestion Submodel ..... 7-116
7.5 VALIDATION OF THE GOLDSIM OUTPUT ..... 7-116
7.5.1 Validation of the GoldSim Output for the Groundwater Scenario ..... 7-116
7.5.2 Validation of the GoldSim Output for the Volcanic Ash Scenario ..... 7-116
7.6 MODEL VALIDATION RANGE ..... 7-117
7.7 EXTERNAL REVIEW OF THE ERMYN MODEL ..... 7-119

8. CONCLUSIONS ..... 8-1
8.1 MODEL OUTPUT ..... 8-1
8.2 BIOSPHERE MODEL LIMITATIONS ..... 8-1

9. INPUTS AND REFERENCES ..... 9-1
9.1 DOCUMENTS CITED ..... 9-1
9.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES ..... 9-10
9.3 DEVELOPED DATA ..... 9-11

ATTACHMENT I ELECTRONIC FILES USED FOR THE MODEL REPORT ..... I-1

ATTACHMENT II ANALYTICAL SOLUTION FOR RADON CONCENTRATIONS IN THE AIR DUE TO RADIUM CONTAMINATED SOIL ..... II-1

ATTACHMENT III CALCULATION OF ABSOLUTE HUMIDITY FROM RELATIVE HUMIDITY ..... III-1

## FIGURES

**Page**


1-1. Overview of the Yucca Mountain Biosphere Model Documentation ..... 1-3
6.1-1. Yucca Mountain in Relation to the Great Basin ..... 6-3
6.1-2. Regional Map of Yucca Mountain and the Amargosa Valley ..... 6-4
6.3-1. Graphical Representation of the Biosphere System for the Groundwater Contamination ..... 6-18
6.3-2. Relationship Among Biosphere Submodels for the Groundwater Scenario ..... 6-21
6.3-3. Representation of a Volcanic Eruption Intersecting the Repository ..... 6-30
6.3-4. Relationship between the Biosphere Submodels for the Volcanic Ash Scenario ..... 6-34
6.7-1. Basic Elements in the GoldSim Environment ..... 6-169
6.8-1. Cover Page for the ERMYN_GW in GoldSim ..... 6-170
6.8-2. Graphical Representation of the Groundwater Scenario in GoldSim ..... 6-171
6.8-3. Nuclide Database Container ..... 6-171
6.8-4. Input Parameters for Crop Transfer Factors ..... 6-172
6.8-5. Radionuclide-Specific Input Parameter Selection ..... 6-173
6.8-6. Calculation of Effective Dose Coefficients and Dose Conversion Factors ..... 6-173
6.8-7. Primary_Rn Container and Selection of the Second Decay Product ..... 6-173
6.8-8. Soil Submodel Container ..... 6-175
6.8-9. Input Parameter Container (*SoilModel_Input*) for the Soil Submodel ..... 6-175
6.8-10. Air Submodel Container ..... 6-177
6.8-11. Input Parameter Container (*AirModel_Input*) for the Air Submodel ..... 6-177
6.8-12. Plant Submodel Container ..... 6-179
6.8-13. Input Parameter Container (*PlantModel_Input*) for the Plant Submodel ..... 6-180
6.8-14. Animal Submodel Container ..... 6-183
6.8-15. Input Parameter Container (AnimalModel_Input) for the Animal Submodel ..... 6-183
6.8-16. Fish Submodel Container ..... 6-185
6.8-17. External Exposure Submodel Container ..... 6-185
6.8-18. Input Parameter Container (*External_Input*) for the External Exposure Submodel ..... 6-186
6.8-19. Inhalation Submodel Container ..... 6-188
6.8-20. Input Parameter Container (Inhalation_Input) for the Inhalation Submodel ..... 6-188
6.8-21. Ingestion Submodel Container ..... 6-190
6.8-22. Input Parameter Container (Ingestion_Input) for the Ingestion Submodel ..... 6-190
6.8-23. Final BDCF Result Container ..... 6-192
6.9-1. Cover Page for the ERMYN_VA Simulation in GoldSim ..... 6-193
6.9-2. Biosphere Model for the Volcanic Ash Scenario ..... 6-194
6.9-3. Nuclide Database Container and Radionuclide List ..... 6-195
6.9-4. Surface Soil Submodel Container ..... 6-197
6.9-5. Air Submodel Container ..... 6-198
6.9-6. Plant Submodel Container ..... 6-199
6.9-7. Animal Submodel Container ..... 6-201
6.9-8. External Exposure Submodel Container ..... 6-202
6.9-9. Inhalation Submodel Container ..... 6-203
6.9-10. Ingestion Submodel Container ..... 6-204
6.9-11. Final BDCF Result Container ..... 6-205

INTENTIONALLY LEFT BLANK

## TABLES

**Page**


4-1. Requirements Applicable to Biosphere Modeling ..... 4-2
6.1-1. Radionuclides of Interest for the TSPA-LA ..... 6-8
6.2-1. Features, Events, and Processes Considered in the ERMYN Model ..... 6-10
6.3-1. Exposure Pathways for the Groundwater Scenario ..... 6-16
6.3-2. Radionuclide Transfer Interaction Matrix for the Groundwater Scenario ..... 6-20
6.3-3. Exposure Pathways for the Volcanic Ash Scenario ..... 6-32
6.3-4. Radionuclide Transfer Interaction Matrix for the Volcanic Ash Scenario ..... 6-33
6.3-5. Alternative Conceptual Models Considered ..... 6-41
6.3-6. FEPs Considered in the Biosphere Conceptual Model ..... 6-42
6.3-7. Radionuclides of Interest and Their Decay Products ..... 6-44
6.4-1. The Primary Radionuclides and Their Decay Chains for Soil ..... 6-52
6.4-2. Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth ..... 6-80
6.4-3. Effective Dose Conversion Factors for Inhalation ..... 6-88
6.4-4. Effective Dose Conversion Factors for Ingestion ..... 6-94
6.4-5. Summary of the Biosphere Submodels for the Groundwater Scenario ..... 6-97
6.5-1. Effective Dose Coefficients for Exposure to Contaminated Ground Surface ..... 6-115
6.5-2. Summary of the Biosphere Submodels for the Volcanic Ash Scenario ..... 6-122
6.6-1. Uncertainty Considerations for All Assumptions Used in the Model ..... 6-126
6.6-2. Summary of Parameters Used in the ERMYN Model for the Two Scenarios ..... 6-129
6.6-3. Summary of Input Parameter Values and Their Distributions ..... 6-136
6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model ..... 6-157
6.7-2. Comparison of Biosphere Models for the TSPA-LA and TSPA-SR ..... 6-165
6.8-1. Radionuclide-Related Input Parameters in the Nuclide_Database Container ..... 6-174
6.8-2. Parameters in the Surface Soil Submodel ..... 6-176
6.8-3. Parameters in the Air Submodel ..... 6-178
6.8-4. Parameters in the Plant Submodel ..... 6-181
6.8-5. Parameters in the Animal Submodel ..... 6-184
6.8-6. Parameters in the Fish Submodel ..... 6-185
6.8-7. Parameters in the External Exposure Submodel ..... 6-187
6.8-8. Parameters in the Inhalation Submodel ..... 6-189
6.8-9. Parameters in the Ingestion Submodel ..... 6-191
6.8-10. Parameters in the Final BDCF results ..... 6-192
6.9-1. Radionuclide Related Input Parameters ..... 6-196
6.9-2. Parameters in the Surface Soil Submodel ..... 6-197
6.9-3. Parameters in the Air Submodel ..... 6-199
6.9-4. Parameters in the Plant Submodel ..... 6-200
6.9-5. Parameters in the Animal Submodel ..... 6-201
6.9-6. Parameters in the External Exposure Submodel ..... 6-202
6.9-7. Parameters in the Inhalation Submodel ..... 6-203
6.9-8. Parameters in the Ingestion Submodel ..... 6-204
6.9-9. Parameters in the Final BDCF results ..... 6-205

## TABLES

**Page**


6.10-1. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 1, $^{239}$Pu) ..... 6-207
6.10-2. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 2, $^{14}$C) ..... 6-210
6.10-3. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 3, $^{226}$Ra) ..... 6-212
6.10-4. Results from Deterministic and Stochastic Runs for the Groundwater Scenario ..... 6-217
6.10-5. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 1, $^{239}$Pu) ..... 6-218
6.10-6. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 2, Ra-226) ..... 6-221
6.10-7. Results from the Deterministic and Stochastic Runs for the Volcanic Ash Scenario ..... 6-224
7.2-1. Assessment Context for the ERMYN, BIOMASS ERB2A, and EPRI-YM Biosphere Models for Groundwater Contamination ..... 7-9
7.2-2. Pathways and Submodels in Seven Biosphere Models ..... 7-12
7.3-1. Summary of Mathematical Model Comparisons ..... 7-13
7.3-2. Comparison of Radionuclide Concentration in Surface Soil ..... 7-17
7.3-3. Comparison of Removal Coefficients for Surface Soil ..... 7-19
7.3-4. Soil Resuspension in the Air Submodel ..... 7-25
7.3-5. Comparison of Radon Release from Radium Contaminated Soil ..... 7-28
7.3-6. Comparison of Radionuclide Concentration in Indoor Air from the Operation of an Evaporative Cooler ..... 7-30
7.3-7. Comparison of Crop Contamination due to Root Uptake ..... 7-33
7.3-8. Comparison of Direct Deposition on Leaf Surfaces Due to the Interception of Irrigation Water ..... 7-39
7.3-9. Comparison of Irrigation Deposition Rate ..... 7-42
7.3-10. Comparison of the Intercept Fraction for Irrigation ..... 7-43
7.3-11. Comparison of Direct Deposition on Leaf Surface Due to the Interception of Resuspended Soil ..... 7-47
7.3-12. Comparison of the Dust Deposition Rate ..... 7-49
7.3-13. Comparison of Interception Fraction for Resuspended Soil ..... 7-50
7.3-14. Comparison of Animal Product Contamination Due to Animal Feed ..... 7-53
7.3-15. Comparison of Animal Product Contamination Due to Drinking Water ..... 7-55
7.3-16. Comparison of Animal Product Contamination Due to Soil Ingestion ..... 7-56
7.3-17. Comparison of Animal Product Contamination Due to Dust Inhalation ..... 7-57
7.3-18. Comparison of Fish Contamination due to Fishpond Water ..... 7-59
7.3-19. Comparison of $^{14}$C Special Model for Soil Contamination ..... 7-62
7.3-20. Comparison of $^{14}$C Special Model for Air Contamination ..... 7-63
7.3-21. Comparison of C-14 Special Model for Plant Contamination ..... 7-65
7.3-22. Comparison of $^{14}$C Special Model for Animal Product Contamination ..... 7-69
7.3-23. Comparison of External Exposure to Contaminated Soil ..... 7-73
7.3-24. Comparison of Inhalation Pathway ..... 7-77

## TABLES

**Page**


7.3-25. Comparison of Water Ingestion Pathway ..... 7-81
7.3-26. Comparison of Crop Ingestion Pathway ..... 7-82
7.3-27. Comparison of Animal Product Ingestion Pathway ..... 7-84
7.3-28. Comparison of Fish Ingestion Pathway ..... 7-85
7.3-29. Comparison of Soil Ingestion Pathway ..... 7-86
7.4-1. Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth ..... 7-89
7.4-2. Effective Equivalent Conversion Factors for Inhalation ..... 7-90
7.4-3. Effective Dose Conversion Factors for Ingestion ..... 7-91
7.4-4. Time to Reach 95-percent Saturation ..... 7-93
7.4-5. Radionuclide Decay Chains Included in the GENII-S and ERMYN Models ..... 7-95
7.4-6. Radon Contribution to the Final $^{226}$Ra Dose ..... 7-96
7.4-7. Radon Release Factors Due to Radium Contaminated Soil ..... 7-97
7.4-8. Comparison of Evaporative Cooler Model ..... 7-99
7.4-9. Comparison of Direct Deposition of Irrigation Water on Crop Surfaces ..... 7-100
7.4-10. Calculated Interception Fraction for Irrigation Water ..... 7-101
7.4-11. Comparison of Direct Deposition of Resuspended Soil on Crop Surfaces ..... 7-102
7.4-12. Numerical Calculation of Animal Uptake Submodel ..... 7-103
7.4-13. Evaluation of Plant Uptake in $^{14}$C Special Submodel ..... 7-105
7.4-14. Effective Dose Coefficients for Air Submersion ..... 7-107
7.4-15. Comparison of Dose Coefficients for Infinite Depth Soil and Air Submersion ..... 7-109
7.4-16. Effective Dose Coefficients for Water Immersion ..... 7-111
7.4-17. Effective Dose Coefficients for Infinite Depth Soil and Water Immersion ..... 7-113
7.4-18. Evaluation of Water Immersion Pathway ..... 7-114
7.4-19. Evaluation of Population and Environmental Related Inhalation Submodel ..... 7-115
7.6-1. Unreasonable Parameters Input Values ..... 7-118
I-1. GoldSim Model Files ..... I-3
I-2. GoldSim Model Verification Files ..... I-3
I-3. Microsoft Excel Files ..... I-4
I-4. GENII-S Files ..... I-4
II-1. Calculation of the Radon Release Factor ..... II-6
II-2. Radon Release Factors Due to Radium Contaminated Soil ..... II-7
III-1. Average Relative Humidity and Temperature at the Weather Station 9 ..... III-4

INTENTIONALLY LEFT BLANK

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACM | alternative conceptual model |
| BDCF | biosphere dose conversion factor |
| CEDE | committed effective dose equivalent |
| DOE | U.S. Department of Energy |
| EDE | effective dose equivalent |
| ERMYN | Environmental Radiation Model for Yucca Mountain, Nevada |
| FEPs | features, events, and processes |
| FGR | Federal Guidance Report |
| IAEA | International Atomic Energy Agency |
| ICRP | International Commission on Radiological Protection |
| LA | license application |
| NRC | U.S. Nuclear Regulatory Commission |
| RMEI | reasonably maximally exposed individual |
| SR | site recommendation |
| TEDE | total effective dose equivalent |
| TSPA | total system performance assessment |
| TSPA-LA | total system performance assessment for the license application |
| TSPA-SR | total system performance assessment for the site recommendation |
| TWP | technical work plan |
| YMP | Yucca Mountain Project |

INTENTIONALLY LEFT BLANK

# 1. PURPOSE

The purpose of this report is to document the biosphere model, the Environmental Radiation Model for Yucca Mountain, Nevada (ERMYN), which describes radionuclide transport processes in the biosphere and associated human exposure that may arise as the result of radionuclide release from the geologic repository at Yucca Mountain. The biosphere model is one of the process models that support the Yucca Mountain Project (YMP) Total System Performance Assessment (TSPA) for the license application (LA), the TSPA-LA. The ERMYN model provides the capability of performing human radiation dose assessments.

This report documents the biosphere model, which includes:

1. Describing the reference biosphere, human receptor, exposure scenarios, and primary radionuclides for each exposure scenario (Section 6.1)

2. Developing a biosphere conceptual model using site-specific features, events, and processes (FEPs), the reference biosphere, the human receptor, and assumptions (Section 6.2 and Section 6.3)

3. Building a mathematical model using the biosphere conceptual model and published biosphere models (Sections 6.4 and 6.5)

4. Summarizing input parameters for the mathematical model, including the uncertainty associated with input values (Section 6.6)

5. Identifying improvements in the ERMYN model compared with the model used in previous biosphere modeling (Section 6.7)

6. Constructing an ERMYN implementation tool (model) based on the biosphere mathematical model using GoldSim stochastic simulation software (Sections 6.8 and 6.9)

7. Verifying the ERMYN model by comparing output from the software with hand calculations to ensure that the GoldSim implementation is correct (Section 6.10)

8. Validating the ERMYN model by corroborating it with published biosphere models; comparing conceptual models, mathematical models, and numerical results (Section 7).

As directed by the technical work plan (TWP) for biosphere modeling (BSC 2003 [DIRS 163602]), the ERMYN model is based on a previous biosphere model (CRWMS M&O 2000 [DIRS 151615]) that supports the TSPA for the site recommendation (SR), the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]). The ERMYN model implements capabilities to address shortcomings of the GENII-S software that was used for the previous biosphere model (GENII-S; Leigh et al. 1993 [DIRS 100464]), addresses site specific concerns, better incorporates the included FEPs into the conceptual model, incorporates recommendations of an International Atomic Energy Agency (IAEA) international review team (IAEA 2001 [DIRS 155188]), addresses acceptance criteria for the review of the LA (NRC 2003 [DIRS 162418]), and addresses biosphere-related issues raised by the U.S. Nuclear Regulatory Commission

(NRC) (Reamer 2001 [DIRS 157090]; Reamer 2001 [DIRS 158380]; Reamer 2001 [DIRS 159894]).

The ERMYN model uses as much site-specific information as possible, and some environmental pathways and model simplifications are specific to the required reference biosphere and human receptor (10 CFR 63.305 [DIRS 156605]). The model is used for environmental radiation dose assessments and can calculate radionuclide-specific doses or provide radionuclide-specific biosphere dose conversion factors (BDCFs) for a human receptor. A BDCF is numerically equal to an all-pathway dose that a defined human receptor receives under specific biosphere conditions when the receptor is exposed to radionuclide contamination in environmental media that arises from a unit concentration of a radionuclide in a source medium. The TSPA-LA model requires radionuclide-specific BDCFs, and the use of BDCFs in the TSPA-LA model is described in Sections 6.4.10 and 6.5.8. The ERMYN model is based on a biosphere with an arid or semi-arid climate and little or no surface water discharge or transport. Limitations of the ERMYN model are discussed in Section 8.2.

To help readers navigate the biosphere model documentation, a graphical representation of the current documentation structure is presented (Figure 1-1). This *Biosphere Model Report* is shown in the middle of the figure. The current biosphere documents are shown with full titles and document identification numbers. Titles without document identification numbers are documentation for the TSPA-LA model, not biosphere model. Some of these documents may be under development and not yet available when this report is issued. This figure provides an overview of how this *Biosphere Model Report* contributes to biosphere modeling in support of the TSPA-LA, and access to the listed documents is not required to understand the contents of the *Biosphere Model Report*. The structure of this figure does not imply that input parameter values from other documents cannot be used in the ERMYN model.

The biosphere model documentation currently consists of nine documents (Figure 1-1): this model report, five input analysis reports, two output analysis reports, and a biosphere FEPs analysis report. The FEPs considered for the biosphere model (Section 6.2) are listed in the *LA FEP List* (DTN: MO0303SEPFEPS2.000 [DIRS 162452]), and the biosphere-related FEPs are listed in the TWP (BSC 2003 [DIRS 163602], pp. 16 to 17). The five analysis reports describe the selection of values and distributions for model input parameters; none of the numerical values used in the mathematical model are developed in this model report. This report describes the biosphere model, which is built in GoldSim software (GoldSim Technology Group 2002 [DIRS 160643]), but it does not contain the numerical results (outputs) of biosphere modeling. Two other reports, one each for the groundwater and volcanic ash exposure scenarios, present the results of the biosphere model (i.e., radionuclide-specific BDCFs for the TSPA-LA). In addition, a biosphere FEPs analysis report summarizes the FEPs in the model and provides justification for excluding FEPs.

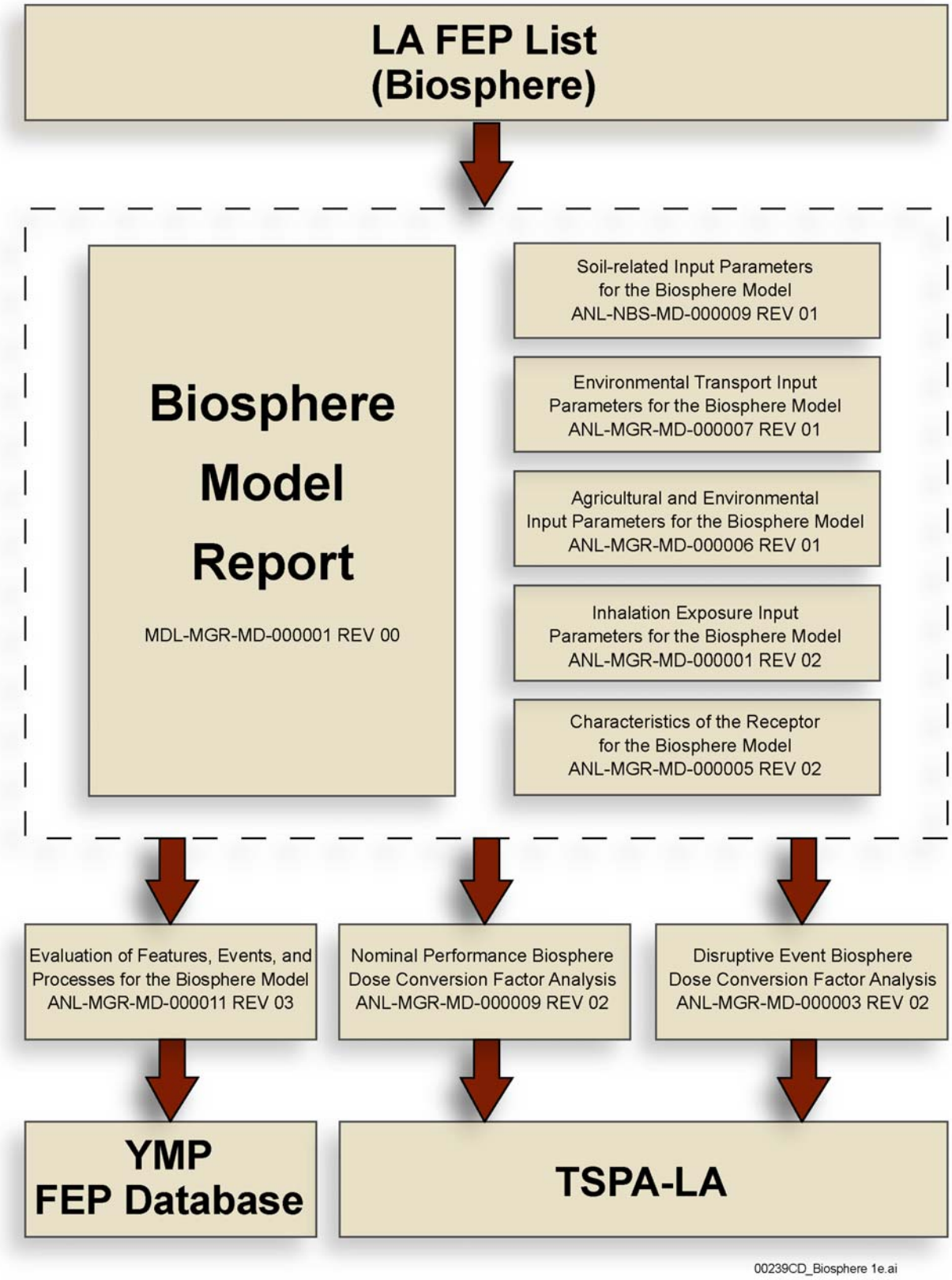



Figure 1-1. Overview of the Yucca Mountain Biosphere Model Documentation

INTENTIONALLY LEFT BLANK

# 2. QUALITY ASSURANCE

As described in the TWP (BSC 2003 [DIRS 163602]), this report documents a scientific model that supports the TSPA-LA, and thus it is a quality affecting activity in accordance with AP-2.27Q [DIRS 159604], *Planning for Science Activities*. Approved quality assurance procedures identified in the TWP (BSC 2003 [DIRS 163602], Section 4) are used to conduct and document the activities described in this report. Electronic data for this analysis are controlled in accordance with the TWP (BSC 2003 [DIRS 163602], Section 8).

This analysis does not require classification of the quality level of natural barriers or other items in accordance with AP-2.22Q [DIRS 163021], *Classification Criteria and Maintenance of the Monitored Geologic Repository Q List*, or other applicable implementing procedures.

INTENTIONALLY LEFT BLANK

# 3. COMPUTER SOFTWARE AND MODEL USE

The ERMYN model is implemented using GoldSim stochastic simulation software, which is a graphical, object-oriented computer program for carrying out dynamic, probabilistic simulations (GoldSim Technology Group 2002 [DIRS 160643]). GoldSim allows for visually creating and manipulating data and equations, which are displayed as graphical objects (referred to as graphical elements in GoldSim).

The GoldSim software (Version 7.50.100) is qualified under the Office of Civilian Radioactive Waste Management, Quality Assurance Program for use on the YMP (software tracking number: 10344-7.5.100-00; BSC 2003 [DIRS 161572]). Software Configuration Management provided a copy of the GoldSim software and installed it on a DELL Precision Workstation 530 computer (CPU# 151555) under the Windows 2000 operating system. GoldSim is appropriate for constructing the ERMYN model, and it is used within the range of validation in accordance with procedure AP-SI.1Q [DIRS 163085], *Software Management*.

For comparisons between the ERMYN and other biosphere models, some calculations are performed using Microsoft Excel 97 SR-2, a commercial, off-the-shelf program. These calculations use standard Excel functions as described in this report. All formulas, inputs, and outputs related to the use of Excel and required to reproduce the computations are documented in the applicable tables of this report or in the files in Attachment I. Qualification of commercial, off-the-shelf software is not required under the software management procedure (AP-SI.1Q [DIRS 163085]).

INTENTIONALLY LEFT BLANK

# 4. INPUTS

## 4.1 DATA AND PARAMETERS

### 4.1.1 Direct Inputs

There are no direct inputs to this model report. This model report describes the development and validation of the ERMYN model, which requires hundreds of input parameters. However, this report does not develop values for the parameters nor does it produce product output from the model. All of the parameter values for the ERMYN model are developed in the input parameter analysis reports (Figure 1-1). BDCF calculations and other interim calculations in this report are only for verifying, and validating the model. Because this report does not produce numerical output results as product output, there are no data or other technical product inputs used as direct inputs, as defined in *Managing Technical Product Inputs* (AP-3.15Q [DIRS 164073]).

### 4.1.2 Other Inputs

Although no data or technical product inputs (AP-3.15Q [DIRS 164073]) are used directly to produce output from this report, a number of sources of information were used for developing, verifying, and validating the model.

**FEPs**—The *LA FEP List* (DTN: MO0303SEPFEPS2.000 [DIRS 162452]) is the source of FEPs for developing this model. This is a comprehensive list of FEPs that may be applicable to the exposure scenarios that might result from storing spent nuclear fuel and high-level radioactive waste in a geologic repository at Yucca Mountain. This is an appropriate list from which to select FEPs for the ERMYN model (Section 6.2).

**Radionuclides of Interest**—Although the mathematical models described in Sections 6.4 and 6.5 apply to any radionuclides, the ERMYN model focuses on radionuclides considered for the TSPA-LA (BSC 2002 [DIRS 160059]). The model output, the ERMYN GoldSim model, is built for only those 28 primary radionuclides (Section 6.1.3). The list includes all radionuclides that could make an important dose contribution during the first million years after establishing a repository at Yucca Mountain; therefore, it is the appropriate list for the ERMYN model.

**Mathematical Equations**—The mathematical representations described in Sections 6.4 and 6.5 are based primarily on a review of published biosphere models. Documents describing the models reviewed are listed in Section 7.1, which identifies models used for, and excluded from, validation. These models are appropriate for the following reasons. They include state-of-the-art methods for environmental radiation models. In total, they include a comprehensive description of the methods available to predict doses from chronic radiation exposure. In addition, at least some part of each model is applicable to the ERMYN conceptual model.

**Parameters**—Distributions of parameters for calculating BDCFs using the ERMYN model were developed in the five analysis reports (BSC 2003 [DIRS 160964]; BSC 2003 [DIRS 161239]; BSC 2003 [DIRS 160976]; BSC 2003 [DIRS 160965]; and BSC 2003 [DIRS 161241]). These parameter values are used in this model report to verify the GoldSim implementation of the model (Section 6.10), to validate the model (Section 7.3), and to conduct numerical comparisons

of alternative conceptual models (ACMs) (Section 7.4). These values (Tables 6.6-2 and 6.6-3) were selected based on the Yucca Mountain exposure scenarios and conditions in the Yucca Mountain region. Therefore, they are applicable to the ERMYN conceptual model and represent reasonable ranges of values for use in this model. These values are based on the equations in Sections 6.4 and 6.5. Thus, they are appropriate for validating the ERMYN mathematical model and for verifying the GoldSim implementation of the model.

## 4.2 CRITERIA

Regulation 10 CFR Part 63 [DIRS 156605], *Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada,* contains regulatory requirements that apply to developing the biosphere model.

The *Project Requirements Document* (Canori and Leitner 2003 [DIRS 161770], Table 2-3) contains three requirements that apply to biosphere modeling (Table 4-1). These requirements are further discussed in Section 4.3.

Table 4-1. Requirements Applicable to Biosphere Modeling

| Requirement Number | Requirement Title | Related Regulation |
|---|---|---|
| PRD-002/T-015 | Requirements for Performance Assessment | 10 CFR 63.114 |
| PRD-002/T-026 | Required Characteristics of the Reference Biosphere | 10 CFR 63.305 |
| PRD-002/T-028 | Required Characteristics of the Reasonably Maximally Exposed Individual | 10 CFR 63.312 |

Source: Canori and Leitner (2003 [DIRS 161770], Table 2-3).

In addition, the following acceptance criteria for NRC staff review for the repository (NRC 2003 [DIRS 162418], Section 2.2.1.3.14) are based on the requirements of 10 CFR 63.114, 10 CFR 63.305, and 10 CFR 63.312, as they relate to biosphere characteristics modeling. These criteria are presented to further describe how the requirements in Table 4-1 should be met. Only the items from the Biosphere Characteristics section (NRC 2003 [DIRS 162418], Section 2.2.1.3.14) that apply to this analysis are presented. Similar acceptance criteria and descriptions from the "Airborne Transport of Radionuclides" and "Redistribution of Radionuclides in Soil" sections of the NRC report (NRC 2003 [DIRS 162418], Sections 2.2.1.3.11 and 2.2.1.3.13, respectively) apply to portions of this analysis.

**Acceptance Criterion 1**–System description and model integration are adequate.

(1) The TSPA adequately incorporates important site features, physical phenomena, and couplings, and consistent and appropriate assumptions are used throughout the biosphere characteristics modeling abstraction process.

(2) The TSPA model abstraction identifies and describes aspects of the biosphere characteristics modeling that are important to repository performance and includes the technical bases for

these descriptions. For example, the reference biosphere should be consistent with the arid or semi-arid conditions in the vicinity of Yucca Mountain.

(3) Assumptions are consistent between the biosphere characteristics modeling and other abstractions. For example, the U.S. Department of Energy (DOE) should ensure that the modeling of FEPs (e.g., climate change, soil types, sorption coefficients, volcanic ash properties, and the physical and chemical properties of radionuclides) is consistent with assumptions in other TSPA abstractions.

**Acceptance Criterion 2**–Data are sufficient for model justification.

(1) The parameter values used in the LA are adequately justified (e.g., behaviors and characteristics of the residents of the Amargosa Valley, Nevada, and the reference biosphere) and consistent with the definition of the reasonably maximally exposed individual (RMEI) in 10 CFR Part 63. Adequate descriptions of how the data are used, interpreted, and appropriately synthesized into the parameters are provided.

(2) Data are sufficient to assess the degree to which FEPs related to biosphere characteristics modeling have been characterized and incorporated in the abstraction. As specified in 10 CFR Part 63, the DOE should demonstrate that FEPs, which describe the biosphere, are consistent with present knowledge of conditions in the region surrounding Yucca Mountain. As appropriate, the DOE sensitivity and uncertainty analyses (including consideration of ACMs) are adequate for determining additional data needs and for evaluating whether additional data would provide new information that could invalidate prior modeling results and affect the sensitivity of the performance of the system to the parameter value or model.

**Acceptance Criterion 3**–Data uncertainty is characterized and propagated through the model abstraction.

(1) Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, do not result in an under-representation of the risk estimate, and are consistent with the definition of the RMEI in 10 CFR Part 63.

(2) The technical bases for the parameter values and ranges in the abstraction, such as consumption rates, plant and animal uptake factors, mass-loading factors, and biosphere dose conversion factors, are consistent with site characterization data and are technically defensible.

(3) Process-level models used to determine parameter values for the biosphere characteristics modeling are consistent with site characterization data, laboratory experiments, field measurements, and natural analog research.

(4) Uncertainty is adequately represented in parameter development for conceptual models and process-level models considered in developing the biosphere characteristics modeling, either through sensitivity analyses, conservative limits, or bounding values supported by data, as necessary. Correlations between input values are appropriately established in the TSPA, and the implementation of the abstraction does not inappropriately bias results.

(5) Where sufficient data do not exist, the definition of parameter values and conceptual models is based on appropriate use of expert elicitation, conducted in accordance with appropriate guidance, such as NUREG-1563 (Kotra et al. 1996 [DIRS 100909]). If other approaches are used, the DOE adequately justifies their uses.

(6) Parameters or models that most influence repository performance, based on the performance measure and time period of compliance specified in 10 CFR Part 63, are identified.

**Acceptance Criterion 4**–Model uncertainty is characterized and propagated through the model abstraction.

(1) Alternative modeling approaches of FEPs are considered and are consistent with available data and current scientific understanding, and the results and limitations of alternative modeling approaches are appropriately considered in the abstraction. Staff should evaluate ACMs of the biosphere or biosphere processes, recognizing that 10 CFR 63.305 and 10 CFR 63.312 place a number of constraints on the biosphere and the characteristics of the RMEI. ACMs focus on exploring the variability and uncertainty in the physical FEPs, mindful of the regulatory constraints. Evaluation of the behavior and characteristics of the RMEI emphasizes understanding the characteristics of the current residents of the Amargosa Valley and the uncertainty and variability in the data used to derive mean values.

(2) Sufficient evidence is provided to show that existing ACMs of features and processes that are important to waste isolation, such as plant uptake of radionuclides from soil, soil resuspension, and the inhalation dose model for igneous events, have been considered.

(3) Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog information, and process-level modeling studies, and the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate.

## 4.3 CODES AND STANDARDS

The biosphere model considers the final rule, *Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada* (10 CFR Part 63 [DIRS 156605]; November 2001). Of particular relevance is 10 CFR 63, Subpart L, *Postclosure Public Health and Environmental Standards*, which describes postclosure individual protection, human intrusion, and groundwater protection standards. The biosphere model also considers the requirements for postclosure performance assessments in 10 CFR 63.114.

# 5. ASSUMPTIONS

The ERMYN model uses 16 assumptions to simplify the conceptual model of biosphere processes and the mathematical representations of the processes. Some of the assumptions apply to both exposure scenarios, while others apply to only one. The assumptions and the justification for using them are given in the remainder of this section.

## 5.1 GROUNDWATER SOURCE

**Assumption 1**–Radionuclide concentrations in the groundwater are constant through time.

**Rationale**–Radionuclides will accumulate in soil that is continuously irrigated with contaminated groundwater until saturation (i.e., equilibrium) conditions are reached; therefore, doses calculated for a specified time will be influenced by groundwater concentrations prior to that time until radionuclide concentrations in the soil are in equilibrium. The time required for the radionuclides considered in this model to reach equilibrium conditions is shorter than the 10,000-year compliance period for the TSPA-LA (Section 7.4.2); therefore, it is assumed that concentrations in groundwater are constant at a concentration defined by the user of the model (e.g., unit concentration of 1 $Bq/m^3$).

In the event that equilibrium conditions for a radionuclide have not been reached and groundwater concentrations are increasing, this assumption will result in overestimating the dose for that radionuclide (Section 6.4.10.4). If concentrations in groundwater are decreasing, the dose may be underestimated. However, it is unlikely that groundwater concentrations will decrease until long after the compliance period of 10,000 years (Section 6.4.10.4).

This assumption allows separate and independent calculations of time-dependent radionuclide concentrations in a TSPA and time-independent BDCFs in the ERMYN, as required by the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2002 [DIRS 160146], p. 72). The assumption requires no further confirmation because it is likely that saturation conditions will be reached in less than 10,000 years and because the dose will not be underestimated if those conditions are not reached by that time.

**Applicability**–This assumption applies to the groundwater scenario (Section 6.4).

## 5.2 CONSIDERATION OF SHORT-LIVED DECAY PRODUCTS

**Assumption 2**–Short-lived decay products (half-life less than 180 d) are always in secular equilibrium with the long-lived primary radionuclides.

**Rationale**–Modeling radionuclide decay and ingrowth can be complicated if every decay product is considered as a function of time. This assumption eliminates the need to consider the dynamics of long decay chains for high atomic number (≥ 82) radionuclides. This assumption is conservative because the activity of a decay product reaches a maximum value when in equilibrium with the long-lived parent radionuclide. This assumption is reasonable because the primary radionuclides have long half-lives (Section 6.3.5), and the primary radionuclides and decay products in the groundwater and the volcanic ash are expected to be in secular equilibrium

with the short-lived decay products. If the radionuclides in a decay chain are transferred to the biosphere or between biosphere components, the secular equilibrium could be perturbed because of different transfer characteristics in the biosphere and groundwater (e.g., due to different leaching rates or transfer factors). However, calculations of radionuclide transfer and doses are based on one-year average values, and a new equilibrium will be reached quickly due to the relatively short-lived decay products. This assumption also is used in the RESRAD code (Yu et al. 2001 [DIRS 159465], Section 3.1). The developed effective dose coefficients and effective dose conversion factors, which are based on this assumption, are compared with results from the RESRAD model to confirm this assumption (Section 7.4.1).

**Applicability**–This assumption applies to both exposure scenarios (Section 6.3.5).

## 5.3 LONG-TERM IRRIGATION, LAND USE, AND CROP ROTATION

**Assumption 3**–Current land use and irrigation practices continue throughout the period of interest on agricultural land. The average irrigation rate for all crops is appropriate for calculating radionuclide concentrations in the soil.

**Rationale**–Based on the current and predicted future climates in the Amargosa Valley (USGS 2001 [DIRS 158378]), irrigation will be required for farming and gardening during the regulatory compliance period of 10,000 yrs. Because irrigation rates differ among crops (BSC 2003 [DIRS 160976], Section 6.5), radionuclide concentrations in the soil will differ among fields depending on the types of crops grown. However, crop rotation is a common agricultural practice in the Amargosa Valley (Horak and Carns 1997 [DIRS 124149], Section 1.b), and crop rotation over long periods will average out the short-term differences in irrigation rates among fields, resulting in an average radionuclide concentration among fields. Therefore, the annual average irrigation rate for all crops is appropriate for calculating the concentration of radionuclides in agricultural soil. This assumption simplifies the surface soil submodel because the long-term irrigation rate does not depend on crop type. This assumption requires no further confirmation because it is based on common agricultural practices.

**Applicability**–This assumption applies to the surface soil submodel for the groundwater scenario (Sections 6.3.1.5 and 6.4.1).

## 5.4 CROP HARVEST REMOVAL AND THE USE OF CONTAMINATED MANURE FOR FERTILIZER

**Assumption 4**–Radionuclides added to the soil due to the use of manure for fertilizer replace radionuclides removed from the soil by harvesting crop.

**Rationale**–Harvesting crops removes radionuclides from cultivated fields, and fertilizing with contaminated fertilizer adds radionuclides. It is reasonable to assume that Amargosa Valley farmers will use manure from a dairy for fertilizer because they currently use manure from the dairy for fertilizer (Horak and Carns 1997 [DIRS 124149], p. 10). This assumption considers the removal of radionuclides from fields in animal feed and soil to be balanced by the addition of radionuclides in animal manure on fields where animal feed is grown. Intake of radionuclides by animals is from feed, soil, and water; therefore, drinking water is an additional source of radionuclides in manure not considered by this assumption. However, the contribution of

radionuclides to animal intake from drinking water is low (about 3 percent; Table 7.4-12) compared to that from animal feed and soil. In addition, only a portion of the radionuclides taken in by animals is transferred to animal products. Therefore, considering that these two processes compensate for each other is valid, and this assumption requires no further confirmation. This assumption eliminates the need to calculate losses from crop harvest removal and gains from cow manure fertilizer. Applying this assumption to the entire Amargosa Valley is realistic because alfalfa is the major crop grown in Amargosa Valley (CRWMS M&O 1997 [DIRS 101090], pp. 3-18 to 3-19; YMP 1999 [DIRS 158212], Tables 10 and 11).

**Applicability**–This assumption applies to the surface soil submodel for both exposure scenarios (Sections 6.3.1.5, 6.3.2.5, 6.4.1.1, and 6.5.1).

## 5.5 RADIONUCLIDE BUILDUP IN SURFACE SOIL

**Assumption 5**–Radionuclide concentrations in irrigated soils are at saturation because of long-term use of contaminated groundwater to irrigate crops.

**Rationale**–When cultivated lands are irrigated with contaminated groundwater over long periods of time, radionuclides accumulate in the soil until a saturation condition is reached (Section 6.4.1). The time to reach saturation depends on the rates of radionuclide addition (i.e., irrigation) and removal from the soil (Equation 6.4.1-4). After equilibrium is reached, radionuclide concentrations remain constant. This is a conservative assumption because the activity concentration of a radionuclide in the soil is highest at equilibrium. It also is reasonable because the regulatory compliance period is 10,000 yrs, and during that period of time, most or all of the radionuclides will reach saturation (Section 7.4.2.1), assuming that current agricultural land use and irrigation practices continue (Assumption 3). Other biosphere models, such as BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522], Tables 22 to 25), also assume equilibrium conditions for dose calculations. This assumption eliminates the need to consider time-dependent radionuclide concentrations in the surface soil, and it permits evaluating biosphere dose contributions separately from the groundwater source in performance assessment (Assumption 1). This assumption is further discussed in Section 6.4.10, where the total dose and BDCF calculations are described. This assumption does not require further confirmation because it is likely that saturation conditions will be reached in less than 10,000 yrs and because the dose will not be underestimated if those conditions are not reached.

**Applicability**–The assumption applies to the surface soil submodel for the groundwater scenario (Sections 6.3.1.5, and 6.4.1).

## 5.6 CROP WEATHERING LOSS AND SURFACE SOIL GAIN

**Assumption 6**–All radionuclides in irrigation water are deposited on the surface of the soil, even when overhead irrigation is used and a fraction of the irrigation water is initially intercepted and absorbed by plant leaves.

**Rationale**–Farmers in the Amargosa Valley, especially the larger commercial operations, irrigate using spray and overhead systems (BSC 2003 [DIRS 160976], Section 6.3.2). When plants are irrigated from above, a portion of water is intercepted and absorbed by the leaves. The total amount of contaminated water eventually deposited on the soil depends on the initial foliar

interception fraction, crop weathering, and the crop growing time. This assumption is conservative because it double-counts the radionuclides remaining on the plant and absorbed through plant leaves because they are also treated as deposited on the soil. This assumption is reasonable because the amount of radioactive material on and in the plant leaves is low compared to the overall irrigation source. It is estimated that a small fraction (< 7 percent) of the radioactivity in the irrigation water is transferred to the edible parts of the crops, while the rest is deposited on the soil or remains in the non-edible portion of the plants and eventually is incorporated into the soil from the non-harvested portions of the plants or contaminated manure (Section 7.4.4.1). This assumption is used in other biosphere models such as GENII (Napier et al. 1988 [DIRS 157927], Section 4.7.4) and BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522], Section 7). This assumption simplifies the mathematical representation of the weathering process, in which a fraction of the intercepted radioactive material is deposited on the soil surface. Based on above discussions, this assumption requires no further confirmation.

**Applicability**–This assumption applies to the surface soil submodel for the groundwater scenario (Sections 6.3.1.5 and 6.4.1). It is also discussed in the plant submodel (Sections 6.3.1.5 and 6.4.3).

## 5.7 CROP ROOTS IN SURFACE SOIL

**Assumption 7**–All crop roots are in the surface soil layer down to the tilling depth.

**Rationale**–In the ERMYN model, soil in cultivated fields and gardens is divided into two compartments (surface soil and deep soil), and only the surface layer is considered part of the biosphere. Although the deep soil would become contaminated due to leaching from the surface soil, radionuclide concentrations in the deep soil are not calculated directly because those radionuclides are considered lost from the biosphere. Because many crops require tilling every year, radionuclides would be uniformly distributed throughout the surface layer over the long term. Thus, the soil tilling depth fits the concept of a surface soil depth. This assumption is reasonable because 80 to 90 percent of the plant roots occur in the upper 60 to 75 percent of the root zone (Jensen et al. 1990 [DIRS 160001], p. 22]. Although crop roots can penetrate into the deep soil compartment, radionuclide concentrations would typically decrease with soil depth due to leaching. This assumption does not underestimate radionuclide concentrations in the crops because the higher radionuclide concentrations in the surface soil are used for calculating crop root uptake. Therefore, the assumption requires no further confirmation.

**Applicability**–This assumption applies to the plant submodel for both exposure scenarios (Sections 6.3.1.5, 6.3.2.5, 6.4.3, and 6.5.3).

## 5.8 ANIMAL FEED

**Assumption 8**–Locally grown fresh forage is the only feed given to beef cattle and dairy cows, and locally produced grain is the only feed given to poultry and laying hens.

**Rationale**–Farm animals become contaminated by ingesting contaminated feed, water, and soil. Among these, animal feed is an important pathway (Section 7.4.5). In the Amargosa Valley, alfalfa and other hays are the most common crops (YMP 1999 [DIRS 158212], Tables 10 and 11), and dry hay used for livestock feed is produced locally and imported from outside the

area (Horak and Carns 1997 [DIRS 124149], p. 12). Water is added to locally grown alfalfa hay and commercial feed before feeding it to animals (Horak and Carns 1997 [DIRS 124149], p. 16). It is reasonable to assume that animals are fed locally grown fresh forage rather than dry hay with water added because they are equivalent, and this assumption simplifies the mathematical model. In addition, although poultry and laying hens could be fed with other types of feed, locally produced grain is the only feed considered in the model. This assumption is conservative because it assumes that all animal feed is locally produced and contaminated; therefore, this assumption requires no further confirmation. This assumption eliminates the need to consider radionuclide concentrations in other types of feed, the fraction of those feeds, and the fraction of imported uncontaminated feed.

**Applicability**–The assumption applies to the plant (Sections 6.3.1.5, 6.4.3, 6.3.2.5, and 6.5.3) and the animal submodels (Sections 6.3.1.5, 6.4.4, 6.3.2.5, and 6.5.4) for both exposure scenarios.

## 5.9 ANIMAL PRODUCT TYPE

**Assumption 9**–People consume animal products from four categories: meat, milk, poultry, and eggs. Meat includes beef, pork, lamb, and game animals; milk is from dairy cows, goats, and sheep; poultry includes chicken, turkey, duck, geese, and game hens; and eggs come from laying hens (chickens) and ducks.

**Rationale**–Farm animals in the Amargosa Valley include cattle, dairy cows, pigs, goats, ostriches, and poultry (YMP 1999 [DIRS 158212], Tables 8 and 9), plus sheep and ducks (Horak and Carns 1997 [DIRS 124149], Tables 5 and 6). There are more cattle than pigs and goats combined, and there are more dairy cows than goats (YMP 1999 [DIRS 158212], Tables 8 and 9). According to the EPA *Food Ingestion Factors* (EPA 1997 [DIRS 152549], Table 11-9) and the U.S. Department of Agriculture *Census of Agriculture, Nevada State and County Data* (USDA 1999 [DIRS 158643], Tables 20, 29, 40), beef, milk from cows, chickens, and chicken eggs are the most frequently consumed products or are the most commonly raised and sold products in each category. Therefore, beef and milk from cows are considered representative of the meat and milk categories, respectively. Because it is difficult to count the number of small animals in the Amargosa Valley, poultry and chicken eggs are used as general categories in the model. These two categories match the categories in the food consumption survey (DOE 1997 [DIRS 100332], Appendix B). This assumption is reasonable because the uncertainty range of transfer coefficients for the selected animal products includes variation in transfer coefficients between selected and unselected animal products. For example, the selected transfer coefficient for meat is $1.3 \times 10^{-5}$ d/kg, with a range of $3.3 \times 10^{-8}$ to $4.7 \times 10^{-3}$ d/kg for plutonium (Table 6.6-3), while the transfer coefficients for pork, sheep meat, and lamb are $8.0 \times 10^{-5}$, $9.4 \times 10^{-5}$, and $3.1 \times 10^{-3}$ d/kg, respectively (IAEA 1994 [DIRS 100458], pp. 38 to 39). Therefore, this assumption requires no further confirmation. This assumption reduces the number of animal-product ingestion pathways for humans and eliminates the need for transfer coefficients for the other types of animal products.

**Applicability**–This assumption applies to the animal submodel for both exposure scenarios (Sections 6.3.1.5, 6.4.4, 6.3.2.5, and 6.5.4).

## 5.10 DOSE COEFFICIENTS FOR EXPOSURE TO CONTAMINATED SOIL

**Assumption 10**–Dose coefficients for an infinite depth of soil are appropriate for estimating external exposure for the groundwater scenario.

**Rationale**–The dose coefficients for soil contaminated to an infinite depth (Eckerman and Ryman 1993 [DIRS 107684], Section II) are based on an infinite isotropic (i.e., a homogeneously contaminated infinite) source and a receptor standing at the air-ground interface (Eckerman and Ryman 1993 [DIRS 107684], p. 11). Under the groundwater scenario, it is reasonable to consider that the contaminated area is infinitely large because the size of contaminated fields is large relative to the area from which the external exposure generally is received. In addition, non-cultivated lands eventually will be contaminated by surface soil transport, although the level of contamination would be lower than cultivated land. This assumption is conservative because only a small portion of Amargosa Valley is irrigated (BSC 2003 [DIRS 160965], Section 6). Regarding the source depth, using dose coefficients based on an infinite depth is reasonable because deep soil will be contaminated by leaching, although at levels lower than those for surface soil. Dose coefficients for an infinite depth and those for a 15-cm depth differ by less than 10 percent for most primary radionuclides (Eckerman and Ryman 1993 [DIRS 107684], Tables III-6 and III-7). Only radionuclides with strong gamma emissions, such as $^{226}$Ra and $^{137}$Cs, have a relatively large difference for the two depths. Because dose coefficients for these radionuclides are greater for a source of infinite depth, this assumption is conservative. This assumption is reasonable for the groundwater scenario and does not underestimate the dose; it does not require further confirmation.

**Applicability**–The assumption applies to the external exposure submodel for the groundwater scenario (Sections 6.3.1.5 and 6.4.7).

## 5.11 EVAPORATIVE COOLER USE AND EXPOSURE TIME

**Assumption 11**–Evaporative coolers do not cause radionuclides to build up in indoor air, radionuclide concentrations in indoor air are constant on days when coolers are used, and the contribution of contaminated aerosols to the outdoor environments is unimportant.

**Rationale**–This assumption is necessary to evaluate radiation doses from aerosols generated by evaporative coolers using contaminated water. To be most effective, evaporative coolers are operated with an open window or door to let air circulate, thus radionuclides do not build up in indoor air because the large volume of airflow would carry contaminated aerosols out of the house. Radionuclide concentrations in indoor air are assumed to be constant on days when evaporative coolers are used. Although coolers cycle on and off to maintain the temperature setting, the period when the cooler is temporarily off usually would be relatively short, and decreases in radionuclide concentrations due to decay and air exchange would be insignificant. The contribution of contaminated aerosols generated from evaporative coolers and transferred to the outdoor air is not important and thus is not further considered because the indoor air is diluted and rapidly dispersed in the large outdoor environment. Therefore, this assumption requires no further confirmation.

**Applicability**–This assumption applies to the air and inhalation submodels for the groundwater scenario (Sections 6.3.1.5, 6.4.2, and 6.4.8).

## 5.12 VOLCANIC ASH SOURCE

**Assumption 12**–On cultivated lands, ash that falls on the ground is tilled into the surface soil, but the soil density does not change when mixed with ash. On non-cultivated lands, ash that falls on the ground may or may not mix with the surface soil, depending on the thickness of the ash, and the ash density does not change when mixed with soil.

**Rationale**–Ash deposited at the location of the receptor is expected to be thin. Under normal, variable wind conditions, ash depths predicted in the TSPA-SR at a location 20 km south of Yucca Mountain, range from about $1 \times 10^{-8}$ cm to $1 \times 10^{1}$ cm. About 66 percent of predicted depths from 300 computer simulations are less than 0.1 mm, about 80 percent are less than 1 mm, and 95 percent are less than 10 mm (CRWMS M&O 2000 [DIRS 153246], Section 3.10.5.1). Therefore, contaminated ash likely would be a thin layer. On cultivated land, plowing and irrigation would uniformly mix the ash and surface soil, and the small amount of ash would not change the soil density. Most land in Amargosa Valley is not plowed or irrigated (BSC 2003 [DIRS 160965], Section 6), and ash falling on non-cultivated land would not be mixed with the surface soil by agricultural practices, although some downward migration of contamination through the soil profile will occur following initial deposition. A thin layer (i.e., a critical thickness) of ash could mix with surface soil. This critical thickness is defined as the layer of soil from which soil particles readily resuspend into the air. If the thickness of the ash layer is less than the critical thickness, it is assumed that the ash and soil can become resuspended due to wind and other disturbing forces and mix in the process. It is assumed that the ash and soil mixing layer would be no more than the critical thickness, and that the ash density remains unchanged when soil is added. If the thickness of the ash layer on non-cultivated land is greater than the critical thickness, no mixing or dilution of the ash occurs because all resuspended particles would be from the top layer of ash. These assumptions are based on current Amargosa Valley land-use patterns, the arid or semiarid climate, and are reasonable, and therefore this assumption requires no further confirmation.

**Applicability**–This assumption applies to the surface soil submodel for the volcanic ash scenario (Sections 6.3.2.5 and 6.5.1).

## 5.13 ASH RESUSPENSION

**Assumption 13**–Resuspended volcanic ash that deposits on plants is from cultivated land, while ash that contributes to the human inhalation dose is from non-cultivated lands.

**Rationale**–After a volcanic eruption, much of the reference biosphere would be contaminated with ash, and ash available for resuspension would come from two sources: cultivated and uncultivated lands. Most of the resuspended particles that deposit on crops would come from the cultivated lands where the crops are grown; therefore cultivated lands are the appropriate source for these particles. However, for the human inhalation dose, uncultivated lands are the appropriate source because cultivated lands cover only a small fraction of Amargosa Valley (BSC 2003 [DIRS 160965], Section 6.1). This assumption does not underestimate the human

inhalation dose because human inhalation is the major pathway in the volcanic ash scenario, and contaminated particles from non-cultivated lands have a higher radionuclide concentration than those from cultivated land (Tables 6.10-5 and 6.10-6). This assumption may underestimate radionuclide concentrations in the crops; but in the volcanic ash scenario, the ingestion pathway contributes less to the all-pathway dose than the inhalation pathway. This assumption does not underestimate the final dose, it simplifies calculating radionuclide concentrations in the air, and it requires no further confirmation.

**Applicability**–This assumption applies to the air submodel for the volcanic ash scenario (Sections 6.3.2.5 and 6.5.2).

## 5.14 TIME DEPENDENT MASS LOADING

**Assumption 14**–After a volcanic eruption, mass loading (i.e., the concentration of resuspended particulates in the air) decreases with time and eventually returns to levels similar to pre-eruption conditions.

**Rationale**–A time-dependent mass loading function is used to avoid overestimating the expected inhalation dose after a volcanic eruption that otherwise would be calculated using a constant and high mass loading value. This assumption is reasonable because levels of resuspended particulates after volcanic eruptions decrease with time (BSC 2003 [DIRS 160965], Section 6.3). The time-dependent function is developed in the ERMYN model, but it will be implemented in the TSPA-LA model. The time-dependent function is documented in BSC (2003 [DIRS 160965], Section 6.3). This assumption requires no further confirmation because it is based on observed changes in mass loading after volcanic eruptions.

**Applicability**–This assumption applies to the air submodel for the volcanic ash scenario (Sections 6.3.2.5 and 6.5.2).

## 5.15 RADON GAS RELEASED FROM VOLCANIC ASH

**Assumption 15**–All $^{222}$Rn from $^{226}$Ra-contaminated volcanic ash is released into the air.

**Rationale**– The thickness of volcanic ash deposited on the ground is anticipated to be relatively thin (Assumption 12). Following the initial deposition, mixing of the ash and soil will occur through atmospheric and mechanical processes affecting the soil surface and through the downward migration of the contaminant into the soil profile. Because of this mixing, and because the ash thickness is not known a priori in the biosphere modeling, predicting the radium concentration profile in the soil is not a straight-forward process and estimating the amount of radon released from such a source would require a radon diffusion submodel, for which data are not available. In the ERMYN model, a simplified method is used in which all radon produced from the contaminated ash is assumed to be released to the atmosphere. The relationship between the concentration of $^{226}$Ra in the surface soil (Bq/m$^2$), radon flux density from the soil (Bq/(m$^2$ s)), and the concentration of $^{222}$Rn in the air (Bq/m$^3$) is derived from available data. This assumption is conservative, as only a fraction of the $^{222}$Rn would be exhaled from the soil and released into the air, and therefore it requires no further confirmation.

**Applicability**–This assumption applies to the air submodel for the volcanic ash scenario (Sections 6.3.2.5 and 6.5.2).

## 5.16 EXTERNAL EXPOSURE FROM THE GROUND SURFACE

**Assumption 16**–Radionuclides in volcanic ash layer are concentrated on the top surface of the ash deposit, and dose conversion factors for surficial contaminants are appropriate.

**Rationale**–The ash layer is expected to be relatively thin (Assumption 12), and it is reasonable to assume that only the ground surface would be contaminated. Therefore, the external exposure submodel from the groundwater scenario, which considers long-term irrigation and soil contaminated to an infinite depth, does not apply to the volcanic ash scenario. By assuming that radionuclides in the ash are on the surface of the ground, external exposure can be calculated using surface contamination methods rather than volumetric methods. This assumption is reasonable because there is considerably more non-cultivated land than cultivated land in the Amargosa Valley (BSC 2003 [DIRS 160965], Section 6), and the mixing of volcanic ash on non-cultivated land would be limited. This approach is conservative because it ignores radiation attenuation in the soil and ash. Therefore, it required no further confirmation. The assumption simplifies calculations and eliminates the dependence of external exposure on ash thickness and location.

**Applicability**–This assumption applies to the external exposure submodel for the volcanic ash scenario (Sections 6.3.2.5 and 6.5.5).

INTENTIONALLY LEFT BLANK

# 6. MODEL DISCUSSION

In this section, the biosphere model (i.e., the ERMYN model) is described. The modeling objectives, including a description of the biosphere system, are discussed in Section 6.1. Model inputs and outputs, and their use in downstream models and analyses, are also discussed in Section 6.1. The ERMYN model is based on as much site-specific information as possible. The FEPs considered in the ERMYN model are listed in Section 6.2. Based on characteristics of the biosphere system, the included FEPs, and the scenarios considered, a biosphere conceptual model is developed (Section 6.3). ACMs, which usually refer to other process models, are considered in the model development (Section 6.3.3). To quantify the radiation dose to a specific receptor, which in the case of the TSPA-LA will be the RMEI, a series of mathematical representations are presented for the groundwater (Section 6.4) and volcanic ash scenarios (Section 6.5). All input parameters required for the mathematical model, including the uncertainty associated with them, are summarized in Section 6.6. Improvements in the ERMYN model compared to the GENII-S model, used in the previous YMP biosphere modeling activities (CRWMS M&O 2000 [DIRS 151615]; CRWMS M&O 2001 [DIRS 152536]; CRWMS M&O 2001 [DIRS 152539]), are identified in Section 6.7. The developed biosphere model, built in the GoldSim software (Section 3), produces BDCFs for the TSPA-LA model. Discussion of the model implementation is given for the groundwater (Section 6.8) and volcanic ash scenarios (Section 6.9). The GoldSim implementation of the ERMYN model is verified in Section 6.10. This report does not develop model inputs or results; these are documented elsewhere as discussed in Section 1 (Figure 1-1).

## 6.1 MODELING OBJECTIVES

The objective of the ERMYN model is to provide capabilities for calculating doses in the TSPA-LA model by building a biosphere model to estimate the annual human radiation dose that would result if unit concentrations of radionuclides are released from the geologic repository into the environment. In general, this biosphere model provides a method for assessing chronic radiation doses with an upper limit to radiation dose of tens of rem (Eckerman et al. 1988 [DIRS 101069], Section II). This is because the dose conversion factors and dose coefficients in the model apply to chronic intakes and low exposure conditions (continuous exposure to low level contamination) and are not appropriate for acute intakes and high exposure conditions (a few exposures to high contamination).

The radionuclides can be released into different environmental media, such as water for the groundwater scenario or soil for the volcanic ash scenario. Because the activity concentration in the media will be developed from other process modeling, a unit activity concentration is considered as the source term in the biosphere model. This approach, using a biosphere process independent from the radionuclide source (BSC 2002 [DIRS 160146], p. 72), is evaluated in Sections 6.4.10 and 6.5.8. All biosphere model inputs are described in Sections 6.4 and 6.5 where the mathematical submodels are presented. All input parameters for generating model outputs are summarized in Section 6.6.

The biosphere model outputs are sets of radionuclide-specific BDCFs that will be used in the TSPA-LA model to calculate human radiation doses. Between the radionuclide source and the

BDCFs is the biosphere model, which contains a representation of radionuclide transfer mechanisms in the biosphere system, along with related assumptions and simplifications, and the representation of the receptor.

It is important to first describe the biosphere system to be modeled. In general, the biosphere system includes the reference biosphere and the human receptor. Conceptually, the biosphere system is composed of a set of specific biotic and abiotic components of the accessible environment and the relationships between these components. These components are the essentials of a reference biosphere as delineated by the final rule (10 CFR 63.305 [DIRS 156605]).

### 6.1.1 Reference Biosphere

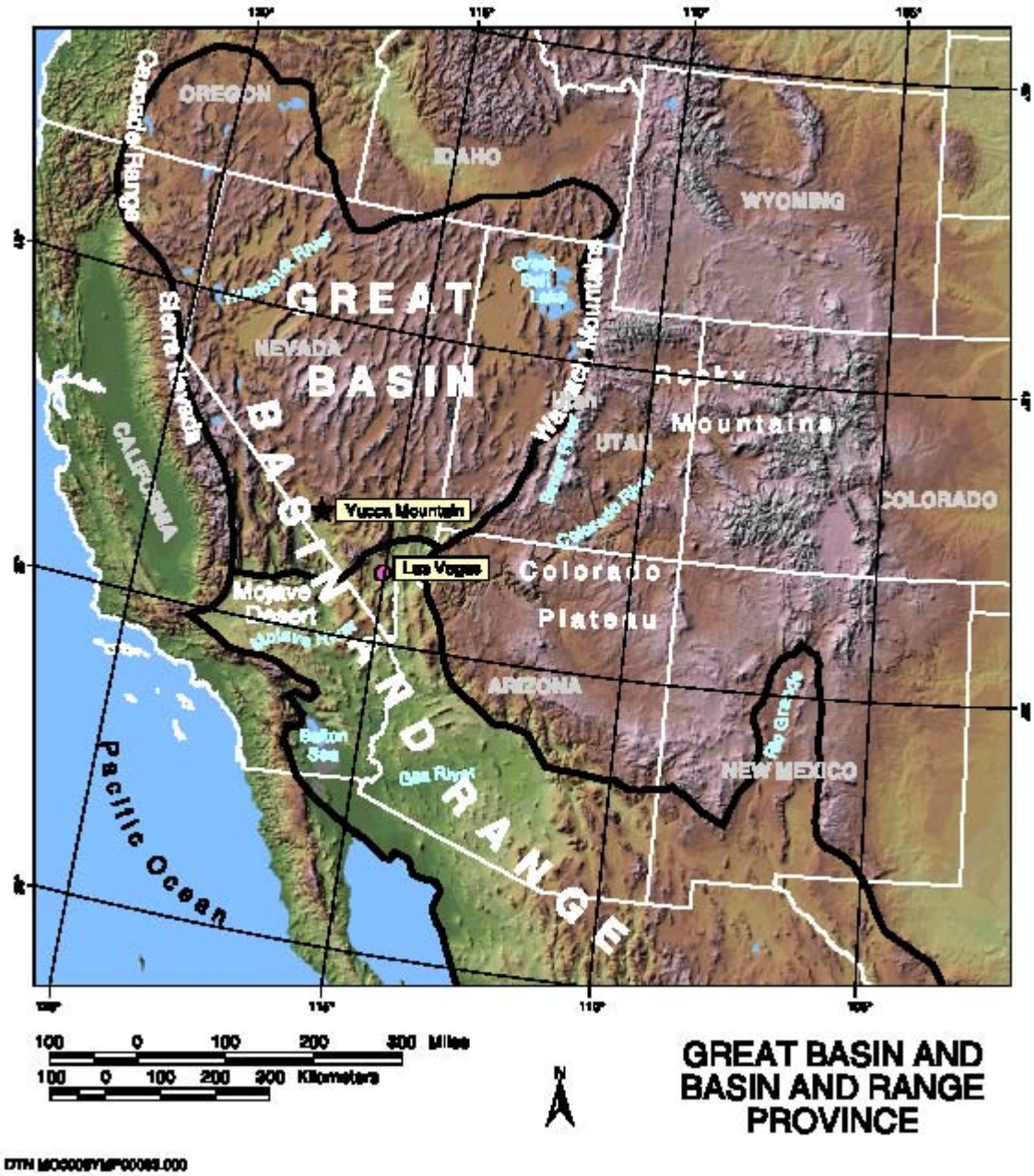
The region surrounding Yucca Mountain characterizes the reference biosphere. The reference biosphere includes characteristics of the geography, geology, physiology, climate, hydrology, and population in the Amargosa Valley. A brief overview of the reference biosphere is presented in this section. As specified by 10 CFR 63.305 [DIRS 156605], the required characteristics of the reference biosphere include FEPs that describe the reference biosphere (Section 6.2), the current conditions of society, biosphere, human biology, and human knowledge (Sections 6.1.1.1 and 6.1.1.3); predicted future conditions of geology, hydrology, and climate consistent with present knowledge (Section 6.1.1.2); and biosphere pathways consistent with arid and semi-arid conditions (Section 6.3). For developing the biosphere model, the characteristics of the reference biosphere are focused on the area around the location of the RMEI, as specified in 10 CFR 63.312 [DIRS 156605]. The regional and site information presented in this section provides an overview of the basis for selecting the FEPs and biosphere pathways considered in the ERMYN model. Other biosphere characteristics, such as those identified by the IAEA international review team (IAEA 2001 [DIRS 155188], Section 4.1), are considered in the model.

#### 6.1.1.1 Geography, Geology, and Physiography

Yucca Mountain is located in Nye County in southern Nevada, approximately 160 km northwest of Las Vegas, in an arid, sparsely populated region in the transition zone between the Great Basin and the Mojave deserts. Yucca Mountain and surrounding areas are in the southern-most part of the Great Basin, a subprovince of the Basin and Range Physiographic Province (Figure 6.1-1). The topography is typical of the Great Basin, which is characterized by more or less regularly spaced, north-south trending mountain ranges and intervening alluvial basins that are formed by faulting.

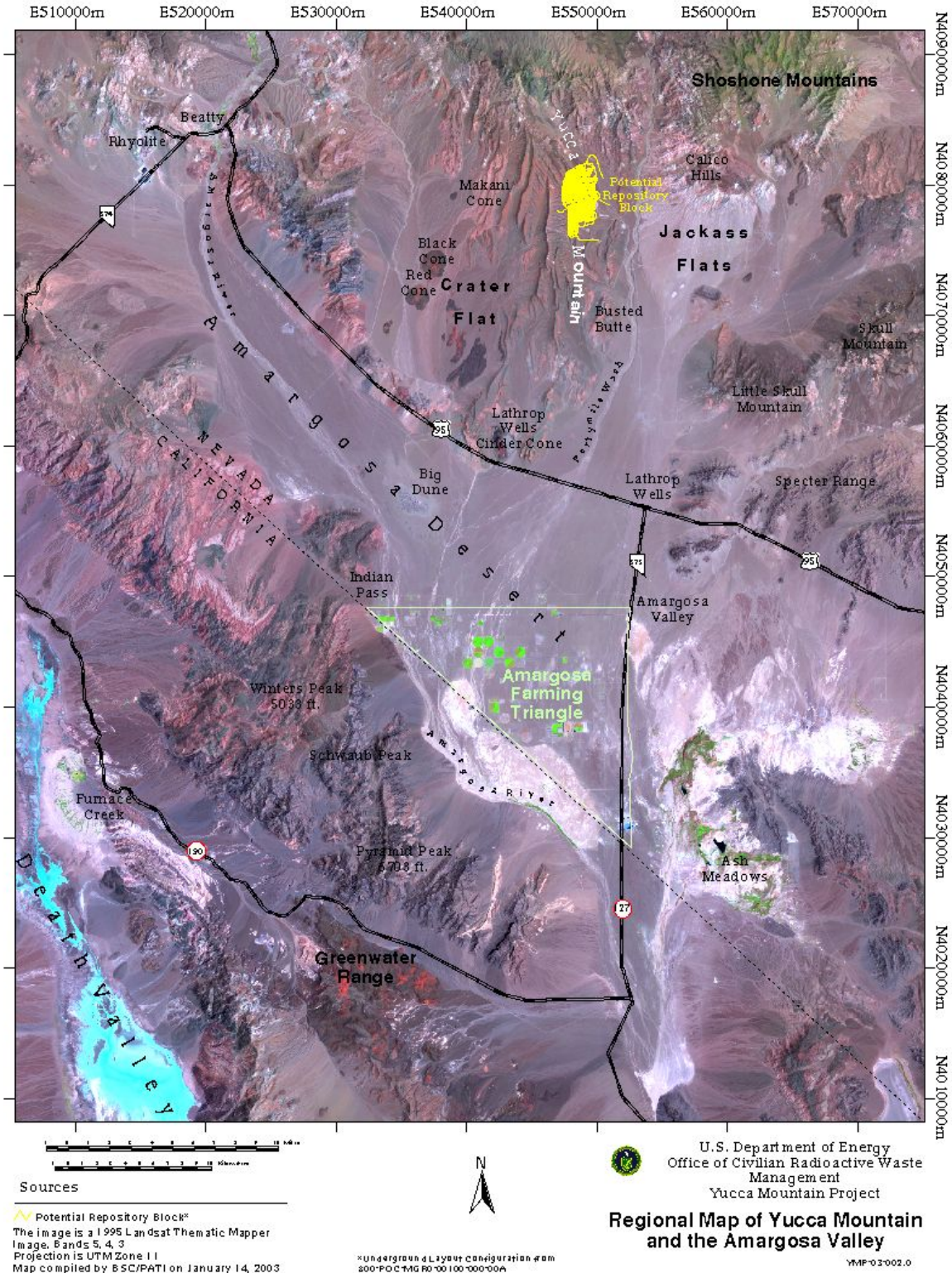
The area surrounding Yucca Mountain can be divided into eight clearly defined physiographic landforms (CRWMS M&O 2000 [DIRS 151945], Section 4.4.2.1). The four landforms most relevant to the biosphere conceptual model are Yucca Mountain, Fortymile Wash, Jackass Flats, and the Amargosa Desert (Figure 6.1-2). Yucca Mountain is an irregularly shaped upland, 6 to 10 km wide and about 40 km long. The crest of the mountain reaches elevations of 1,500 to 1,930 m, about 650 m higher than the floors of adjacent washes in Crater Flats and Jackass Flats. Yucca Mountain is composed of fine-grained volcanic rocks and is formed from fault blocks that tilt eastward, such that the fault-bounded west-facing slopes are generally high, steep, and

straight, which contrasts with the gentler and often deeply dissected east-facing slopes. Drainage from the west flank of the mountain flows southward down narrow fault-controlled canyons and out into Crater Flat. Drainage from the east flank flows southeastward down Yucca, Drill Hole, and Dune Washes into Fortymile Wash.




NOTE: Names of specific geographical points are not necessary to the technical content of this document.

Figure 6.1-1. Yucca Mountain in Relation to the Great Basin




NOTE: Names of specific geographical points are not necessary to understand the technical content of this document.

Figure 6.1-2. Regional Map of Yucca Mountain and the Amargosa Valley

Fortymile Wash is a large ephemeral wash that drains an approximately 620-$km^2$ area east and northeast of Yucca Mountain. From its headwaters northeast of Yucca Mountain, it flows southward through Fortymile Canyon and continues down the south-sloping piedmont that forms the west end of Jackass Flat. Along this latter reach, the wash cuts a nearly linear trench through the alluvial deposits, 150 to 600-m wide and up to 25-m deep. This trench gradually decreases downslope until the wash merges with the Amargosa Desert basin.

Jackass Flats is an alluvial basin, 8- to 10-km wide and nearly 20-km long, that lies east of Yucca Mountain and Fortymile Wash. Jackass Flats is formed principally by piedmonts that slope away from highlands to the north, east, and south, merge in the central basin area, and descend gradually westward and southwestward towards Fortymile Wash.

The Amargosa Desert is a broad northwest-trending basin approximately 80-km long and up to 30-km wide. The basin is one of the largest in the southern Great Basin. The basin floor slopes gently southeastward from elevations of about 975 m at the north end (near Beatty, Nevada) to about 600 m toward the south end. The Amargosa River, which catches runoff from the Yucca Mountain area, extends southeastward through the basin, eventually ending in Death Valley.

#### 6.1.1.2 Climate

The regional climate is characterized by low precipitation, hot summers, cool winters, and low relative humidity (CRWMS M&O 2000 [DIRS 151945], Section 6.2). The Sierra Nevada mountain range, a dominant feature in the region, is a major barrier to moist air moving east from the Pacific Ocean and creates a rain shadow. Annual average precipitation in the region ranges from 100 to 200 mm (4 to 8 inches) and decreases from higher to lower elevations. About 50 percent of the annual precipitation is from frontal storms during November through April. Precipitation during the summer months often occurs as localized thunderstorms that may create floods and runoff. Precipitation often varies between years by a factor of 2. Temperatures vary through the year. Average maximum daytime temperatures are about 35°C (95°F) in July and 11°C (52°F) in January. Although the average nighttime temperature in January is above freezing, 2°C (36°F), freezing temperatures occur. Low precipitation and warm temperatures keep atmospheric humidity low. Annual average relative humidity is less than 20 percent.

The combination of low precipitation, warm temperatures, and low humidity results in high rates of evaporation and the loss of moisture by plants via transpiration. Shrubs adapted to periodic drought and extremes in temperatures dominate the native vegetation in the region (CRWMS M&O 1996 [DIRS 102235]). Shrubs cover 20 to 30 percent of the ground depending on precipitation.

Geological and biological media provide a historical record of the types and periodicity of climate change in the Yucca Mountain region. Future climate predictions indicate that the modern interglacial climate at Yucca Mountain should persist for another 400 to 600 yrs. After that, the climate shifts to a warmer and wetter monsoon climate (lasting 900 to 1,400 yrs) and then to a cooler and wetter glacial transition climate for 8,000 to 8,700 yrs (USGS 2001 [DIRS 158378], p. 66).

#### 6.1.1.3 Groundwater, Human Activities, and Agriculture

Water in the aquifers beneath Yucca Mountain generally flows from north to south (D'Agnese et al. 1997 [DIRS 100131]). Therefore, groundwater flows from the repository area south to the Amargosa Valley (Figure 6.1-2). If radionuclides are released into the groundwater or the air at Yucca Mountain, groundwater flow and wind patterns suggest that some of these radionuclides would spread south and east into the Amargosa Valley region.

The nearest human residents to Yucca Mountain (in the direction of groundwater flow) live in the Amargosa Valley. At the time of the 2000 census, it was estimated that 1,176 people in 429 households resided in the approximately 1,300-$km^2$ Amargosa Valley Census County Division (Bureau of the Census 2001 [DIRS 156858]). Residents living closest to the potential repository are located at the intersection of U.S. Highway 95 and Nevada State Route 373 (Figure 6.1-2), which is approximately 20 to 21 km south of Yucca Mountain. Soil conditions at this location generally are similar to those further downgradient where farming currently is practiced (CRWMS M&O 1999 [DIRS 107736]).

At the time of the 2000 census, there was a general store, community center, senior center, library, medical clinic, elementary school, restaurant, hotel-casino, and a motel in the Amargosa Valley, but it generally is a rural agrarian area. Most of the agriculture, and the majority of the population, are located approximately 30 km south of Yucca Mountain in the Amargosa farming triangle, which is bounded by the Amargosa Farm Road on the north, Nevada State Route 373 on the east, and the California-Nevada border running from northwest to southeast.

Agriculture mainly involves growing feed (e.g., alfalfa) for farm animals; however, gardening and animal husbandry are common (YMP 1999 [DIRS 158212]). Commercial agriculture in the Amargosa Valley farming triangle includes a dairy (approximately 5,000 cows) and a fish farm (approximately 15,000 catfish and bass; YMP 1999 [DIRS 158212], Tables 9 and 11). There are approximately 1,400 acres planted in alfalfa, 300 acres in other hay, 100 acres in pistachios, 16 acres in fruit trees, and 10 acres in grapes. Agriculture depends entirely on irrigation, and local wells provide water for household, agriculture, horticulture, and animal husbandry. There are no naturally occurring surface waters (i.e., perennial lakes and streams) in the area.

### 6.1.2 Human Receptor

Characteristics of the RMEI, the human receptor for the TSPA-LA, are specified in regulation 10 CFR 63.312 [DIRS 156605]. The RMEI:

(a) Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination.

(b) Has a diet and life style representative of the people now residing in the Amargosa Valley, Nevada. Projections based on surveys of these people are used to determine the current diets and life styles, and mean values of these factors are used in assessments conducted for 10 CFR 63.311 and 10 CFR 63.321.

(c) Uses groundwater with average concentrations of radionuclides based on an annual water demand of 3000 acre-feet.

(d) Drinks groundwater (2 L/d) from wells at the location specified in paragraph (a).

(e) Is an adult metabolically and physiologically consistent with present knowledge of adults.

These requirements are used for developing the external exposure time, inhalation exposure time, and food consumption rates (BSC 2003 [DIRS 161241], Section 6). A food consumption survey of the residents of the Amargosa Valley was conducted (DOE 1997 [DIRS 100332]). The recent census data indicates that although the Amargosa Valley is a rural community, most of the residents do not work in the agricultural business (Bureau of the Census 2002 [DIRS 159728], Table P49).

The characteristics of the human receptor are based on the adult metabolic and physiological properties of the "reference man" (ICRP 1975 [DIRS 101074]). These characteristics are used in developing dosimetric parameters, including the dose coefficients for external exposure and dose conversion factors for inhalation and ingestion. These parameters, taken from Federal Guidance Report (FGR)-11 (Eckerman et al. 1988 [DIRS 101069]) and FGR-12 (Eckerman and Ryman 1993 [DIRS 107684]), are based on the International Commission on Radiological Protection (ICRP) 30 dosimetric methodology (ICRP 1978 [DIRS 101076]; ICRP 1979 [DIRS 110386; ICRP 1980 [DIRS 110351]; ICRP 1981 [DIRS 153056]; ICRP 1981 [DIRS 110352]; ICRP 1982 [DIRS 153057]).

Although the ERMYN model is based on the requirements of 10 CFR Part 63 for the RMEI, it can be used to evaluate doses to human receptors with other dietary and lifestyle characteristics, and can use dosimetric methods other than those of ICRP-30.

### 6.1.3 Exposure Scenarios and Radionuclides of Interest

In the biosphere model, two human exposure scenarios are considered: the groundwater exposure scenario (groundwater scenario) and the volcanic ash exposure scenario (volcanic ash scenario). The scenarios are considered separately because the initial radionuclide source terms, the radionuclide transport mechanisms in the biosphere, and the human exposure pathways are different. The groundwater scenario applies to TSPA modeling cases that consider a groundwater release of radionuclides from the repository at Yucca Mountain. TSPA scenario classes considered for TSPA-LA include the nominal scenario class and the disruptive scenario classes (BSC 2002 [DIRS 160146], pp. 47-48). The nominal scenario class represents the most plausible evolution of the repository system and includes favorable future conditions and potentially adverse future conditions. The disruptive event scenario classes are developed using combinations of FEPs that have a low probability of occurrence but may produce potentially adverse future conditions. The disruptive event scenario classes include the igneous scenario class, which in turn includes the igneous intrusion and volcanic eruption cases, and the seismic scenario class, as well as a special case of the stylized analysis of human intrusion into the repository.

For the groundwater scenario, radionuclides enter the biosphere from a well that extracts contaminated groundwater from an aquifer. Human exposure arises from using the contaminated water for domestic and agricultural purposes. BDCFs for the groundwater scenario apply to the TSPA-LA modeling cases that consider groundwater releases of radionuclides. The nominal

scenario class and some modeling cases from the disruptive scenario classes (i.e., igneous intrusion and human intrusion) may result in the release of radionuclides to groundwater. Dose assessments for such releases involve BDCFs for the groundwater scenario.

The volcanic ash scenario applies to the volcanic eruption modeling case of the igneous scenario class. The biosphere model for the volcanic ash scenario, and thus the BDCFs generated using this model, support only the volcanic eruption modeling case of the disruptive event scenario classes. The remaining disruptive event scenario classes result in radionuclide releases to groundwater and are supported by the biosphere model for the groundwater scenario.

The radionuclides of interest (Table 6.1-1) for the biosphere model depend on the exposure scenario, as discussed in *Radionuclide Screening* (BSC 2002 [DIRS 160059]). Two exposure scenarios (groundwater and volcanic ash), and therefore two lists of radionuclides, are applicable for the TSPA-LA. Characteristics of the biosphere for the groundwater and volcanic ash scenarios are discussed in detail in the following sections. The biosphere model is the same for most radionuclides for both exposure scenarios. However, two radionuclides, $^{14}C$ and $^{222}Rn$ (a decay product of $^{226}Ra$), are modeled differently because of the volatility of $^{14}C$, the large amount of stable carbon ($^{12}C$) in the environment, and the gaseous release of $^{222}Rn$.

Table 6.1-1. Radionuclides of Interest for the TSPA-LA

| Radionuclide | Groundwater Scenario | | Volcanic Ash Scenario | |
|---|---|---|---|---|
| | $1 \times 10^2$ to $2 \times 10^4$ yrs | $2 \times 10^4$ to $1 \times 10^6$ yrs | $1 \times 10^2$ to $2 \times 10^4$ yrs | $2 \times 10^4$ to $1 \times 10^6$ yrs |
| Carbon-14 | C-14 | C-14 | | |
| Chlorine-36 | | Cl-36 | | |
| Selenium-79 | | Se-79 | | |
| Strontium-90 | Sr-90 | | Sr-90 | |
| Technetium-99 | Tc-99 | Tc-99 | | Tc-99 |
| Tin-126 | | Sn-126 | | Sn-126 |
| Iodine-129 | I-129 | I-129 | | |
| Cesium-135 | Cs-135 | Cs-135 | | |
| Cesium-137 | Cs-137 | | Cs-137 | |
| Lead-210 | | Pb-210 | | Pb-210 |
| Radium-226 | Ra-226 | Ra-226 | | Ra-226 |
| Actinium-227 | Ac-227 | Ac-227 | Ac-227 | Ac-227 |
| Thorium-229 | Th-229 | Th-229 | Th-229 | Th-229 |
| Thorium-230 | | Th-230 | | Th-230 |
| Thorium-232 | | Th-232 | | Th-232 |
| Protactinium-231 | Pa-231 | Pa-231 | | Pa-231 |
| Uranium-232 | U-232 | | U-232 | |
| Uranium-233 | U-233 | U-233 | U-233 | U-233 |
| Uranium-234 | U-234 | U-234 | U-234 | U-234 |
| Uranium-236 | | U-236 | | U-236 |
| Uranium-238 | U-238 | U-238 | | U-238 |
| Neptunium-237 | Np-237 | Np-237 | | Np-237 |
| Plutonium-238 | Pu-238 | | Pu-238 | |
| Plutonium-239 | Pu-239 | Pu-239 | Pu-239 | Pu-239 |
| Plutonium-240 | Pu-240 | Pu-240 | Pu-240 | Pu-240 |
| Plutonium-242 | | Pu-242 | | Pu-242 |
| Americium-241 | Am-241 | | Am-241 | |
| Americium-243 | Am-243 | Am-243 | Am-243 | Am-243 |
| Number of Radionuclides | 20 | 23 | 12 | 18 |

Source: BSC (2002 [DIRS 160059], Section 7).

## 6.2 BIOSPHERE FEATURES, EVENTS, AND PROCESSES

Biosphere FEPs, along with some assumptions and simplifications, are the fundamental elements used to build the biosphere conceptual model. The biosphere system and associated chemical, physical, and biological processes are characterized by appropriate FEPs.

In accordance with the TWP (BSC 2003 [DIRS 163602], Section 2), biosphere-related FEPs are identified based on a review of the LA FEP List (DTN: MO0303SEPFEPS2.000 [DIRS 162452]). From this list, 31 FEPs were selected and included in the ERMYN model (Table 6.2-1), based, in part, on the conclusions of a previous FEPs analysis (BSC 2003 [DIRS 160057]). These FEPs (referred to as the included FEPs) represent elements of the arid to semi-arid environment in the Yucca Mountain area and the possible processes leading to radionuclide transport in the environment. These FEPs are presented in Table 6.2-1 with the LA FEP number, FEP name, FEP description, and brief comments on how the FEP is incorporated into the model. Detailed information on how each FEP is incorporated into the exposure scenarios is provided in Section 6.3.4.

Screening arguments for the excluded biosphere-related FEPs (excluded from the ERMYN model and the TSPA-LA) will be presented in a revision of the biosphere FEPs analysis report (BSC 2003 [DIRS 160057]), as shown in Figure 1-1. Most of these FEPs are inconsistent with the requirements of the reference biosphere or the RMEI (10 CFR Part 63 [DIRS 156605]), and some are excluded based on low probability of occurrence.

Relationships among the biosphere-related FEPs, the biosphere conceptual model, and the exposure scenarios are more fully examined in Section 6.3. As a tool to illustrate the movement of radionuclides through the biosphere compartments, a radionuclide transfer interaction matrix (Table 6.3-2 and Table 6.3-4) links each included FEP in the matrix for each exposure scenario. The matrices demonstrate that all included FEPs are considered in the biosphere conceptual model (Section 6.3.4).

In addition, the disposition of the included FEPs in the biosphere mathematical model, submodels, and associated equations and parameters are discussed in Section 6.7.1. Because of the relationship between the biosphere model and the TSPA-LA (Sections 6.4.10 and 6.5.8), only the results of the biosphere model (i.e., the BDCF distributions) will be used for direct input to the TSPA-LA model. Therefore, the disposition of biosphere-related FEPs will be through the BDCFs to the TSPA-LA.

Table 6.2-1. Features, Events, and Processes Considered in the ERMYN Model

| LA FEP Number | FEP Name | FEP Description [a] | FEP Consideration |
|---|---|---|---|
| 1.2.04.07.0A | Ashfall | Finely-divided waste particles are carried up a volcanic vent in an ash cloud and deposited on the land surface. | This is the radionuclide source for the volcanic ash exposure scenario. Local contamination arises from initially deposited ash in the original form, initially deposited ash mixed with uncontaminated soil, or from ash redistributed from remote locations. |
| 1.3.01.00.0A | Climate change, global | Climate change may affect the long-term performance of the repository. This includes the effects of long-term change in global climate (e.g., glacial-interglacial cycles) and shorter-term change in regional and local climate. Climate typically is characterized by temporal variations in precipitation and temperature. | The biosphere model includes climate change using predictions based on the geologic record from the Yucca Mountain region. Although the conceptual model does not change, some agricultural parameter values for the current climate (based on the Amargosa Valley) differ from those for a future climate (based on an analog site). |
| 1.4.07.01.0A | Water management activities | Water management is accomplished through a combination of dams, reservoirs, canals, pipelines, and collection and storage facilities. Water management activities could have a major influence on the behavior and transport of contaminants in the biosphere. | This FEP is included in the biosphere model through local irrigation practices. |
| 1.4.07.02.0A | Wells | One or more wells drilled for human (e.g., drinking water and bathing) or agricultural uses (e.g., irrigation and animal husbandry) may intersect the contaminant plume. | For the groundwater scenario, the well is the point where the source of radionuclides enters the environment. |
| 2.2.08.11.0A | Groundwater discharge to surface at or near receptor location | Radionuclides transported in groundwater as solutes or solid materials (colloids) from the far field to the biosphere will discharge at specific “entry” points that are at or near the receptor location. Surface discharge points may be to holding ponds, to unsaturated soils, or through wells used for irrigation, livestock, or drinking water supply | The ERMYN model implicitly includes this FEP because the model applies to the use of any contaminated water if the reference biosphere and the characteristics of the RMEI remain unchanged. |
| 2.3.02.01.0A | Soil type | Soil type is determined by many different factors (e.g., formative process, geology, climate, vegetation, and land use). Physical and chemical attributes of surface soils (e.g., organic matter content and pH) may influence the mobility of contaminants. | This FEP is used to select input parameter values that depend on soil-types. |

Table 6.2-1. Features, Events, and Processes Considered in the ERMYN Model (continued)

| LA FEP Number | FEP Name | FEP Description [a] | FEP Consideration |
|---|---|---|---|
| 2.3.02.02.0A | Radionuclide accumulation in soils | Radionuclide accumulation in soils may occur as a result of upwelling of contaminated groundwater (e.g., leaching or evaporation at discharge locations) or deposition of contaminated water or particulates (e.g., irrigation water, runoff, and atmospheric deposition). | The ERMYN model includes this FEP by assuming that radionuclides in the soil are at the equilibrium concentration. |
| 2.3.02.03.0A | Soil and sediment transport in the biosphere | Contaminated sediments can be transported to and through the biosphere by fluvial, and, to a lesser extent, aeolian processes. Sediment transport and redistribution may concentrate or dilute radionuclides in the biosphere. Transport by glacial processes is addressed in FEP 1.3.05.00.0A. Transport through the actions of living organisms (bioturbation) is addressed in FEP 2.3.09.01.0A. | Removal of radionuclides from the top layer of soil by wind erosion is considered in the biosphere model. |
| 2.3.04.01.0A | Surface water transport and mixing | Contaminants released from the repository might enter the biosphere through discharge of groundwater into a lake or river. Transport and mixing within surface water bodies affects the subsequent behavior and transport of contaminants in the biosphere. Transport and mixing includes dilution, sedimentation, aeration, streamflow, and river meander. | The ERMYN model implicitly includes this FEP because it applies to the use of any contaminated water if the characteristics of the reference biosphere and the RMEI remain unchanged. |
| 2.3.11.01.0A | Precipitation | Precipitation is an important control on the amount of recharge. Precipitation transports solutes as it flows downward through the subsurface or escapes as runoff. The amount of precipitation depends on climate. | Precipitation is used to derive values for parameters that depend on the overall water balance (e.g., leaching and irrigation rates). |
| 2.3.11.02.0A | Surface runoff and flooding | Surface runoff and evapotranspiration are components in the water balance, together with precipitation and infiltration. They can also be important vehicles for dispersing contaminants. Surface runoff produces erosion, and it can feed washes, arroyos, and impoundments, where flooding may lead to increased recharge. | Similar to precipitation, surface runoff and evapotranspiration are used to derive values for parameters that depend on the overall water balance (e.g., leaching and irrigation rates). |

Table 6.2-1. Features, Events, and Processes Considered in the ERMYN Model (continued)

| LA FEP Number | FEP Name | FEP Description [a] | FEP Consideration |
|---|---|---|---|
| 2.3.13.01.0A | Biosphere characteristics | The conditions that exist in the biosphere are likely to change over time in a largely unpredictable manner due to natural and anthropogenic events and processes. These biosphere conditions or characteristics can influence contaminant transport and affect the long-term performance of the repository. Biosphere characteristics include climate, vegetation, plant and animal populations, and microbes. | This FEP encompasses the principal components, conditions, and characteristics of the reference biosphere that influence contaminant transport and long-term performance of the repository. This FEP includes the natural environment (e.g., climate, soils, flora, and fauna) and human activities. Relationships among these components are the foundation of the biosphere model. |
| 2.4.01.00.0A | Human characteristics (physiology, metabolism) | This FEP addresses human characteristics, which include physiology, metabolism, and variability among individual humans. | Elements of human physiology and metabolism are inherent in the dose conversion factors (conversion factors from radionuclide intake to dose) used in the ERMYN model. |
| 2.4.04.01.0A | Human lifestyle | Human lifestyle, including everyday household activities and leisure activities, will influence the critical exposure pathways to humans. | Human lifestyle information is used to select values for exposure parameters, which, in addition to food and water consumption rates, include the amount of time spent indoors and outdoors for work and recreation. |
| 2.4.07.00.0A | Dwellings | This FEP addresses human dwellings, and the ways in which dwellings affect human exposures. Exposure pathways are influenced by building materials and location. | This FEP is incorporated into the ERMYN model through consideration of the characteristics of the dwellings in Amargosa Valley and their effects on the inhalation and external exposure pathways. |
| 2.4.08.00.0A | Wild and natural land and water use | This FEP addresses human uses of wild and natural lands (e.g., forests and coastlines) and water (e.g., lakes, rivers, and oceans) that may affect the long-term performance of the repository. Wild and natural land use will be primarily controlled by natural factors (e.g., topography and climate). | This FEP is incorporated in the ERMYN model by combining the consumption of game with the consumption rate for all meats and by considering the time the REMI spends in that environment. |
| 2.4.09.01.0B | Agricultural land use and irrigation | Agricultural areas exist near Yucca Mountain, particularly in the direction of groundwater flow. Current practices include irrigation, ploughing, fertilization, crop storage, soil modification, and soil amendment. Existing practices may play an important role in determining exposure pathways and doses. | These features are represented in the model through irrigation techniques, irrigation rates, crop storage times, depth of plowing, and other agricultural practices in the Amargosa Valley. |

Table 6.2-1. Features, Events, and Processes Considered in the ERMYN Model (continued)

| LA FEP Number | FEP Name | FEP Description [a] | FEP Consideration |
|---|---|---|---|
| 2.4.09.02.0A | Animal farms and fisheries | Domestic livestock or fish could become contaminated through the intake of contaminated feed, water, or soil. Such contamination would then enter the foodchain. | These features are represented in the model by consumption rates of locally produced feed, contaminated water, and contaminated soil, and by their effects on radionuclide concentrations in locally produced animal products and fish. |
| 2.4.10.00.0A | Urban and industrial land and water use | This FEP addresses urban and industrial uses of land and water (e.g., industry, urban development, earthworks, and energy production) that may affect the long-term performance of the repository. Urban and industrial land use are controlled by natural factors (e.g., topography and climate) and human factors (e.g., economics and population density). | The ERMYN model implicitly includes urban industrial land and water use through the proportion of time that the REMI spends away from the agricultural environment. |
| 3.1.01.01.0A | Radioactive decay and in-growth | . Radioactivity is the spontaneous disintegration of an unstable atomic nucleus that results in the emission of subatomic particles. Radioactive isotopes are known as radionuclides. Radioactive decay of the fuel in the repository changes the radionuclide content in the fuel with time and generates heat. Radionuclide quantities in the system at any time are the result of the radioactive decay and the growth of daughter products as a consequence of that decay (i.e., ingrowth). Over a 10,000-year performance period, these processes will produce daughter products that need to be considered in order to adequately evaluate the release and transport of radionuclides to the accessible environment. | This FEP is included in the development of effective dose coefficients (for external dose) and effective dose conversion factors (for inhalation and ingestion dose). These factors include dose contributions from short-lived decay products of the primary radionuclides. Radionuclide decay and ingrowth is also included in calculations of radionuclide build up in the soil and in the environmental pathways to humans. |
| 3.2.10.00.0A | Atmospheric transport of contaminants | Atmospheric transport includes radiotoxic and chemotoxic species in the air as gas, vapor, particulates or aerosol. Transport processes include wind, plowing, irrigation, degassing, saltation, and precipitation. | Atmospheric transport of radionuclides is included in the ERMYN model through the effects of resuspension, dispersion, and deposition on particulate materials, aerosols (evaporative cooler), and gases (radon and $^{14}C$). |
| 3.3.01.00.0A | Contaminated drinking water, foodstuffs, and drugs | This FEP addresses human diet and fluid intake. Consumption of food, water, soil, drugs, and other items will affect human exposure to radionuclides. Other influences include water filtration, dilution of diet with uncontaminated food, and food preparation techniques. | Consumption of contaminated food, water, soil, and other items is considered in the ingestion exposure pathway of the ERMYN model. |

Table 6.2-1. Features, Events, and Processes Considered in the ERMYN Model (continued)

| LA FEP Number | FEP Name | FEP Description [a] | FEP Consideration |
|---|---|---|---|
| 3.3.02.01.0A | Plant uptake | Uptake of contaminants by plants could affect potential exposure pathways. Plant uptake from contaminated soils and irrigation water is possible. Particulate deposition onto plant surfaces is also possible. These plants may be used as feed for livestock or consumed directly by humans. | Two plant uptake routes are included in the model: root uptake and direct deposition on crops due to the interception of irrigation water and dust. Crops considered in the model include leafy vegetables, other vegetables, fruit, grain, and animal feed. |
| 3.3.02.02.0A | Animal uptake | Livestock and fish may accumulate radionuclides by ingesting water, feed, soil, and sediment, and by inhaling aerosols and particulates. Depending on the species, humans may directly consume the animals, or they may consume the animal product (e.g., milk, eggs). | Three mechanisms of animal uptake are included in the model: consumption of contaminated water, feed, and soil. Radionuclide concentrations are calculated using steady-state transfer factors. Animal products include meat, milk, poultry, and eggs. |
| 3.3.02.03.0A | Bio-accumulation | Contaminants may accumulate in different organisms, including members of the critical group, affecting impacts. Bioconcentration and biomagnification are related processes. | This FEP only applies to the uptake of radionuclides by fish due to the use of groundwater in fish farming. Radionuclide accumulation by terrestrial plants and animals is addressed under FEP 3.3.02.01.0A (Plant Uptake) and FEP 3.3.02.02.0A (Animal Uptake). For humans, these processes are inherently addressed in the dose conversion factors used to calculate dose (see FEP 2.4.01.00.0A, Human characteristics). |
| 3.3.03.01.0A | Contaminated non-food products and exposure | Contaminants may be concentrated in various products, including clothing (e.g., hides, leather, linen, and wool), furniture (e.g., wood and metal), building materials (e.g., stone, clay for bricks, wood, and dung), fuel (e.g., peat), tobacco, and pets. | Contamination of these products mainly causes external exposure. This FEP is implicitly considered in the model because contamination levels for these products, in general, are lower than those in contaminated soil. |
| 3.3.04.01.0A | Ingestion | Ingestion results in human exposure to repository-derived radionuclides through eating contaminated foodstuffs or drinking contaminated water. | This FEP is addressed through the ingestion rates of contaminated locally-produced food and groundwater. |
| 3.3.04.02.0A | Inhalation | Two inhalation pathways are likely: inhalation of gases and vapors emanating directly from the ground, and inhalation of suspended particulate matter (e.g., radon decay products, dust, smoke, pollen, and soil particles). | This FEP is addressed through the inhalation of resuspended particles, aerosols from evaporative coolers, and gases (e.g., radon, and $^{14}C$). |

Table 6.2-1. Features, Events, and Processes Considered in the ERMYN Model (continued)

| LA FEP Number | FEP Name | FEP Description [a] | FEP Consideration |
|---|---|---|---|
| 3.3.04.03.0A | External exposure | External exposure results from contact, use, or exposure to contaminated materials. | Exposure to contaminated soil is included in the model. Building shielding is considered for indoor external exposure from outdoor contaminated soil. The model does not include other external exposure pathways (e.g., air submersion and water immersion). |
| 3.3.05.01.0A | Radiation doses | The radiation dose is calculated from exposure rates (external, inhalation, and ingestion) and dose conversion factors. The latter are based on radiation type, human metabolism, metabolism of the element of concern in the human body, and exposure duration. | Results of the ERMYN model (i.e., BDCFs) will support the TSPA-LA model in calculating the final radiation dose. |
| 3.3.08.00.0A | Radon and radon daughter exposure | This FEP addresses human exposure to radon and radon decay products. $^{226}$Ra occurs in nuclear fuel waste and it gives rise to $^{222}$Rn gas, the radioactive daughters of which can be harmful to humans and animals upon inhalation. | A pathway for exposure to $^{222}$Rn is included in the model because of the expected presence of $^{226}$Ra in groundwater and volcanic ash. |

NOTE: [a] FEP Description is based on the LA FEP list (DTN: MO0303SEPFEPS2.000 [DIRS 162452]), which is considered to be the source of these FEPs.

## 6.3 BIOSPHERE CONCEPTUAL MODEL

In the previous section, the biosphere-related FEPs, and the methods for including them in the ERMYN model, are discussed. The biosphere conceptual model is constructed by considering these FEPs for a specific exposure scenario. To make it easier to understand, the conceptual model is presented in a logical framework that relates a contamination source to a human radiation dose using all possible mechanisms for radionuclide transport in the environment and human exposure pathways. In this section, the biosphere conceptual models for the groundwater (Section 6.3.1) and volcanic ash scenarios (Section 6.3.2) are discussed. Although many transport processes and exposure pathways are the same for both scenarios, they differ because of the different environmental media that is initially contaminated (i.e., groundwater and volcanic ash). Other issues related to the conceptual model are discussed later, including ACMs (Section 6.3.3), individual FEPs applicable to specific exposure scenarios (Section 6.3.4), and short-lived decay products (Section 6.3.5).

### 6.3.1 Conceptual Model for the Groundwater Exposure Scenario

An exposure scenario is a well-defined, connected sequence of FEPs that describes characteristics of current and possible future biosphere where radionuclide transport occurs, and circumstances of human exposure. The reference biosphere and the human receptor (Section 6.1) are fundamental concepts of the groundwater exposure scenario, or simply groundwater scenario. The description of the groundwater scenario (Section 6.3.1.1) includes

background information on the biosphere system. Based on site-specific information, radionuclide transport in various environmental media is examined using the radionuclide transfer interaction matrix (Table 6.3-2). These environmental media and exposure modes are considered as subsystems of the overall biosphere system.

#### 6.3.1.1 Scenario Description

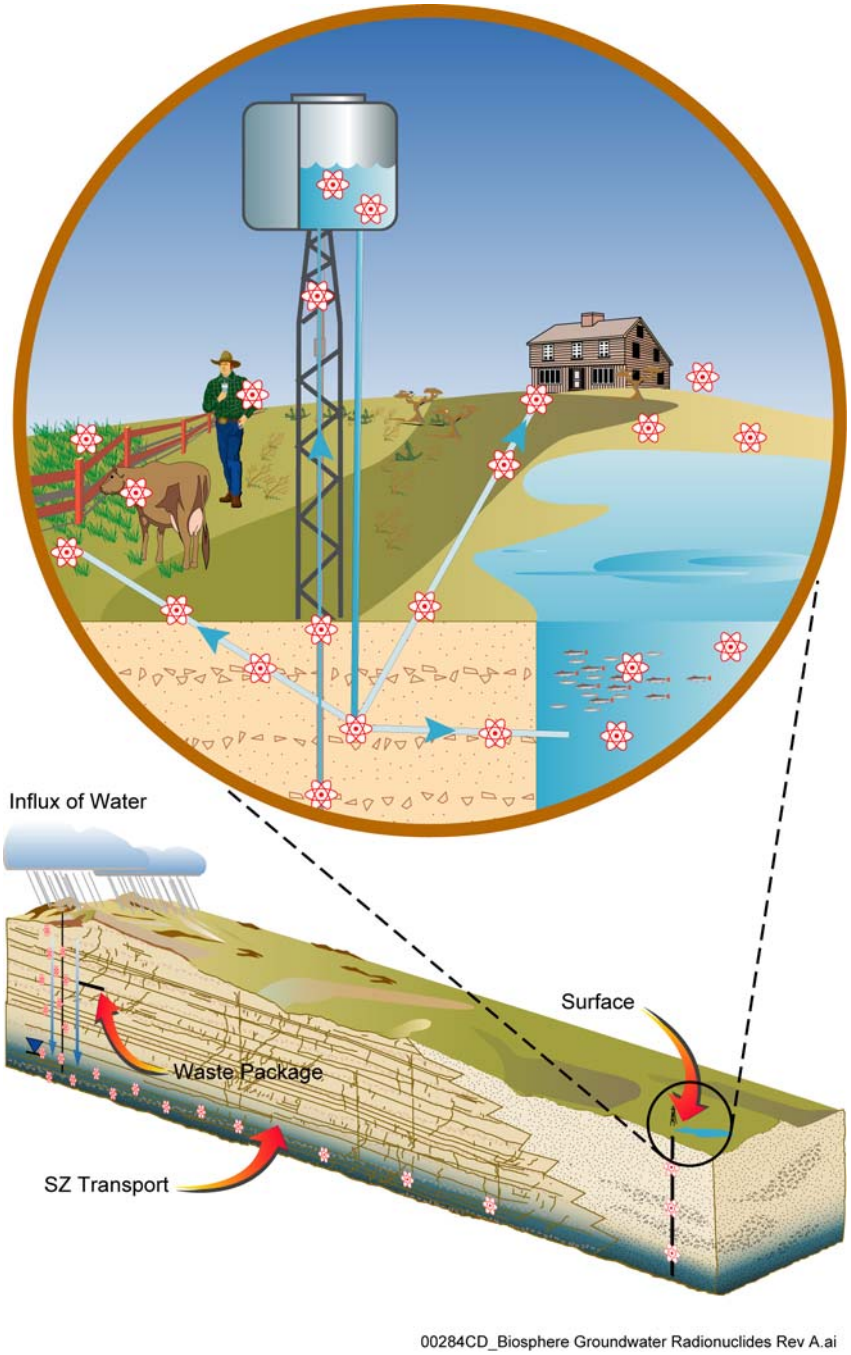
Under the groundwater exposure scenario, radionuclides would be released into the biosphere from contaminated groundwater drawn from a well. Human exposure, then, would arise when the local community, where the receptor resides, uses the contaminated water for domestic and agricultural purposes. There is no evidence to suggest the widespread use of water treatment in the Amargosa Valley, and there is only a small quasi-municipal system where a water standard could be enforced (State of Nevada 1997 [DIRS 110951]). In the model, no credit is taken for water treatment before use, and radionuclide concentrations in the well water are considered to be equal to concentrations in the groundwater, and groundwater is the source for all water needs, including drinking water, irrigation, and other domestic uses. The groundwater scenario is used to evaluate the radiological consequences of nominal performance of the geologic repository and performance under disrupted conditions (igneous intrusions and seismic events) that can lead to radionuclide releases into the groundwater (BSC 2002 [DIRS 160146], Section 4).

Environmental transport pathways are the routes by which radionuclides move from the source to the environmental media. Human exposure pathways arise when people are exposed, internally or externally, to the contaminated media (Figure 6.3-1). The environmental transport pathways, the media, and the exposure pathways are identified in the discussion of biosphere FEPs (Section 6.2). Six environmental media (water, soil, air, plants, animals, and fish) and three human exposure pathways (external exposure, inhalation, and ingestion) are considered (Table 6.3-1). These pathways are representative of a rural community and consistent with arid and semi-arid conditions.

Table 6.3-1. Exposure Pathways for the Groundwater Scenario

| Environmental Medium | Exposure Mode | Exposure Pathways | Examples of Typical Activities |
|---|---|---|---|
| Water | Ingestion | Water intake. | Drinking water and water-based beverages and water used in food preparation. |
| Soil | Ingestion | Inadvertent soil ingestion. | Recreational activities, occupational activities, gardening, fresh fruit, and consumption of fresh vegetables. |
| Soil | External | External radiation exposure. | Activities on contaminated soil. |
| Air | Inhalation | Breathing resuspended particles, gases ($^{222}Rn$ and progeny, plus $^{14}CO_2$), and aerosols from evaporative coolers. | Outdoor activities, including soil-disturbing activities related to work and recreation. Domestic activities, including sleeping. |
| Plants | Ingestion | Consumption of locally produced crops: leafy vegetables, other vegetables, fruit, and grain. | Eating contaminated crop foodstuffs. |
| Animals | Ingestion | Consumption of locally produced animal products: meat, poultry, milk, and eggs. | Eating contaminated animal product foodstuffs. |
| Fish | Ingestion | Consumption of locally produced freshwater fish. | Eating fish. |

The future climate for the region around Yucca Mountain is predicted to be cooler and wetter (USGS 2001 [DIRS 158378]) than the current climate. Climate change is incorporated into the ERMYN model by using different values for input parameters that are influenced by temperature and precipitation (Table 6.6-2). In addition, different sets of BDCFs will be calculated for the current and future climate states. A wetter climate may cause the water table to rise and discharge groundwater at springs in the Yucca Mountain area. The ERMYN model applies to the discharge of groundwater from springs if use of and exposure to water remains the same, there is no mixing of contaminated and uncontaminated water (or other processes that would cause the radionuclide concentrations to change), and there are no permanent rivers or lakes (these features would require additional pathways that are not in the ERMYN model; for example, water immersion due to swimming and external exposure due to contaminated sediments). These limitations are summarized in Section 8.2.




NOTE: SZ = saturated zone

Figure 6.3-1. Graphical Representation of the Biosphere System for the Groundwater Contamination

### 6.3.1.2 Identification of Biosphere Model Components

As defined in AP-SIII.10Q [DIRS 164074], a conceptual model is a set of hypotheses consisting of assumptions, simplifications, and idealizations that describe the essential aspects of a system, process, or phenomenon. The biosphere conceptual model provides a description of the biosphere system, the essential components, and the mechanisms of interaction between the biosphere components. It also presents a logical way to evaluate human radiation dose from exposure to radionuclides released from the repository at Yucca Mountain.

As described in Section 6.1, a biosphere system consists of the reference biosphere and a human receptor. The number of biosphere components depends on the radionuclide exposure scenario. For the groundwater scenario, there are seven biosphere components, six foodstuffs, and the human receptor:

- Water–groundwater from a well is the source of radionuclides in the biosphere.
- Soil–cultivated soil from farmland and gardens, limited to surface soil down to the tilling depth.
- Atmosphere–including outdoor air and indoor air.
- Plants–crops for humans and farm animal consumption; grown in the cultivated soil and irrigated with contaminated water.
- Animals–animal products for human consumption; raised by humans using contaminated local fodder and contaminated water.
- Fish–raised at a fish farm using contaminated groundwater.
- Human Receptor–exposed through external exposure, inhalation, and ingestion of the contaminated media listed above; for the TSPA-LA, input information for the receptor is based on the RMEI.

The aquifer, the source of groundwater, is not a part of the biosphere; it is part of the geosphere. The biosphere-geosphere interface is through the extraction of well water. The biosphere model does not include processes related to long-range atmospheric transport and dispersion of airborne radionuclides. However, the ERMYN model considers airborne activity resulting from resuspension of contaminated soil and gaseous emission of radionuclides from soil to air followed by atmospheric dilution. In the ERMYN model, radionuclides are removed from the biosphere by leaching and erosion, but these transport mechanisms do not provide radionuclide sources in any subsequent model. The ERMYN model includes radioactive decay.

### 6.3.1.3 Radionuclide Transfer Interaction Matrix

After the components of a biosphere system are defined, radionuclide transport between components is considered. A radionuclide transfer interaction matrix is constructed to identify the important processes leading to radionuclide transfer between biosphere components (Table 6.3-2). The diagonal elements in the interaction matrix represent the biosphere

components (features of the biosphere), and the off-diagonal elements represent the interactions between components (biosphere processes defined by the FEPs). By convention, the direction of interaction between components is clockwise. For example, in Table 6.3-2, the element in Row 2 and Column 4 (Element [2,4]), refers to the transfer of radionuclides from the surface soil to the plants via root uptake. Off-diagonal elements with a dash (-) indicate that interactions between the two components are not included in the ERMYN model. For all off-diagonal elements with interactions, radionuclide transfer mechanisms are discussed in the conceptual model section and evaluated quantitatively in the mathematical model section.

Table 6.3-2. Radionuclide Transfer Interaction Matrix for the Groundwater Scenario

| i,j | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| **1** | **SOURCE** (groundwater) | irrigation | evaporation | irrigation interception | ingestion of water | bio-accumulation (water use in fisheries) | drinking water ingestion |
| **2** | leaching [a] | **SURFACE SOIL** | particle resuspension, gas release, soil erosion [a] | root uptake | soil ingestion | - | soil ingestion, external exposure |
| **3** | - | dust deposit | **AIR** | dust deposition, photosynthesis | - | - | Inhalation of particulates, gases, and aerosols |
| **4** | - | weathering, harvest removal | - | **PLANTS** (crops) | ingestion of feed | - | crop ingestion |
| **5** | - | fertilization | - | - | **ANIMALS** (animal products) | - | animal product ingestion |
| **6** | - | - | - | - | - | **FISH** | fish ingestion |
| **7** | - | - | - | - | - | - | **HUMAN** (receptor) |

NOTES: [a] Leaching and soil erosion are modeled in the soil submodel only as removal mechanisms. The possibility that the removed radionuclides could become a new source is not considered.

### 6.3.1.4 Submodels for the Groundwater Scenario

To illustrate radionuclide transfer among biosphere components (Figure 6.3-2), the conceptual model is divided into seven parts matching the seven biosphere components (diagonal elements) in the interaction matrix (Table 6.3-2). The human receptor component, however, is further divided into three parts that represent the three major dose pathways. All of these parts are considered as submodels, except for groundwater, which is the radionuclide source for this

scenario. The final box in the figure, "Results: BDCF," is not considered a submodel, rather it represents the output of the biosphere model.

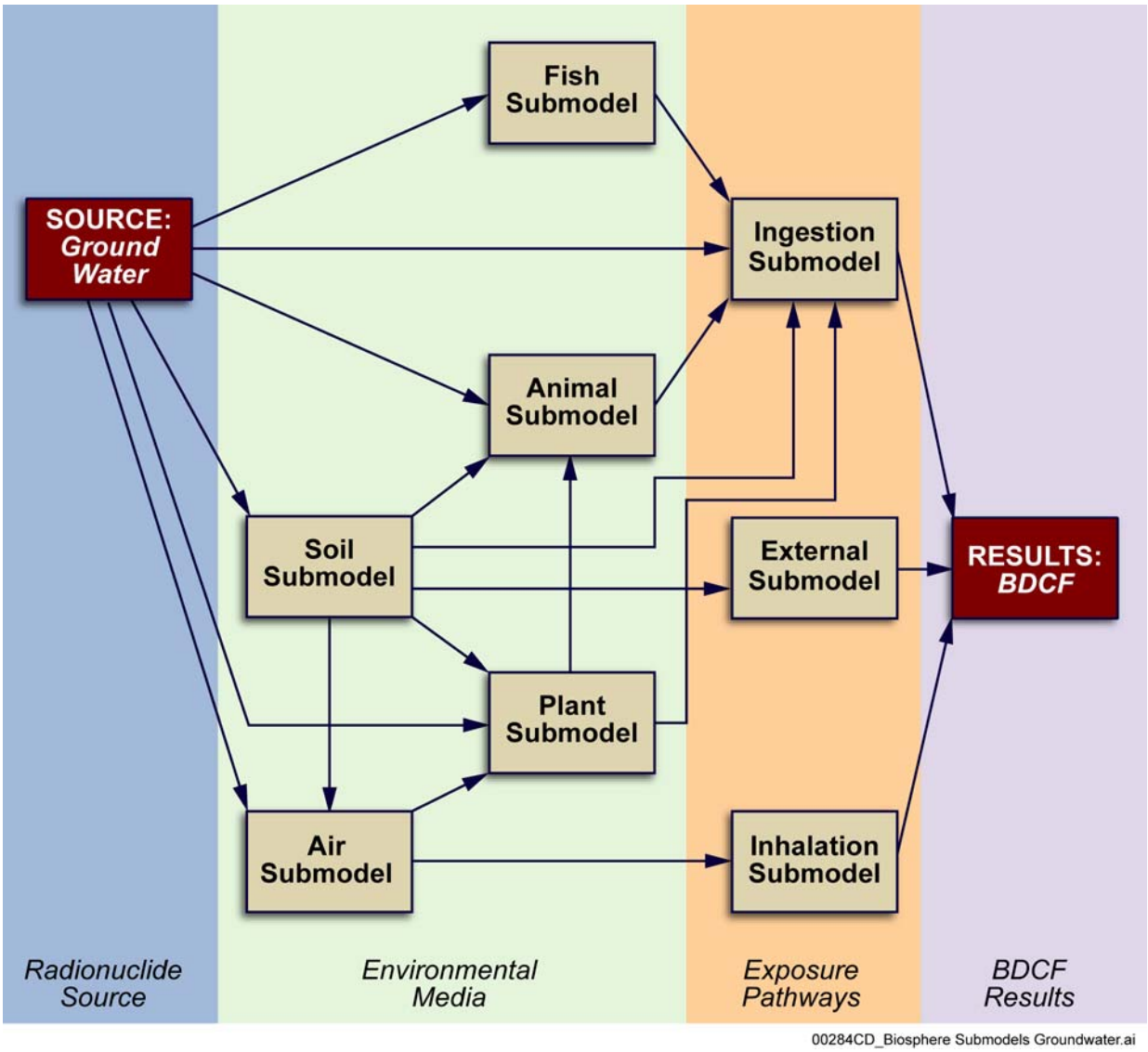



Figure 6.3-2. Relationship Among Biosphere Submodels for the Groundwater Scenario

In Figure 6.3-2, arrows point in the direction of radionuclide transfer between biosphere components in the ERMYN model. For example, groundwater is used for human drinking water (to ingestion submodel), animal drinking water (to animal submodel), irrigation water (to soil and plant submodels), fish pond water (to fish submodel), and evaporative cooler water (to air submodel).

A special submodel is used to calculate $^{14}C$ concentrations in the surface soil, air, crops, and animal products because the transfer mechanisms for this radionuclide are different from the others in the model. This special submodel is an additional submodel and is discussed separately. The direction of $^{14}C$ transfer is the same as shown in the radionuclide transfer interaction matrix (Table 6.3-2) and in the relationships among the biosphere submodels (Figure 6.3-2).

### 6.3.1.5 Description of Conceptual Model for the Groundwater Scenario

The conceptual model for the groundwater scenario includes groundwater, surface soil, air, plants, animals, fish, and the human receptor. The radionuclide transfer interaction matrix (Table 6.3-2) illustrates the radionuclide transfer mechanisms among the biosphere components. Separation of this model into nine submodels makes the conceptual and mathematical models easier to comprehend.

**Groundwater Source**–For the groundwater scenario, the source of radionuclides is water from an agricultural well ("well water" in 10 CFR 63.312 [DIRS 156605]). The agricultural well provides the interface between the geosphere and biosphere. Radionuclide concentrations in the well water are considered to equal the groundwater concentrations (Section 6.3.1.1), so the groundwater can be considered as the source of radionuclides in the biosphere model. The well is the interface between the geosphere and biosphere. To generate BDCFs with the biosphere model, the activity concentration of a radionuclide in groundwater is assumed to be constant at a predetermined concentration (e.g., 1 $Bq/m^3$; Assumption 1). The groundwater source is not considered a submodel because no radionuclide transport is modeled to or from the groundwater and it is the source term for the groundwater scenario. Two FEPs, contaminated groundwater discharge to surface within the reference biosphere (FEP 2.2.08.11.0A) and surface water transport and mixing (FEP 2.3.04.01.0A), are implicitly considered in the conceptual model for the groundwater scenario because the outcome of biosphere modeling (i.e., BDCFs) is insensitive to the source of the groundwater (e.g., well or spring) as long as the reference biosphere remains unchanged. The model is insensitive to surface water as long as the surface water contains the same concentration as the groundwater. Mixing of groundwater with uncontaminated surface water is not considered in the ERMYN model because there are no sources of uncontaminated water in the reference biosphere.

**Surface Soil Submodel**–The purpose of the surface soil submodel, or simply the soil submodel, is to calculate the radionuclide concentration in surface soil (i.e., the root zone or tilling depth). The source of radionuclides in the surface soil is contaminated groundwater used for crop irrigation (Table 6.3-2, Element [1,2]). Based on agricultural practices in Amargosa Valley, groundwater is the only source of irrigation water. Because the objective of the postclosure dose assessment is to predict the future dose from the repository, the biosphere conceptual model assumes long-term irrigation using contaminated groundwater (Assumption 3). This results in

the addition of radionuclides to cultivated lands, leading to a buildup of radionuclides in the irrigated soil. When overhead irrigation is used, radionuclides in irrigation water can be intercepted by crop leaves. However, crop weathering by wind and other mechanisms (Table 6.3-2, Element [4,2]) will displace some initially intercepted radionuclides onto the soil. Therefore, the biosphere conceptual model conservatively assumes that all radionuclides in the crop irrigation water reach the soil (Assumption 6).

Besides the groundwater source, contaminated fertilizer (animal manure and non-harvested plant residue) could contribute additional radionuclides to the surface soil (Table 6.3-2, Element [5,2]). However, over the long term (i.e., 10,000 yrs), most radioactivity incorporated into crops likely would be recycled in the form of animal manure or the non-edible parts of crops. Therefore, the addition of radionuclides to the surface soil due to contaminated fertilizer is considered to compensate for the removal of radionuclides from the surface soil due to crop harvest removal (Table 6.3-2, Element [4,2]). This assumption is justified in Section 5 (Assumption 4), and it simplifies the mathematical model.

Contaminated resuspended dust deposited on the surface of the soil is another possible radionuclide source (Table 6.3-2, Element [3,2]). However, dust deposition on the surface soil could be balanced by particle resuspension (Table 6.3-2, Element [2,3]). Thus, these two mechanisms are not numerically modeled in the surface soil submodel. Furthermore, dust could originate from non-irrigated, uncontaminated soils, such that the radioactivity in the deposited dust would be less than that in the resuspended particles. These two processes (deposition and resuspension) are associated with surface soil erosion, which is a removal mechanism in this submodel, as discussed below.

Processes in the conceptual model that result in the removal of radionuclides from the surface soil are radioactive decay, leaching to the deep soil (Table 6.3-2, Element [2,1]), surface soil wind erosion (Table 6.3-2, Element [2,3]), and the gaseous release (Table 6.3-2, Element [2,3]) of $^{222}$Rn and $^{14}$C. Some published biosphere models include crop harvest as a removal mechanism, but the ERMYN model does not, as discussed above. Radionuclides removed by leaching and wind erosion are not tracked in the ERMYN model. Contaminated surface soil could be blown from the relatively small amount of irrigated land and deposited on the relatively large amount of non-irrigated land. Because of leaching, radionuclides that infiltrate below the plant root zone could be incorporated into the deep unsaturated zone and unavailable to plants.

Because of the continuous addition of radionuclides to the surface soil with only fractional removals over long periods of time, the surface soil eventually would become saturated with radionuclides. Under equilibrium conditions, radionuclide concentrations in the surface soil would not change with time. In the ERMYN model, the soil submodel is constructed based on the assumption that equilibrium conditions already have been reached. This assumption is justified in Section 5.5 (Assumption 5), and it eliminates the need to calculate time-dependent BDCFs.

Leaching removal is a function of deep water percolation and soil characteristics, including radionuclide-specific solid-liquid partition coefficients. The initial condition is that water and soil are free of radionuclides from the repository at Yucca Mountain.

The output from the soil submodel is used in most of the remaining submodels (Figure 6.3-2) because the modeling of many environmental transport and exposure pathways depend in some way on the radionuclide concentration in surface soil.

**Air Submodel**–The air submodel is used to calculate radionuclide concentrations in the air. Inputs to the air submodel come from the surface soil submodel or directly from contaminated water. Three air contamination processes are considered: resuspension of contaminated soil particles (Table 6.3-2, Element [2,3]), generation of contaminated aerosols by evaporative coolers (Table 6.3-2, Element [1,3]), and the gaseous release of radionuclides from the soil (Table 6.3-2, Element [2,3]).

Resuspension of contaminated soil may be caused by natural forces (e.g., wind) or human activities (e.g., tilling). Radionuclide concentrations in the air depend on particle sizes, mineral composition of the soil particles, and the ability of the soil particles to sorb radionuclides. Resuspended particles deposit on crop leaves (Table 6.3-2, Element [3,4]) and directly on the soil surface (Table 6.3-2, Element [3,2]). Contaminated resuspended particles are a source of radionuclides for human inhalation (Table 6.3-2, Element [3,7]). In the submodel, contaminated resuspended particles come from the surface soil of irrigated land, although resuspended particles also could come from uncontaminated soil. The most important sources of resuspended particulates would be human dust-generating activities, such as farming (Chow et al. 1993 [DIRS 162999]; Chow 1999 [DIRS 145212]). Therefore, all resuspended particles are considered to come from contaminated soils. Resuspended particles, transported from the outdoors, are also considered in indoor environments.

The air submodel includes an enhancement factor, which accounts for differences between the activity concentration in resuspended particles and the activity concentration in the soil (resuspension source). For crop deposition, the enhancement factor is 1.0 because all resuspended particles can deposit on crop leaves, and radionuclide concentrations in airborne particles are equal to the concentrations in surface soil per unit of mass. For human inhalation, radionuclide concentrations in resuspended particles can be higher or lower than those in the surface soil and might differ among environments. Therefore, the enhancement factor is environment specific.

Some radionuclides may be released from soil to air as gasses. This mechanism is only of concern for radionuclides that are gases, produce gaseous progeny, or form gaseous compounds (e.g., $^{222}Rn$ and $^{14}C$). Radon, a decay product of $^{226}Ra$, is a radioactive gas that leads to a chain of short-lived progeny. The release of $^{222}Rn$ is considered only from accumulated radium in soil because little radon would be released directly from water (Section 6.4.2.3). Radon concentrations are considered separately for indoor and outdoor environments. Carbon-14 is released from soil as radioactive carbon dioxide gas ($^{14}CO_2$). In this form, the $^{14}CO_2$ could be taken up by plants during photosynthesis and may contribute to human inhalation exposure. Concentrations of gaseous species in the air are affected by atmospheric mixing and dilution. Gases released from the soil contribute to radionuclide concentrations in indoor and outdoor air.

Radionuclide concentrations in indoor air would be affected by the use of contaminated groundwater in evaporative coolers. Evaporative coolers work by forcing air through a wet, porous surface (i.e., a pad), resulting in the evaporation of water and the cooling of air. When

water evaporates in the coolers, some of the contaminants in the water would be released into indoor air. Radionuclide concentrations in the air would depend on the water evaporation rate, the inlet air flow rate, and the fraction of radionuclides transferred from the water to air. Air leaving the house would carry the radioactive contaminants outdoors, where they would be an unimportant contribution to the outdoor inhalation dose because of atmospheric dilution (Assumption 11).

The activity concentrations of radionuclides in the air (as particles, gases, and aerosols) are the outputs of the air submodel. These concentrations are important inputs for calculating the contribution from the inhalation pathways, and they provide inputs for the direct deposition of particles on crop leaves and carbon uptake by photosynthesis in the plant submodel (Figure 6.3-2 and Table 6.3-2).

**Plant Uptake Submodel** (i.e., the plant submodel)–The purpose of the plant submodel is to calculate radionuclide concentrations in crops consumed by humans and farm animals. The plant submodel receives input from the soil submodel, the air submodel, and directly from the contaminated water source. The mechanisms of radionuclide transfer to crops in the submodel are root uptake (Table 6.3-2, Element [2,4]), direct deposition on crop leaves from irrigation water (Table 6.3-2, Element [1,4]), and resuspended particles (Table 6.3-2, Element [3,4]).

Root uptake is modeled based on an equilibrium between radionuclide concentrations in the soil and crops. It is assumed that plant roots grow only in the surface soil compartment (Assumption 7). Direct deposition is modeled as a continuous process occurring during the crop growing time, accompanied by the continuous removal of radionuclides by weathering. Two types of direct deposition, irrigation water and resuspended particles, are considered in the submodel. The fraction of irrigation water intercepted depends on irrigation practices and plant biomass. The fraction of resuspended particles intercepted is a function of plant type and biomass. These two processes are modeled using empirical equations. The activity remaining on the crops may be translocated in whole or in part to the edible portion of the plants. Radionuclides removed from crop surfaces by weathering would be eventually incorporated into the soil surface, which is not separately tracked, as discussed in the surface soil submodel.

For the groundwater scenario (Section 6.1.3), four types of crops are considered for human consumption: leafy vegetables, other vegetables, fruit, and grain. In addition, fresh forage is considered for beef cattle and dairy cow feed. The grain used for human consumption is also considered as the only feed for poultry and laying hens. It is also assumed that fresh forage for beef cattle and dairy cows would be available year around (Assumption 8). Radionuclide concentrations would differ among crop types due to different irrigation rates, growing times, and other agricultural parameters.

The output of the plant submodel, activity concentrations of radionuclides in crops, is used as input to calculate the contribution to the human ingestion pathway from consumption of crop foodstuffs, as well as the contamination of animal products via ingestion of feed (Figure 6.3-2 and Table 6.3-2).

**Animal Uptake Submodel** (i.e., the animal submodel)–Ingestion of contaminated crops (Table 6.3-2, Element [4,5]), water (Table 6.3-2, Element [1,5]), and soil (Table 6.3-2,

Element [2,5]) may contribute to radionuclide uptake by farm animals, and the animal submodel includes these three environmental transport pathways. Radionuclide uptake by inhalation is another potential radionuclide transfer process for animals; however, this is not an important pathway (Section 7.4.5) and is excluded from the submodel.

An equilibrium approach is used to assess radionuclide concentrations in animal products, where the equilibrium is between the rate of animal activity intake and the activity concentration in an animal product. The total animal intake of radionuclides is the sum of intakes from contaminated feed, water, and soil. Four types of animal products (meat, poultry, milk, and eggs) are considered in the submodel, where meat is representative of beef, pork, and lamb; milk is representative of milk from cows and sheep; poultry is representative of chickens, turkeys, ducks, geese, and game hens; and eggs are representative of those from laying hens and ducks (Assumption 9).

The output of the submodel, radionuclide concentrations in animal products, is used as input to calculate the contribution from the consumption of animal products in the human ingestion pathways (Figure 6.3-2 and Table 6.3-2).

**Fish Submodel**–The fish submodel is used to calculate radionuclide concentrations in farm-raised fish. The ERMYN model includes fish because there is a fish farm in the Amargosa Valley, with about 15,000 catfish and bass in 1998 and 1999 (YMP 1999 [DIRS 158212], Tables 8 and 9). Radionuclide accumulation in the fish is considered to be caused exclusively by the use of contaminated water in the fishponds.

The radionuclide transfer from water to fish is through a bioaccumulation process (Table 6.3-2, Element [1,6]) that is based on equilibrium conditions between radionuclide concentrations in the water and concentrations in the edible parts of fish. This submodel may be better applied to fish in rivers, lakes, or reservoirs where fish and fish food are in equilibrium with the contaminated water. In the Amargosa Valley, fish are given commercial feed (Roe 2002 [DIRS 160674]), which is likely to be uncontaminated because it is not produced locally. Therefore, using bioaccumulation factors results in an upper bound analysis. Resuspended radioactive particles could be deposited into fishponds, but it is shown that this additional source is small compared to the contaminated water source (Section 6.4.5).

The output for the submodel, activity concentration in fish, is used to calculate the contribution of fish consumption to the human ingestion pathway (Figure 6.3-2 and Table 6.3-2).

**Carbon-14 Submodel**–The environmental transport pathways of $^{14}C$ are different from those considered for other radionuclides. While most radionuclides are in solid form, carbon can move in the environment as a gas. Moreover, stable carbon is an abundant and ubiquitous element in the environment. As for the other radionuclides, groundwater is the source of $^{14}C$, and the calculation of $^{14}C$ concentrations in the soil are based on equilibrium conditions between $^{14}C$ gains and losses from surface soil. The most important process resulting in the loss of this radionuclide from surface soil, gaseous emission, is unique to gases and is not considered for other radionuclides. After it is released into the atmosphere, $^{14}CO_2$ could be incorporated into crops via photosynthesis. The predominant transport pathway to plants is foliar uptake via stomata. The uptake of $^{14}C$ may also occur via the root system; however, root uptake plays a

smaller role than foliar uptake. Following plant uptake, $^{14}C$ may move into the animal food chain. Consumption of drinking water and soil are additional sources of $^{14}C$ intake by animals. All of these processes are incorporated into the conceptual model.

Modeling the transport of $^{14}C$ in the biosphere is carried out using a special $^{14}C$ submodel. The concentration of $^{14}C$ in air is calculated based on the steady-state concentration of $^{14}C$ in the surface soil, with the rate of loss controlled primarily by the gaseous emission loss rate of $^{14}CO_2$ from the soil. In the air, $^{14}C$ is subject to mixing due to atmospheric processes, which are modeled using air movement in a mixing cell of defined dimensions. The uptake of $^{14}C$ by biota is modeled using a specific activity approach that is based on steady state conditions between the environmental media involved, such that the ratio of $^{14}C$ to stable carbon in the environment is fixed. The specific activity approach is used to calculate $^{14}C$ concentrations in crop and animal products. The bioaccumulation of $^{14}C$ in fish is assessed using the same method as that used for other radionuclides, which is based on the ratio of concentrations between water and the edible parts of fish. After the media concentrations of $^{14}C$ are calculated, the dose assessment is carried out using the same approach as is used for other radionuclides.

**External Exposure Submodel**–The purpose of the external exposure submodel is to calculate the dose resulting from external radiation exposure, which would occur as a result of direct exposure to radiation emitted by radioactive materials outside the human body. The annual effective dose equivalent (EDE) is calculated for this pathway. For environmental dose assessments, these materials typically include soil, air, and water. The corresponding exposures are referred to as ground exposure, air submersion, and water immersion, respectively. The conceptual model considers only one of these exposure pathways: exposure to emissions from radionuclides in the soil (Table 6.3-2, Element [2,7]). The ERMYN model does not include air submersion or water immersion because they contribute relatively little to the annual dose (Section 7.4.8). Radiation sources of concern in the soil are radionuclides with gamma and high energy beta rays, which are penetrating and could deposit energy in human organs and tissues.

External exposure from other types of media (e.g., building material, furniture, and clothing; see FEP 3.3.03.01.0A) also is possible. However, few or no building materials, clothes, or other materials are produced in the Amargosa Valley using contaminated water. Furthermore, it is assumed that the size and depth of contaminated soils are infinite (Assumption 10) and residents are considered to be exposed to contaminated soil at all times while within the valley. Thus, the soil exposure time would be longer than for other contaminated media, and therefore it is reasonable to not evaluate exposures from these types of media in the ERMYN model.

This submodel considers indoor and outdoor external exposure to radionuclides in the soil. For outdoor exposures, radiation doses depend on radionuclide concentrations in the soil, the duration of exposure, and the dose coefficients that convert exposure to dose. For indoor exposures, the shielding effect of dwellings reduces the level of exposure. Although the radionuclide concentrations in the soil used as input to this submodel apply to the surface soil, the dose coefficients apply to soil contaminated to an infinite depth. This choice of dose coefficients is considered appropriate because the radiation contributing to external exposure may also originate in the deep soil contaminated due to long-term radionuclide leaching from the surface soil.

The output of the external exposure submodel, annual dose from external exposure, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-2).

**Inhalation Submodel**–The purpose of the inhalation submodel is to calculate radiation doses due to the inhalation of radionuclides. The 50-yr committed effective dose equivalent (CEDE) resulting from annual intake of radionuclides by inhalation is calculated for this pathway. Three sources of contamination are considered in this submodel: resuspended particles, gaseous emissions from the soil, and aerosols generated by evaporative coolers (Table 6.3-2, Element [3,7]). These sources are provided by the air submodel.

In addition to radionuclide concentrations in the air, inhalation doses depends on the duration of inhalation exposure, the breathing rate, and the intake-to-dose conversion factors. Human breathing rates and exposure times differ by activity, occupation, work location, and other factors related to the behavior of the receptor. To account for differences and uncertainty in those behaviors, breathing rates and exposure times differ among environments and among population groups (Section 6.4.7.1) that comprise the receptor (RMEI).

The output of the inhalation submodel, annual committed inhalation dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-2).

**Ingestion Submodel**–The ingestion submodel is used to calculate radiation doses due to the ingestion of radionuclides. The 50-yr CEDE resulting from annual intake of radionuclides by ingestion is calculated for this pathway. Inputs to the ingestion submodel are radionuclide concentrations in the groundwater (Table 6.3-2, Element [1,7]), and the outputs from the soil (Element [2,7]), plant (Element [4,7]), animal (Element [5,7]), and fish submodels (Element [6,7]).

Eleven ingestion exposure pathways are considered for the groundwater scenario, including the use of untreated, contaminated groundwater; inadvertent soil ingestion; and consumption of four types of plant foodstuffs, four types of animal products, and fish. The concentrations in these media are combined with the corresponding consumption rates and dose conversion factors and used to produce ingestion doses.

The output of the ingestion submodel, annual committed ingestion dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-2).

**BDCFs and ERMYN Model Results**–The all-pathway dose is the sum of the radionuclide-specific annual doses from the external, inhalation, and ingestion exposure pathways. The all-pathway dose is expressed in terms of the total effective dose equivalent (TEDE) from annual intake (10 CFR 63.311 [DIRS 156605]). For purposes of assessing doses to the RMEI, the TEDE is the sum of the EDE for external exposures and the CEDE for internal exposures (10 CFR 63.2 [DIRS 156605]). The BDCFs, in units of (Sv/yr)/(Bq/m$^3$), are numerically equal to the all-pathway dose from a unit activity concentration in the groundwater. The calculation of each radionuclide concentration as a function of time in the groundwater will be carried out in the TSPA-LA model, and total annual dose will be the sum of the products of the radionuclide-specific BDCFs and the time-dependent activity concentrations of radionuclides in the groundwater.

### 6.3.2 Conceptual Model for the Volcanic Ash Exposure Scenario

Similar to the groundwater scenario, the volcanic ash exposure scenario (or simply the volcanic ash scenario) is discussed in this section. The biosphere conceptual model for the volcanic ash scenario uses the same reference biosphere and human receptor as the groundwater scenario. The major difference is the radionuclide source, which is contaminated volcanic ash deposited on the surface of the ground, rather than contaminated groundwater. In this scenario, water is uncontaminated. Because the radionuclide sources are different, some of the radionuclide transfer mechanisms between biosphere components differ.

#### 6.3.2.1 Scenario Description

The volcanic ash scenario is used to evaluate the radiological consequences of a volcanic eruption at the repository, which is one of the igneous scenarios considered for the TSPA-LA (BSC 2002 [DIRS 160146], p. 50). For this scenario, volcanic ash deposited on the ground is the radionuclide source. The contaminated volcanic ash could come directly from a volcanic eruption as the initial source, or it could be resuspended and transported into the biosphere by wind (aeolian processes) or flooding (fluvial processes). These differing deposition processes are not considered in the ERMYN model. The ERMYN model is concerned with radionuclide transport in the biosphere and human exposure after the ash is deposited on the ground, regardless of the deposition process. On cultivated soils, volcanic ash would mix with surface soil and contaminate crops and animal products, which would contribute to the human ingestion dose. On non-cultivated lands, the volcanic ash could be resuspended into the air, causing human inhalation doses. The volcanic ash also may cause external exposure to humans. The ERMYN model uses a predefined (e.g., 1 $Bq/m^2$) concentration of a radionuclide deposited on the ground. A graphical representation of the volcanic ash scenario (Figure 6.3-3) shows dispersion, initial deposition, and radionuclide transfer in the biosphere.

In biosphere modeling for the TSPA-SR, volcanic eruptions are represented by three phases. The first phase, eruption and deposition, is when the ash is transported and dispersed in the atmosphere, and subsequently deposited on the ground. The second phase, a transition, is when the volcanic ash is resuspended into the air at concentrations higher than those experienced before the eruption. The last phase, a steady-state, is when particle concentrations in the air return to pre-eruption levels (CRWMS M&O 2001 [DIRS 152536]). The evolution of the post-eruption biosphere is modeled in the ERMYN through time-dependent, multi-component BDCFs that apply to both post-eruption phases.

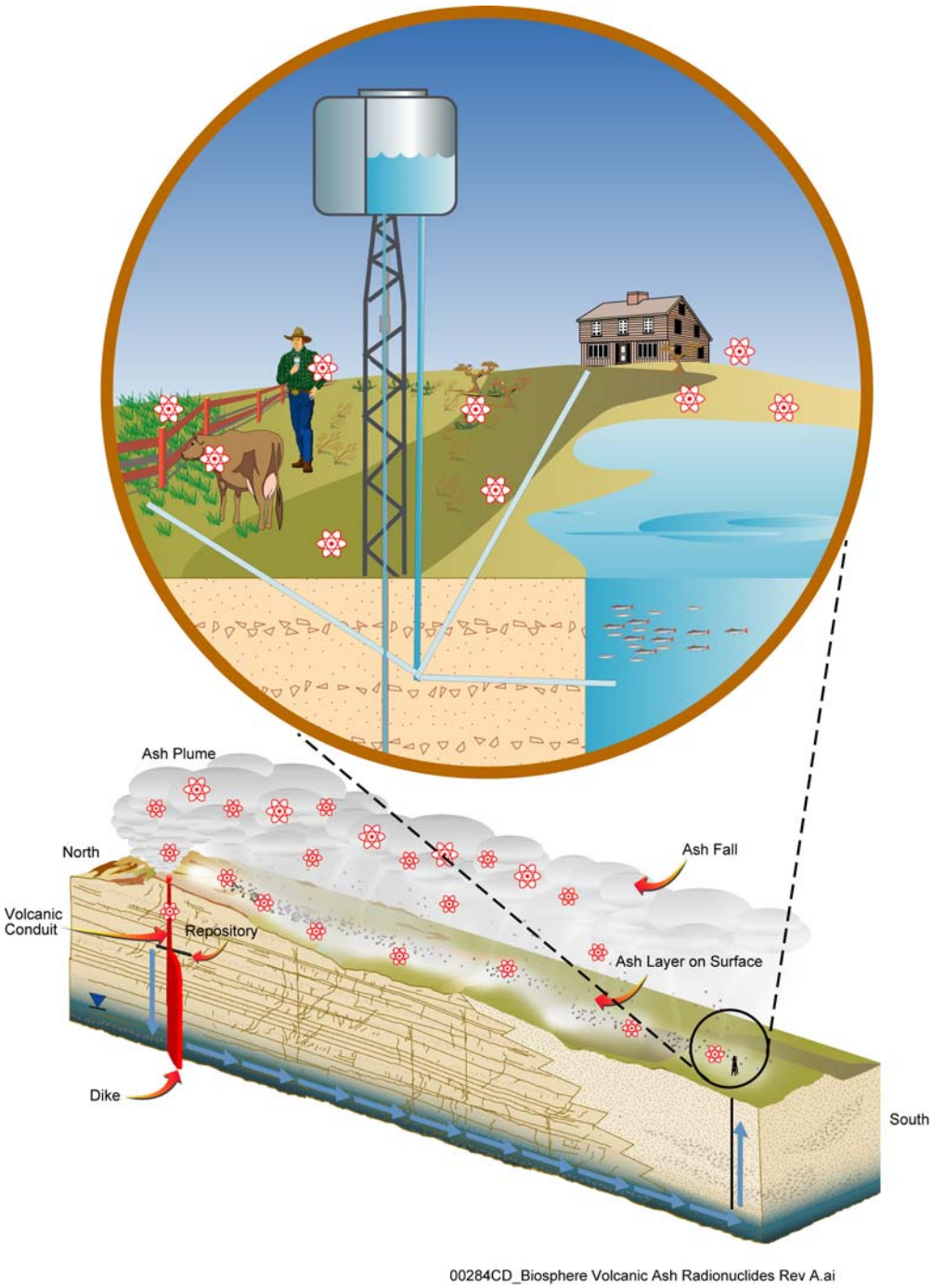



Figure 6.3-3. Representation of a Volcanic Eruption Intersecting the Repository

During the eruption phase, radiation doses to humans mainly come from inhalation. Because exposure times depend on the length of the volcanic eruption, radiation doses during the eruption phase will be calculated in the TSPA-LA using the dose factors developed in one of the biosphere analysis reports. Volcanic ash deposited on cultivated and non-cultivated land is addressed differently in the ERMYN model. For each radionuclide, the BDCF contains three factors. The first factor includes the ingestion dose (from volcanic ash deposited on cultivated land that contaminates foodstuffs) and external exposure (which does not depend on dust levels or ash thickness). The second factor includes the increased inhalation dose from the resuspension of volcanic ash from non-cultivated lands after an eruption, which is a function of time and ash thickness. This factor decreases with time after the eruption until it becomes zero. The third factor is similar to the second, except that it remains constant over time, and represents the inhalation dose after airborne particle concentrations return to pre-eruption levels.

The deposition and subsequent redistribution of volcanic ash constitute a sequence of events that are relatively limited in duration. Therefore, long-term radionuclide accumulation in surface soils would not occur, and radionuclide concentrations in the surface soil would only vary with the amount of deposited and redistributed volcanic ash. Changes in radionuclide concentrations in volcanic ash in the biosphere due to radionuclide decay, ash redistribution, and wind erosion are not considered in the ERMYN model, but they are considered in the calculation of the source term in the TSPA-LA model.

Similar to the groundwater scenario, human exposure for the volcanic ash scenario (Table 6.3-3) arises from the contamination of environmental media. These environmental media and exposure modes are identified from the biosphere FEPs (Section 6.2). Only four media (soil, air, plants, and animals) are considered to be contaminated due to ash deposition. Groundwater is not contaminated in this scenario, and therefore fish are considered to be uncontaminated. Even if contaminated ash deposits on the surface of the fish ponds, the activity is not like to be available for uptake by the fish as readily as if it were dissolved in the groundwater. In addition, inhalation is the dominant pathway under this scenario (Section 6.10), and the fish contribution is likely to be unimportant. The exposure pathways in the ERMYN model for the volcanic ash scenario are typical of an area affected by a volcano eruption, and the biosphere characteristics are consistent with arid and semi-arid conditions.

In comparison to the groundwater scenario, fewer exposure pathways are considered in the volcanic ash scenario because water is uncontaminated. Three pathways are eliminated (ingestion of drinking water, ingestion of locally produced fish, and inhalation of indoor aerosols generated by an evaporative cooler), and the inhalation of $^{14}C$ gas is not considered because $^{14}C$ is not a primary radionuclide in this scenario (Table 6.1-1). For the pathways in both scenarios, the calculation methods are similar.

Table 6.3-3. Exposure Pathways for the Volcanic Ash Scenario

| Environmental Medium | Exposure Mode | Exposure Pathways | Examples of Typical Activities |
|---|---|---|---|
| Soil | Ingestion | Inadvertent soil ingestion. | Recreational activities, occupational activities, gardening, consumption of fresh fruit and vegetables. |
| Soil | External | External radiation exposure. | Activities on or near contaminated soils. |
| Air | Inhalation | Breathing of airborne particulates; breathing of gases ($^{222}$Rn and progeny). | Outdoor activities, including soil-disturbing activities related to work and recreation. Domestic activities, including sleeping. |
| Plants | Ingestion | Consumption of locally produced crops, including leafy vegetables, other vegetables, fruit, and grain. | Eating and drinking plant materials. |
| Animals | Ingestion | Consumption of locally produced animal products, including meat, poultry, milk, and eggs. | Eating and drinking animal products. |

### 6.3.2.2 Identification of Biosphere Model Components

Based on Table 6.3-3, six biosphere components are considered in the conceptual model for the volcanic ash scenario:

- Volcanic ash–deposited on the surface of the soil (initial source of contamination)
- Soil–cultivated land (limited to the tilling depth), and uncultivated land (limited to the critical thickness of soil that could be readily resuspended)
- Atmosphere–including outdoor and indoor air
- Plants–crops for human and farm animals; irrigated with uncontaminated water
- Animals–animal products for humans consumption; raised using ash-contaminated local fodder and uncontaminated water
- Human Receptor–exposed through external exposure, inhalation, and ingestion of contaminated environmental media.

Although contaminated volcanic ash is a biosphere component, it is considered to be mixed with surface soil after initial deposition, producing a mixture of contaminated ash and soil. The atmospheric transport of contaminated volcanic ash, followed by deposition and redistribution, will be modeled in the TSPA-LA. However, the ERMYN model considers airborne activity resulting from the resuspension of contaminated ash (or the ash-soil mixture) and gaseous emission of relevant radionuclides from ash (or the ash-soil mixture).

### 6.3.2.3 Radionuclide Transfer Interaction Matrix

The radionuclide transfer interaction matrix (Table 6.3-4) for the volcanic ash scenario is constructed based on the identified biosphere components, radionuclide transfer between the components, and the included FEPs (Section 6.2). An explanation of the interaction matrix concept and notation is presented in Section 6.3.1.3.

The first diagonal element is the radionuclide source, volcanic ash. Because groundwater is considered to be uncontaminated, the element for fish is not considered in the matrix, and there are no intersections of Column 6 with any row in the matrix (Column 6 is retained in the matrix to maintain consistency with Table 6.3-2). All major exposure pathways are considered, including ingestion of contaminated crops and animal products, inhalation of a contaminated ash-soil mixture, and external exposure from contaminated ash on the ground.

Table 6.3-4. Radionuclide Transfer Interaction Matrix for the Volcanic Ash Scenario

| (i, j) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 | **SOURCE** (volcanic ash) | ashfall | - | - | - | - | - |
| 2 | - | **SURFACE SOIL** (ash or ash-soil mixture) | particle resuspension, gas release | root uptake | soil ingestion | - | soil ingestion, ground exposure |
| 3 | - | particle deposition | **AIR** | particle deposition | - | - | inhalation of particulates and gas |
| 4 | - | weathering, harvest removal | - | **PLANTS** (crops) | feed ingestion | - | crop ingestion |
| 5 | - | fertilization | - | - | **ANIMALS** (animal products) | - | animal product ingestion |
| 6 | - | - | - | - | - | **FISH** | **-** |
| 7 | - | - | - | - | - | **-** | **HUMAN** (receptor) |

### 6.3.2.4 Submodels for the Volcanic Ash Scenario

To understand radionuclide transport among biosphere components (Figure 6.3-4), the biosphere conceptual model is divided into the six parts that are consistent with the components in the interaction matrix (Table 6.3-4). Considering the human receptor component to be composed of three parts, there are eight parts considered. Relationships among these parts or submodels (Figure 6.3-4) show important mechanisms of radionuclide migration from the source through the media to the human receptor. The BDCF box (Figure 6.3-4) is not considered a submodel, rather it represents the results of the ERMYN model.

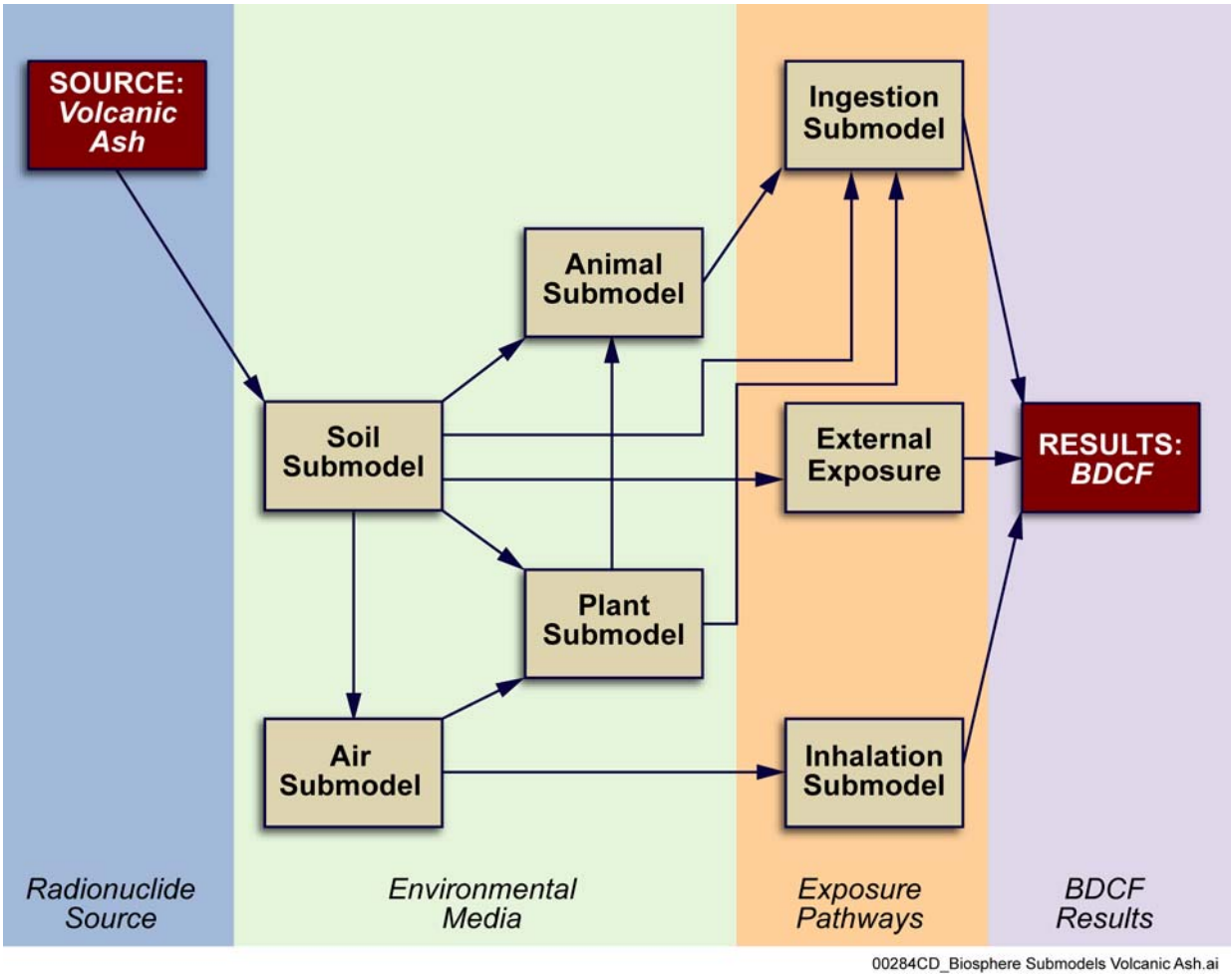



Figure 6.3-4. Relationship between the Biosphere Submodels for the Volcanic Ash Scenario

### 6.3.2.5 Description of Conceptual Model for the Volcanic Ash Scenario

The biosphere conceptual model for the volcanic ash scenario is based on the radionuclide transfer interaction matrix (Table 6.3-4). Because many radionuclide transfer mechanisms are the same in the groundwater and volcanic ash scenarios, the submodels are similar. The following description of the volcanic ash conceptual model focuses on the differences between the two scenarios.

**Volcanic Ash Source**–Volcanic ash deposited on the ground is the source of radionuclides for the volcanic ash scenario. In the biosphere model, activity concentrations of radionuclides in the deposited ash are defined as a constant in units of $Bq/m^2$. The source, ash, is not considered a submodel because it is an input to the biosphere model.

**Surface Soil Submodel**–The surface soil submodel converts the volcanic ash source from areal radionuclide concentrations ($Bq/m^2$) to radionuclide concentrations in a mass of ash (or the ash-soil mixture; Bq/kg) on the ground. Because of different soil-mixing mechanisms on cultivated and non-cultivated lands, and because of the different contributions to human radiation exposure, the consequences of volcanic ash deposition are calculated differently for these two areas. When deposited on cultivated land (Table 6.3-4, Element [1,2]), volcanic ash would be mixed with surface soil due to plowing and irrigation (Element [2,1]). When deposited on non-cultivated land, ash would be mixed with native soil and windblown dust if the layer is thin, or it would remain undiluted if the layer is thick (Assumption 12).

On cultivated lands, ash would mix with surface soils and lose the characteristics of the original ash (e.g., ash density) because there would be a small amount of ash compared with a large amount of surface soil. In the submodel, the ash-soil mixture is treated as regular soil except that it is contaminated. The contaminated soil is the source of contamination for crops and animal products, and it is the source for inadvertent soil ingestion because soil ingestion by humans likely would be from consuming crops, particularly those that would be unwashed.

On non-cultivated lands, ash would not readily mix with surface soil because the land would not be tilled and irrigated and because the low amount of precipitation would limit downward migration of radionuclide through the soil profile. If the ash layer is thin, resuspension and subsequent redeposition could mix the volcanic ash and surface soil particles. To characterize this type of mixing, a critical thickness (a hypothetical layer of soil from which soil particles would be more readily resuspended) must be considered. If the deposited ash thickness is thinner than the critical thickness, the ash would mix with the top layer of host soil, but the ash characteristics are assumed to remain unchanged even when mixing with the host soil particles occurs (Assumption 12). If the deposited layer of ash is greater than the critical thickness, this type of mixing will not occur, as all resuspended particles would originate, at least initially, from the top layer of original ash. Therefore, to convert the volcanic ash source term from areal radionuclide concentration ($Bq/m^2$) to mass radionuclide concentration in ash (or its soil mixture; Bq/kg), the thickness of the deposited ash is required. The converted radionuclide concentrations of ash (or the ash-soil mixture) are used to calculate radionuclide concentrations in the air. This is the source of radionuclide resuspension used for human inhalation.

As discussed for the groundwater scenario, some radionuclide transfer mechanisms, including harvest removal, fertilization, and crop weathering, are implicitly considered in the surface soil submodel. Other removal mechanisms (including radionuclide decay, leaching from surface soils, and wind erosion) are incorporated to track changes in the source term, rather than as radionuclide transfer in the biosphere (Section 6.3.2.2). Unlike the groundwater scenario, where soil contamination could be deep, volcanic ash deposition would be relatively shallow. Thus, the source for any external exposure is considered to be contained in a thin layer on the top of the ground (Assumption 16).

There are several outputs from this submodel. The activity concentration of radionuclides on cultivated lands is used to calculate the contamination of crops and animal products, and it is used to calculate the activity intake from inadvertent soil ingestion. The activity concentrations on non-cultivated lands are used to calculate the contamination in the air, which contributes to human inhalation. The surface concentration of radionuclides is used to calculate external exposure. The relationships among these submodels are shown in Figure 6.3-4.

**Air Submodel**–The purpose of the air submodel is to calculate radionuclide concentrations in the air from the resuspension of contaminated ash-soil particles and from the gaseous release of $^{222}$Rn from deposited volcanic ash (Table 6.3-4, Element [2,3]). Because there would be relatively little cultivated land compared with the total amount of the ash-contaminated land, it is assumed that human inhalation dose comes only from non-cultivated land (Assumption 13). Soil resuspended from cultivated land is the source of contaminated soil particles for deposition on plants.

An elevated concentration of airborne particulates (mass loading) is expected after a volcanic eruption (BSC 2003 [DIRS 160965], Section 6.2), but mass loading would decrease with time (Assumption 14) because the ash eventually would settle onto the ground and mix with surface soil. Some human activities cause elevated mass loading relative to average levels (BSC 2003 [DIRS 160965], Sections 6.1.1 and 6.2.1). Therefore, mass loading is related to human activity, similar to that for the groundwater scenario. Radon gas released from deposited ash is considered, but the evaluation of $^{222}$Rn concentrations in the air is simplified by using a radon release factor from $^{226}$Ra contaminated ground (Assumption 15).

The output of the submodel, the activity concentrations of radionuclides in the air, is used for calculating the radionuclide intake by inhalation of contaminated air and the direct deposition of ash on plant surfaces (Figure 6.3-4).

**Plant Submodel**–The purpose of the plant submodel is to calculate radionuclide concentrations in various crops that would be consumed by humans and farm animals. Crop contamination is assumed to come from cultivated land where deposited volcanic ash and surface soil are uniformly mixed (Assumption 12). Two mechanisms cause the contamination of crops: plant root uptake due to contaminated surface soil (Table 6.3-4, Element [2,4]) and direct deposition on plants of airborne particulates (Element [3,4]).

Except for the absence of direct deposition of irrigation water on crop leaves, radionuclide transfer mechanisms from soil to plants and from particulates to plants are the same as those used in the groundwater scenario. The crop types also are the same in both scenarios.

Output from the submodel, activity concentrations of radionuclides in crops, is used as input to calculate radionuclide intake by ingestion of contaminated crops and to calculate the contamination of animal products (Figure 6.3-4 and Table 6.3-4).

**Animal Submodel**–The purpose of the animal submodel is to calculate radionuclide concentrations in animal products using two radionuclide transfer mechanisms for animal products: ingestion of contaminated soil (Table 6.3-4, Element [2,5]) and feed (Element [4,5]).

Except for removing the transfer mechanism for ingesting contaminated water, other submodel treatments (including animal product types and equilibrium conditions) are the same as those in the groundwater scenario. The output of the submodel, the activity concentration of radionuclides in animal products, is used to calculate radionuclide intake by ingestion of contaminated animal products (Figure 6.3-4).

**External Exposure Submodel**–The purpose of the external exposure submodel is to calculate human radiation exposure from contaminated volcanic ash deposited on the surface of the ground (Table 6.3-4, Element [2,7]). The annual EDE is calculated for this pathway. As discussed for the surface soil submodel, the ash deposit is anticipated to be relatively shallow. It is assumed that all radionuclides will stay on the ground surface (Assumption 16), and external exposure does not depend on the thickness of the ash. As in the groundwater scenario, air submersion and other external exposures from contaminated media are not considered in the submodel because they contribute relatively little to the overall external dose to the human receptor, as shown in Section 7.4.8.

The evaluation method for doses from external exposure to radionuclides on the surface of the ground are similar to the external exposure submodel used in the groundwater scenario, except that the surface source and the dose coefficients are different. The output of the submodel, annual doses from external exposure, contribute to the all-pathway dose, which is then used to calculate BDCFs.

**Inhalation Submodel**–The purpose of the inhalation submodel is to calculate human radiation doses due to the inhalation of radionuclides. Due to increased mass loading after a volcanic eruption, emphasis is placed on evaluating the inhalation pathway associated with breathing resuspended volcanic ash. The 50-yr CEDE resulting from annual intake of radionuclides by inhalation is calculated for this pathway. Two types of contaminated sources are considered to cause human inhalation dose: contaminated resuspended particulates and radon gas (Table 6.3-4, Element [3,7]).

To account for variation in ash thickness (discussed in the soil submodel) and changes in mass loading over time (discussed for the air submodel), the inhalation dose depends on the thickness of the ash and changes over time as dust levels decrease. These functions of time and ash thickness will be carried into the TSPA-LA model. Similar to the inhalation submodel for the groundwater scenario, the inhalation dose depends on airborne concentrations, breathing rates, and exposure time. Breathing rates and exposure times are related to human activities, and exposure time varies among population groups (Section 6.4.7.1). These parameters are linked to human activities and population groups to incorporate uncertainty from those parameters into the submodel.

The output of the inhalation submodel, annual inhalation dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-4).

**Ingestion Submodel**–The purpose of the ingestion submodel is to calculate the radiation dose from ingestion of radionuclides. The 50-yr CEDE resulting from annual intake of radionuclides by ingestion is calculated for this pathway. The ingestion submodel includes eight contaminated foodstuffs: four types of plants (leafy vegetables, other vegetables, fruit, and grain) (Table 6.3-4,

Element [4,7]) and four types of animal products (meat, poultry, milk, and eggs) (Element [5,7]), plus inadvertent soil ingestion (Element [2,7]). Inputs to this submodel are the radionuclide concentrations in foodstuffs and the soil.

These media concentrations, when combined with the corresponding consumption rates and dose conversion factors, are used to produce ingestion doses. The output of the ingestion submodel, annual ingestion dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-4).

**BDCFs and ERMYN Model Results**–The all-pathway dose is the sum of the radionuclide-specific annual doses from the external, inhalation, and ingestion exposure pathways. The all-pathway dose is expressed in terms of TEDE. The BDCFs (Sv/yr)/(Bq/$m^2$) are numerically equal to the all-pathway dose from a unit activity concentration in the deposited volcanic ash. The calculation of radionuclide concentrations in volcanic ash will be carried out in the TSPA-LA model. The total dose calculated in the TSPA-LA model will be the sum of the products of the radionuclide-specific BDCFs, considering changes in mass loading with time and the deposited ash thickness, and the time-dependent activity concentrations of radionuclides in the volcanic ash for all of the radionuclides in the TSPA-LA model.

### 6.3.3 Alternative Conceptual Models

Performance assessment for a repository at Yucca Mountain must consider ACMs of features and processes that are consistent with available data and current scientific understanding, and they must evaluate the effects that ACMs have on the performance of the geologic repository (10 CFR 63.114(c) [DIRS 156605]). From the guidelines for the treatment of ACMs in the TSPA-LA (BSC 2002 [DIRS 158592], Section 2), a conceptual model can only be alternative if it:

- Differs in important ways from the selected conceptual model
- Is consistent with available data and current scientific understanding
- Is reasonable, which has been interpreted as implying that there is some precedent for the alternative, such as prior use by other analysts, and that there is a physical basis for the alternative.

Based on this definition of an ACM, there are no alternative groundwater or volcanic ash conceptual models applicable to the entire reference biosphere. However, there are ACMs for submodels and components. This section identifies ACMs from published biosphere models that differ from the corresponding submodel or parts of submodel in the ERMYN model (Table 6.3-5). These ACMs are screened and evaluated qualitatively and quantitatively, and mathematical representations of these ACMs are presented and compared with the calculations used in the validation of ERMYN model (Section 7.3). Finally, numerical comparisons between the ACMs and the ERMYN model are performed, and justifications are provided for why ACMs are not selected (Section 7.4).

The ACMs come from five published biosphere models with corresponding submodels or parts of submodels that are compared with the ERMYN model (Section 7.1.2). These published biosphere models are GENII/GENII-S (Napier et al. 1988 [DIRS 157927]; Leigh et al. 1993 [DIRS 100464]), BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522]), RESRAD (Yu et al. 2001 [DIRS 159465]), EPRI-YM (Smith et al. 1996 [DIRS 101085]), and NCRP-129 (NCRP 1999 [DIRS 155894]). To be considered as an ACM, submodels or parts of submodels must be conceptually or mathematically different from those in the ERMYN model. Mathematical simplifications or different treatments, such as numerical or analytical methods, are not considered to be ACMs. Brief descriptions of the seven identified ACMs are presented below and summarized in Table 6.3-5.

**ACM 1, Radon Release from Soil** (Air Submodel)–The selected conceptual model for radon is based on a radon release factor from radium contaminated soil. An ACM relies on modeling radon transport in the soil and the atmosphere (Yu et al. 2001 [DIRS 159465]). A numerical comparison between the selected model and the ACM shows that the $^{222}$Rn concentrations are comparable (Section 7.4.3). Because the ACM required more input data, it is not selected.

**ACM 2, Evaporative Cooler** (Air Submodel)–The selected conceptual model for evaporative coolers is based on evenly evaporating contaminated water into the airflow of an evaporative cooler. An ACM calculates radionuclide concentrations based on evaporation and differences in humidity. An evaluation of these two methods shows that they produce equivalent results (Section 7.4.3).

**ACM 3, Direct Deposition of Irrigated Water** (Plant Submodel)–The ERMYN model considers radionuclides in irrigation water to be directly translocated into edible plant parts with accumulation and weathering occurring during the growing period. This conceptual model is also used in published biosphere models (e.g., GENII-S and RESRAD). An ACM presented in BIOMASS ERB2A considers two processes, movement of deposited radionuclides from external plant surfaces into the plant tissues, and movement of radionuclides from plant tissues into edible parts of the crop. This ACM applies weathering to contaminants that remain on external plant surfaces, and food-processing losses are considered. This ACM may be conceptually more realistic than simulating radionuclide transfers directly from water to edible portions of the plants, but it is not commonly used because the input data typically are not available. The two models are evaluated using the same input values, or using default data used in BIOMASS ERB2A (Sections 7.4.4). This ACM and the approach used in the ERMYN model produce comparable results for reasonable input values.

**ACM 4, Direct Deposition of Airborne Particulates** (Plant Submodel)–In the ERMYN model, resuspended soil deposited on crop leaves is treated in the same manner as intercepted irrigation water. Other published biosphere models take a different approach. An ACM is based on a contamination factor for the external contamination of crops, which is similar to a soil-to-plant transfer factor. Differences between the ERMYN model and the ACM are evaluated (Section 7.4.4) using the same input values when the parameters are comparable or using default data from the published ACM. The evaluation shows that the ERMYN model and the ACM approaches produce comparable results for reasonable input values.

**ACM 5, Animal Product Contamination** (Animal Submodel)–The ERMYN model considers animal contamination resulting from the consumption of contaminated water, soil, and feed. The GENII-S model only includes the consumption of water and feed, and the BIOMASS ERB2A model includes an additional pathway, inhalation of contaminated air by animals. These animal transport pathways are compared to determine their relative importance (Section 7.4.5). Soil ingestion is an important contributor to the total activity concentration in meat and therefore is included in the ERMYN model. The inhalation of contaminated dust contributes little to concentrations in meat, and therefore it is not included.

**ACM 6, Carbon-14 Special Submodel** ($^{14}C$ Submodel)–The ERMYN $^{14}C$ conceptual submodel is based on experimental results (Yu et al. 2001 [DIRS 159465], Section L) and concerns the release of $^{14}CO_2$ gas from soil. The ERMYN considers external exposure, inhalation of $^{14}CO_2$ gas, and soil ingestion pathways, and includes the uptake of $^{14}CO_2$ gas into plants during photosynthesis. An ACM in GENII-S only considers the uptake of $^{14}C$ by roots. The two submodels are compared to evaluate any differences (Section 7.4.7). BIOMASS ERB2A presents another $^{14}C$ ACM, but it requires input parameters that are not available. The mathematical representations are compared (Section 7.3.6), but numerical comparisons are not conducted because of the lack of appropriate input values. The GENII-S ACM is not used because the ERMYN $^{14}C$ special submodel is more realistic and results in higher $^{14}C$ concentrations in plants (Section 7.4.7).

**ACM 7, Environment-Specific Inhalation Submodel** (Inhalation Submodel)–In the ERMYN model, inhalation exposure is considered to be a function of environment and human activity because many model parameters (e.g., mass loading, breathing rate, and exposure time) are related to human activities. Similar models, called microenvironmental models, have been used to assess exposure to particulate matter and other contaminants (Duan 1982 [DIRS 162466]; Klepeis 1999 [DIRS 160094]; Mage 1985 [DIRS 162465]). The previous biosphere model and all of the compared biosphere models use average values for these input parameters (Section 7.3.8). An evaluation (Section 7.4.9) numerically compares the ERMYN method with those in the other models. The approaches produce comparable results for reasonable model input values. The environment-specific approach is used in the ERMYN model because uncertainty associated with the input parameters can be considered.

Table 6.3-5. Alternative Conceptual Models Considered

| Alternative Conceptual Model | Overview | Screening Assessment and Basis |
|---|---|---|
| Radon release from soil (Air Submodel) | This ACM considers radon transport in the soil and the atmosphere, which requires more input data. The ERMYN model does not include these processes and uses a simple release factor. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.3.1) showing that the ACM and the ERMYN model produce comparable results. |
| Evaporative cooler (Air Submodel) | This ACM considers an inhalation dose from aerosols generated from evaporative coolers and is based on calculating radionuclide concentrations in the air due to an increase in humidity. The ERMYN model uses a submodel based on the amount of water evaporated rather than an increase in humidity. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.3.2) showing that this ACM and the ERMYN model produce equivalent results. |
| Direct deposition of irrigated water (Plant Submodel) | This ACM considers two processes, one where the deposited radionuclide move from external plant surfaces into the plant tissues, and then from plant tissues into the edible portion of the crop. Weathering is applied only to contaminants that remain on external plant surfaces. Food processing loss is also considered in the ACM. The ERMYN model conceptual model considers the radionuclides in irrigation water to be directly translocated to the edible parts of plants with weathering and accumulation during the growing period, but without food preparation loss. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.4.1) showing that this ACM and the ERMYN model produce comparable results. |
| Direct deposition of airborne particulates (Plant Submodel) | This ACM is based on the crop external contamination. This contamination factor is very similar to a soil-to-plant transfer factor. The ERMYN model conceptual model considers the deposited airborne particles on crop leaves acting the same way as the intercepted irrigation water. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.4.3) showing that this ACM and the ERMYN model produce comparable results for reasonable input values. |
| Animal product contamination (Animal Submodel) | Two pathways are considered in this ACM. They are animal inhalation of contaminated air and animal soil ingestion. The ERMYN conceptual model excludes the inhalation of contaminated air, but it includes animal soil ingestion. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.5) showing that soil ingestion is important but that inhalation of contaminated air is not. |
| $^{14}C$ special submodel ($^{14}C$ Special Submodel) | This ACM considered root uptake only. The ERMYN model includes external exposure, inhalation of $^{14}C$ gas, soil ingestion pathways, and $^{14}C$ transfer into plants through photosynthesis. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.7) showing that the selected $^{14}C$ special submodel considers more processes of $^{14}C$ contamination in plants than this ACM, which results in a higher $^{14}C$ concentration in plants. |
| Environment-specific inhalation submodel (Inhalation Submodel) | This ACM uses average values of input parameters for inhalation exposure. ERMYN model considers inhalation exposure as a function of the environment because many model parameters, such as mass loading, breathing rate and exposure time, differ among environments and activities. | This ACM is screened from the biosphere model based on an analysis (Section 7.4.9) showing that the ACM and the ERMYN model produce comparable results. In addition, it is easier to address uncertainty in the input parameters using environment-specific values. |

### 6.3.4 FEPs Considered in the Biosphere Conceptual Model

The radionuclide transfer interaction matrixes, Table 6.3-2 for the groundwater scenario and Table 6.3-4 for the volcanic ash scenario, also serve as a tool to map the included FEPs into the biosphere submodels. To document that the conceptual models address all included FEPs, Table 6.3-6 provides a list of the included FEPs, shows where each FEP is mapped in the interaction matrixes, and lists the submodels where each FEP is addressed. The disposition of these FEPs in the biosphere mathematical model, submodels, and associated equations and parameters is discussed in Section 6.7.1.

Table 6.3-6. FEPs Considered in the Biosphere Conceptual Model

| LA FEP Number | FEP Name | Matrix for Groundwater [a] | Matrix for Volcanic Ash [b] | Biosphere Submodels [c] |
|---|---|---|---|---|
| 1.2.04.07.0A | Ashfall | - | (1,1) (1,2) | Soil, Air |
| 1.3.01.00.0A | Climate change, global | (2,2) (4,4) (6,6) (3,7) | (4,4) | Soil, Plant, Fish, $^{14}C$, Inhalation |
| 1.4.07.01.0A | Water management activities | (1,4) (1,6) | - | Plant, Fish |
| 1.4.07.02.0A | Wells | (1,1) | - | Soil, Air, Plant, Animal, Fish, Ingestion |
| 2.2.08.11.0A | Groundwater discharge to surface at or near receptor location | (1,1) | - | Soil, Air, Plant, Animal, Fish, Ingestion |
| 2.3.02.01.0A | Soil type | (2,2) (4,4) | (2,2) (4,4) | Soil, Plant, $^{14}C$ |
| 2.3.02.02.0A | Radionuclide accumulation in soils | (1,2) (2,1) (2,2) (3,2) (4,2) (5,2) | (4,2) (5,2) | Soil |
| 2.3.02.03.0A | Soil and sediment transport in the biosphere | (2,3) (3,2) | (2,3) (3,2) | Soil, Air |
| 2.3.04.01.0A | Surface water transport and mixing | (1,1) | - | Soil, Air, Plant, Animal, Fish, Ingestion |
| 2.3.11.01.0A | Precipitation | (2,2) (4,4) | - | Soil, Plant, $^{14}C$ |
| 2.3.11.02.0A | Surface runoff and flooding | (2,2) | - | Soil |
| 2.3.13.01.0A | Biosphere characteristics | (2,2) (3,3) (4,4) (6,6) (3,7) | (2,2) (3,3) (4,4) | Soil, Air, Plant, Fish, $^{14}C$, Inhalation |
| 2.4.01.00.0A | Human characteristics (physiology, metabolism) | (7,7) | (7,7) | External exposure, Inhalation, Ingestion |
| 2.4.04.01.0A | Human lifestyle | (7,7) | (7,7) | External exposure, Inhalation, Ingestion |
| 2.4.07.00.0A | Dwellings | (1,3) (2,7) (3,7) | (2,7) (3,7) | Air, External exposure, Inhalation |
| 2.4.08.00.0A | Wild and natural land and water use | (5,5) (2,7) (5,7) | - | Air, External exposure, Ingestion |
| 2.4.09.01.0B | Agricultural land use and irrigation | (2,2) (3,3) (4,4) (5,5) (6,6) | (2,2) (3,3) (4,4) (5,5) | Soil, Air, Plant, Animal, $^{14}C$, Fish |
| 2.4.09.02.0A | Animal farms and fisheries | (5,5) (6,6) | (5,5) | Animal, Fish |
| 2.4.10.00.0A | Urban and industrial land and water use | (2,7) | (2,7) | Soil, Air, $^{14}C$, External exposure, Inhalation |
| 3.1.01.01.0A | Radioactive Decay and In-growth | All [d] | All [d] | Soil, Air, Plant, Animal, External exposure, Inhalation, Ingestion |
| 3.2.10.00.0A | Atmospheric transport of contaminants | (1,3) (2,3) | (2,3) | Air, $^{14}C$ |
| 3.3.01.00.0A | Contaminated drinking water, foodstuffs, and drugs | (4,4) (5,5) (6,6) | (4,4) (5,5) | Plant, Animal, Fish, Ingestion |

Table 6.3-6. FEPs Considered in the Biosphere Conceptual Model (continued)

| LA FEP Number | FEP Name | Matrix for Groundwater [a] | Matrix for Volcanic Ash [b] | Biosphere Submodels [c] |
|---|---|---|---|---|
| 3.3.02.01.0A | Plant uptake | (1,4) (2,4) (3,4) | (2,4) (3,4) | Plant, $^{14}C$ |
| 3.3.02.02.0A | Animal uptake | (1,5) (2,5) (4,5) | (2,5) (5,5) | Animal, $^{14}C$ |
| 3.3.02.03.0A | Bioaccumulation | (1,6) | - | Fish |
| 3.3.03.01.0A | Contaminated non-food products and exposure | (2,7) | (2,7) | External Exposure |
| 3.3.04.01.0A | Ingestion | (1,7) (2,7) (4,7) (5,7) (6,7) | (2,7) (4,7) (5,7) | Ingestion |
| 3.3.04.02.0A | Inhalation | (3,7) | (3,7) | Inhalation |
| 3.3.04.03.0A | External exposure | (2,7) | (2,7) | External exposure |
| 3.3.05.01.0A | Radiation doses | (1,7) (2,7) (3,7) (4,7) (5,7) (6,7) | (2,7) (3,7) (4,7) (5,7) | External exposure, Inhalation, Ingestion |
| 3.3.08.00.0A | Radon and radon daughter exposure | (2,3) (3,7) | (2,3) (3,7) | Air, Inhalation |

Source: The LA FEP list (DTN: MO0303SEPFEPS2.000 [DIRS 162452]) is the source of FEPs for the biosphere model.

NOTES:

[a] Elements of the radionuclide transfer interaction matrix for the groundwater scenario shown in Table 6.3-2. Index "i" in (i,j) indicates the row in the matrix, while index "j" in (i,j) indicates the column in the matrix. The linkage between the elements in the matrix and FEPs is based on the biosphere model and the FEP description.

[b] Elements of the radionuclide transfer interaction matrix for the volcanic ash scenario shown in Table 6.3-4. Index "i" in (i,j) indicates the row in the matrix, while index "j" in (i,j) indicates the column in the matrix.

[c] Relationships among the submodels are shown in Figures 6.3-2 and 6.3-4.

[d] "All" means that radionuclide decay is considered in the all radionuclide transport in environment media and all human exposure pathways.

### 6.3.5 Radionuclide Decay and Ingrowth

The TSPA-LA will be conducted for the suite of radionuclides identified as important contributors to the total dose from radionuclides released from the repository at Yucca Mountain (BSC 2002 [DIRS 160059], Section 7). Consistent with the TSPA-LA, the ERMYN model considers the same suite of primary radionuclides (Section 6.1.3). The primary radionuclides are long-lived and are accompanied by short-lived decay products, which are included in the ERMYN model to correctly account for the radiological consequences of the decay chains.

Radionuclides with high atomic numbers (≥ 82) typically have long chains of radioactive decay products. The consideration of radionuclide decay and ingrowth as a function of time for all members of a decay chain, although conceptually simple, can be computationally intensive and frequently adds little value to analyses that only consider long-lived radionuclides. Therefore, in the ERMYN model, radionuclides with half-lives less than 180 d are treated as if they were always in secular equilibrium with the parent radionuclides (Assumption 2). The secular equilibrium of the parent and progeny applies to the entire biosphere system.

This assumption eliminates the need to consider long decay chains from radionuclides with high atomic numbers. This assumption is reasonable, considering the long time frame of the TSPA modeling. This approach also does not underestimate the concentrations of decay products because the activity concentration of short-lived radionuclides is highest when in secular equilibrium with the long-lived parents (the activity concentrations are equal). The dose

contributions of the primary radionuclide and the short-lived decay products can be determined using the activity concentration of the primary radionuclide and the effective dose conversion factors or effective dose coefficients, which are produced by adding the dose conversion factors or dose coefficients for the parent radionuclide and those for the short-lived decay products as modified by the branching fraction of the decay products.

The radionuclides of interest for TSPA-LA (Table 6.1-1), with their short-lived ($T_{1/2}$ < 180 d) decay products, associated branching ratios, and half-lives, are shown in Table 6.3-7. The table is divided into five sections including:

- Relatively light radionuclides that decay to a stable nuclide or have only one or two radioactive decay products
- Uranium series radionuclides (4n +2)
- Thorium series radionuclides (4n)
- Actinium series radionuclides (4n + 3)
- Neptunium series radionuclides (4n + 1).

The method of combining dose contributions of decay products with those of their parents is discussed in the sections about the external exposure (Sections 6.4.7 and 6.5.5), inhalation (Section 6.4.8), and ingestion submodels (Section 6.4.9).

Table 6.3-7. Radionuclides of Interest and Their Decay Products

| Primary Radionuclide | | Decay Product [d] | Terminal Nuclide | |
|---|---|---|---|---|
| Radionuclide | Half-life (yr) [c] | (branching fraction if not 100%, half-life) | Nuclide | Half-life (yr) [e] |
| C-14 | 5730 | - | N-14 | * |
| Cl-36 | 3.01E5 | - | Ar-36 (1.9%)<br>S-36 (98.1%) | *<br>* |
| Se-79 | 6.5E4 | - | Br-79 | * |
| Sr-90D[a] | 29.12 | Y-90 (64.0 hr) | Zr-90 | * |
| Tc-99 | 2.13E5 | - | Ru-99 | * |
| Sn-126D | 1E5 | Sb-126m (19.0 min)<br>Sb-126 (14%, 12.4 d) | Te-126 | * |
| I-129 | 1.57E7 | - | Xe-129 | * |
| Cs-135 | 2.3E6 | - | Ba-135 | * |
| Cs-137D | 30.0 | Ba-137m (94.6%, 2.552 min) | Ba-137 | * |
| Pu-242 | 3.763E5 | - | U-238 | 4.468E+09 |
| U-238D | 4.468E9 | Th-234 (24.10 d)<br>Pa-234m (99.80%, 1.17 min)<br>Pa-234 (0.33%, 6.7 hr) | U-234 | 2.445E+05 |
| Pu-238 | 87.74 | - | U-234 | 2.445E+05 |
| U-234 | 2.445E5 | - | Th-230 | 7.7E+04 |
| Th-230 | 7.7E4 | - | Ra-226 | 1.60E+03 |
| Ra-226D | 1.60E3 | Rn-222 (3.8235 d)<br>Po-218 (3.05 min)<br>Pb-214 (99.98%, 26.8 min)<br>At-218 (0.02%, 2 sec)<br>Bi-214 (19.9 min)<br>Po-214 (99.98%, $1.64 \times 10^{-4}$ sec)<br>Tl-210 (0.02%, 1.3 min) | Pb-210 | 2.23E+01 |

Table 6.3-7. Radionuclides of Interest and Their Decay Products (continued)

| Primary Radionuclide | | Decay Product [d] | Terminal Nuclide | |
|---|---|---|---|---|
| Radionuclide | Half-life (yr) [c] | (branching fraction if not 100%, half-life) | Nuclide | Half-life (yr) [e] |
| Pb-210D | 22.3 | Bi-210 (5.012 d)<br>Po-210 (138.38 d) | Pb-206 | * |
| Pu-240 | 6.537E3 | - | U-236 | 2.3415E+07 |
| U-236 | 2.3415E7 | - | Th-232 | 1.405E+10 |
| Th-232 | 1.405E10 | - | Ra-228 | 5.75E+00 |
| Ra-228D[b] | 5.75 | Ac-228 (6.13 hr) | Th-228 | 1.9131E+00 |
| U-232 | 72 | - | Th-228 | 1.9131E+00 |
| Th-228D | 1.9131 | Ra-224 (3.66 d)<br>Rn-220 (55.6 sec)<br>Po-216 (0.15 sec)<br>Pb-212 (10.64 hr)<br>Bi-212 (60.55 min)<br>Po-212 (64.07%, 0.305 µ-sec)<br>Tl-208 (35.93%, 3.07 min) | Pb-208 | * |
| Am-243D | 7.38E3 | Np-239 (2.355 d) | Pu-239 | 2.406E+04 |
| Pu-239 | 2.4065E4 | - | U-235 | 7.038E+08 |
| U-235D | 7.038E8 | Th-231 (25.52 hr) | Pa-231 | 3.276E+04 |
| Pa-231 | 3.276E4 | - | Ac-227 | 2.1773E+01 |
| Ac-227D | 21.773 | Th-227 (98.62%, 18.718 d)<br>Fr-223 (1.38%, 21.8 min)<br>Ra-223 (11.434 d)<br>Rn-219 (3.96 sec)<br>Po-215 (1.78 millisec)<br>Pb-211 (36.1 min)<br>Bi-211 (2.14 min)<br>Tl-207 (99.72%, 4.77 min)<br>Po-211 (0.28%, 0.516 sec) | Pb-207 | * |
| Am-241 | 432.2 | - | Np-237 | 2.14E+06 |
| Np-237D | 2.14E6 | Pa-233 (27.0 d) | U-233 | 1.585E+05 |
| U-233 | 1.585E5 | - | Th-229 | 7.34E+03 |
| Th-229D | 7.34E3 | Ra-225 (14.8 d)<br>Ac-225 (10.0 d)<br>Fr-221 (4.8 min)<br>At-217 (32.3 millisec)<br>Bi-213 (45.65 min)<br>Po-213 (97.84%, 4.2 µ-sec)<br>Tl-209 (2.16%, 2.2 min)<br>Pb-209 (3.253 hr) | Bi-209 | * |

NOTES:

[a] "D" indicates that the radionuclide is treated with the short-lived ($T_{1/2}$ < 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Radionuclide half-life values from Eckerman and Ryman (1993 [DIRS 107684], Table A.1).

[d] Source: Eckerman and Ryman (1993 [DIRS 107684], Table A.1).

[e] A "*" denotes a stable nuclide.

If the half-life of a decay product is longer than 180 d, but not long enough to be considered a primary radionuclide for the TSPA-LA, the decay product is treated in the same way as the long-lived parent. That is, the radionuclide is tracked individually in the ERMYN model, including the calculation of the BDCF. The BDCF for an individually tracked decay product is added to the BDCF for the parent (Table 6.3-7), assuming the secular equilibrium of the parent and decay

products in the source (i.e., groundwater or volcanic ash). However, following release, the decay product is transported in the environment independently of the parent. For example, $^{232}U$ decays to $^{228}Th$. $^{228}Th$ is not a primary radionuclide for the TSPA-LA, but the half-life is sufficiently long that it exhibits different environmental transport behaviors, especially as related to leaching, soil-to-plant transfer, and transfer from animal feed to animal products.

If a decay product of a primary radionuclide also is a primary radionuclide, the activity of this radionuclide arising from the decay of the parent radionuclide and the activity that is originally present in the source, as a primary radionuclide, are tracked independently in the biosphere model. For example, $^{243}Am$ and $^{239}Pu$ are primary radionuclides, but $^{243}Am$ decays to $^{239}Pu$, so there are two sources of $^{239}Pu$. If groundwater containing both of these primary radionuclides is used for irrigation, the total activity concentration of $^{239}Pu$ in the soil results from $^{239}Pu$ in the groundwater and from $^{239}Pu$ produced in the soil by the decay of $^{243}Am$. These two fractions of $^{239}Pu$ are independently accounted for in the biosphere model, and the activity concentrations in the soil depend on the concentrations of the primary radionuclides (i.e., $^{239}Pu$ and $^{243}Am$, respectively) in the groundwater source. Ingrowth of decay products in the soil is discussed in Section 6.4.1.2.

## 6.4 MATHEMATICAL MODEL FOR THE GROUNDWATER SCENARIO

The objective of the groundwater biosphere model (Section 6.1) is to calculate BDCFs (Sv/yr)/(Bq/m$^3$) for the TSPA-LA model. The source term for the groundwater scenario is the activity concentration of a radionuclide in groundwater (Bq/m$^3$). This is a time-dependent quantity, calculated outside the biosphere model by the TSPA-LA model, and it will be unknown until the TSPA-LA model is realized. It is assumed in the biosphere model that the radionuclide concentration in groundwater does not change over time (Assumption 1). The radiation dose can be calculated as a product of the source term (activity concentration in groundwater) and the BDCF, which is source-term independent. A BDCF for the groundwater scenario is numerically equal to an all-pathway dose that the RMEI receives under specific biosphere conditions (Section 6.3.1) when the RMEI is exposed to a unit concentration of radionuclide contamination in environmental media that arises from a unit concentration of the radionuclide in groundwater.

The mathematical model for the groundwater scenario, similar to the biosphere conceptual model for the groundwater scenario (Section 6.3.1), is presented as a series of submodels. The relationship among the submodels (Figure 6.3-2) is described in Section 6.3.1. The same notation is used for the same parameter in all submodels so that the linkage between submodels can be traced. Because the ERMYN is largely derived from the GENII-S biosphere model, the two models share most mathematical equations, which were originally described in Napier et al. (1988 [DIRS 157927]). For the equations in Sections 6.4 and 6.5 taken from the GENII/GENII-S model, the source is not specifically referenced; but if the equation is from another source, the source is cited. In Section 7.3, each submodel described in this section is compared with other published biosphere models for model validation, and the sources of equations in the ERMYN are described in detail.

### 6.4.1 Surface Soil Submodel

The surface soil submodel is designed to evaluate radionuclide accumulation in, and removal from, the upper layer of the soil (down to the tilling depth) where all plant roots are assumed to be located (Assumption 7). For the groundwater scenario, surface soil is contaminated as a result of using contaminated groundwater for irrigation. The surface soil submodel is based on the BIOMASS ERB2A model (BIOMASS 2000 [DIRS 154522], Section 7).

If contaminated groundwater is used to irrigate cultivated soils, radionuclide concentrations in the soil will build up at a rate determined by the physical and chemical properties of the soil and the radionuclides. On land irrigated for a long time, radionuclide concentrations depend on the rate of accumulation and removal, and they will reach saturation (equilibrium) concentrations when the rates of addition and removal are equal. Long-lived isotopes of elements that bind readily to soil particles will not reach equilibrium concentrations for thousands of years, whereas relatively short-lived or mobile radioisotopes will approach equilibrium concentrations after only a few years (Section 7.4.2).

#### 6.4.1.1 Primary Radionuclides in the Surface Soil

Radionuclides can be removed from the surface soil by leaching into the deep soil, surface soil erosion, crop harvest removal, and radioactive decay. Although crop harvesting may be an important mechanism for radionuclide removal on cultivated lands, this mechanism is not considered in the biosphere model because it is considered to compensate for the reintroduction of radionuclides into the soil when contaminated cow manure is used as fertilizer (Assumption 4).

Because irrigation rates differ among crop types, radionuclide concentrations in the surface soil depend on the specific use of cultivated land. However, crop rotation over a longer period of time would average out the differing radionuclide concentrations caused by different crop irrigation levels (Assumption 3). Therefore, it is reasonable to use an average annual irrigation rate to estimate long-term radionuclide concentrations in surface soil. The long-term concentration is used to evaluate radionuclide uptake from soil by plants and to evaluate inhalation, inadvertent soil ingestion, and external exposures. Using this simplification, the average activity concentration of a radionuclide in the surface soil does not depend on the crop type.

The mathematical representation of the primary radionuclide addition and removal processes in the surface soil is expressed by the following differential equation and the initial condition. Decay product ingrowth in the surface soil is discussed in the next subsection.

$$\begin{cases} \dfrac{dCs_i(t)}{dt} = Cw_i(t)\, IR(t) - (\lambda_{d,i} + \lambda_{l,i} + \lambda_e)\, Cs_i(t) \\ Cs_i(t) = 0, \ when\, t = 0 \end{cases} \qquad \text{(Eq. 6.4.1-1)}$$

where

| | | |
|---|---|---|
| $Cs_i(t)$ | = | activity concentration of radionuclide $i$ in surface soil per unit area at time $t$ (Bq/m$^2$) |
| $i$ | = | primary radionuclide index, used for entire biosphere model |
| $t$ | = | time variable (yr) |
| $Cw_i(t)$ | = | activity concentration of radionuclide $i$ in the groundwater at time $t$ (Bq/m$^3$) |
| $IR(t)$ | = | annual average irrigation rate on land (annual irrigation rate) (m/yr) |
| $\lambda_{d,i}$ | = | radioactive decay constant for radionuclide $i$ (/yr); this can be calculated from radionuclide half-life (Table 6.3-7) using the conversion $\ln(2)/T_{d,i}$, where $T_{d,i}$ is half-life of radionuclide $i$ (yr) |
| $\lambda_{l,i}$ | = | average annual leaching removal constant for radionuclide $i$ (/yr) |
| $\lambda_e$ | = | average annual surface soil erosion removal constant (/yr). |

When radionuclide concentrations in the surface soil reach saturation, they do not change with time, $\frac{dCs_i(t)}{dt} = 0$, and they are not time dependent $Cs_i(t) = Cs_i$. As noted previously, it is assumed in the biosphere model that radionuclide concentrations in groundwater do not change over the time of modeling interest: $Cw_i(t) = Cw_i$ (Assumption 1).

The average crop irrigation rate in Equation 6.4.1-1, $IR(t)$, is an annual average irrigation rate deposited on the soil, which is developed based on the irrigation rates for individual crop types. The typical range of irrigation rates is from 0.5 to 1.0 m/yr (BSC 2003 [DIRS 160976], Section 6.5). The average irrigation rate is time-dependent because of climate changes predicted for the Yucca Mountain region. However, for a defined climate, the average irrigation is not a function of time: $IR(t) = IR$. As discussed in the FEPs (Section 6.2), climate change does not change the overall biosphere conceptual model as long as the general characteristics of the biosphere are consistent with the arid and semi-arid climate. The model can be adopted for different climates within these boundaries through selection of climate-dependent parameter values, such that they match the desired climate.

The leaching removal constant, $\lambda_{l,i}$, is an element-specific input parameter. This important parameter is discussed further in Section 6.4.1.3. The surface soil erosion removal constant, $\lambda_e$, represents the rate of radionuclide loss from the surface soil due to wind erosion. The value of this radionuclide-independent parameter is strongly site-specific and depends on environmental characteristics and land use. This parameter is further discussed in Section 6.4.1.4.

When the radionuclide concentration in the groundwater and the crop irrigation rate are not time-dependent, the analytical solution of Equation 6.4.1-1 is expressed as

$$Cs_i(t) = \frac{Cw_i\ IR}{\lambda_{d,i} + \lambda_{l,i} + \lambda_e}\left[1 - e^{-(\lambda_{d,i} + \lambda_{l,i} + \lambda_e)t}\right] \qquad \text{(Eq. 6.4.1-2)}$$

All parameters in Equation 6.4.1-2 are defined in Equation 6.4.1-1. The term $\lambda_{d,i} + \lambda_{l,i} + \lambda_e$ can be replaced with one parameter, the effective removal constant, $\lambda_{eff,i}$. Thus, Equation 6.4.1-2 can be expressed as

$$Cs_i(t) = \frac{Cw_i\ IR}{\lambda_{eff,i}}\left(1 - e^{-\lambda_{eff,i}\,t}\right) \qquad \text{(Eq. 6.4.1-3)}$$

The effective removal constant is an important parameter that determines the rate at which radionuclides approached saturation concentrations in the surface soil. For example, the time ($t$) required for soil concentrations to reach 95 percent of the saturation value can be derived from Equation 6.4.1-3, which is equal to $\ln(20)/\lambda_{eff,i}$. Although it theoretically takes an infinite amount of time to reach saturation, the time to reach a fixed percentage of the saturation value would be finite, and 95 percent is a close approximation to saturation. It takes about 10 to 2,500 yrs for the radionuclides considered in the model to reach the 95 percent saturation concentration in surface soils (Section 7.4.2).

With time, radionuclide concentrations eventually would reach the saturation concentration (Assumption 5). The saturation concentration in the soil, $Cs_i$, is expressed as the ratio of the radionuclide addition rate to the removal rate

$$Cs_i = \frac{Cw_i\ IR}{\lambda_{eff,i}} \qquad \text{(Eq. 6.4.1-4)}$$

The activity concentration of a radionuclide in surface soil calculated from Equation 6.4.1-4 is given in units of activity per unit area (Bq/m$^2$). It can be converted to activity concentration in Bq per unit mass of surface soil using

$$Cs_{m,i} = \frac{Cs_i}{\rho_s} \qquad \text{(Eq. 6.4.1-5)}$$

where

| | | |
|---|---|---|
| $Cs_{m,i}$ | = | saturation activity concentration of radionuclide $i$ in surface soil per unit mass (Bq/kg) |
| $Cs_i$ | = | saturation activity concentration of radionuclide $i$ in surface soil per unit area (Bq/m$^2$) (defined in Equation 6.4.1-4) |
| $\rho_s$ | = | areal density of surface soil (kg/m$^2$). |

Surface soil density is calculated in the submodel using

$$\rho_s = \rho \times d \qquad \text{(Eq. 6.4.1-6)}$$

where

| | | |
|---|---|---|
| $\rho$ | = | bulk density of surface soil (kg/m$^3$) |
| $d$ | = | depth of surface soil (m). |

The soil bulk density ranges from about 1,400 to 1,600 kg/m$^3$ (Table 6.6-3). The depth of the surface soil, based on tillage depth, ranges from 5 to about 30 cm (Table 6.6-3).

In the biosphere model, soil is divided into two compartments: the surface soil layer encompassing the crop root zone, and the deep soil where radionuclides are assumed inaccessible to plants (Assumption 7). The depth of the surface soil controls the partition between these two

compartments, and therefore controls the effective "capacity" of the compartment for the amount of radionuclides available for further mobilization in the biosphere (e.g., by crop uptake).

This method is assumed to be valid for long-lived radionuclides and for the conditions of sustained irrigation with water containing constant concentrations of given radionuclides (Assumption 1). This approach does not underestimate radionuclide concentrations in surface soil because it is assumed that equilibrium conditions exist in the soil.

### 6.4.1.2 Radionuclide Decay and Ingrowth in the Surface Soil

Radionuclide decay and ingrowth in surface soil due to introduction of primary radionuclides in irrigation water are considered in this section. These decay products have long half-lives (half-life of greater than 180 days) and may or may not be primary radionuclides (short-lived decay products are assumed to be secular equilibrium with the parent radionuclides; Assumption 2). The buildup of decay products in the surface soil is considered separately from the primary radionuclides (Section 6.4.1.1) because decay product concentrations in the soil are calculated differently. The radiation dose contribution from the decay products is included with the primary radionuclide.

For decay chains in the surface soil, decay products are produced at the rate that the parent radionuclides decay. Removal mechanisms include decay of the decay product, leaching from the surface soil, and removal by soil erosion. The general differential equation (Lamarsh 1983 [DIRS 149069], Section 2.9) describing the rate of change in the number of atoms of the decay product is given by

$$\begin{cases} \dfrac{dN_l(t)}{dt} = \lambda_{d,l-1}\, N_{l-1}(t) - (\lambda_{d,l} + \lambda_{l,l} + \lambda_e)\, N_l(t) \\ N_l(t) = N_{l-1}(t) = 0, \text{ when } t = 0 \end{cases} \qquad \text{(Eq. 6.4.1-7)}$$

where

| | | |
|---|---|---|
| $N_l(t)$ | = | number of atoms for the $l^{th}$ decay product in a decay chain in the surface soil |
| $N_{l-1}(t)$ | = | number of atoms for the $(l\text{-}1)^{th}$ decay product in a decay chain in the surface soil |
| $l$ | = | index of radionuclide decay chain ($l \geq 1$) |
| $\lambda_{d,l-1}$ | = | radioactive decay constant for the $(l\text{-}1)^{th}$ decay product (/yr) |
| $\lambda_{d,l}$ | = | radioactive decay constant for the $l^{th}$ decay product (/yr) |
| $\lambda_{l,l}$ | = | average annual leaching removal constant ($\lambda_l$) for the $l^{th}$ decay product (/yr) |
| $\lambda_e$ | = | average annual surface soil erosion removal constant (/yr). |

If the number of atoms in Equation 6.4.1-7 is multiplied by the decay constant, $\lambda_{d,l}$, and divided by the soil surface area, $A$, the resulting expression can be used to calculate the rate of change of activity concentration of a radionuclide in the surface soil equation (Lamarsh 1983 [DIRS 149069], Section 2.9), such that Equation 6.4.1-7 becomes

$$\begin{cases} \dfrac{dCs_l(t)}{dt} = \lambda_{d,l}\, Cs_{l-1}(t) - (\lambda_{d,l} + \lambda_{l,l} + \lambda_e)\, Cs_l(t) \\ Cs_l(t) = Cs_{l-1}(t) = 0, \text{ when } t = 0 \end{cases} \qquad \text{(Eq. 6.4.1-8)}$$

where

$Cs_l(t) = \dfrac{\lambda_{d\,l}\, N_l(t)}{A}$ = activity concentration of a decay product $l$ in surface soil (Bq/m$^2$)

$Cs_{l-1}(t) = \dfrac{\lambda_{d\,l-1}\, N_{l-1}(t)}{A}$ = activity concentration of a primary radionuclide if ($l$ = 1) or a decay product ($l$-1) in surface soil (Bq/m$^2$)

$l$ = index of radionuclide decay chain, $l$ = 0 for a primary radionuclide and Equation 6.4.1-1 is used; $l$ = 1 for the first decay product

and the other parameters are defined in Equation 6.4.1-7.

When the activity concentration in surface soil, $Cs_l(t)$, is a function of time, the analytical solution of Equation 6.4.1-8 for each decay product of the primary radionuclide can be complicated. However, the solutions for all radionuclides in a decay chain can be obtained analytically when the activity concentration in the soil is evaluated at saturation for the primary radionuclides and the decay products (Assumption 5), that is, $\dfrac{dCs_l(t)}{dt} = 0$. The solution can be expressed as

$$Cs_l = \frac{\lambda_{d,l}}{\lambda_{d,l} + \lambda_{l,l} + \lambda_e} Cs_{l-1} = \frac{\lambda_{d,l}}{\lambda_{eff,l}} Cs_{l-1} \qquad \text{(Eq. 6.4.1-9)}$$

where

$Cs_l$ = saturation activity concentration of a decay product $l$ in surface soil (Bq/m$^2$)

$Cs_{l-1}$ = saturation activity concentration of a primary radionuclide if $l$ = 1, or a decay product ($l$-1) in surface soil (Bq/m$^2$)

$\lambda_{eff,l}$ = effective removal constant for the $l^{th}$ decay product (/yr)

and the other parameters are defined in Equation 6.4.1-7.

For surface soil, Equation 6.4.1-9 describes relationships among activity concentrations for consecutive members of decay chains produced by the decay of primary radionuclides. For short-lived decay products, the decay constant ($\lambda_d$) is approximately equal to the effective removal constant ($\lambda_{eff}$), and the activity concentration in the soil is the same as that for the immediate predecessor, thereby demonstrating that for short-lived radionuclides, the secular equilibrium is not perturbed by the other physical removal processes.

The activity concentrations of decay products in the soil are expressed as a constant fraction of the parent concentrations (Equation 6.4.1-9), which simplifies the calculation of activity concentrations for decay products in the surface soil. Also, by combining short-lived radionuclides with their longer-lived parents (Section 6.3.5), the number of radionuclides in a

decay chain can be reduced. However, even if reduced, the number of primary radionuclides in a decay chain could be as high as six (see $^{242}$Pu, Table 6.3-7). The concentrations of decay products in the soil depended on the decay constants and the effective removal constants (Equation 6.4.1-9). Typical effective removal constants for the radionuclides of interest to biosphere modeling range from $1 \times 10^{-4}$/yr to $1 \times 10^{-1}$/yr (Section 7.4.2). If radionuclides have a long half-life (on the order of $1 \times 10^{5}$ yr), which corresponds to a small decay constant ($< 1 \times 10^{-5}$/yr), it is not necessary to include them as a decay product of the parent primary radionuclide. Thus, these radionuclides can be considered decay chain "stoppers" for a decay chain originating with a primary radionuclide. The radionuclides that meet this condition are: $^{238}$U, $^{234}$U, $^{236}$U, $^{232}$Th, $^{235}$U, $^{237}$Np, and $^{233}$U which terminate the decay chains of $^{242}$Pu, $^{238}$U/$^{238}$Pu, $^{240}$Pu, $^{236}$U, $^{239}$Pu, $^{241}$Am, and $^{237}$Np, respectively (Table 6.3-7).

By combining short-lived decay products with their longer-lived predecessors, and neglecting the contribution from very long-lived decay products and their progeny, the number of decay chain members that are explicitly considered in the ERMYN model is reduced. The abridged chains are shown in Table 6.4-1.

Table 6.4-1. The Primary Radionuclides and Their Decay Chains for Soil

| Primary Radionuclide | 1st Long-lived Decay Product | 2nd Long-lived Decay Product | 3rd Long-lived Decay Product |
|---|---|---|---|
| U-234 | Th-230 | Ra-226D | Pb-210D |
| Th-230 | Ra-226D | Pb-210D | – |
| Ra-226D[a] | Pb-210D | – | – |
| Th-232 | Ra-228D | Th-228D | – |
| Ra-228D[b] | Th-228 | –- | – |
| U-232 | Th-228 | – | – |
| Am-243D | Pu-239 | – | – |
| U-235D[b] | Pa-231 | Ac-227D | – |
| Pa-231 | Ac-227D | – | – |
| U-233 | Th-229D | – | – |

NOTES: Table entries derived from Table 6.3-7 using the method discussed in this section.

[a] A "D" after a radionuclide symbol denotes that the radionuclide is treated together with its short-lived (< 180 d) decay product.

[b] $^{228}$Ra and $^{235}$U are not primary radionuclides (Table 6.1-1), but their half-lives are long enough to consider them separately from the parent radionuclides, and they are treated as a primary radionuclide in the decay chain (Section 6.3.5).

Only the decay chain for $^{234}$U includes a third long-lived decay product, (Pb-210D; Table 6.4-1). The contribution to the $^{234}$U dose from $^{226}$Ra, with additional consideration of $^{222}$Rn and progeny, is expected to be higher than the dose contribution from Pb-210D and progeny because of the inhalation dose contribution from radon progeny. Therefore, the third decay product, Pb-210D, of the abbreviated $^{234}$U decay chain is not considered (see Table 6.10-3). This reduced the number of decay products from primary radionuclides that are explicitly modeled in the ERMYN model to at most two. In Section 7.4.2.2, the radionuclide decay chains used in the GENII-S and ERMYN models are compared to verify that all of the decay products are properly considered.

### 6.4.1.3 Radionuclide Leaching from the Surface Soil

The residence time of radionuclides in the soil can influence the contribution to the total exposure of the receptor. Therefore, the biosphere assessment must account for the removal of radionuclides by leaching from the surface soil to the deep soil. Radionuclides removed from the surface soil by leaching would no longer be available to many of the environmental transport and receptor exposure pathways. In an arid climate, leaching may be enhanced by overwatering, which is a common practice to prevent the buildup of salts deposited in soil from irrigation water (BSC 2003 [DIRS 160976], Section 6.9). Under wetter conditions, such as those predicted to occur in the future at Yucca Mountain, leaching also would occur when excess precipitation flows through the surface soil, primarily during the winter.

The process of leaching contaminants from the surface soil is evaluated using element-specific leaching coefficients. Leaching coefficients are calculated using a relationship developed by Baes and Sharp (1983 [DIRS 109606]). This equation is used in other biosphere models as discussed in the model comparison section (Section 7.3.1.1). The equation for the leaching removal constant, $\lambda_{l,i}$, is expressed as

$$\lambda_{l,i} = \frac{OW}{d \times \theta \left(1 + \frac{\rho}{\theta} Kd_i\right)} \qquad \text{(Eq. 6.4.1-10)}$$

where

| | | |
|---|---|---|
| $OW$ | = | crop overwatering rate (m/yr) |
| $\theta$ | = | volumetric water content of soil (dimensionless) |
| $Kd_i$ | = | solid-liquid partition coefficient for radionuclide *i* in surface soil (Bq/kg $_{solid}$)/(Bq/m$^3$ $_{liquid}$) = (m$^3$ $_{liquid}$ /kg $_{solid}$) |

and the other parameters are defined in Equations 6.4.1-1 and 6.4.1-6.

In arid regions, the overwatering rate usually is determined by calculating the amount of water required to flush accumulated salts out of the surface soil to maintain productivity. The value of this parameter is on the order of 10 cm/yr (BSC 2003 [DIRS 160976]). The volumetric water content of soil is defined as the fraction of the soil volume representing water-filled porosity. The value of this parameter depends on soil texture and ranges from less than 0.1 (dry soils) to 0.4-0.5 (water-saturated soils), with typical values of about 0.2-0.3. The partition coefficient depend on soil characteristics, with values ranging over several orders of magnitude (i.e., $1 \times 10^{-3}$ to $1 \times 10^{0}$ m$^3$/kg; BSC 2003 [DIRS 161239]).

### 6.4.1.4 Surface Soil Erosion

Under natural conditions, the rate of soil removal by erosion generally is in approximate equilibrium with the rate of soil development from soil forming processes, and under these conditions, soil depth is relatively constant (Troeh et al. 1980 [DIRS 110012], p. 4). Human activities tend to accelerate the rate of soil removal. The removal of surface soil by erosion would result in the loss of radionuclides attached to the soil particles. The rate of radionuclide removal from surface soils is quantified in the ERMYN model using a surface soil erosion

removal constant ($\lambda_e$), as introduced in Equation 6.4.1-1. The erosion rate is developed in BSC (2003 [DIRS 161239]), and the surface soil erosion removal constant is evaluated as

$$\lambda_e = \frac{ER}{d \times \rho} \qquad \text{(Eq. 6.4.1-11)}$$

where

*ER* = annual average erosion rate for the surface soil (kg/(m$^2$ yr))
and the other parameters are defined in Equations 6.4.1-1 and 6.4.1-6.

### 6.4.2 Air Submodel

The air submodel addresses the transport of radionuclides from contaminated water and soil to the air. Particle transport from soil to air is considered to occur primarily via resuspension. The release of radioactive gasses from the soil for species such as radon or carbon dioxide results predominantly from diffusion caused by concentration gradients at the soil-air interface. The transport of radionuclides from water to air also may result from the use of evaporative coolers.

#### 6.4.2.1 Resuspended Particles from Surface Soil

Resuspension is the process by which material deposited from the atmosphere onto the ground is subsequently returned to the atmosphere. In the ERMYN model, radionuclide concentrations in the air are used to estimate the inhalation dose (Section 6.4.8) and crop contamination by the deposition of resuspended particles onto plant surfaces (Section 6.4.3). Radionuclide concentrations in the air are estimated differently for the inhalation exposure and for particulate deposition on crops, primarily because of the differences in mass loading among environments.

For direct deposition on crops, the activity concentration of resuspended particles is linked to the activity concentration in the local surface soil. The relationship between these quantities is expressed as

$$Ca_{p,i} = S \times Cs_{m,i} = \frac{S}{\rho_s} Cs_i \qquad \text{(Eq. 6.4.2-1)}$$

where

$Ca_{p,i}$ = activity concentration of radionuclide *i* in the air from soil resuspension (Bq/m$^3$)
$Cs_{m,i}$ = saturation activity concentration of radionuclide *i* in the surface soil per unit mass (Bq/kg) (Equation 6.4.1-5)
$S$ = mass concentration of resuspended particles; mass loading (kg/m$^3$)
$Cs_i$ = saturation activity concentration of radionuclide *i* in the surface soil per unit area (Bq/m$^2$)
$\rho_s$ = areal density of surface soil (kg/m$^2$) (Equation 6.4.1-6).

The mass loading of resuspended particulates, *S*, (Equation 6.4.2-1), is characteristic of cultivated fields and is developed based on annual average values (BSC 2003 [DIRS 160965]).

The activity concentration of resuspended particles, used for the assessment of direct inhalation doses, is calculated for five environments associated with human activities. In addition, the

enhancement factor for the activity concentration of resuspended particulates, $f_{enhance}$, is defined as the ratio of activity concentration of resuspended particles (Bq/kg) to total surface soil activity concentration for a given radionuclide (Bq/kg). This factor is used for inhalation because humans tend to inhale small particles, and the activity concentration in soil is a function of particle size (NCRP 1999 [DIRS 155894], Section 4.2). The particle size distribution for resuspended soil is different from the particle size distribution of the host soil because resuspension preferentially affects smaller particles under typical conditions. The enhancement factor accounts for the fact that the activity concentration of resuspended particulates may be different from that of the soil where they originated. Specifically, for soil particles contaminated by irrigation water, the contaminant would be adsorbed onto particles in the form of a thin film on the particle surface. The surface coating would result in an increased activity concentration for smaller particles compared to that of larger particles because surface area per unit mass is greater for smaller particles. The enhancement factor is discussed in BSC (2003 [DIRS 161239], Section 6.6).

To account for variation and uncertainty in the characteristics of the RMEI and concentrations of radionuclides in the biosphere, the ERMYN uses a micro-environmental modeling approach to calculate inhalation dose and external exposure. For micro-environmental models, the total exposure environment (i.e., the biosphere) is divided into segments, or environments, with different concentrations of contaminants. The contaminant concentration, time spent exposed to the contaminant, and intake rate or exposure factor (e.g., breathing rate and shielding factor) is determined for each environment, and the total dose is calculated as the sum of the dose from all environments (Mage 1985 [DIRS 162465], pp. 409 and 410). Micro-environmental models are commonly used to evaluate exposure to particulate matter and other contaminants (Duan 1982 [DIRS 162466]; Mage 1985 [DIRS 162465]; Klepeis 1999 [DIRS 160094]). Radionuclide concentrations in the air are calculated as

$$Ca_{h,i,n} = f_{enhance,n}\, Cs_{m,i}\, S_n = f_{enhance,n} \frac{S_n}{\rho_s} Cs_i \qquad \text{(Eq. 6.4.2-2)}$$

where

| | | |
|---|---|---|
| $Ca_{h,i,n}$ | = | activity concentration of radionuclide $i$ in the air from soil resuspension for the assessment of human inhalation exposure in environment $n$ (Bq/m$^3$) |
| $f_{enhance,n}$ | = | enhancement factor for the activity concentration of resuspended particulates in environments $n$ (dimensionless) |
| $S_n$ | = | concentration of total resuspended particulates (mass loading) for evaluation of inhalation exposure for environment $n$ (kg/m$^3$) |
| $n$ | = | index of the environments (see below) |

and the other parameters are defined in Equation 6.4.2-1.

Five environments associated with different human activities are considered in the ERMYN model, four in the contaminated area: active outdoors ($n$ = 1), inactive outdoors ($n$ = 2), active indoors ($n$ = 3), asleep indoors ($n$ = 4), and one outside of the contaminated area ($n$ = 5). Activity concentrations in the air outside the contaminated area is zero. These mutually exclusive environments represent behavioral and environmental combinations for which the receptor would receive a substantially different rate of exposure via inhalation or external exposure.

**Active Outdoors**–This category includes time spent outdoors in contaminated areas conducting activities that would resuspend soil, including dust-generating activities while working (e.g., plowing, excavating, and livestock operations) and recreating outdoors (e.g., gardening, landscaping, and riding horses or motorbikes). Because dust concentrations decrease rapidly after the dust-disturbing activities cease (e.g., Pinnick et al. 1985 [DIRS 159577], pp. 103 and 104), this category is limited to the time when the activities are occurring.

**Inactive Outdoors**–This category includes time spent outdoors in contaminated areas engaged in activities that do not resuspend soil (e.g., sitting, swimming, walking, barbecuing, and equipment maintenance). This category also includes time spent commuting within the contaminated area because the major roads in the Amargosa Valley are paved, and commuting generally resuspends little soil.

**Active Indoors**–This category includes time spent indoors in contaminated areas, awake, and including work time. This value is calculated as the amount of time not spent in the other environments.

**Asleep Indoors**–This category includes time spent indoors in contaminated areas sleeping.

**Away from Potentially Contaminated Area**–This category includes time spent away from areas potentially contaminated by groundwater or ash, including time spent commuting to work and working outside the contaminated areas.

The mass concentration of resuspended particulates in the air, $S_n$, depends on the environment and the type of activities conducted there. Values of mass loading range over several orders of magnitude, from $6 \times 10^{-8}$ kg/m$^3$ for indoor environments to $1 \times 10^{-5}$ kg/m$^3$ for dusty outdoor environments (BSC 2003 [DIRS 160965], Section 7).

### 6.4.2.2 Aerosols from Evaporative Cooler Operation

About 73 percent of the residents in Amargosa Valley used evaporative coolers during 1997 (DOE 1997 [DIRS 100332], p. 20), and these coolers might transfer water-borne contaminants to the indoor air. Thus, the ERMYN model must include an estimate of the radionuclide concentrations in indoor air when evaporative coolers are in operation so that the radiation dose for the human receptor who inhales the contaminated air can be evaluated. Based on how evaporative coolers operate and the conservation of radioactivity (i.e., activity transferred to air is equal to the loss of activity from water), the equation $(Ca_{e,i})(F_{air}) = (f_{evap})(M_{water})(Cw_i)$ is rearranged, and radionuclide concentrations in indoor air are estimated as

$$Ca_{e,i} = f_{evap} \frac{M_{water}}{F_{air}} Cw_i \qquad \text{(Eq. 6.4.2-3)}$$

where

| | | |
|---|---|---|
| $Ca_{e,i}$ | = | activity concentration of radionuclide $i$ in the air resulting from the operation of an evaporative cooler (Bq/m$^3$) |
| $f_{evap}$ | = | fraction of radionuclides in water transferred to indoor air (dimensionless) |
| $M_{water}$ | = | water evaporation rate (water use) for an evaporative cooler (m$^3$/hr) |
| $F_{air}$ | = | air flow rate for an evaporative cooler (m$^3$/hr) |

$Cw_i$ = activity concentration of radionuclide *i* in the groundwater (Bq/m$^3$).

The fraction of radionuclides that remain in the reservoir, bleed-off water, or in the pads of evaporative cooler are not further modeled because it becomes a regular water source for irrigation or sewage, or is removed when the pads are replaced, and therefore may not cause direct exposure. Evaporation and air flow rates are estimated based on specifications of residential evaporative cooling units. The typical evaporation rate is about 20 L/hr, and typical air flow rates range from 2,000 to 10,000 m$^3$/hr (BSC 2003 [DIRS 160964]). The fraction of radionuclides transferred from the water to the indoor air is an important parameter that is not available in the literature, but the theoretical range is from 0 to 1 (BSC 2003 [DIRS 160964]).

Radon, primarily $^{222}$Rn, released from evaporative coolers is not considered in this submodel, and justification is provided in Section 7.4.3.1. The calculation of activity concentrations in the air resulting from evaporative coolers does not include consideration of radionuclide buildup in the indoor air. This is because the air flow associated with the use of these coolers would result in dilution and elimination of the airborne radionuclides (Assumption 11).

### 6.4.2.3 Radon Exhalation from Surface Soil

The inhalation of radon decay products is a major, and in many cases, the dominant dose contributor of internal radiation when radium isotopes are present in the soil (Yu et al. 2001 [DIRS 159465], p. C-3). Radon-222, a decay product of $^{226}$Ra (a primary radionuclide; Table 6.3-7), is the most common radon isotope. Other radon isotopes, such as $^{220}$Rn and $^{219}$Rn, are less important because they are short-lived and their parent radium isotopes, $^{224}$Ra, and $^{223}$Ra, respectively, are short-lived and are not designated as radionuclides of interest in the TSPA-LA. In addition, FEP 3.3.08.00.0A describes the consideration of $^{222}$Rn (Table 6.2-1). Thus, $^{222}$Rn is the only radon isotope considered in the ERMYN.

**Outdoor Radon Concentration**–The concentration of radon outdoors is estimated from the amount of radon exhaled from the soil. A screening calculation, based on the concentration ratio (i.e., the release factor of $^{222}$Rn) of $^{222}$Rn activity in the air to $^{226}$Ra activity in the soil (NCRP 1999 [DIRS 155894], Section 4.3.6) is used to estimate the concentration of radon in outdoor air as

$$Ca_{g,Rn-222,n=1\&2} = f_{m,Rn-222}\, Cs_{m,Ra-226} \qquad \text{(Eq. 6.4.2-4)}$$

where

$Ca_{g,Rn-222,n=1\&2}$ = activity concentration of $^{222}$Rn in outdoor air ($n$ = 1 and 2 for active outdoor and inactive outdoor; defined in Equation 6.4.2-2) (Bq/m$^3$)

$f_{m,\,Rn-222}$ = concentration ratio of $^{222}$Rn activity in the air to $^{226}$Ra activity in soil (radon release factor) (kg/m$^3$)

$Cs_{m,Ra-226}$ = activity concentration of $^{226}$Ra in surface soil (Bq/kg).

Using an average outdoor $^{222}$Rn concentration value of 10 Bq/m$^3$ and an average $^{226}$Ra concentration in the soil of 40 Bq/kg (NCRP 1999 [DIRS 155894], Section 4.3.6), the release factor for $^{222}$Rn would be 0.25 (Bq/m$^3$)/(Bq/kg). This value is large compared to the resuspension contribution for $^{226}$Ra. For example, using a typical mass loading of about $1 \times 10^{-8}$ to $1 \times 10^{-6}$ kg/m$^3$ (Table 6.6-3) and a $^{226}$Ra concentration in the soil of 1 Bq/kg, the $^{226}$Ra

concentration in the air due to resuspension would be $1 \times 10^{-8}$ to $1 \times 10^{-6}$ Bq/m$^3$, whereas the $^{222}$Rn concentration in the air would be 0.25 Bq/m$^3$.

**Indoor Radon Concentration**–The method for calculating the indoor concentration of radon, taken from RESRAD (Yu et al. 2001 [DIRS 159465], Equation C.12), was developed for a single-story house built on contaminated soil, assuming steady-state conditions between the rate of radon entry into the house and the rate of removal. The main sources of indoor radon are the soil beneath the house and the entry of outdoor air. The surface soil beneath the house contains the saturation concentration of $^{226}$Ra, consistent with the approach of modeling radionuclide concentrations in the soil used in the ERMYN model and to eliminate speculation on previous land use. This approach provides upper bound for the indoor radon concentration because it is unlikely that all houses would be built on soil that was continuously irrigated over a period of time sufficiently long to reach saturation concentration of $^{226}$Ra. Indoor radon concentration is expressed as

$$Ca_{g,\,Rn-222,n=3\&4} = \frac{J_{indoor}}{v\ H} + Ca_{g,Rn-222,n=1\&2} \qquad \text{(Eq. 6.4.2-5)}$$

where

| | | |
|---|---|---|
| $Ca_{g,Rn-222,n=3\&4}$ | = | activity concentration of $^{222}$Rn in indoor air ($n$ = 3 and 4 for active indoor and asleep indoor; defined in Equation 6.4.2-2) (Bq/m$^3$) |
| $J_{indoor}$ | = | radon flux density from the house floor (Bq/(m$^2$ sec)) |
| $H$ | = | interior wall height of the house (m) |
| $v$ | = | house ventilation rate, or air exchange rate (/sec). This parameter had two values, a normal rate ($v_n$) and a higher rate used when evaporative coolers are in operation ($v_e$) |

and the other parameters are defined in Equation 6.4.2-4.

The radon flux density from the floor of the house can be expressed as a proportion of the total radon flux density from contaminated outdoor soil, when soil beneath the house is also considered contaminated, as

$$J_{indoor} = f_{house} \times J_{outdoor} \qquad \text{(Eq. 6.4.2-6)}$$

where

| | | |
|---|---|---|
| $J_{outdoor}$ | = | radon flux density from outdoor contaminated soil (Bq/(m$^2$ sec)) |
| $f_{house}$ | = | fraction of radon released into a house from soil beneath the house (dimensionless). |

By combining the Equations 6.4.2-5 and 6.4.2-6, the indoor radon concentration can be calculated as

$$Ca_{g,\,Rn-222,n=3\&4} = Ca_{g,\,Rn-222,n=1\&2}\left(\frac{f_{house}}{v_n\ \ H}\frac{J_{outdoor}}{Ca_{g,Rn-222,n=1\&2}}+1\right)$$

$$= Ca_{g,\,Rn-222,n=1\&2}\left(\frac{f_{house}}{CF_{Rn-222}\ v_n\ \ H}+1\right) \qquad \text{(Eq. 6.4.2-7)}$$

$$= Ca_{g,\,Rn-222,n=1\&2}\ \ IF_{n,Rn-222}$$

where

$CF_{Rn\text{-}222}$ = ratio of $^{222}$Rn concentration in outdoor air to $^{222}$Rn flux density from outdoor soil (sec/m)

$IF_{n,Rn\text{-}222}$ = indoor $^{222}$Rn increase factor for normal ventilation rate (dimensionless)

and the other parameters are defined in Equations 6.4.2-5, and 6.4.2-6.

During operation of an evaporative cooler, the increase in indoor radon concentration relative to the outdoor concentration would be relatively low because of the high ventilation rate. The indoor radon concentration during that period can be estimated by

$$Ca_{g,\,Rn-222,e} = Ca_{g,\,Rn-222,n=1\&2}\left(\frac{f_{house}}{CF_{Rn-222}\ v_e\ \ H}+1\right) \qquad \text{(Eq. 6.4.2-8)}$$

$$= Ca_{g,\,Rn-222,n=1\&2}\ \ IF_{e,Rn-222}$$

where

$Ca_{g,Rn\text{-}222,e}$ = activity concentration of $^{222}$Rn in indoor air during evaporative cooler operation (Bq/m$^3$)

$IF_{e,Rn\text{-}222}$ = indoor $^{222}$Rn increase factor for a high ventilation rate during evaporative cooler operation (dimensionless)

and the other parameters are defined in Equation 6.4.2-5 and 6.4.2-6.

Radon enters the indoor space through cracks and other openings in the floor and foundations. The fraction of radon released into a house from soil would depend on the type and number of such openings in the floor in the house (typical range of 0.01 to 0.25; Table 6.6-3). The fraction retained in the house would primarily depend on the ventilation rate. Ventilation rates would depend on ambient temperatures because during cold weather, residents would be expected to close up their houses to retain heat, but during warmer weather, they would be expected to open their houses to allow ventilation. Ventilation rates range from about 0.3 to 2.9 air exchanges per hour; however, when evaporative coolers are in operation, house air exchange rates range from 1 to 30 exchanges per hour (BSC 2003 [DIRS 160964], Section 6.6.2). Similar to the radon release factor, $f_{m,\,Rn\text{-}222}$, the ratio of the concentration of $^{222}$Rn in outdoor air to $^{222}$Rn flux density from radium contaminated outdoor soil is based on a global average value, about 300 sec/m (10 Bq/m$^3$ to 0.033 Bq/(m$^2$ sec)) (BSC 2003 [DIRS 160964], Section 6.6). Because of evaporative coolers, indoor radon concentrations must be considered separately when the cooler is turned on or off, as discussed in Section 6.4.8.4.

The radon contribution from evaporative coolers and household water use is excluded from the ERMYN model, as justified in Section 7.4.3.1.

### 6.4.3 Plant Submodel

If groundwater is contaminated, irrigated crops become contaminated by the deposition of radionuclides onto the above-ground plant parts and through root uptake of radionuclides from the soil. The plant submodel includes both processes.

Radionuclides would be deposited on plant surfaces from contaminated irrigation water and from resuspension of contaminated surface soil. Some of the radionuclides intercepted by crops would be retained on, or in, the plant and some would be removed by weathering. Contamination of plants by direct deposition would be important for elements that have low rates of root uptake (e.g., actinides: plutonium, neptunium, and americium). For environmentally mobile elements (e.g., technetium, iodine, and chlorine), root uptake usually is more important than direct deposition (see values of transfer factors; Table 6.6-3). Radionuclide concentrations in the surface soil are considered in the surface soil submodel (Section 6.4.1), and radionuclide concentrations in the air are considered in the air submodel (Section 6.4.2).

Soil splash due to irrigation or rain is an additional mechanism used in some biosphere models (e.g., BIOMASS 2000 [DIRS 154522], Section 7). However, the process of soil splash is considered equivalent to direct deposition of resuspended particles on plant surfaces (Section 6.4.3.3). Therefore, soil splash is not considered separately in the ERMYN model. Furthermore, none of the published biosphere models consider dust deposition combined with irrigation or rain splash. For model validation, this ACM 4 (direct deposition of airborne particulates) is compared with the methods used in the plant submodel (Section 7.4.4.1).

Based on the typical approach used in assessments of environmental radionuclide releases, the ERMYN model includes four types of crops consumed by humans: leafy vegetables, other vegetables, fruit, and grain. Leafy vegetables include plants such as lettuce, spinach, and cabbage, the edible portions of which (i.e., the leaves) grow above ground, are exposed, and can be eaten directly with little processing (Napier et al. 1988 [DIRS 157927], Section 4.7.4). Other vegetables include root crops (e.g., carrots and potatoes) and crops where the edible parts are unlikely to be exposed directly (e.g., peas and beans that grow inside pods). Fruits include a variety of products such as berries, grapes, currants, melons, pomes (e.g., apples), and drupes (e.g., peaches). Grains include seed-producing crops such as wheat, corn, and barley.

In addition to crops consumed by humans, crops consumed by animals are considered in the plant submodel. Fresh forage (e.g., alfalfa) consumed by beef cattle and dairy cows, and grain fed to poultry and egg-laying hens are considered (see Assumption 8 about animal diets). The mathematical submodel presented in this section applies to all types of crops, but some input parameters are crop-type specific.

The plant submodel does not include radionuclide decay following harvest because the radionuclides of interest are long-lived and decay little during short-term storage. The activity concentration in crops is calculated for the wet-weight of the edible plant portions. The three environmental transport processes (roots, water, and dust) are considered independent, and the total activity concentration in crops is the sum of the three contributions, estimated as

$$Cp_{i,j} = Cp_{root,i,j} + Cp_{water,i,j} + Cp_{dust,i,j} \qquad \text{(Eq. 6.4.3-1)}$$

where

| | | |
|---|---|---|
| $Cp_{i,j}$ | = | activity concentration of radionuclide *i* in crop type *j*, (Bq/kg $_{wet}$) |
| *j* | = | crop-type index; j = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain (used for human and poultry), and 5 for fresh forage feed (used for beef cattle and dairy cows) |
| $Cp_{root,i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* contributed from plant root uptake (Bq/kg $_{wet}$) |
| $Cp_{water,i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* contributed from direct deposition on crop leaves due to interception of contaminated irrigation water (Bq/kg $_{wet}$) |
| $Cp_{dust,i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* contributed from the direct deposition on crop leaves due to interception of resuspended particles from contaminated soil (Bq/kg $_{wet}$). |

### 6.4.3.1 Root Uptake

The radionuclides in the contaminated irrigation water would be transferred to the crops through root uptake. The extent to which plant roots absorb radionuclides from the soil depends on the physiology of the plant, the properties of the soil, and the characteristics of the radionuclide. The uptake of radionuclides by plants usually is considered proportional to radionuclide concentrations in the soil.

The surface soil submodel is used to calculate radionuclide concentrations in the surface layer of the soil. It is assumed that all roots remain in the surface layer, which maximizes the uptake of radionuclides in the submodel (Assumption 7). This approach eliminates the need to determine the fraction of roots in the surface soil. If radionuclides are taken up by the plant roots, the contamination will be internal to the plants and not subject to removal by weathering or food processing. The activity concentration of radionuclides in crops from root uptake is estimated as

$$Cp_{root,i,j} = Cs_{m,i}\ F_{s \to p,i,j}\ DW_j \qquad \text{(Eq. 6.4.3-2)}$$

where

| | | |
|---|---|---|
| $Cs_{m,i}$ | = | activity concentration of radionuclide *i* in surface soil (Bq/kg $_{dry\ soil}$) |
| $F_{s \to p,i,j}$ | = | soil-to-plant transfer factor for radionuclide *i* and crop type *j* (Bq/kg $_{dry\ plant}$ per Bq/kg $_{dry\ soil}$) |
| $DW_j$ | = | dry-to-wet weight ratio for edible part of plant (kg $_{dry\text{-}plant}$ /kg $_{wet\text{-}plant}$). |

The soil-to-plant transfer factor is defined as the ratio of activity concentration of a given radionuclide in dry soil to the activity concentration in dry plants. Observed values of transfer factors vary widely, mainly because of different soils, vegetation types, and environmental conditions (UNSCEAR 2000 [DIRS 158644], p. 39). Because the values of transfer factors represent crop types, rather than the individual crop species, there is uncertainty associated with this parameter. The values of radionuclide-specific and crop-type-specific soil-to-plant transfer factors are developed in BSC (2003 [DIRS 160964]), which also includes a more detailed discussion of the transfer factors. The dry-to-wet weight ratio is represented by the fraction of

dry weight of foodstuff in the total (wet) weight of the foodstuff. Typical values range from a few percent for leafy vegetables to about 90 percent for grain (BSC 2003 [DIRS 160976]).

### 6.4.3.2 Uptake Following Foliar Interception of Irrigation Water

Radionuclide transfer to plants through foliar uptake involves three processes: interception, translocation, and retention (IAEA 1994 [DIRS 100458], Section 2). Interception is the process by which radionuclide contaminants in the atmosphere are deposited on plant surfaces in wet (irrigation water) or dry (resuspended soil) forms. The plant submodel includes two mechanisms of radionuclide uptake from the deposition of contaminants on plants: leaf uptake following interception of irrigation water (this section) and leaf uptake following interception of resuspended particles (Section 6.4.3.3).

Translocation is the process by which chemical elements, initially deposited on the leaf surface, move from the site of deposition to the edible parts of the plant, including parts not directly affected by deposition. The fraction of radionuclides translocated depends on the plant species, the chemical and physical forms of the radionuclides, the stage of plant development, and weathering conditions. In this submodel, translocation refers to that portion of activity initially deposited on a plant surface that contributes to activity in edible parts of the plant, regardless of the external or internal nature of contamination.

Retention is the result of weathering and other field losses, in which a fraction of the radionuclides initially intercepted by foliage is detached from plant surfaces and deposited on the ground. In the ERMYN model, the calculation of activity deposited on leaves is based on daily average irrigation rates per crop type and is carried out within the plant submodel. The activity deposited on the ground is calculated based on the average annual irrigation rate for all crops, which incorporates crop rotation and land use changes, and is carried out within the soil submodel. These two irrigation rates are linked assuming that the activity deposited on the ground is not depleted by foliar deposition (Assumption 6).

In the arid to semi-arid region at Yucca Mountain, crops must be irrigated frequently. Therefore, deposition of radionuclides on plant surfaces by irrigation is modeled as a quasi-continuous process throughout the plant growing season. Radionuclide concentrations in crops due to leaf uptake from contaminated irrigation water sprayed on plants is expressed as

$$Cp_{water,i,j} = \frac{Dw_{i,j}\ f_{o,j}\ Rw_j\ T_j}{\lambda_w\ Y_j}\left(1 - e^{-\lambda_w\ t_{g,j}}\right) \qquad \text{(Eq. 6.4.3-3)}$$

where

| | | |
|---|---|---|
| $Dw_{i,j}$ | = | deposition rate of radionuclide *i* due to application of irrigation water on crop type *j* (Bq/(m$^2$ d)) |
| $f_{o,j}$ | = | fraction of irrigation applied using overhead methods for plant type *j* (dimensionless) |
| $Rw_j$ | = | interception fraction of irrigation water for crop type *j* (dimensionless) |
| $T_j$ | = | translocation factor for crop type *j* (dimensionless) |
| $\lambda_w$ | = | weathering constant (per d), which can be calculated from weathering half-life ($T_w$ in units of day) by $\lambda_w = \ln(2) / T_w$ |

$t_{g,j}$ = crop growing time for crop type $j$ (d)
$Y_j$ = crop yield or wet biomass for crop type $j$ ($kg_{wet\ weight}/m^2$).

For overhead irrigation (i.e., sprinkler or spray), the rate of radionuclide deposition onto the crops, $Dw_{i,j}$, is the product of the irrigation rate and the radionuclide concentration in the water. In this submodel, the radionuclide deposition rate from irrigation water is estimated as

$$Dw_{i,j} = Cw_i \, IRD_j \qquad \text{(Eq. 6.4.3-4)}$$

where

$IRD_{,j}$ = daily average irrigation rate for crop type $j$ during the growing season (m/d) and the other parameter is defined in Equation 6.4.1-1.

The daily irrigation rates for crops vary during the growing season; therefore, a daily average rate over the entire the growing season is used in the submodel. As noted previously, the daily average irrigation rate for a crop (Equation 6.4.3-4) and the annual average irrigation rate on land (Equation 6.4.1-1) serve different purposes. The daily average irrigation rate for a crop type is used to calculate activity deposited on the crop leaves in the plant submodel. The annual average irrigation rate is used to calculate the activity deposited on surface soil. The two irrigation rates are determined based on overwatering requirements, precipitation, and evapotranspiration in BSC (2003 [DIRS 160976]).

The fraction of water applied using overhead irrigation methods, $f_{o,j,}$ is not considered in other biosphere models. However, the rate of contaminant deposition on leaves depends on how irrigation water is applied, and some irrigation methods (e.g., flood and drip irrigation) that cause little foliar deposition are used in the Amargosa Valley (BSC 2003 [DIRS 160976]). Thus, this parameter, which is crop-type specific with values ranging from zero to one, is used to incorporate variation related to site-specific irrigation methods.

The interception fraction for irrigation water, $Rw_j$, quantifies the initial fraction of radionuclides deposited on plant surfaces following irrigation with contaminated water. The possible range for this parameter is 0 to 1. Values for the irrigation interception fraction can be determined using empirical equations or values from the literature. In this submodel, the interception fraction is estimated using an empirical equation (Hoffman et al. 1989 [DIRS 124110]) that is based on crop biomass and the amount and intensity of precipitation and irrigation. The empirical equation was developed using multiple regression analysis on data from experiments where simulated rain was applied to three types of plants: clover, fescue, and mixed grasses. The simulated rain contained five radionuclides: $^{131}I$, $^{7}Be$, $^{141}Ce$, $^{95}Nb$, and $^{85}Sr$. $^{131}I$ and $^{7}Be$ were applied in the form of dissolved species in irrigation water, but the remaining radionuclides were used as tracers in the form of insoluble polystyrene microspheres (Hoffman et al. 1992 [DIRS 124114]). Because the majority of radioactive contaminants in the Yucca Mountain groundwater would be soluble, the results of the $^{131}I$ and $^{7}Be$ experiments are of interest for the groundwater scenario.

The experiments indicate that anionic $^{131}I$, present as periodate ($IO_4^-$), is essentially removed with water after the vegetation surface became saturated, and that cationic $^{7}Be^{2+}$ is adsorbed to, or settles out on, the plant surfaces. The discrepancy between the behavior of the anionic and

cationic species is consistent with a negative charge on the plant surface. Hoffman et al. (1995 [DIRS 124120]) show similar experimental results involving six soluble radionuclides, including $^{51}Cr$ (as $CrO_4^{2-}$), $^{85}Sr$ (as $Sr^{2+}$), $^{109}Cd$ (as $Cd^{2+}$), $^{7}Be$ (as $Be^{2+}$), $^{131}I$ (as $I^-$), and $^{35}S$ (as $SO_4^{2-}$). The results indicate that $^{7}Be$ has the highest interception fraction, while $^{131}I$ has the lowest.

The empirical equation for the interception fraction, *Rw*, from Hoffman et al. (1989 [DIRS 124110]), which is based on the results of experiments with $^{7}Be$ and $^{131}I$, is expressed as

$$Rw_j = K_1\, DB_j^{\,K_2}\, IA_j^{\,K_3}\, I^{K_4} \qquad \text{(Eq. 6.4.3-5)}$$

where

| | | |
|---|---|---|
| $Rw_j$ | = | interception fraction of irrigation water for crop type *j* (dimensionless) |
| $K_1, K_2, K_3$, *and* $K_4$ | = | empirical constants ($K_1$ is in units of $(kg/m^2)^{-K2}$ $(mm)^{-K3}$ $(cm/hr)^{-K4}$, and $K_2$, $K_3$ *and* $K_4$ are dimensionless) |
| $DB_j$ | = | standing biomass of crop type *j* (in units of kg $_{\text{dry weigh}}/m^2$) |
| $IA_j$ | = | amount of irrigation per application event for crop type *j* (value in units of mm) |
| $I$ | = | irrigation intensity (value in units of cm/hr). |

Because this is a regression equation from experimental data, values for the input parameters must be used in the units specified above. The empirical constants in Equation 6.4.3-5, developed based on given parameter units for standing biomass, irrigation amount, and irrigation intensity, depend on the plant type and contaminant form. The recommended values (Hoffman et al. (1989 [DIRS 124110]) are:

| | | | |
|---|---|---|---|
| $K_1$ = 2.29 | for beryllium ($Be^+$); | $K_1$ = 1.54 | for iodine ($I^-$) |
| $K_2$ = 0.695 | for beryllium ($Be^+$); | $K_2$ = 0.697 | for iodine ($I^-$) |
| $K_3$ = -0.29 | for beryllium ($Be^+$); | $K_3$ = -0.909 | for iodine ($I^-$) |
| $K_4$ = -0.341 | for beryllium ($Be^+$); | $K_4$ = -0.049 | for iodine ($I^-$) |

Because radionuclides in the groundwater may be present as different species, the empirical constants cannot be determined unequivocally. Therefore, the ERMYN model uses a simplified approach based on the empirical constants for beryllium. This approach results in the highest values of the irrigation interception fraction because the experimental results indicate that beryllium cations, $Be^{2+}$, in the simulated rain water have the highest interception fraction among the species tested (Hoffman et al. (1989 [DIRS 124110]; Hoffman et al. (1995 [DIRS 124120]).

The standing biomass of the growing crop, *DB*, is a crop-type-specific parameter that represents the capacity of the plants to intercept irrigation water. A typical range for dry biomass is 0.1 to 1.0 $kg/m^2$ (BSC 2003 [DIRS 160976], Section 6.1).

The amount of irrigation per irrigation event, *IA*, in the experiment ranged from 1 to 30 mm, while the experimental irrigation (or rain) intensity, *I*, ranged from 1.4 to 12.2 cm/hr (Hoffman et al. 1995 [DIRS 124120]). Some parameter values representative of crop irrigation in arid and semi environments exceed the ranges used in these experiments (BSC 2003 [DIRS 160976]).

Therefore, a numerical evaluation is used to ensure that the use of this equation is valid (Section 7.4.4.2).

The translocation factor, $T_j$ (Equation 6.4.3-3), is the ratio of activity on 1 $m^2$ of edible plant parts at harvest ($Bq/m^2$) to the activity retained on 1 $m^2$ of foliage at the time of deposition ($Bq/m^2$) (IAEA 1994 [DIRS 100458], p. 12). This factor is equal to the fraction of a chemical element initially deposited on the leaf surface that is absorbed and translocated to the edible plant parts. The possible range for this parameter is zero to one (BSC 2003 [DIRS 160964]).

Radionuclide concentrations on vegetation may be reduced by a variety of processes (e.g., the actions of wind, washout, surface abrasion, volatilization, and growth of new tissue) other than by radioactive decay. These processes can be described by a first order removal submodel with an aggregated weathering constant or weathering rate (IAEA 2001 [DIRS 158519], Section 5.1.1.2). Similar to radionuclide half-life and decay constants, the relationship between the weathering half-life, $T_w$, and the weathering constant, $\lambda_w$, is $T_w = \ln 2/\lambda_w$. The weathering half-life describes the time that it would take for the amount of contaminant deposited on a plant to be reduced to one-half of the initial value. The range of values for the weathering half-life reported in the literature is 6 to 56 d (Till and Meyer 1983 [DIRS 101895], p. 5-36). A typically used value for the weathering half-life is 14 d (BSC 2003 [DIRS 160964], Section 6.2.2.3). There is evidence that the weathering half-life may depend on the plant type and the radionuclide (Smith et al. 1996 [DIRS 101085], p. 5-30); however, this dependence usually is not included in biosphere models.

The crop growing time, $t_{g\,j}$, depends on the crop type and climatic conditions (BSC 2003 [DIRS 160976], Section 6.4). The crop growing time and weathering rate are used in the exponential term in Equation 6.4.3-3. Because the typical value of the weathering half-life is 14 d, the system is considered to reach equilibrium after about three weathering half-lives, a period typically shorter than the crop growing time. Therefore, calculations of activity concentration in crops resulting from the foliar interception of contaminant usually are insensitive to the value of the crop growing time.

The wet yield of crops, $Y_j$, is used to describe the mass of edible plant parts grown per unit area of farmland. This is a crop-type-specific parameter. The range of crop yields for agricultural and garden crops typically grown in southern Nevada is about 0.6 $kg/m^2$ for grain to about 4 $kg/m^2$ for other vegetables (BSC 2003 [DIRS 160976], Section 6.11).

### 6.4.3.3 Uptake by Foliar Interception of Airborne Particulates

The other environmental transport pathway leading to radionuclide contamination of plant surfaces is deposition of resuspended soil, particularly on foliar surfaces. The mathematical representation of this process is similar to that used to represent plant uptake by foliar interception of irrigation water (Equation 6.4.3-3). The radionuclide concentration in crops contributed from uptake by foliar interception of airborne particulates is expressed as

$$Cp_{dust,\,i,j} = \frac{Da_i\, Ra_j\, T_j}{\lambda_w\, Y_j}\left(1 - e^{-\lambda_w\, t_{g,j}}\right) \qquad \text{(Eq. 6.4.3-6)}$$

where

$Da_i$ = deposition rate of radionuclide *i* with resuspended particulates (Bq/(m$^2$ d))
$Ra_j$ = interception fraction for airborne particulates for crop type *j* (dimensionless); see Eq. 6.4.3-8
and the other parameters are defined in Equations 6.4.3-1 and 6.4.3-3.

The deposition rate of contaminated airborne particles, $Da_i$, quantifies the combined effect of contaminant removal from the atmosphere by several processes, such as gravitational settling, diffusion, and turbulent transport. The deposition rate, which can be derived by letting a uniform volumetric activity fall with an average velocity representative of the assembly of particulates for a defined period of time, is mathematically represented as

$$Da_i = 8.64 \times 10^4 Ca_{p,i} V_d \qquad \text{(Eq. 6.4.3-7)}$$

where

$Ca_{p,i}$ = activity concentration of radionuclide *i* in the air used for evaluation of activity deposition on crops (Bq/m$^3$), see Eq. 6.4.2-1
$V_d$ = dry deposition velocity for airborne particulates (m/sec)
$8.64 \times 10^4$ = unit conversion factor (sec/d).

The dry deposition velocity for airborne particulates, $V_d$, is a function of particle size. For climatic conditions in the Amargosa Valley, the appropriate velocity ranges from $5 \times 10^{-4}$ to $3 \times 10^{-2}$ m/s (BSC 2003 [DIRS 160964], Section 6.2.2.1).

The interception fraction for airborne particulates, $Ra_j$, quantifies the initial fractional deposition of radionuclides on plant surfaces from dry deposition. This parameter is crop-type dependent with a range from zero to one. The value of this parameter can be selected from the literature or calculated using an empirical formula. An empirical formula, selected to estimate the value of the interception fraction for airborne particulates, is

$$Ra_j = 1.0 - e^{-a_j DB_j} \qquad \text{(Eq. 6.4.3-8)}$$

where

$a_j$ = an empirical factor for crop type *j* (m$^2$/kg $_{\text{dry biomass}}$)
and the other parameters are defined in Equations 6.4.3-5 and 6.4.3-6.

This empirical equation, including the values of the empirical factor is adopted from the GENII-S model. The recommended values for this factor are 2.9 for leafy vegetables, fresh forage feed, and grain; and 3.6 for root, other vegetables, and fruit (Napier et al. 1988 [DIRS 157927], Section 4.7.4). This empirical formula is modified to use dry biomass (BSC 2003 [DIRS 160976], Section 6.1) rather than wet standing biomass of growing vegetation times the dry-to-wet biomass ratio (Section 7.3.3.3).

### 6.4.4 Animal Submodel

The animal food chain involves the transfer of radionuclides from animal feed, water, and soil to animal products consumed by the receptor. In this submodel, humans consume meat, poultry,

milk, and eggs, four food categories commonly used in radiological assessment models. The regional food consumption survey (DOE 1997 [DIRS 100332]), the basis for calculating consumption rates of locally produced animal products in the Amargosa Valley (BSC 2003 [DIRS 161241]), also includes these four categories. This submodel does not consider the inhalation of contaminated air by animals (Section 6.3.1).

Beef is the representative animal product for all meat (including beef, pork, wild game, and other meat; Assumption 9). To incorporate the use of wild and natural land and water (FEP 2.4.08.00.0A), consumption rates for local game were obtained from the Amargosa Valley food consumption survey (DOE 1997 [DIRS 100332]). The consumption rate for meat is then calculated by combining the consumption rates for wild game and all other meats (BSC 2003 [DIRS 161241], Section 6.4.2). This is done because game could eat crops from irrigated farmlands and drink from irrigation canals and fish ponds. Milk from cows is the representative milk product, chickens are the representative poultry, and chicken eggs are the representative type of eggs (Assumption 9).

Beef cattle and dairy cows are raised using locally grown fresh forage, and poultry and laying hens are fed locally grown grain (Assumption 8). Animals drink contaminated groundwater. Radionuclide concentrations in the soil consumed by animals is based on the long-term concentration obtained using the annual average irrigation rate (Section 6.4.1). Radionuclide decay is not considered in the animal submodel because of the long half-life of the primary radionuclides (Table 6.3-7).

Radionuclide concentrations in animal products are calculated based on a media equilibrium model that uses transfer coefficients to relate the daily radionuclide intake by animals to radionuclide concentrations in animal products. The transfer coefficients represent the fraction of daily radionuclide intake (Bq/d) that transfer into the animal product (based on mass, Bq/kg, or volume, Bq/L). The daily radionuclide intake includes contributions from feed, water, and ingested soil. Radionuclide concentrations in animal products ($Cd_{i,k}$) are estimated as

$$Cd_{i,k} = Cd_{feed\ i,k} + Cd_{water\ i,k} + Cd_{soil\ i,k} \qquad \text{(Eq. 6.4.4-1)}$$

where

| | | |
|---|---|---|
| $Cd_{i,k}$ | = | activity concentration of radionuclide $i$ in animal product $k$ (Bq/kg $_{\text{fresh weight}}$ or Bq/L for milk) |
| $k$ | = | animal product index; $k$ = 1 for beef, 2 for milk, 3 for poultry, 4 for eggs |
| $Cd_{feed\ i,k}$ | = | activity concentration of radionuclide $i$ in animal product $k$ due to ingestion of contaminated animal feed (Bq/kg or Bq/L for milk) |
| $Cd_{water\ i,k}$ | = | activity concentration of radionuclide $i$ in animal product $k$ due to ingestion of contaminated water (Bq/kg or Bq/L for milk) |
| $Cd_{soil\ i,k}$ | = | activity concentration of radionuclide $i$ in animal product $k$ due to ingestion of contaminated soil (Bq/kg or Bq/L for milk). |

### 6.4.4.1 Animal Feed

The radionuclide concentrations in specific animal products from the ingestion of contaminated feed is given by

$$Cd_{feed\ i,k} = Fm_{i,k}\ Cp_{i,j}\ Qf_k \qquad \text{(Eq. 6.4.4-2)}$$

where

| | | |
|---|---|---|
| $Fm_{i,k}$ | = | animal intake-to-animal product transfer coefficient for radionuclide *i* and animal product *k* (d/kg $_{\text{fresh weight}}$ or d/L for milk) |
| $Cp_{i,j}$ | = | activity concentration of radionuclide *i* in animal feed *j* (Bq/kg fresh weight) |
| $j$ | = | animal feed index; $j$ = 5 fresh forage for beef ($k$ = 1) and milk ($k$ = 3), while $j$ = 4 grain for poultry ($k$ = 2) and egg hens ($k$ = 4) |
| $k$ | = | animal product index; see above |
| $Qf_k$ | = | animal consumption rate of feed (kg/d). |

The radionuclide concentrations in animal feed are taken from the plant submodel. The transfer coefficient for individual animal products depend on the element, the chemical form, and the type of animal product. Direct measurements of transfer coefficients are scarce (IAEA 1994 [DIRS 100458], p. 38). Many published values are derived from sources other than explicit experimental data, such as stable element concentrations in feed and animal tissues, extrapolation from single dose tracer experiments, and the assumption of analogous behavior by chemically-similar elements. Therefore, uncertainty in the transfer coefficient values is considerable for most elements. The range of values for transfer coefficients are orders of magnitude (e.g., $1 \times 10^{-5}$ to $1 \times 10^{-1}$ d/kg or d/L), depending on the element and product type (BSC 2003 [DIRS 160964], Section 6.3).

The animal feed consumption rates depend on the species, mass, age, growth rate, and other variables. The values used in biosphere models are for mature animals. Variation in consumption rates reported in the literature is relatively low. Typical values for animal feed are 30 to 70 kg/d for beef cattle and dairy cows, and about 0.12 to 0.4 kg/d for poultry and laying hens (BSC 2003 [DIRS 160964], Section 6.3).

### 6.4.4.2 Animal Drinking Water

Radionuclide concentrations in animal products contributed from ingestion of contaminated drinking water is estimated as

$$Cd_{water\ i,k} = Fm_{i,k}\ Cw_i\ Qw_k \qquad \text{(Eq. 6.4.4-3)}$$

where

| | | |
|---|---|---|
| $Cw_i$ | = | activity concentration of radionuclide *i* in the groundwater (Bq/L) |
| $Qw_k$ | = | animal consumption rate of drinking water (L/d) |

and the other parameters are defined in Equation 6.4.4-2.

As with animal feed, consumption rates for drinking water are based on mature animals, they are animal-type specific, and the data in the literature show little variation. Typical consumption

rates from the literature are 50 to 160 L/d for beef cattle and dairy cows and about 0.3 L/d for poultry and laying hens (BSC 2003 [DIRS 160964], Section 6.3).

#### 6.4.4.3 Animal Soil Ingestion

Ingestion of contaminated soil is another source of radionuclide intake for animals. This pathway is important because of the high soil saturation concentrations for some radionuclides. The radionuclide concentration in animal products contributed from the ingestion of contaminated soil is estimated as

$$Cd_{soil\,i,k} = Fm_{i,k}\, Cs_{m,i}\, Qs_k \qquad \text{(Eq. 6.4.4-4)}$$

where

$Cs_{m,i}$ = saturation activity concentration of radionuclide *i* in the surface soil per unit mass (Bq/kg)

$Qs_k$ = animal consumption rate of soil (kg/d)

and the other parameters are defined in Equation 6.4.4-2.

As in the other cases, inadvertent soil ingestion is estimated for mature animals, and the values are animal-type specific. Typical consumption rates for beef cattle and dairy cows are 1 kg/d or less (BSC 2003 [DIRS 160964], Section 6.3.2). The saturation activity concentration of radionuclides in the surface soil is taken from the surface soil submodel.

### 6.4.5 Fish Submodel

The ERMYN model includes radionuclide transport through an aquatic food chain because there is a fish farm in Amargosa Valley (YMP 1999 [DIRS 158212], Tables 8 and 9), which was fully operational from 1988 until at least 1999 (Roe 2002 [DIRS 160674]). The primary customer for the catfish was the Nevada Division of Wildlife, which used the fish to stock ponds and lakes in southern Nevada. The farm owner also allowed individuals, including residents of Amargosa Valley, to fish the ponds.

Most models for assessing radionuclide transport in aquatic systems are based on the observation that aquatic organisms assimilate radionuclides proportional to radionuclide concentrations in the water (Napier et al. 1998 [DIRS 157927] and Yu et al. [DIRS 159465]). These models are based on equilibrium systems and use equilibrium concentration ratios (also called bioaccumulation factors) to quantify the uptake of radionuclides by aquatic organisms. The bioaccumulation factor is the ratio of the activity concentration in edible portions animal tissue to that in the water (Bq/kg wet to Bq/L). In natural aquatic systems, fish receive radionuclides directly from water and feed. In the Amargosa Valley fish farm, the fish consume commercial feed, which is produced outside the Amargosa Valley and presumably is uncontaminated (Roe 2002 [DIRS 160674]. Therefore, models based on equilibrium concentrations in various components of the aquatic system provide an upper bound for the activity concentration in Amargosa Valley fish. Radionuclide concentrations in fish are expressed as

$$Cf_i = Cw_{f,i}\, BF_i \qquad \text{(Eq. 6.4.5-1)}$$

where

| | | |
|---|---|---|
| $Cf_i$ | = | activity concentration of radionuclide *i* in fish (Bq/kg $_{wet}$) |
| $Cw_{f,i}$ | = | activity concentration of radionuclide *i* in fishpond water, at the time of harvest (Bq/L) |
| $BF_i$ | = | bioaccumulation factor for radionuclide *i* in freshwater fish (L/kg). |

The bioaccumulation factors are element- and species-specific, and for a given element and species, bioaccumulation factors range over several orders of magnitude (BSC 2003 [DIRS 160964], Section 6.4; IAEA 2001 [DIRS 158519], p. 72).

The calculation of radionuclide bioaccumulation in farm-raised fish uses the activity concentration in pond water at the time of harvest. Due to the need to replace water lost by evaporation and the relatively long fish-breeding cycle, the activity concentration in pond water may be higher than that in the groundwater used to fill the ponds. Therefore, a water concentration modifying factor is used to account for the increase in activity concentration due to evaporation. The fish submodel parameters are developed in BSC (2003 [DIRS 160964], Section 6.4). The activity concentration in the fish is calculated as

$$Cf_i = Cw_i \; MF_i \; BF_i \qquad \text{(Eq. 6.4.5-2)}$$

where

| | | |
|---|---|---|
| $Cw_i$ | = | activity concentration of radionuclide *i* in groundwater (Bq/L) |
| $MF_i$ | = | water concentration modifying factor for radionuclide *i* (dimensionless) |

and the other parameters are defined in Equation 6.4.5-1.

Radionuclides also might enter the fish ponds by the deposition of resuspended soil particles. The total amount of deposited material is estimated using a submodel similar to that for direct deposition on crops (plant submodel; Equation 6.4.3-7). Equation 6.4.3-7 uses equations from the air (Equation 6.4.2-1) and surface soil submodels (Equations 6.4.1-4 and 6.4.1-5). Using typical values, $Cw$ = 1 Bq/m$^3$, $IR$ = 1 m/yr, $\lambda_{eff}$ = 0.001/yr, $\rho_s$ = 250 kg/m$^2$, $V_d$ = 0.008 m/sec, and $S = 1 \times 10^{-7}$ kg/m$^3$ (Table 6.6-3, and Table 7.4-4), the annual deposition rate for contaminated airborne particles is $Da$ = 0.1 Bq/(m$^2$ yr). This deposition rate is lower than the activity added annually to the fishponds per unit surface area to replace the water lost by evaporation, which is about 2 Bq/(m$^2$ yr). This value was calculated based on a unit concentration in water ($Cw$ = 1 Bq/m$^3$) and an annual evaporation rate of 2 m/yr (BSC 2002 [DIRS 160964], Section 6.4). Water evaporation from the fishponds is incorporated into the water concentration modifying factor ($MF$).

### 6.4.6 Carbon-14 Special Submodel

Carbon-14 is a primary radionuclide for the groundwater scenario (Section 6.1.3). Because carbon is so common in the environment and because the $^{14}$C transport pathways differ from those of other radionuclides, $^{14}$C transport in the biosphere is considered differently than other radionuclides. Possible $^{14}$C transport pathways include emission from the soil, uptake by crops through roots, uptake by crops through leaves (via photosynthesis), and accumulation in animal products. The ERMYN model includes $^{14}$C as in the $^{14}$C special submodel for the groundwater scenario.

In the groundwater scenario, $^{14}C$ initially is introduced into the soil from contaminated irrigation water. Subsequently, a fraction of the $^{14}C$ is released by gaseous emission into the atmosphere as $^{14}CO_2$. In the atmosphere, $^{14}CO_2$ becomes incorporated into crops via photosynthesis, resulting in increased levels of $^{14}C$ in the crops. The uptake of $^{14}C$ in crops may also occur via the root system; however, root uptake is less important than foliar uptake (BIOMASS 2001 [DIRS 159468], T3FM/WD01, p. 47).

The RESRAD (Yu et al. 2001 [DIRS 159465], Appendix L) and BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522], Appendix A) models include $^{14}C$ special submodels that address the transport of gaseous carbon species from soil through the atmosphere and into plants. These $^{14}C$ special submodels are based on experimental results, which indicated that $^{14}C$ is quickly released from the soil as $^{14}CO_2$. The BIOMASS model also considers the direct absorption of $^{14}C$ by plant leaves from intercepted irrigation water.

The ERMYN $^{14}C$ special submodel is based on RESRAD (Yu et al. 2001 [DIRS 159465], Appendix L). This submodel comparison is discussed in Section 7.3.6. The following are considered for developing the $^{14}C$ special submodel:

- The $^{14}C$ special submodel should include all important exposure pathways for the other radionuclides.

- For inhalation exposure, the airborne sources of $^{14}C$ are gaseous species of carbon released from the soil following irrigation with $^{14}C$-contaminated groundwater. This approach differs from the other radionuclides, where resuspended contaminated soil is the source for inhalation exposure.

- To assess the activity concentration of $^{14}C$ gas in the air, a finite area is irrigated at the average annual irrigation rate. The resulting activity concentration in the air is required to evaluate the inhalation dose and plant leaf uptake.

- Long-term accumulation of $^{14}C$ in the soil is not considered because of the rapid loss of $^{14}C$ from the soil primarily by emission of $^{14}CO_2$.

#### 6.4.6.1 Carbon-14 in Soil

Mechanisms of $^{14}C$ loss from soil include leaching, soil erosion, and radioactive decay, similar to the other radionuclides. However, $^{14}C$ transport in the environment is controlled by an additional loss mechanism, emission loss, which is not applicable to other primary radionuclides. Due to the volatility of $^{14}C$ in soil, it is quickly released via gaseous emission as $^{14}CO_2$. Sheppard et al. (1991 [DIRS 159545]) measured the rate of $^{14}C$ loss from soil in outdoor lysimeter experiments. Carbon loss from the soil, measured by the emission rate (the evasion rate in RESRAD), is 12/yr for clay and loamy soils, and 22/yr for sandy and organic soils (Yu et al. 2001 [DIRS 159465] p. L-16). Thus, $^{14}C$ concentrations in surface soil reach equilibrium within 1 to 2 months. Emission is the dominant mechanism for removing $^{14}C$ from the soil. In comparison, losses due to leaching, radioactive decay, and soil erosion are slight (Table 7.4-4).

The calculation of $^{14}C$ concentration in the soil is based on equilibrium conditions between $^{14}C$ gains and losses. Using a differential equation similar to Equation 6.4.1-1 and the solution similar to Equation 6.4.1-4, the concentration of $^{14}C$ in the soil is expressed as

$$Cs_{C-14,j} = \frac{Cw_{C-14}\ IR_j}{\lambda_{d,C-14} + \lambda_{l,C-14} + \lambda_e + \lambda_{a,C-14}} \qquad \text{(Eq. 6.4.6-1)}$$

where

| | | |
|---|---|---|
| $Cs_{C\text{-}14,j}$ | = | activity concentration of $^{14}C$ in surface soil for the crop type or exposure pathway $j$ (Bq/m$^2$) |
| $j$ | = | crop-type or pathway index; $j$ = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain, and 5 for fresh forage; $j$ = 0 for the pathways including inhalation, soil ingestion, and external exposure |
| $Cw_{C\text{-}14}$ | = | activity concentration of $^{14}C$ in irrigation water (Bq/m$^3$) |
| $IR_{,j}$ | = | crop irrigation rate; $j$ = 1 to 5 for individual crop types ($IRD_j$) and $j$ = 0 for the average annual irrigation rate (m/yr) |
| $\lambda_{d,C\text{-}14}$ | = | radioactive decay constant for $^{14}C$ (per yr) |
| $\lambda_{l,C\text{-}14}$ | = | leaching removal constant for $^{14}C$ (per yr) |
| $\lambda_e$ | = | the surface soil erosion removal constant (per yr) |
| $\lambda_{a,C\text{-}14}$ | = | emission rate constant of $^{14}C$ from the soil to the air (per yr). |

Because crops take up $^{14}C$ from the local soil and air, and because $^{14}C$ is released rapidly from the soil, irrigation in the $^{14}C$ submodel is considered locally and only during the crop growing season. Therefore, the daily average irrigation rate for crop type $j$, $IRD_j$, introduced in the plant submodel, is considered appropriate. This input parameter is used in the $^{14}C$ submodel with a simple conversion of units from m/d to m/yr. This conversion is needed because all removal rates are in units of per year. Modifying this equation to convert all removal rates to units of per day gives the same results. The average annual irrigation rate for farmland, $IR$, in the surface soil submodel is used for calculating the dose from inhalation, soil ingestion, and external exposure.

Equation 6.4.6-1 is analogous to Equation 6.4.1-4, except that the effective removal constant, $\lambda_{eff}$, includes an additional loss term to account for emission. The $^{14}C$ emission loss constant depends on the soil type, but not strongly (Yu et al. 2001 [DIRS 159465] p. L-16).

### 6.4.6.2 Carbon-14 in the Air

Due to the volatility of $^{14}C$, the activity concentration of this radionuclide in the air can not be modeled using the soil resuspension submodel. A separate submodel for the gaseous release of $^{14}C$ from the soil (as $CO_2$) is used to predict $^{14}C$ concentrations in the air. The flux density of gaseous $^{14}C$ from soil to air is estimated as

$$EVSN_j = Cs_{C-14,j}\ \lambda_{a,C-14} \qquad \text{(Eq. 6.4.6-2)}$$

where

$EVSN_j$ = average flux density of gaseous $^{14}C$ from contaminated soil for the crop exposure pathway $j$ (Bq/(m$^2$ yr))

and the other parameters are defined in Equation 6.4.6-1.

If $Cs_{C\text{-}14,j}$ in Equation 6.4.6-2 is substituted using Equation 6.4.6-1, the flux density of gaseous $^{14}C$ from the soil is almost equal to the total deposition rate of $^{14}C$ ($Cw_{C\text{-}14,j} \times IR_j$) because the emission loss constant ($\lambda_{a,C\text{-}14}$ = 22/yr; Table 6.6-3) is much larger than the remaining components of the effective removal constant ($\lambda_{d,C\text{-}14} + \lambda_{l,C\text{-}14} + \lambda_e$ = 0.01/yr; Table 7.4-4). This indicates that the atmosphere, rather than the soil, is the main source of $^{14}C$ available for further dispersion in the environment. It must be noted that the gaseous $^{14}C$ flux of concern to biosphere modeling originates from irrigated land only. After it is released into the air, $^{14}C$ is diluted by mixing with uncontaminated air. The $^{14}C$ concentration in the air above cropland irrigated by contaminated groundwater is estimated using the total $^{14}C$ release rate and the potential mixing volume of air as

$$Ca_{g,C-14,j} = \frac{EVSN_j \times \mathrm{A}}{3.16\times10^7\ H_{mix}\ U\ \sqrt{A}} = \frac{EVSN_j \times \sqrt{\mathrm{A}}}{3.16\times10^7\ H_{mix}\ U} \qquad \text{(Eq. 6.4.6-3)}$$

where

| | | |
|---|---|---|
| $Ca_{g,C\text{-}14,j}$ | = | activity concentration of $^{14}C$ in the air for the crop type or exposure pathway $j$ (Bq/m$^3$) |
| $A$ | = | surface area of irrigated land (m$^2$), which is calculated by $W/IR$, where $W$ was annual total groundwater usage (m$^3$/yr) and $IR$ is annual average irrigation rate (m/yr) defined in Section 6.4.1.1 |
| $H_{mix}$ | = | mixing height of gaseous $^{14}CO_2$ (m) |
| $U$ | = | annual average wind speed (m/sec) |
| $3.16 \times 10^7$ | = | unit conversion factor from year to seconds based on 1 yr = 365.25 d (sec/yr) |

and the other parameters are defined in Equation 6.4.6-2.

The airborne concentration of $^{14}C$ depends on crop types or exposure pathways. The surface area of irrigated land, $A$, is estimated using an annual water demand of 3,000 acre-feet (10 CFR 63.312 [DIRS 156605]) and the average annual irrigation rate. The square root of irrigated area, $A$, is the estimated length of one side of the square with surface area A. The mixing height of gaseous $^{14}C$, $H_{mix}$, depends on the specific pathway and is less for crop uptake than for human uptake. The same is true for the annual average wind speed, $U$, which is slower close to the ground in the plant growing zone than it is in the human breathing zone. Values for the parameters in Equation 6.4.6-3 are developed in BSC (2003 [DIRS 160964], Section 6.7).

The RESRAD model (Yu et al. 2001 [DIRS 159465], p. L-15) uses an additional parameter to account for the fraction of time when wind is blowing over the contaminated area and towards the receptor. In the RESRAD model, the value of this parameter is 0.5 because the receptor is

located at the edge of a relatively small contaminated area. In the ERMYN model, the receptor is located within the contaminated area, where wind blowing from any direction exposes the receptor. Therefore, wind direction is not considered in the ERMYN model.

### 6.4.6.3 Carbon-14 in Crops

In the environment, the transport of $^{14}C$ follows that of stable carbon (Yu et al. 2001 [DIRS 159465], p. L-15). Two transport pathways are considered for the uptake of $^{14}C$ by plants: direct root uptake of $^{14}C$ and leaf uptake of $^{14}CO_2$ released from soil to the atmosphere by gaseous emission. The latter mechanism is dominant because plants acquire most carbon from the atmosphere during photosynthesis (Yu et al. 2001 [DIRS 159465], p. L-18). In the biosphere model, the activity concentration of $^{14}C$ in crops resulting from root uptake is calculated as

$$Cp_{root\ \mathrm{C-14},\,j} = \frac{Cs_{C-14,\,j}}{\rho_s} \frac{Fs \times fc_{plant,\,j}}{fc_{soil}} \qquad \text{(Eq. 6.4.6-4)}$$

where

| | | |
|---|---|---|
| $Cp_{root\ C\text{-}14,j}$ | = | activity concentration of $^{14}C$ in the edible parts of crop type $j$ resulting from root uptake (Bq/kg $_{\text{wet weight}}$ ) |
| $j$ | = | crop-type index; which is the same as that defined in Equation 6.4.6-1, except it does not include $j = 0$. |
| $Cs_{C\text{-}14,j}$ | = | activity concentration of $^{14}C$ in surface soil for crop type $j$ (Bq/m$^2$) |
| $\rho_s$ | = | areal density of surface soil (kg/m$^2$) |
| $fc_{plant,j}$ | = | fraction of stable carbon in crop type $j$ (dimensionless, based on kg $_{\text{carbon}}$ /kg $_{\text{wet crop}}$) |
| $Fs$ | = | fraction of soil-derived carbon in plants (dimensionless) |
| $fc_{soil}$ | = | fraction of stable carbon in soil (dimensionless, based on kg $_{\text{carbon}}$/kg $_{\text{soil}}$). |

The fraction of stable carbon in the soil, $fc_{soil}$, is defined as the mass of carbon per unit mass of soil. The fraction varies depending on soil type, with a typical value on the order of a few percent (BSC 2003 [DIRS 160964]). A value of 0.03 is recommended for the RESRAD model (Yu et al. 2001 [DIRS 159465], p. L-17).

The activity concentration of $^{14}C$ in crops resulting from the uptake through the leaves via photosynthesis is estimated as

$$Cp_{leaf\ \mathrm{C-14},\,j} = Ca_{C-14,\,j} \frac{Fa \times fc_{plant,\,j}}{fc_{air}} \qquad \text{(Eq. 6.4.6-5)}$$

where

| | | |
|---|---|---|
| $Cp_{leaf\ C\text{-}14,j}$ | = | activity concentration of $^{14}C$ in edible parts of crop type $j$ resulting from leaf uptake (Bq/kg $_{\text{wet weight}}$ ) |
| $Ca_{C\text{-}14,j}$ | = | activity concentration of $^{14}C$ in the air for the crop type $j$ (Bq/m$^3$) |
| $Fa$ | = | fraction of air-derived carbon in plants (dimensionless) |
| $fc_{air}$ | = | concentration of stable carbon in the air (kg $_{\text{carbon}}$/m$^3$). |

The concentration of stable carbon in the air, $fc_{air}$, can be derived from the average global value, about $1.8 \times 10^{-4}$ kg/m$^3$ (BSC 2003 [DIRS 160964], Section 6.7). By combining Equation 6.4.6-4 and Equation 6.4.6-5, Equation 6.4.6-6, the total concentration of $^{14}$C in plants, can be obtained as

$$Cp_{C-14,j} = fc_{plant,j}\left[\left(Fa\frac{Ca_{g,C-14,j}}{fc_{air}}\right)+\left(Fs\frac{Cs_{C-14,j}}{\rho_s\ fc_{soil}}\right)\right] \qquad \text{(Eq. 6.4.6-6)}$$

where

$Cp_{C-14,j}$ = activity concentration of $^{14}$C in edible parts of crop type $j$ (Bq/kg $_{\text{wet weight}}$) and the other parameters are defined in Equations 6.4.6-4 and 6.4.6-5.

The fraction of carbon in plants derived from air, $Fa$, ranges from 0 to 1, and experiments indicate that the fraction of carbon in plants derived from air is close to 1 (Yu et al. 2001 [DIRS 159465], p. L-17). A value of $Fa = 0.98$ is recommended for the RESRAD model (Yu et al. 2001 [DIRS 159465], p. L-20). The fraction of carbon in plants derived from soil, $Fs$, is complementary to the fraction of carbon in plants derived from air (i.e., $Fs = 1-Fa$), with a value of about 0.02 (Yu et al. 2001 [DIRS 159465], p. L-17).

The fraction of stable carbon in plants, $fc_{plant,j}$, is crop-type specific, and defined as the mass of carbon per unit wet mass of a plant. Default values for this parameter in the RESRAD and GENII-S models are 0.09 for fruits, vegetables, and fresh forage, and 0.40 for grain (BSC 2003 [DIRS 160964], Section 6.7).

### 6.4.6.4 Carbon-14 in Animal Products

The activity concentration of $^{14}$C in animal products is derived from the animal feed, soil, and drinking water. The transfer of $^{14}$C from feed to animal products is modeled using the same route as that of stable carbon. The $^{14}$C activity concentration in animal products is calculated as

$$Cd_{C-14,k} = \frac{(Cp_{C-14,j}\times Qf_k)+(Cw_{C-14}\times Qw_k)+(Cs_{C-14}\times Qs_k)}{(fc_{plant,j}\times Qf_k)+(fc_{water}\times Qw_k)+(fc_{soil}\times Qs_k)}\times fc_{anim,k} \qquad \text{(Eq. 6.4.6-7)}$$

where

$Cd_{C-14,k}$ = activity concentration of $^{14}$C in animal product $k$ (Bq/kg)
$Cw_{C-14}$ = activity concentration of $^{14}$C in groundwater (Bq/L)
$fc_{water}$ = concentration of stable carbon in farm animal water, kg/L
$fc_{anim,k}$ = fraction of stable carbon in animal product $k$ (dimensionless, based on kg $_{\text{carbon}}$/kg $_{\text{animal product}}$)
and the other parameters are defined in Equations 6.4.4-1 to 6.4.4-4, 6.4.6-1, and 6.4.6-6.

The concentration of stable carbon in water, $fc_{water}$, is on the order of $1 \times 10^{-5}$ kg/L (BSC 2003 [DIRS 160964]). The fraction of stable carbon in animal products, $fc_{anim,k}$, is animal-product dependent. The GENII and RESRAD models use 0.24 for beef, 0.2 for poultry, 0.07 for milk, and 0.15 for eggs (BSC 2003 [DIRS 160964]).

By comparing the three $^{14}C$ sources (feed, water, and soil), the main source for animal $^{14}C$ intake is from feed, as there is only a small amount of carbon in water and soil (Napier et al. 1988 [DIRS 157927] p. 4.89).

#### 6.4.6.5 Carbon-14 in Fish

The activity concentration of $^{14}C$ in fish is calculated using the method developed for other radionuclides, as discussed in Section 6.4.5.

### 6.4.7 External Exposure Submodel

The dose received from external sources of radiation is attributed to high energy beta- and gamma-emitting radionuclides in contaminated media such as soil, air, and water. For external exposure, radiation emitters are external to the human body, and therefore exposure occurs only when a person is near or in contact with the contaminated media. The primary external exposure pathways include exposure to contamination on or in the ground (ground exposure), air submersion, and water immersion.

External exposure of the human receptor can be evaluated using radionuclide media concentrations, exposure times, and dose coefficients. Dose coefficients, tabulated in FGR-12 (Eckerman and Ryman 1993 [DIRS 107684]), convert media concentrations into EDEs per unit exposure time. In this section, the EDE from external exposure is referred to as dose from external exposure.

#### 6.4.7.1 Exposure to Contaminated Soil

The dose coefficients for external exposure to contaminated soils given in the FGR-12 are derived for a source, which when seen from the location of an exposed individual, is uniform and effectively semi-infinite in extent (Eckerman and Ryman 1993 [DIRS 107684], p. 2). For consistency, it is assumed that the same exposure geometry applies to the human receptor in the ERMYN model (Assumption 10). For the groundwater scenario, the irrigated area is limited in extent, and although non-cultivated areas could become contaminated by surface soil transport, the contamination levels would be lower than those on the irrigated land. However, due to crop rotation and changes in land use over the long period considered for evaluation of repository performance, areas not farmed at any given time may have been irrigated previously and thus are considered to remain contaminated. Therefore, it is conservative to assume that the surface soil is contaminated at saturation radionuclide concentrations (see the surface soil submodel, Section 6.4.1).

The annual dose to a receptor from external exposure to primary radionuclide *i* in contaminated soil may include contributions from other primary radionuclides formed in the soil as a result of radioactive decay of radionuclide *i*, as explained in Section 6.3.5. The combined dose is estimated as

$$D_{ext,i} = \sum_l D_{ext,l} = \sum_l EDCi_{soil,l} \frac{Cs_l}{d} \left[ \sum_n f_{ext,l,n} \left( \sum_m PP_m \, (3600 \times t_{n,m}) \right) \right] \quad \text{(Eq. 6.4.7-1)}$$

where

| | | |
|---|---|---|
| $D_{ext,i}$ | = | annual dose from external exposure to primary radionuclide *i* in soil (Sv/yr) |
| $D_{ext,l}$ | = | dose from external exposure to long-lived radionuclide *l* (Table 6.4-1) in a decay chain of a primary radionuclide *i* (Sv/yr) |
| $l$ | = | index of long-lived radionuclide in a decay chain; $l = 0$ for primary radionuclide, |
| $EDCi_{soil,l}$ | = | effective dose coefficient for exposure to soil contaminated to an infinite depth for a long-lived radionuclide *l* in a decay chain of a primary radionuclide *i* (Sv/sec per Bq/m$^3$). Calculation of effective dose coefficients is discussed in Section 6.4.7.2 |
| $Cs_l$ | = | saturation activity concentration in surface soil for a long-lived radionuclide *l* in a decay chain of a primary radionuclide *i* (Bq/m$^2$) |
| $d$ | = | depth of surface soil (m) |
| $f_{ext,l,n}$ | = | external shielding factor for exposure to radionuclide *l* in the soil at environment *n* (dimensionless) |
| $n$ | = | environment index; $n = 1$ for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area |
| $m$ | = | population group index; $m = 1$ for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for non-workers |
| $PP_m$ | = | fraction of total population in population group *m* (population proportion) (dimensionless) |
| $t_{n,m}$ | = | exposure times of population group *m* spent in environment *n* (exposure time) (hr/yr) |
| 3600 | = | unit conversion of hours to seconds; 3,600 (sec/hr). |

To account for variation and uncertainty in the amount of time the receptor would spend in environment *n* (Section 6.4.2.1), four mutually exclusive population groups, *m*, are considered. These groups represent the range of behaviors that would most influence the amount of time that people are exposed to radionuclides via external exposure and inhalation. Variation among individuals in these exposure pathways is influenced primarily by the amount of time they spent indoors and outdoors within contaminated areas (and the amount of time they spent away from contaminated areas). For adults, variation among these time factors primarily is a function of occupational characteristics, as people working outside the contaminated area generally would experience less exposure than people who remain within the area, and people who work outdoors would be exposed at a different level than those who remained indoors. Therefore, the categories are based on work location and type of occupation. Estimates of the proportion of the adult population of Amargosa Valley in each group are developed in BSC (2003 [DIRS 161241] Section 6.3.1).

**Local Outdoor Workers**–This group includes residents who work outdoors and disturb (and therefore resuspend) contaminated soil.

**Local Indoor Workers**–Local indoor workers are residents who work indoors (or outdoors in enclosed vehicles) in areas contaminated by groundwater or ash. The proportion of the population in this group is calculated as the proportion not in the other groups.

**Commuters**–This group includes residents who work outside the contaminated area.

**Non-workers**–Non-workers are residents who are unemployed or otherwise not in the labor force, including retired persons.

The effective dose coefficient for exposure to soil contaminated to an infinite depth, $EDCi_{soil\ l}$, is a radionuclide-specific parameter. Unlike the submodels for crop contamination, the external exposure submodel uses an infinite depth of contaminated soil, rather than the depth of the surface soil. This difference accounts for emissions from radionuclides that leach out of the surface soil into the deep soil, but that still could contribute to the radiation field above the air-ground interface. Radionuclide concentrations in the surface soil are used to calculate the external exposure, even though radionuclide concentrations in the deep soil might not be contaminated at the same high level. As discussed in Section 6.3.5, the short-lived decay products are assumed to be in equilibrium with the long-lived parent radionuclides, and their dose coefficients are combined with the parent dose coefficient to produce an effective dose coefficient. The development of effective dose coefficients, which includes contributions from the short-lived decay products, is discussed in Section 6.4.7.2.

The saturation activity concentration of radionuclide $i$ and its decay product $l$ in soil, $Cs_i$ and $Cs_l$, respectively, are calculated using Equation 6.4.1-4 and Equation 6.4.1-9, which are discussed with respect to the surface soil submodel (Section 6.4.1).

In the submodel, an external shielding factor, $f_{ext,\ l,n}$, is used to account for the reduction in external exposure offered by dwellings. For the outdoors ($n$ = 1, 2, and 5), where normally there would be no shielding, the value for $f_{ext,\ l,}$ is equal to one. For indoor environments ($n$ = 3 and 4), shielding is radionuclide dependent because of radiation characteristics. Shielding factor values range from 0 to 1; however, the typical values, even for the most penetrating radiation emissions, do not exceed 0.4 (BSC 2003 [DIRS 161241], Section 6.6). Radionuclides with strong gamma rays have a higher factor than radionuclides with weak gamma or beta rays.

The external exposure time, $t_{n,m}$, is the annual duration that population group $m$ spend in environment $n$ (BSC 2003 [DIRS 161241]). The fraction of the total population in population group $m$, $PP_m$, is based on current Amargosa Valley census data (BSC 2003 [DIRS 161241]). The exposure time for the active-indoor category and the proportion of indoor-workers are calculated as 1 minus the sum of the other exposure times and population proportions, respectively. The method is provided in BSC (BSC 2003 [DIRS 161241], Section 6.3), and calculations are carried in the ERMYN to incorporate the uncertainty of these parameters.

The external exposure submodel does not include air submersion exposure because air contamination is a secondary process following the resuspension of contaminated surface soil. Because most of the radionuclides of interest are long-lived alpha emitters, the inhalation dose is higher than any subsequent air submersion dose. The external exposure submodel does not include water immersion exposure because of the emission characteristics of the radionuclides

involved (primarily long-lived alpha emitters) and the relatively short exposure times expected in water. Justification for excluding these two pathways is presented in the validation section (Section 7.4.8).

#### 6.4.7.2 Effective Dose Coefficients for Exposure to Contaminated Soil

Dose coefficients for exposure to soil contaminated to an infinite depth are evaluated in BSC (2003 [DIRS 161241], Section 6.5). As discussed in Section 6.3.5, the dose contributions from short-lived decay products are combined with those of their long-lived parent radionuclides. The development of the combined, or effective, dose coefficients is shown in Table 6.4-2. The first column in the table contains the names of the primary radionuclides, followed by a "D" if short-lived decay products are included. The second column lists the short-lived decay products, the dose contributions of which are combined with those of the parent radionuclide. Dose coefficients for the individual radionuclides are shown in the third column. The effective dose coefficients, calculated by summing the dose coefficients for all short-lived decay products under a primary radionuclide, with consideration of the branching fraction, are given in the last column of the table. The calculation method can be expressed as

$$EDCi_{soil,i} = \sum_{s} DCF_{soil,s} \times BN_s \qquad \text{(Eq. 6.4.7-2)}$$

where

$DCF_{soil,s}$ = dose coefficient for exposure to soil contaminated to an infinite depth for short-lived radionuclide $s$ in the decay chain of primary radionuclide $i$ (Sv/sec per Bq/m$^3$)

$s$ = index of short-lived radionuclide decay chain under a primary radionuclide $i$

$BN_s$ = branching fraction for short-lived radionuclide $s$ in the decay chain of primary radionuclide $i$ (dimensionless)

and the other parameter is defined in Equation 6.4.7-1

The values shown in Table 6.4-2 are for demonstration purposes only. The ERMYN model uses branching fractions and dose coefficients as inputs to calculate effective dose coefficients in GoldSim (Section 6.8).

Table 6.4-2. Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth

| Primary Radionuclide | Decay Product [c] (branching fraction if not 100%, half-life) | Dose coefficient ($DCF_{soil}$) [d] (Sv/sec)/(Bq/m$^3$) | Effective dose coefficient ($EDCi_{soil}$) (Sv/sec)/(Bq/m$^3$) |
|---|---|---|---|
| C-14 | - | 7.20E-23 | 7.20E-23 |
| Cl-36 | - | 1.28E-20 | 1.28E-20 |
| Se-79 | - | 9.96E-23 | 9.96E-23 |
| Sr-90D[a] | | 3.77E-21 | 1.32E-19 |
| | Y-90 (64.0 hr) | 1.28E-19 | |
| Tc-99 | - | 6.72E-22 | 6.72E-22 |
| Sn-126D | | 7.89E-19 | 6.34E-17 |
| | Sb-126m (19.0 min) | 4.98E-17 | |
| | Sb-126 (14%, 12.4 d) | 9.16E-17 | |
| I-129 | - | 6.93E-20 | 6.93E-20 |
| Cs-135 | - | 2.05E-22 | 2.05E-22 |
| Cs-137D | | 4.02E-21 | 1.83E-17 |
| | Ba-137m (94.6%, 2.552 min) | 1.93E-17 | |
| Pu-242 | - | 6.85E-22 | 6.85E-22 |
| U-238D | | 5.52E-22 | 8.13E-19 |
| | Th-234 (24.10 d) | 1.29E-19 | |
| | Pa-234m (99.80%, 1.17 min) | 4.80E-19 | |
| | Pa-234 (0.33%, 6.7 hr) | 6.18E-17 | |
| Pu-238 | - | 8.10E-22 | 8.10E-22 |
| U-234 | - | 2.15E-21 | 2.15E-21 |
| Th-230 | - | 6.47E-21 | 6.47E-21 |
| Ra-226D | | 1.70E-19 | 5.99E-17 |
| | Rn-222 (3.8235 d) | 1.26E-20 | |
| | Po-218 (3.05 min) | 3.02E-22 | |
| | Pb-214 (99.98%, 26.8 min) | 7.18E-18 | |
| | At-218 (0.02%, 2 sec) | 3.13E-20 | |
| | Bi-214 (19.9 min) | 5.25E-17 | |
| | Po-214 (99.98%, $1.64 \times 10^{-4}$ sec) | 2.75E-21 | |
| | Tl-210 (0.02%, 1.3 min) [e] | 0.00E+00 | |
| Pb-210D | | 1.31E-20 | 3.27E-20 |
| | Bi-210 (5.012 d) | 1.93E-20 | |
| | Po-210 (138.38 d) | 2.80E-22 | |
| Pu-240 | - | 7.85E-22 | 7.85E-22 |
| U-236 | - | 1.15E-21 | 1.15E-21 |
| Th-232 | - | 2.79E-21 | 2.79E-21 |
| Ra-228D[b] | | 0.00E+00 | 3.20E-17 |
| | Ac-228 (6.13 hr) | 3.20E-17 | |
| U-232 | - | 4.83E-21 | 4.83E-21 |
| Th-228D | | 4.25E-20 | 5.46E-17 |
| | Ra-224 (3.66 d) | 2.74E-19 | |
| | Rn-220 (55.6 sec) | 1.23E-20 | |
| | Po-216 (0.15 sec) | 5.58E-22 | |
| | Pb-212 (10.64 hr) | 3.77E-18 | |
| | Bi-212 (60.55 min) | 6.27E-18 | |
| | Po-212 (64.07%, 0.305 μ-sec) | 0.00E+00 | |
| | Tl-208 (35.93%, 3.07 min) | 1.23E-16 | |

Table 6.4-2. Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth (continued)

| Primary Radionuclide | Decay Product [c] (branching fraction if not 100%, half-life) | Dose coefficient ($DCF_{soil}$) [d] (Sv/sec)/(Bq/m$^3$) | Effective dose coefficient ($EDCi_{soil}$) (Sv/sec)/(Bq/m$^3$) |
|---|---|---|---|
| Am-243D | | 7.60E-19 | 4.79E-18 |
| | Np-239 (2.355 d) | 4.03E-18 | |
| Pu-239 | - | 1.58E-21 | 1.58E-21 |
| U-235D | | 3.86E-18 | 4.06E-18 |
| | Th-231 (25.52 hr) | 1.95E-19 | |
| Pa-231 | - | 1.02E-18 | 1.02E-18 |
| Ac-227D | | 2.65E-21 | 1.08E-17 |
| | Th-227 (98.62%, 18.718 d) | 2.79E-18 | |
| | Fr-223 (1.38%, 21.8 min) | 1.06E-18 | |
| | Ra-223 (11.434 d) | 3.23E-18 | |
| | Rn-219 (3.96 sec) | 1.65E-18 | |
| | Po-215 (1.78 millisec) | 5.44E-21 | |
| | Pb-211 (36.1 min) | 1.64E-18 | |
| | Bi-211 (2.14 min) | 1.37E-18 | |
| | Tl-207 (99.72%, 4.77 min) | 1.06E-19 | |
| | Po-211 (0.28%, 0.516 sec) | 2.55E-19 | |
| Am-241 | - | 2.34E-19 | 2.34E-19 |
| Np-237D | | 4.17E-19 | 5.88E-18 |
| | Pa-233 (27.0 d) | 5.46E-18 | |
| U-233 | - | 7.48E-21 | 7.48E-21 |
| Th-229D | | 1.72E-18 | 8.55E-18 |
| | Ra-225 (14.8 d) | 5.90E-20 | |
| | Ac-225 (10.0 d) | 3.41E-19 | |
| | Fr-221 (4.8 min) | 8.22E-19 | |
| | At-217 (32.3 millisec) | 9.49E-21 | |
| | Bi-213 (45.65 min) | 4.10E-18 | |
| | Po-213 (97.84%, 4.2 µ-sec) | 0.00E+00 | |
| | Tl-209 (2.16%, 2.2 min) | 6.92E-17 | |
| | Pb-209 (3.253 hr) | 4.14E-21 | |

NOTES: DC = dose coefficients

[a] A "D" indicates that the radionuclide is treated with its short-lived (< 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Eckerman and Ryman (1993 [DIRS 107684], Table A.1).

[d] Dose coefficient source (BSC 2003 [DIRS 161241], Section 6.5).

[e] Half-life of Tl-210 is taken from Lide and Frederikse (1997 [DIRS 103178], p.11-125).

### 6.4.8 Inhalation Exposure Submodel

The inhalation submodel is used to calculate radiation doses caused by the inhalation of contaminated air. The inhalation dose is estimated using radionuclide concentrations in the air, parameters describing conditions of human exposure, and dose conversion factors for inhalation exposure that convert radionuclide intake to CEDE. Activity concentrations in the air are discussed in Section 6.4.2 (air submodel). In contrast to external exposure, where emissions

arise from outside the human body, inhalation and ingestion exposures arise from radiation emitted inside the body, and the exposure continues for as long as the radionuclides are in the body. Therefore inhalation and ingestion doses are presented in terms of the CEDE, which represents the EDE integrated over the 50-yr commitment period. The CEDE, although delivered over the commitment period, is assigned to the period of intake (1 yr). Analogous to the external exposure submodel, the CEDE is referred to as the dose or the annual dose. This submodel includes three types of air contamination: resuspension of contaminated soil (Section 6.4.2.1), aerosols from evaporative coolers (Section 6.4.2.2), and gaseous emissions from soil, which includes exhalation of $^{222}$Rn (Section 6.4.2.3) and gaseous emissions of $^{14}$C (Section 6.4.6.2). The total inhalation dose is the sum of the doses resulting from these three inhalation exposure pathways, expressed as

$$D_{inh,i} = D_{inh,p,i} + D_{inh,e,i} + D_{inh,g,i} \qquad \text{(Eq. 6.4.8-1)}$$

where

| | | |
|---|---|---|
| $D_{inh,i}$ | = | annual dose from inhalation exposure to radionuclide *i* (Sv/yr) |
| $D_{inh,p,i}$ | = | annual dose from inhalation exposure to radionuclide *i* in resuspended particles (Sv/yr) |
| $D_{inh,e,i}$ | = | annual dose from inhalation exposure to radionuclide *i* resulting from the operation of an evaporative cooler (Sv/yr) |
| $D_{inh,g,i}$ | = | annual dose from inhalation exposure to radionuclide *i* resulting from gaseous emission from the soil (Sv/yr). This term applies only to the inhalation of $^{222}$Rn gas and the inhalation of $^{14}CO_2$. |

### 6.4.8.1 Inhalation of Resuspended Particles

Exposure from the inhalation of radionuclides in resuspended particles depends on a number of factors, including activity concentrations in air, indoor and outdoor exposure times, the particle size distribution, the radionuclide, the chemical form of the radionuclide, and the breathing rate of the receptor. Although the resuspension pathway usually is not an important contributor to long-term exposure for most locations, it is potentially important in the dusty environments associated with some human activities (NCRP 1999 [DIRS 155894], p. 59).

As discussed for the air submodel (Section 6.4.2), radionuclide concentrations in the air, $Ca_{h,i,n}$, are calculated for five environments associated with human activities and characterized by different concentrations of resuspended particles. The receptor used for the performance assessment of the repository is the RMEI, the characteristics of which are based on the lifestyles and behaviors of people residing in the Amargosa Valley. Evaluation of the inhalation exposure to the RMEI involves considering various population groups within the Amargosa Valley population. Therefore, parameter values for this pathway depend on the environment, the population group, or both. The inhalation submodel includes five environments, four in the contaminated area (active outdoors, inactive outdoors, active indoors, and asleep indoors) and one away from the contaminated area. The population groups include commuters, local outdoor workers, local indoor workers, and non-workers (Section 6.4.7).

Annual doses resulting from the inhalation of primary radionuclides should also include exposure to radionuclides in the decay chain (as discussed for the surface soil submodel; Section 6.4.1.2) because the resuspended particles would come from the surface soil where radionuclides would build up during long-term irrigation. The combined dose is estimated as

$$D_{inh,p,i} = \sum_{l} D_{inh,p,l} = \sum_{l} EDCF_{inh\ l} \left[ \sum_{n} Ca_{h,l,n}\ BR_n \sum_{m} \left( PP_m\ t_{n,m} \right) \right] \quad \text{(Eq. 6.4.8-2)}$$

where

| | | |
|---|---|---|
| $D_{inh,p,i}$ | = | annual dose from inhalation exposure to primary radionuclide *i* in resuspended particles (Sv/yr) |
| $D_{inh,p,l}$ | = | annual dose from inhalation exposure to long-lived radionuclide *l* in a decay chain of primary radionuclide *i* in resuspended particles (Sv/yr) |
| $l$ | = | radionuclide index for a decay chain, *l* = 0 for primary radionuclide, 1 for the first long-lived decay product, 2 for the second long-lived decay product |
| $EDCF_{inh,l}$ | = | effective dose conversion factor for inhalation of long-lived radionuclide *l* in a decay chain of primary radionuclide *i* (Sv/Bq). Calculation of effective dose conversion factors is discussed in Section 6.4.8.5 |
| $n$ | = | environment index; *n* = 1 for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area |
| $Ca_{h,l,n}$ | = | activity concentration of radionuclide *l* in a decay chain of primary radionuclide *i* in air for environment *n* (Bq/m$^3$) |
| $BR_n$ | = | breathing rate for environment *n* (m$^3$/hr) |
| $m$ | = | population group index; *m* = 1 for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for non-workers |
| $PP_m$ | = | fraction of the total population in population group *m* (population proportion) (dimensionless) |
| $t_{n,m}$ | = | annual amount of time that population group *m* spends in environment *n* (exposure time) (hr/yr). |

The effective dose conversion factor for inhalation of radionuclide *l*, $EDCF_{inh\ l,}$ includes contributions from the short-lived decay products. The development of this parameter is described in Section 6.4.8.5. The inhalation exposure time, $t_{n,m}$, is the annual amount of time that population *m* spends in environment *n*, depending on the characteristics of the receptor (BSC 2003 [DIRS 161241]). The breathing rate, $BR_n$ varies among environments.

### 6.4.8.2 Inhalation of Aerosols from Evaporative Coolers

In 1997, about 73 percent of surveyed Amargosa Valley residents used evaporative coolers (DOE 1997 [DIRS 100332], p. 20). Therefore, this submodel includes the inhalation of radionuclides introduced into indoor air by coolers as an exposure pathway. During the operation of evaporative coolers, the indoor air exchange rate is high, the residence time for the air inside the dwelling is short, and only the primary radionuclides and decay products in secular equilibrium in the groundwater are considered in this portion of the submodel.

Evaporative coolers are not expected to result in a large transport of outdoor particulates into the indoor space because the cooler pads filter out the particulates. The potential contribution of contaminated indoor air to the outdoors and to outdoor inhalation exposure is not incorporated in the submodel because the dilution of that air would be large.

Evaporative coolers are not usually operated year-round; most people use them only during the hotter months (DOE 1997 [DIRS 100332]. Therefore, the indoor inhalation exposure time is modified by an evaporative cooler use factor that represents the fraction of time when evaporative coolers are used. Even during the use period, evaporative coolers are not operated continuously. However, it is assumed that indoor radionuclide concentrations do not decrease when an evaporative cooler is temporarily turned off (Assumption 11).

The inhalation dose attributable to evaporative cooler operation is estimated, using a method similar to Equation 6.4.8-2, as

$$D_{inh,e,i} = EDCF_{inh,i}\ Ca_{e,i}\ f_{cooler}\ f_{use} \sum_{n=3}^{4} BR_n \left( \sum_m PP_m\ t_{n,m} \right) \qquad \text{(Eq. 6.4.8-3)}$$

where

| | | |
|---|---|---|
| $D_{inh,e,i}$ | = | annual dose from inhalation of primary radionuclide *i* from evaporative cooler operation (Sv/yr) |
| $EDCF_{inh,i}$ | = | effective dose conversion factor for inhalation of radionuclide *i* (Sv/Bq) |
| $Ca_{e,i}$ | = | activity concentration of radionuclide *i* in indoor air attributable to the evaporative cooler operation (Bq/m$^3$) |
| $n$ | = | environment index ($n$ = 3 or $n$ = 4 denotes an indoor environment) |
| $f_{cooler}$ | = | fraction of houses with evaporative coolers (dimensionless) |
| $f_{use}$ | = | annual evaporative cooler use factor (dimensionless) |

and the other parameters are defined in Equation 6.4.8.2.

The activity concentration of radionuclides in indoor air attributable to the operation of evaporative coolers is discussed in the air submodel (Section 6.4.2.2). The annual evaporative cooler use factor and the fraction of houses with evaporative coolers are developed based on a site-specific survey in Amargosa Valley (DOE 1997 [DIRS 100332]) and temperatures representative of current and future predicted climatic conditions there, as documented in BSC (2003 [DIRS 161241]).

### 6.4.8.3 Inhalation of Carbon-14

This submodel includes another potential inhalation exposure pathway: the inhalation of gaseous $^{14}C$ released from irrigated soil. After $^{14}C$ is released from soil as $^{14}CO_2$, it is dispersed in the outdoor and indoor environments. There are no mechanisms to greatly change the indoor concentration of $^{14}C$ relative to the outdoor concentration, so both are considered the same. The inhalation dose from $^{14}C$ is calculated using a method similar to that used to calculate the inhalation dose from resuspended particulates (Section 6.4.8.1)

$$D_{inh,g,C-14} = \sum_n D_{inh,g,C-14,n}$$
$$= DCF_{inh,C-14}\ Ca_{g,C-14} \sum_n BR_n \left( \sum_m PP_m\ t_{n,m} \right) \qquad \text{(Eq. 6.4.8-4)}$$

where

| | | |
|---|---|---|
| $D_{inh,g,C-14}$ | = | annual dose from inhalation of gaseous $^{14}C$ (Sv/yr) |
| $D_{inh,g,C-14,n}$ | = | annual dose from inhalation of gaseous $^{14}C$ for environment *n* (Sv/yr) |
| $Ca_{g,C-14}$ | = | activity concentration of $^{14}C$ in air (Bq/m$^3$) |
| $DCF_{inh,C-14}$ | = | dose conversion factor for inhalation of $^{14}C$ (Sv/Bq) |

and the other parameters are defined in Equations 6.4.6.3, 6.4.8-1, and 6.4.8-2.

### 6.4.8.4 Inhalation of Radon Decay Products

The release of $^{222}Rn$ from the soil, and its subsequent decay in the air through a series of short-lived decay products, causes an inhalation dose. In the soil, $^{226}Ra$ is considered to have originated from irrigation water or from radioactive decay of other radionuclides initially present in irrigation water (Section 6.4.1.2).

The dose due to inhalation of radon decay products is evaluated separately for indoor environments when evaporative coolers are off and when they are in operation because of the increase in ventilation caused by the operation of coolers. The total radon dose from $^{222}Rn$ decay products is evaluated as

$$D_{inh,g,Rn-222} = \sum_n D_{inh,g,Rn-222,n}$$
$$= \sum_{n=1}^{5} Ca_{g,Rn-222,n}\ F_n\ DCF_{inh,Rn-222,n}\ BR_n \left( \sum_m PP_m\ t_{n,m} \right) + \qquad \text{(Eq. 6.4.8-5)}$$
$$\sum_{n=3}^{4} Ca_{g,Rn-222,e}\ f_{cooler}\ f_{use}\ DCF_{inh,Rn-222,n}\ BR_n \left( \sum_m PP_m\ t_{n,m} \right)$$

where

| | | |
|---|---|---|
| $D_{inh,g,Rn-222}$ | = | annual dose from inhalation of $^{222}Rn$ decay products (Sv/yr) |
| $D_{inh,g,Rn-222\ n}$ | = | annual dose from inhalation of $^{222}Rn$ decay products for environment *n* (Sv/yr) |
| $Ca_{g,Rn-222,n}$ | = | activity concentration of $^{222}Rn$ in environment *n* (Bq/m$^3$) |
| $F_n$ | = | correction factor to account for the use of evaporative coolers in indoor environment *n* (dimensionless), 1 for *n* =1 & 2, and ($1 - f_{cooler} \times f_{use}$) for *n* = 3 & 4 |
| $Ca_{g,Rn-222,e}$ | = | activity concentration of $^{222}Rn$ in indoor air at a high ventilation rate during evaporative cooler in operation (Bq/m$^3$) |
| $DCF_{inh,Rn-222,n}$ | = | dose conversion factor for inhalation of $^{222}Rn$ decay products for environment *n* (Sv/Bq) |

and the other parameters are defined in Equations 6.4.8-1, 6.4.8-2, and 6.4.8-3.

The dose conversion factor for the inhalation of $^{222}$Rn decay products for environment *n* can be further expressed as

$$DCF_{inh,Rn-222,n} = DCF_{inh,Rn-222}\ EF_{Rn-222,n} \qquad \text{(Eq. 6.4.8-6)}$$

where

| | | |
|---|---|---|
| $EF_{Rn\text{-}222,\,n}$ | = | equilibrium factor for $^{222}$Rn decay products for environment *n* (dimensionless) |
| $DCF_{inh,\,Rn\text{-}222}$ | = | dose conversion factor for inhalation of $^{222}$Rn decay products in equilibrium. |

The equilibrium factor permits estimating the potential alpha energy concentration from the measurement of radon gas (here $^{222}$Rn), and is defined as the ratio of the actual potential alpha energy concentration to that prevailing if all decay products in the $^{222}$Rn series are in equilibrium with the parent radon. The equilibrium factor depends on the environment, such as indoors and outdoors (BSC 2003 [DIRS 160964], Section 6.6). By combining Equations 6.4.8-5 and 6.4.8-6, the inhalation dose from the $^{222}$Rn decay products is evaluated as

$$\begin{aligned} D_{inh,g,Rn-222} &= \sum_n D_{inh,g,Rn-222,n} \\ &= DCF_{inh,Rn-222} \sum_{n=1}^{5} Ca_{g,Rn-222,n}\ F_n\ EF_{Rn-222,n}\ BR_n \left( \sum_m PP_m\ t_{n,m} \right) + \\ &\quad DCF_{inh,Rn-222} \sum_{n=3}^{4} Ca_{g,Rn-222,e}\ f_{cooler}\ f_{use}\ EF_{Rn-222,n}\ BR_n \left( \sum_m PP_m\ t_{n,m} \right) \end{aligned} \qquad \text{(Eq. 6.4.8-7)}$$

where the parameters are defined in Equations 6.4.8-3, 6.4.8-5, and 6.4.8-6.

For the TSPA-LA, $^{222}$Rn is a decay product of $^{226}$Ra, not a primary radionuclide. This radon inhalation dose contribution is added into the BDCF for $^{226}$Ra or to radionuclides that have $^{226}$Ra as a decay product.

The calculation of dose from radon decay products is based on the indoor and outdoor concentrations of radon gas. The indoor radon concentration is equal to outdoor radon concentration plus a contribution of radon from soil beneath the house, which depends on the house ventilation rate. Two ventilation rates are considered in the submodel: a high rate when coolers are in use, and a low rate when coolers are not in use. When evaporative coolers are in use, the contribution of radon from soil beneath the house would be limited because the high ventilation rate would prevent radon buildup. However, when evaporative coolers are not in operation, or for houses that had no evaporative cooler, a higher radon contribution from soil beneath the house would be expected. Radon from household water use (e.g., showers and evaporative coolers) typically is of minor importance (Section 7.4.3.1). Therefore, the submodel does not include this pathway.

### 6.4.8.5 Effective Dose Conversion Factor for Inhalation

The effective inhalation dose conversion factors used in the ERMYN model are based on dose conversion factors obtained from FGR-11 (Eckerman et al. 1988 [DIRS 101069], Table 2.1). These factors represent the radionuclide-specific CEDE for the 50-yr commitment period per unit activity intake. As discussed in Section 6.3.5, the dose contributions from short-lived decay products are combined with those of the long-lived parent radionuclide to produce effective dose conversion factors. The development of the effective inhalation dose conversion factors is shown in Table 6.4-3. The calculation method can be expressed as

$$EDCF_{inh,i} = \sum_{s} DCF_{inh,s} \times BN_s \qquad \text{(Eq. 6.4.8-8)}$$

where

$DCF_{inh,s}$ = dose conversion factor for inhalation for short-lived radionuclide $s$ in the decay chain of primary radionuclide $i$ (Sv/Bq)

$s$ = index of short-lived radionuclide decay chain under a primary radionuclide $i$

$BN_s$ = branching fraction for short-lived radionuclide $s$ in the decay chain of primary radionuclide $i$ (dimensionless)

and the other parameter is defined in Equation 6.4.8-2.

Similar to Table 6.4-2, the values in Table 6.4-3 are for demonstration purposes only. The ERMYN model uses branching fractions and dose conversion factors as inputs to calculate the effective dose conversion factors in GoldSim (Section 6.8).

The inhalation dose conversion factor for some radionuclides have different values depending on the chemical compound of the radionuclide and the lung clearance class. Because the chemical form of radionuclides in the biosphere is not known, the highest values of dose conversion factors from among those available generally are chosen. However, the highest inhalation dose conversion factor value for $^{90}Sr$ is for the chemical compound $SrTiO_3$, which is not a common chemical compound expected in the biosphere (Rittmann 1993 [DIRS 107744], Section 2), so it is not used. The justification for selecting inhalation dose conversion factors is provided in BSC (2003 [DIRS 161241], Section 6.5).

Table 6.4-3. Effective Dose Conversion Factors for Inhalation

| Primary Radionuclide | Lung Clearance Class | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Conversion Factor ($DCF_{inh}$) [d] (Sv/Bq) | Effective Dose Conversion Factor ($EDCF_{inh}$) (Sv/Bq) |
|---|---|---|---|---|
| C-14 | $CO_2$ | - | 6.36E-12 | 6.36E-12 |
| Cl-36 | W | - | 5.93E-09 | 5.93E-09 |
| Se-79 | W | - | 2.66E-09 | 2.66E-09 |
| Sr-90D[a] | D | | 6.47E-08 | 6.70E-08 |
| | Y | Y-90 (64.0 hr) | 2.28E-09 | |
| Tc-99 | W | - | 2.25E-09 | 2.25E-09 |
| Sn-126D | W | | 2.69E-08 | 2.74E-08 |
| | D | Sb-126m (19.0 min) | 9.17E-12 | |
| | W | Sb-126 (14%, 12.4 d) | 3.17E-09 | |
| I-129 | D | - | 4.69E-08 | 4.69E-08 |
| Cs-135 | D | - | 1.23E-09 | 1.23E-09 |
| Cs-137D | D | | 8.63E-09 | 8.63E-09 |
| | - | Ba-137m (94.6%, 2.552 min) | 0.00E+00 | |
| Pu-242 | W | - | 1.11E-04 | 1.11E-04 |
| U-238D | Y | | 3.20E-05 | 3.20E-05 |
| | Y | Th-234 (24.10 d) | 9.47E-09 | |
| | - | Pa-234m (99.80%, 1.17 min) | 0.00E+00 | |
| | Y | Pa-234 (0.20%, 6.7 hr) | 2.20E-10 | |
| Pu-238 | W | - | 1.06E-04 | 1.06E-04 |
| U-234 | Y | - | 3.58E-05 | 3.58E-05 |
| Th-230 | W | - | 8.80E-05 | 8.80E-05 |
| Ra-226D | W | | 2.32E-06 | 2.32E-06 |
| | - | Rn-222 (3.8235 d) | 0.00E+00 | |
| | - | Po-218 (3.05 min) | 0.00E+00 | |
| | D | Pb-214 (99.98%, 26.8 min) | 2.11E-09 | |
| | - | At-218 (0.02%, 2 sec) | 0.00E+00 | |
| | D | Bi-214 (19.9 min) | 1.78E-09 | |
| | - | Po-214 (99.98%, $1.64 \times 10^{-4}$ sec) | 0.00E+00 | |
| | - | Tl-210 (0.02%, 1.3 min) [e] | 0.00E+00 | |
| Pb-210D | D | | 3.67E-06 | 6.26E-06 |
| | W | Bi-210 (5.012 d) | 5.29E-08 | |
| | D | Po-210 (138.38 d) | 2.54E-06 | |
| Pu-240 | W | - | 1.16E-04 | 1.16E-04 |
| U-236 | Y | - | 3.39E-05 | 3.39E-05 |
| Th-232 | W | - | 4.43E-04 | 4.43E-04 |
| Ra-228D[b] | W | | 1.29E-06 | 1.37E-06 |
| | D | Ac-228 (6.13 hr) | 8.33E-08 | |
| U-232 | Y | - | 1.78E-04 | 1.78E-04 |

Table 6.4-3. Effective Dose Conversion Factors for Inhalation (continued)

| Primary Radionuclide | Lung Clearance Class | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Conversion Factor (*DCF*$_{inh}$) [d] (Sv/Bq) | Effective Dose Conversion Factor (*EDCF*$_{inh}$) (Sv/Bq) |
|---|---|---|---|---|
| Th-228D | Y | | 9.23E-05 | 9.32E-05 |
| | W | Ra-224 (3.66 d) | 8.53E-07 | |
| | - | Rn-220 (55.6 sec) | 0.00E+00 | |
| | - | Po-216 (0.15 sec) | 0.00E+00 | |
| | D | Pb-212 (10.64 hr) | 4.56E-08 | |
| | D | Bi-212 (60.55 min) | 5.83E-09 | |
| | - | Po-212 (64.07%, 0.305 µ-sec) | 0.00E+00 | |
| | - | Tl-208 (35.93%, 3.07 min) | 0.00E+00 | |
| Am-243D | W | | 1.19E-04 | 1.19E-04 |
| | W | Np-239 (2.355 d) | 6.78E-10 | |
| Pu-239 | W | - | 1.16E-04 | 1.16E-04 |
| U-235D | Y | | 3.32E-05 | 3.32E-05 |
| | Y | Th-231 (25.52 hr) | 2.37E-10 | |
| Pa-231 | W | - | 3.47E-04 | 3.47E-04 |
| Ac-227D | D | | 1.81E-03 | 1.82E-03 |
| | Y | Th-227 (98.62%, 18.718 d) | 4.37E-06 | |
| | D | Fr-223 (1.38%, 21.8 min) | 1.68E-09 | |
| | W | Ra-223 (11.434 d) | 2.12E-06 | |
| | - | Rn-219 (3.96 sec) | 0.00E+00 | |
| | - | Po-215 (1.78 millisec) | 0.00E+00 | |
| | D | Pb-211 (36.1 min) | 2.35E-09 | |
| | - | Bi-211 (2.15 min) | 0.00E+00 | |
| | - | Tl-207 (99.72%, 4.77 min) | 0.00E+00 | |
| | - | Po-211 (0.28%, 0.516 sec) | 0.00E+00 | |
| Am-241 | W | - | 1.20E-04 | 1.20E-04 |
| Np-237D | W | | 1.46E-04 | 1.46E-04 |
| | Y | Pa-233 (27.0 d) | 2.58E-09 | |
| U-233 | Y | - | 3.66E-05 | 3.66E-05 |
| Th-229D | W | | 5.80E-04 | 5.85E-04 |
| | W | Ra-225 (14.8 d) | 2.10E-06 | |
| | D | Ac-225 (10.0 d) | 2.92E-06 | |
| | - | Fr-221 (4.8 min) | 0.00E+00 | |
| | - | At-217 (32.3 millisec) | 0.00E+00 | |
| | D | Bi-213 (45.65 min) | 4.63E-09 | |
| | - | Po-213 (97.84%, 4.2 µ-sec) | 0.00E+00 | |
| | - | Tl-209 (2.16%, 2.2 min) | 0.00E+00 | |
| | D | Pb-209 (3.253 hr) | 2.56E-11 | |

NOTES: DCF = dose conversion factor.

[a] A "D" indicates that the radionuclide is treated with its short-lived (< 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Eckerman and Ryman (1993 [DIRS 107684], Table A.1).

[d] Dose conversion factor source (BSC 2003 [DIRS 161241], Section 6.5).

[e] Half-life of Tl-210 is taken from Lide and Frederikse (1997 [DIRS 103178] p.11-125).

### 6.4.9 Ingestion Exposure Submodel

When contaminated groundwater is used to produce food for humans or farm animals, the ingestion of that food should result in a radiation dose. Inadvertent ingestion of contaminated soil also results in a radiation dose. The ingestion submodel addresses human doses from ingesting contaminated drinking water, four types of crops (leafy vegetables, other vegetables, fruits, and grain), four types of animal products (meat in the form of beef, poultry, milk, and eggs), freshwater fish, and soil. The ingestion dose, analogous to the inhalation dose, is calculated as the CEDE for the 50-yr committed period resulting from 1 year of intake.

The methods for calculating activity concentrations in contaminated crops, animal products, and fish are discussed with respect to the plant (Section 6.4.3), animal (Section 6.4.4), and fish submodels (Section 6.4.5), respectively. The source of water for human consumption, animal consumption, irrigation, and fish farming is untreated groundwater. The rate of inadvertent soil ingestion by adults is used in the submodel, but purposeful soil ingestion is excluded. The total ingestion dose for a radionuclide includes contributions from all of these sources, and is expressed as

$$D_{ing,i} = D_{ing,w,i} + D_{ing,p,i} + D_{ing,d,i} + D_{ing,f,i} + D_{ing,s,i} \qquad \text{(Eq. 6.4.9-1)}$$

where

| | | |
|---|---|---|
| $D_{ing\ i}$ | = | annual dose from ingestion of radionuclide *i* (Sv/yr) |
| $D_{ing,w,i}$ | = | annual dose from ingestion of radionuclide *i* in drinking water (Sv/yr) |
| $D_{ing,p,i}$ | = | annual dose from ingestion of radionuclide *i* in crops (Sv/yr) |
| $D_{ing,d,i}$ | = | annual dose from ingestion of radionuclide *i* in animal products (Sv/yr) |
| $D_{ing,f,i}$ | = | annual dose from ingestion of radionuclide *i* in fish (Sv/yr) |
| $D_{ing,s,i}$ | = | annual dose from inadvertent ingestion of radionuclide *i* in surface soil (Sv/yr). |

These ingestion pathways are discussed in detail in the following subsections.

All short-lived radionuclides (half-life less than 180 d) are assumed to be in equilibrium with the long-lived primary radionuclides, and the effective dose conversion factors for the long-lived primary radionuclides includes their dose contribution (Assumption 2). In addition, for pathways such as ingestion of crops, animal products, and soil, the contribution due to radionuclide decay and ingrowth in surface soil is added into the primary radionuclides. The method is discussed in Section 6.4.1.2.

#### 6.4.9.1 Ingestion of Drinking Water

The drinking water pathway generally is an important ingestion pathway for the groundwater scenario (CRWMS M&O 2001 [DIRS 152539], p. 78). For this pathway, the primary radionuclides are assumed to be in the groundwater and accompanied by their short-lived decay products. The annual dose from ingestion of radionuclides in drinking water is expressed as

$$D_{ing,w,i} = EDCF_{ing,i}\ Cw_i\ Uw \qquad \text{(Eq. 6.4.9-2)}$$

where

| | | |
|---|---|---|
| $EDCF_{ing,i}$ | = | effective dose conversion factor for ingestion of radionuclide *i* (Sv/Bq); calculation of effective dose conversion factors for ingestion is discussed in Section 6.4.9.6 |
| $Cw_i$ | = | activity concentration of radionuclide *i* in groundwater (Bq/L) |
| $Uw$ | = | annual consumption rate of contaminated drinking water by humans (L/yr). |

The development of effective ingestion dose conversion factors is discussed in Section 6.4.9.6. The annual water consumption rate for the receptor is specified in 10 CFR 63.312(d) ([DIRS 156605]) as 2 L/d (730 L/yr).

### 6.4.9.2 Ingestion of Crop Foodstuffs

Ingestion of crops also is an important pathway for the groundwater scenario (CRWMS M&O 2001 [DIRS 152539], p. 78). Radionuclide decay during storage (between harvest and consumption) is not considered because only long-lived primary radionuclides are of concern for the biosphere model. The annual dose to a receptor from ingestion of primary radionuclide *i* in foodstuffs should include all radionuclides (*l*) in a decay chain (if one exists), as discussed in the surface soil submodel (Section 6.4.1.2). The annual dose from ingestion of contaminated crops is expressed as

$$D_{ing,p,i} = \sum_l D_{ing,p,l} = \sum_l \left[ EDCF_{ing,l} \sum_j \left( Cp_{l,j}\, Up_j \right) \right] \qquad \text{(Eq. 6.4.9-3)}$$

where

| | | |
|---|---|---|
| $D_{ing,p,i}$ | = | annual dose from ingestion of primary radionuclide *i* in crops (Sv/yr) |
| $D_{ing,p,l}$ | = | annual dose from ingestion of long-lived radionuclide *l* in decay chain of primary radionuclide *i* in crops (Sv/yr) |
| $l$ | = | index of radionuclide decay chain, $l = 0$ for primary radionuclide |
| $EDCF_{ing\ l}$ | = | effective dose conversion factor for ingestion of radionuclide *l* in decay chain of primary radionuclide *i* (Sv/Bq) |
| $Cp_{l,j}$ | = | activity concentration of primary radionuclide *l* in the crop type *j* (Bq/kg) |
| $j$ | = | index of crop type, $j = 1$ for leafy vegetables, 2 for other vegetables, 3 for fruit, and 4 for grain |
| $Up_j$ | = | annual consumption rate of locally produced crop type *j* (kg/yr). |

The activity concentrations of radionuclides in crops is discussed in the plant submodel (Section 6.4.3). The consumption rates used in Equation 6.4.9-3 apply only to locally produced crops (BSC 2003 [DIRS 161241]); imported crops are considered to be uncontaminated.

### 6.4.9.3 Ingestion of Animal Products

Animal product foodstuffs may become contaminated if animals are raised using contaminated feed and water. This submodel does not include radionuclide decay during storage of feed, but it

does include contributions from radionuclide decay chains. For animals, all feed and water is contaminated. The annual dose from ingestion of contaminated animal products is expressed as

$$D_{ing,d,i} = \sum_{l} D_{ing,d,l} = \sum_{l} \left[ EDCF_{ing,l} \sum_{k} \left( Cd_{l,k}\, Ud_{k} \right) \right] \qquad \text{(Eq. 6.4.9-4)}$$

where

| | | |
|---|---|---|
| $D_{ing,d,i}$ | = | annual dose from ingestion of primary radionuclide *i* (Sv/yr) |
| $D_{ing,d,l}$ | = | annual dose from ingestion of radionuclide *l* in decay chain of primary radionuclide *i* in animal products (Sv/yr) |
| $Cd_{l,k}$ | = | activity concentration of primary radionuclide *l* in the animal product type *k* (Bq/kg) |
| $k$ | = | index of animal products, *k* = 1 for meat, 2 for poultry, 3 for milk, and 4 for eggs |
| $Ud_k$ | = | annual consumption rate of locally produced animal product type *k* (kg/yr) |

and the other parameter is defined in Equation 6.4.9-3.

The activity concentrations of radionuclides in animal products are discussed in the animal submodel (Section 6.4.4). The consumption rates in Equation 6.4.9-4 apply only to locally-produced animal products (BSC 2003 [DIRS 161241]); imported animal products are considered to be uncontaminated.

### 6.4.9.4 Ingestion of Fish

The ingestion of locally produced fish is another potential exposure pathway in the groundwater scenario. As discussed for the fish submodel (Section 6.4.5), groundwater is used as a water source for fishponds. Radionuclide decay and ingrowth in the ponds is not considered because fishpond water is not expected to be used for very long (Roe 2002 [DIRS 160674]). All short-lived decay products are considered to be in equilibrium with the long-lived parent radionuclide (Section 6.4.5). Contaminated groundwater is the only water source for fish. The annual dose from ingestion of contaminated fish is calculated as

$$D_{ing,f,i} = EDCF_{ing,i}\, Cf_{i}\, Uf \qquad \text{(Eq. 6.4.9-5)}$$

where

| | | |
|---|---|---|
| $D_{ing,f,i}$ | = | annual dose from ingestion of primary radionuclide *i* in fish (Sv/yr) |
| $Cf_i$ | = | activity concentration of primary radionuclide *i* in fish (Bq/kg) |
| $Uf$ | = | annual consumption rate of locally produced fish (kg/yr). |

The parameter, $EDCF_{ing,i}$, is defined in Equation 6.4.9-2. Activity concentrations in fish are discussed in the fish submodel (Section 6.4.5). The consumption rates used in Equation 6.4.9-5 apply only to locally produced fish (BSC 2003 [DIRS 161241], Section 6.4); imported fish is considered to be uncontaminated.

### 6.4.9.5 Inadvertent Soil Ingestion

In the groundwater scenario, soils are contaminated during irrigation, and the duration of irrigation is assumed to be sufficiently long that radionuclides and decay products accumulate in the soil and reach equilibrium (Assumption 5). As a result, soils contain more radioactivity than any other biosphere component. To account for radionuclide consumed with contaminated soil, the ERMYN model includes inadvertent soil consumption as an ingestion pathway. Modeling activity concentrations in the soil involves tracking the accumulation and loss of all decay products of a primary radionuclide (Section 6.4.1.2). The annual dose from inadvertent ingestion of contaminated soil is calculated as

$$D_{ing,s,i} = \sum_{l} D_{ing,s,l} = \sum_{l} \left( EDCF_{ing,l}\ Cs_{m,l}\ Us \right) \qquad \text{(Eq. 6.4.9-6)}$$

where

$D_{ing,s,i}$ = annual dose from ingestion of primary radionuclide *i* in the surface soil (Sv/yr)

$D_{ing,s,l}$ = annual dose from ingestion of long-lived radionuclide *l* in the decay chain of a primary radionuclide *i* in the surface soil (Sv/yr)

$Cs_{m,l}$ = mass-based activity concentration of primary radionuclide *l* in the surface soil (Bq/kg)

$Us$ = annual consumption rate of contaminated soil (kg/yr)

and the other parameter is defined in Equation 6.4.9-3.

Activity concentrations of radionuclides in the surface soil is discussed in the surface soil submodel (Section 6.4.1). Estimates of soil ingestion rates usually have wide uncertainty distributions, and typical values for adults are on the order of several tens to a few hundred milligrams per day (BSC 2003 [DIRS 161241], Section 6.4).

### 6.4.9.6 Effective Dose Conversion Factor for Ingestion

The effective ingestion dose conversion factors used in the ERMYN model are based on dose conversion factors from FGR-11 (Eckerman et al. 1988 [DIRS 101069], Table 2.2), which represent the CEDE for the 50-yr commitment period per unit of activity intake of a radionuclide. As discussed in Section 6.3.5, dose contributions from short-lived decay products are combined with those of the long-lived parent radionuclide to produce effective dose conversion factors. The development of effective ingestion dose conversion factors is shown in Table 6.4-4. The calculation method can be expressed as

$$EDCF_{ing,i} = \sum_{s} DCF_{ing,s} \times BN_{s} \qquad \text{(Eq. 6.4.9-7)}$$

where

$DCF_{ing,s}$ = dose conversion factor for ingestion for short-lived radionuclide *s* in the decay chain of primary radionuclide *i* (Sv/Bq)

$s$ = index of short-lived radionuclide decay chain under a primary radionuclide *i*

$BN_s$ = branching fraction for short-lived radionuclide *s* in the decay chain of

primary radionuclide *i* (dimensionless)

other parameter is defined in Equation 6.4.9.2.

Similar to Table 6.4-2, the values in Table 6.4-4 are for demonstration purposes only. The ERMYN model uses branching fractions and dose conversion factors as inputs to calculate the effective dose conversion factors in GoldSim (Section 6.8).

The ingestion dose conversion factors for some radionuclides have several values, depending on the chemical form of the radionuclides. Because the chemical form of radionuclides in the biosphere is not known, the highest values of dose conversion factors from among the available choices are selected. The justification for selecting ingestion dose conversion factors is provided in BSC (2003 [DIRS 161241], Section 6.5).

Table 6.4-4. Effective Dose Conversion Factors for Ingestion

| Primary Radionuclide | Fractional Uptake | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Conversion Factor ($DCF_{ing}$) [d] (Sv/Bq) | Effective Dose Conversion Factor ($EDCF_{ing}$) (Sv/Bq) |
|---|---|---|---|---|
| C-14 | 1.0 | - | 5.64E-10 | 5.64E-10 |
| Cl-36 | 1.0 | - | 8.18E-10 | 8.18E-10 |
| Se-79 | 8E-1 | - | 2.35E-09 | 2.35E-09 |
| Sr-90D[a] | 3E-1 | | 3.85E-08 | 4.14E-08 |
| | 1E-4 | Y-90 (64.0 hr) | 2.91E-09 | |
| Tc-99 | 8E-1 | - | 3.95E-10 | 3.95E-10 |
| Sn-126D | 2E-2 | | 5.27E-09 | 5.70E-09 |
| | 1E-2 | Sb-126m (19.0 min) | 2.54E-11 | |
| | 1E-2 | Sb-126 (14%, 12.4 d) | 2.89E-09 | |
| I-129 | 1.0 | - | 7.46E-08 | 7.46E-08 |
| Cs-135 | 1.0 | - | 1.91E-09 | 1.91E-09 |
| Cs-137D | 1.0 | | 1.35E-08 | 1.35E-08 |
| | - | Ba-137m (94.6%, 2.552 min) | 0.00E+00 | |
| Pu-242 | 1E-3 | - | 9.08E-07 | 9.08E-07 |
| U-238D | 5E-2 | | 6.88E-08 | 7.25E-08 |
| | 2E-4 | Th-234 (24.10 d) | 3.69E-09 | |
| | - | Pa-234m (99.80%, 1.17 min) | 0.00E+00 | |
| | 1E-3 | Pa-234 (0.33%, 6.7 hr) | 5.84E-10 | |
| Pu-238 | 1E-3 | - | 8.65E-07 | 8.65E-07 |
| U-234 | 5E-2 | - | 7.66E-08 | 7.66E-08 |
| Th-230 | 2E-4 | - | 1.48E-07 | 1.48E-07 |

Table 6.4-4. Effective Dose Conversion Factors for Ingestion (continued)

| Primary Radionuclide | Fractional Uptake | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Conversion Factor ($DCF_{ing}$) [d] (Sv/Bq) | Effective Dose Conversion Factor ($EDCF_{ing}$) (Sv/Bq) |
|---|---|---|---|---|
| Ra-226D | 2E-1 | | 3.58E-07 | 3.58E-07 |
| | - | Rn-222 (3.8235 d) | 0.00E+00 | |
| | - | Po-218 (3.05 min) | 0.00E+00 | |
| | 2E-1 | Pb-214 (99.98%, 26.8 min) | 1.69E-10 | |
| | - | At-218 (0.02%, 2 sec) | 0.00E+00 | |
| | 5E-2 | Bi-214 (19.9 min) | 7.64E-11 | |
| | - | Po-214 (99.98%, $1.64\times10^{-4}$ sec) | 0.00E+00 | |
| | - | Tl-210 (0.02%, 1.3 min) [e] | 0.00E+00 | |
| Pb-210D | 2E-1 | | 1.45E-06 | 1.97E-06 |
| | 5E-2 | Bi-210 (5.012 d) | 1.73E-09 | |
| | 1E-1 | Po-210 (138.38 d) | 5.14E-07 | |
| Pu-240 | 1E-3 | - | 9.56E-07 | 9.56E-07 |
| U-236 | 5E-2 | - | 7.26E-08 | 7.26E-08 |
| Th-232 | 2E-4 | - | 7.38E-07 | 7.38E-07 |
| Ra-228D[b] | 2E-1 | | 3.88E-07 | 3.89E-07 |
| | 1E-3 | Ac-228 (6.13 hr) | 5.85E-10 | |
| U-232 | 5E-2 | - | 3.54E-07 | 3.54E-07 |
| Th-228D | 2E-4 | | 1.07E-07 | 2.18E-07 |
| | 2E-1 | Ra-224 (3.66 d) | 9.89E-08 | |
| | - | Rn-220 (55.6 sec) | 0.00E+00 | |
| | - | Po-216 (0.15 sec) | 0.00E+00 | |
| | 2E-1 | Pb-212 (10.64 hr) | 1.23E-08 | |
| | 5E-2 | Bi-212 (60.55 min) | 2.87E-10 | |
| | - | Po-212 (64.07%, 0.305 µ-sec) | 0.00E+00 | |
| | - | Tl-208 (35.93%, 3.07 min) | 0.00E+00 | |
| Am-243D | 1E-3 | | 9.79E-07 | 9.80E-07 |
| | 1E-3 | Np-239 (2.355 d) | 8.82E-10 | |
| Pu-239 | 1E-3 | - | 9.56E-07 | 9.56E-07 |
| U-235D | 5E-2 | | 7.19E-08 | 7.23E-08 |
| | 2E-4 | Th-231 (25.52 hr) | 3.65E-10 | |
| Pa-231 | 1E-3 | - | 2.86E-06 | 2.86E-06 |
| Ac-227D | 1E-3 | | 3.80E-06 | 3.99E-06 |
| | 2E-4 | Th-227 (98.62%, 18.718 d) | 1.03E-08 | |
| | 1.0 | Fr-223 (1.38%, 21.8 min) | 2.33E-09 | |
| | 2E-1 | Ra-223 (11.434 d) | 1.78E-07 | |
| | - | Rn-219 (3.96 sec) | 0.00E+00 | |
| | - | Po-215 (1.78 millisec) | 0.00E+00 | |
| | 2E-1 | Pb-211 (36.1 min) | 1.42E-10 | |
| | - | Bi-211 (2.14 min) | 0.00E+00 | |
| | - | Tl-207 (99.72%, 4.77 min) | 0.00E+00 | |
| | - | Po-211 (0.28%, 0.516 sec) | 0.00E+00 | |
| Am-241 | 1E-3 | - | 9.84E-07 | 9.84E-07 |
| Np-237D | 1E-3 | | 1.20E-06 | 1.20E-06 |
| | 1E-3 | Pa-233 (27.0 d) | 9.81E-10 | |

Table 6.4-4. Effective Dose Conversion Factors for Ingestion (continued)

| Primary Radionuclide | Fractional Uptake | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Conversion Factor ($DCF_{ing}$) [d] (Sv/Bq) | Effective Dose Conversion Factor ($EDCF_{ing}$) (Sv/Bq) |
|---|---|---|---|---|
| U-233 | 5E-2 | - | 7.81E-08 | 7.81E-08 |
| Th-229D | 2E-4 | | 9.54E-07 | 1.09E-06 |
| | 2E-1 | Ra-225 (14.8 d) | 1.04E-07 | |
| | 1E-3 | Ac-225 (10.0 d) | 3.00E-08 | |
| | - | Fr-221 (4.8 min) | 0.00E+00 | |
| | - | At-217 (32.3 millisec) | 0.00E+00 | |
| | 5E-2 | Bi-213 (45.65 min) | 1.95E-10 | |
| | - | Po-213 (97.84%, 4.2 µ-sec) | 0.00E+00 | |
| | - | Tl-209 (2.16%, 2.2 min) | 0.00E+00 | |
| | 2E-1 | Pb-209 (3.253 hr) | 5.75E-11 | |

NOTES: DCF = dose conversion factor.

[a] A "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short-lived (< 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Eckerman and Ryman (1993 [DIRS 107684], Table A.1).

[d] Dose conversion factor source (BSC 2003 [DIRS 161241], Section 6.5).

[e] Half-life of Tl-210 is taken from Lide and Frederikse (1997 [DIRS 103178] p.11-125).

### 6.4.10 All-pathway Dose and Biosphere Dose Conversion Factor Calculations

Input to the TSPA from the biosphere model consists of radionuclide-specific BDCFs from all exposure pathways. BDCFs for the groundwater scenario are numerically equal to annual doses to the receptor for a unit activity concentration of a specific radionuclide in groundwater. This section explains how the BDCFs are calculated.

#### 6.4.10.1 All-pathway Doses

The all-pathway annual dose for an individual primary radionuclide, expressed in terms of the TEDE, is the sum of the annual dose from external exposure and the CEDE from the annual radionuclide intake into the body by ingestion and inhalation. The annual dose for a radionuclide *i* includes any contributions from the decay products, and is calculated as

$$D_{all,i} = D_{ext,i} + D_{inh,i} + D_{ing,i} \qquad \text{(Eq. 6.4.10-1)}$$

where

$D_{all,i}$ = all-pathway annual dose from internal and external exposure to primary radionuclide *i* (Sv/yr)
$D_{ext,i}$ = annual dose from external exposure to primary radionuclide *i* (Sv/yr)
$D_{inh,i}$ = annual dose from inhalation exposure to radionuclide *i* (Sv/yr)
$D_{ing,i}$ = annual dose from ingestion exposure to radionuclide *i* (Sv/yr).

### 6.4.10.2 Biosphere Dose Conversion Factors for the Groundwater Scenario

Contaminated groundwater is the only source of radionuclides in the biosphere under the groundwater scenario. The dose from all exposure pathways discussed in previous sections is linearly proportional to this source, as summarized in Table 6.4-5. As shown in Table 6.4-5, all quantities calculated in the submodels, including radionuclide concentrations in the environmental media and the dose from various exposure pathways, are proportional to the radionuclide concentration in the groundwater. Thus, the biosphere model contribution to the dose assessment is separated from the source (i.e., radionuclide concentration in the groundwater). The biosphere contributions are the BDCFs. In the ERMYN model, all-pathway doses could be calculated for any concentration of radionuclides in the water. To obtain the BDCFs, the all-pathway doses are divided by their respective radionuclide concentrations in the water. Thus, the BDCF for a radionuclide is numerically equal to the dose for a unit activity concentration of this radionuclide in the water. For the groundwater scenario, the BDCFs are calculated as

$$BDCF_i = \frac{D_{all,i}}{Cw_i} \qquad \text{(Eq. 6.4.10-2)}$$

where

$BDCF_i$ = BDCF for radionuclide *i* in the groundwater scenario (Sv/yr per Bq/m$^3$)
$D_{all\ i}$ = all-pathway annual dose for radionuclide *i* (Sv/yr)
$Cw_i$ = activity concentration of radionuclide *i* in groundwater (Bq/m$^3$).

To support the dose calculations, different sets of BDCFs will be generated for current and future climate states.

Table 6.4-5. Summary of the Biosphere Submodels for the Groundwater Scenario

| Submodel | Quantity Calculated in Submodel | Section | Simplified Equation [a] | Equation Number |
|---|---|---|---|---|
| Soil | Activity concentration of a primary radionuclide in surface soil | 6.4.1.1 | $Cs_i = K1\ Cw_i$ | 6.4.1-4 |
| | Activity concentration of a decay product in surface soil | 6.4.1.2 | $Cs_i = K2\ Cs_i = K2\ K1\ Cw_i$ | 6.4.1-9 |
| Air | Activity concentration of a radionuclide in air from soil resuspension | 6.4.2.1 | $Ca_i = K3\ Cs_i = K3\ K1\ Cw_i$ | 6.4.2-1, 6.4.2-2 |
| | Activity concentration of a radionuclide in air from operation of evaporative cooler | 6.4.2.2 | $Ca_i = K4\ Cw_i$ | 6.4.2-3 |
| | Activity concentration of radon gas in air | 6.4.2.3 | $Ca_{Rn\text{-}222} = K5\ Cs_{Ra\text{-}226} = K5\ K1\ Cw_{Ra\text{-}226}$ | 6.4.2-4 |

Table 6.4-5. Summary of the Biosphere Submodels for the Groundwater Scenario (continued)

| Submodel | Quantity Calculated in Submodel | Section | Simplified Equation [a] | Equation Number |
|---|---|---|---|---|
| Plant | Activity concentration of a radionuclide in crops from root uptake | 6.4.3.1 | $Cp_i = K6\ Cs_i = K6\ K1\ Cw_i$ | 6.4.3-2 |
| | Activity concentration of a radionuclide in crops from foliar interception of irrigation water | 6.4.3.2 | $Cp_i = K7\ Cw_i$ | 6.4.3-3, 6.4.3-4 |
| | Activity concentration of a radionuclide in crops from foliar interception of resuspended soil | 6.4.3.3 | $Cp_i = K8\ Ca_i = K8\ K3\ K1\ Cw_i$ | 6.4.3-6, 6.4.3-7 |
| Animal | Activity concentration of a radionuclide in animal product from animal feed | 6.4.4.1 | $Cd_i = K9\ Cp_i = K9\ K10\ Cw_i$ | 6.4.4-2 |
| | Activity concentration of a radionuclide in animal product from drinking water | 6.4.4.2 | $Cd_i = K11\ Cw_i$ | 6.4.4-3 |
| | Activity concentration of a radionuclide in animal product from soil ingestion | 6.4.4.3 | $Cd_i = K12\ Cs_i = K12\ K1\ Cw_i$ | 6.4.4-4 |
| Fish | Activity concentration of a radionuclide in fish | 6.4.5 | $Cf_i = K13\ Cw_i$ | 6.4.5-2 |
| $^{14}C$ | Activity concentration of $^{14}C$ in soil | 6.4.6.1 | $Cs_{C\text{-}14} = K14\ Cw_{C\text{-}14}$ | 6.4.6-1 |
| | Activity concentration of $^{14}C$ in air | 6.4.6.2 | $Ca_{C\text{-}14} = K15\ Cs_{C\text{-}14} = K15\ K1\ Cw_{C\text{-}14}$ | 6.4.6-2, 6.4.6-3 |
| | Activity concentration of $^{14}C$ in crops | 6.4.6.3 | $Cp_{C\text{-}14} = K16\ Cs_{C\text{-}14} + K17\ Ca_{C\text{-}14} = K18\ Cw_{C\text{-}14}$ | 6.4.6-6 |
| | Activity concentration of $^{14}C$ in animal products | 6.4.6.4 | $Cd_{C\text{-}14} = K19\ Cp_{C\text{-}14} + K20\ Cw_{C\text{-}14} + K21\ Cs_{C\text{-}14} = K22\ Cw_{C\text{-}14}$ | 6.4.6-7 |
| External Exposure | External exposure dose | 6.4.7.1 | $D_{ext,\ i} = K23\ Cs_i = K23\ K1\ Cw_i$ | 6.4.7-1 |
| Inhalation | Inhalation dose from airborne particulates | 6.4.8.1 | $D_{inh,\ i} = K24\ Ca_i = K24\ K3\ K1\ Cw_i$ | 6.4.8-2 |
| | Inhalation dose from evaporative cooler operation | 6.4.8.2 | $D_{inh,\ i} = K25\ Ca_i = K25\ K4\ Cw_i$ | 6.4.8-3 |
| | Inhalation dose from $^{14}C$ | 6.4.8.3 | $D_{inh,\ C\text{-}14} = K26\ Ca_{C\text{-}14} = K27 Cw_{C\text{-}14}$ | 6.4.8-4 |
| | Inhalation dose from radon decay products | 6.4.8.4 | $D_{inh,\ Rn\text{-}222} = K28\ Ca_{Rn\text{-}222} = K29\ Cw_{Ra\text{-}226}$ | 6.4.8-7 |
| Ingestion | Ingestion dose from water | 6.4.9.1 | $D_{ing,\ i} = K30\ Cw_i$ | 6.4.9-2 |
| | Ingestion dose from crops | 6.4.9.2 | $D_{ing,\ i} = K31\ Cp_i = K31\ K32\ Cw_i$ | 6.4.9-3 |
| | Ingestion dose from animal products | 6.4.9.3 | $D_{ing,\ i} = K33\ Cd_i = K34\ Cw_i$ | 6.4.9-4 |
| | Ingestion dose from fish | 6.4.9.4 | $D_{ing,\ i} = K35\ Cf_i = K35\ K13\ Cw_i$ | 6.4.9-5 |
| | Ingestion dose from soil | 6.4.9.5 | $D_{ing,\ i} = K36\ Cs_i = K36\ K1\ Cw_i$ | 6.4.9-6 |

NOTES:

[a] The proportionality constants, K1, K2, …… in this table can be derived from the Equation Number. These constants are used to show that the dose is proportional to the source, $Cw_i$, the groundwater concentration.

### 6.4.10.3 Pathway Contribution to Dose

The all-pathway dose is the sum of doses from all exposure pathways in the ERMYN model, which are addressed in Sections 6.4.7, 6.4.8, and 6.4.9. Therefore, the ERMYN model can be

used to determine the importance of individual exposure pathways. The annual all-pathway dose is the sum of the component pathway doses, expressed as

$$D_{all,i} = \sum_p D_{p,i} = D_{ext,i} + D_{inh,i} + D_{ing,i}$$
$$= D_{ext,i} + D_{inh,p,i} + D_{inh,\mathrm{e},i} + D_{inh,\mathrm{g},i} + D_{ing,w,i} + D_{ing,p,i,1} + D_{ing,p,i,2} + D_{ing,p,i,3} \quad \text{(Eq. 6.4.10-3)}$$
$$+ D_{ing,p,i,4} + D_{ing,d,i,1} + D_{ing,d,i,2} + D_{ing,d,i,3} + D_{ing,d,i,4} + D_{ing,f,i} + D_{ing,s,i}$$

where

$D_{all,i}$ = annual all-pathway dose for primary radionuclide *i* (Sv/yr)
$D_{p,i}$ = annual dose from exposure pathway *p* for primary radionuclide *i* (Sv/yr)
and the other parameters are defined in Equations 6.4.7-1, 6.4.8-1, and 6.4.9-2 to 6.4.9-6.

By analogy, the all-pathway BDCF for individual radionuclides are calculated as the sum of pathway BDCFs, which can be expressed, using Equation 6.4.10-2, as

$$BDCF_i = \sum_p BDCF_{p,i} \quad \text{(Eq. 6.4.10-4)}$$

where

$BDCF_{p,i}$ = BDCF of individual pathway *p* for radionuclide *i* (Sv/yr per Bq/m$^3$)
and the other parameters are defined in Equation 6.4.10-2 and 6.4.10-3.

The ERMYN model can be used to calculate doses and BDCFs for individual radionuclides in the decay chain of a primary radionuclide, which can provide insight into the importance of individual members of the decay chain following long-term irrigation and radionuclide buildup in surface soil.

### 6.4.10.4 Use of BDCFs in the Total System Performance Assessment Model

The assessment of annual doses will be carried out in the TSPA model using the BDCFs as input parameters. The TSPA model will be used to calculate groundwater concentrations at the source of the groundwater in the biosphere (the well or spring) for each radionuclide. Annual doses from individual radionuclides can be estimated as

$$D_{all,i}(t) = BDCF_i \times Cw_i(t) \quad \text{(Eq. 6.4.10-5)}$$

where

$D_{all,i}(t)$ = time dependent all-pathway annual dose for radionuclide *i* (Sv/yr)
$Cw_i(t)$ = time dependent activity concentration of radionuclide *i* in groundwater (Bq/m$^3$)
and the other parameter is defined in Equation 6.4.10-2.

The total annual dose is the sum of annual doses from the individual radionuclides tracked by the TSPA model. These individual radionuclides, referred to as primary radionuclides, include the contribution from the short-lived decay products (half-life < 180 d). The annual dose, the final output from the TSPA-LA model, will be used to determine compliance with individual protection standard. The total annual dose will be calculated in the TSPA-LA as

$$D_{total}(t) = \sum_i D_{all,i}(t) \qquad \text{(Eq. 6.4.10-6)}$$

where

$D_{total}(t)$ = time-dependent total annual dose to a defined receptor resulting from radionuclides released from the repository, including contributions from all radionuclides considered in the TSPA (Sv/yr)

and the other parameter is defined in Equation 6.4.10-5.

Equation 6.4.10-6 is based on a linear relationship between radionuclide concentrations in the groundwater and the resulting dose. BDCFs are calculated based on a constant activity concentration of radionuclides (Assumption 1) and saturation radionuclide concentrations (Assumption 5). Saturation conditions will be reached if irrigation is sustained for a sufficiently long period of time, which would differ among radionuclides (ranging from years to a few thousand years; Section 6.4.1) and would depend on radionuclide addition and removal rates from the soil. After saturation concentrations are reached, those concentrations would remain constant if the irrigation continues and the agricultural practices, climate, and soil characteristics remain unchanged (Assumption 3).

In the soil, radionuclides such as the isotopes of thorium, plutonium, and americium, have low removal rates, but they also have low rates of buildup, taking on the order of a few thousand years to approach saturation. The assumption of approximately constant radionuclide concentrations in the groundwater may not be valid for long time frames. The annual dose for a point in time, *t*, is calculated using activity concentrations in the groundwater at time *t*, *Cw(t)*. Therefore, the product of the groundwater concentration and the BDCF represents the dose that would result if the same radionuclide concentration in the water persisted before time *t* long enough for the radionuclide to reach saturation. This calculation is conservative if radionuclide concentrations in the groundwater increase, which would be expected for the 10,000-yr compliance period. If radionuclide concentrations in the groundwater decrease quickly with time, the decrease in the true radionuclide buildup in the soil would be slower (i.e., the activity concentration in the soil would be higher) than predicted by this submodel. However, in the biosphere model, it is assumed that irrigation on the same farmland would continue for long periods of time (Assumption 3). If irrigation is not sustained, this may compensate for a long-term decrease in activity levels in the groundwater. In addition, during the period of time when the activity concentration in the groundwater is expected to decrease, the time step in the TSPA model will be long, and the concentrations will be constant during the time step. Therefore, the ERMYN model is unlikely to underestimate the dose to the receptor, regardless of the point in time.

## 6.5 MATHEMATICAL MODEL FOR THE VOLCANIC ASH SCENARIO

The mathematical model described in this section is based on the conceptual model for the volcanic ash scenario (Section 6.3.2). Similar to the groundwater scenario, the goal of this mathematical model is to calculate BDCFs for the TSPA-LA model. Because variation in radionuclide concentrations in deposited volcanic ash is not part of the biosphere model, BDCFs are calculated based on a unit source in volcanic ash deposited on the ground (1 Bq/m$^2$). The TSPA-LA model will calculate radiation dose as a product of the time-dependent source term and the source-independent BDCF. The time-dependent source term is subject to radioactive decay, volcanic ash redistribution, surface soil erosion, and other removal mechanisms.

The mathematical model consists of individual submodels. The relationship among the submodels is shown in Figure 6.3-4 and described in Section 6.3.2. In the mathematical model, linkages among the submodels can be traced by the consistent use of notation among submodels. As described for the conceptual model (Section 6.3.2.5), there are seven submodels, two fewer than in the groundwater scenario (the fish and $^{14}$C submodels are not relevant). The main difference between the two scenarios is the release source. However, the radionuclide transfers among submodels are similar, and therefore many of the assumptions and simplifications for the groundwater scenario apply to the volcanic ash scenario. The final dose calculations, the BDCFs, and their use in the TSPA-LA model, is discussed in Section 6.5.8.

### 6.5.1 Surface Soil Submodel

The surface soil submodel for the volcanic ash scenario differs from the groundwater scenario (Section 6.4.1) primarily because a volcanic eruption would spread ash over a large area (i.e., the entire Yucca Mountain region), while irrigating would contaminate the relatively small farming area. The scenarios also differ because radionuclides would not accumulate in the surface soil because they are not continuously added to the environment, as is the case for contaminated irrigation water.

The radionuclide source for this scenario is volcanic ash deposited on the surface of the ground (Bq/m$^2$). The source, $Cs_i(t)$, is time dependent because of radionuclide decay, volcanic ash redistribution, surface erosion, and other removal mechanisms. This time-dependent source, calculated using the disruptive events submodel in the TSPA-LA model, is not directly used in the ERMYN model. To calculate the biosphere contribution for the dose assessment, this source term is separated into two parts, such that

$$Cs_i(t) = Cs_i \times ST_i(t) \qquad \text{(Eq. 6.5.1-1)}$$

where

| | | |
|---|---|---|
| $Cs_i(t)$ | = | time dependent activity concentration of radionuclide $i$ in ash deposited on the ground surface (Bq/m$^2$) |
| $i$ | = | index of primary radionuclide |
| $Cs_i$ | = | activity concentration of radionuclide $i$ in ash deposited on the ground surface (Bq/m$^2$) |
| $ST_i(t)$ | = | time function of volcanic ash source term for radionuclide $i$ (dimensionless). |

Equation 6.5.1-1 is a mathematical treatment of the volcanic ash source, such that the time dependent source, $Cs_i(t)$, could be considered a constant, unit source of radionuclide *i* in ash deposited on the ground (Bq/m$^2$). Because a unit source is considered in the ERMYN model, the biosphere contribution to the TSPA-LA is the BDCFs, and the time function of the volcanic ash source term, $ST_i(t)$, is numerically equal to $Cs_i(t)$.

Two important factors, land use and ash thickness, are considered in this submodel because the concentration of resuspended radionuclides would differ on cultivated and uncultivated lands. On agricultural and other cultivated land (e.g., gardens), the ash deposit would be uniformly mixed with surface soil during tilling, such that a mix of soil and ash would be resuspended. On uncultivated land, undiluted ash would be resuspended from thick deposits, and a mix of ash and soil would be resuspended from thin deposits.

Radionuclide decay and ingrowth in the source are a function of time. Short-lived decay products (half-life < 180 d) are in equilibrium with parent radionuclides (Assumption 2), similar to the groundwater scenario (Section 6.3.5). Dose contributions from short-lived decay products are included with the long-lived primary radionuclides. For a long-lived decay product that also is a primary radionuclide, the ERMYN model does not consider ingrowth, rather ingrowth is considered in the time dependent source ($ST_i(t)$). For a relatively long-lived decay product that is not a primary radionuclide (e.g., $^{228}$Th from $^{232}$U), the BDCF of the decay product is initially developed based on secular equilibrium with the long-lived primary radionuclide in volcanic ash source, and then it is added to the BDCF for the primary radionuclide.

### 6.5.1.1 Cultivated Land

On cultivated lands, irrigation and tilling uniformly mix the volcanic ash with uncontaminated surface soil to the depth of the root zone (Assumption 12). However, the ash could be thicker than the tilling depth if a large quantity of ash is deposited at the location of the receptor or if a large quantity of ash is transported to the farm fields by fluvial processes. If that happens, radionuclide concentrations in the surface soil would be the same as those in the volcanic ash because the volcanic ash would not be mixed with uncontaminated surface soil and the ash below the root zone would not contribute to crop contamination. However, thick deposits are unlikely on cultivated fields in the Amargosa Valley. Therefore, to simplify the computations, regardless of the ash thickness, radionuclide concentrations in the surface soil of cultivated lands are calculated based on the total amount radionuclides in the ash deposited on the ground (Bq/m$^2$).

Areal radionuclide concentrations in the surface soil are converted to radionuclide mass concentrations in the surface soil, similar to the groundwater soil submodel. Because only a thin layer of ash is expected (CRWMS M&O 2000 [DIRS 153246], Section 3.10.5.1), the soil bulk density is assumed to remain unchanged after it is mixed with volcanic ash (Assumption 12). This assumption allows surface soil density to be considered as an independent input parameter that is not a function of thickness of ash deposited on the top of the surface soil. The activity concentration in surface soil mass can then be converted by

$$Cs_{m,i} = \frac{Cs_i}{\rho \times d} = \frac{Cs_i}{\rho_s} \qquad \text{(Eq. 6.5.1-2)}$$

where

$Cs_{m,i}$ = activity concentration of radionuclide *i* in a mixture of soil and ash on cultivated land (Bq/kg)

$\rho$ = bulk density of the surface soil (kg/m$^3$)

$d$ = depth of the surface soil in the cultivated land (m)

$\rho_s$ = areal density of surface soil (kg/m$^2$)

and the other parameters are defined in Equation 6.5.1-1.

These soil related parameters are expected to be the same as those used for the groundwater scenario (BSC 2003 [DIRS 161239]). The radionuclide concentration in a mixture of soil and ash on cultivated land is used to estimate radionuclide transfers to plant foodstuffs, animal products, and via inadvertent soil ingestion. These processes are modeled in the plant, animal, and ingestion submodels, respectively. Radionuclide concentrations in the surface soil would not change with the thickness of deposited volcanic ash because the contaminated ash would be uniformly diluted in the surface soil to the tilling depth.

#### 6.5.1.2 Non-Cultivated Land

On non-cultivated lands, volcanic ash would not quickly mix with surface soil, and the proportion of resuspended particles comprised of contaminated ash (versus clean soil) depends on the thickness of the ash deposit. To account for this process, a critical thickness is considered in the submodel. The critical thickness is the layer from which particles are resuspended, which is, at most, a few millimeters thick (BSC 2003 [DIRS 160964]). If the ash thickness is equal to or greater than the critical thickness, only ash is resuspended because clean soil is covered by too much ash to be resuspended, and only a portion of the ash would be available for resuspension. If the deposit is thinner than the critical thickness, the resuspended material would be a mix of ash particles and clean soil.

The calculated areal activity concentration in the deposited ash (Bq/m$^2$) is the same regardless of the ash thickness relative to the critical thickness. If the ash thickness is less than the critical thickness, the entire volume of ash (and all of the activity it contains) and uncontaminated soil, which together are within the critical thickness, is resuspended. If the ash thickness is greater than the critical thickness, the volume of ash (and the activity it contains within the critical thickness) is resuspended. Under these conditions, the volume of resuspended ash does not contain all of the activity that is initially deposited because the entire volume of ash (and all of the activity) will not be available for resuspension. Thus, the activity concentration per unit mass without dilution can be expressed as a fraction of the activity concentration per unit mass when there is dilution. The ratio of critical thickness to ash thickness is the fraction used for the calculation.

Radionuclide concentrations in the resuspended material (i.e., the mass of mixed ash and soil or the undiluted original ash) would depend on the ash thickness ($d_a$) and the critical thickness ($d_c$). Ash thickness will be calculated in the TSPA-LA model. Similar to Equation 6.5.1-2, the mass concentration is calculated as

$$Cs_{mc,i}(d_a) = \begin{cases} \dfrac{Cs_i}{\rho_a \times d_c} = Cs_{mc,i} & \text{when } d_a < d_c \\ \dfrac{Cs_i}{\rho_a \times d_a} = \dfrac{Cs_i}{\rho_a \times d_c}\dfrac{d_c}{d_a} = Cs_{mc,i}\dfrac{d_c}{d_a} & \text{when } d_a \geq d_c \end{cases} \qquad \text{(Eq. 6.5.1-3)}$$

where

| | | |
|---|---|---|
| $Cs_{mc,i}(d_a)$ | = | activity concentration of radionuclide *i* in volcanic ash or in the mix of ash and dust of non-cultivated land (Bq/kg) |
| $\rho_a$ | = | bulk density of volcanic ash (kg/m$^3$) |
| $d_c$ | = | critical thickness for resuspension on non-cultivated lands (m) |
| $d_a$ | = | thickness of ash deposited on the ground (m) |
| $Cs_{mc\ i}$ | = | activity concentration of radionuclide *i* in the mass of resuspendable ash or in the mix of ash and dust (Bq/kg) |

and the other parameters are defined in Equation 6.5.1-1.

The bulk density of volcanic ash, $\rho_a$, is lower than the soil bulk density (BSC 2003 [DIRS 161239]).

Equation 6.5.1-3 is rewritten as

$$Cs_{mc,i}(d_a) = Cs_{mc,i} \times f(d_a) \qquad \text{(Eq. 6.5.1-4)}$$

where f(da), a function of volcanic ash thickness (dimensionless), can be expressed as

$$f(d_a) = \begin{cases} 1 & \text{when } d_a < d_c \\ \dfrac{d_c}{d_a} & \text{when } d_a \geq d_c \end{cases} \qquad \text{(Eq. 6.5.1-5)}$$

and the other parameters are defined in Equation 6.5.1-3.

The radionuclide concentration of volcanic ash or mixed ash and soil for non-cultivated land, as defined in Equation 6.5.1-4 and Equation 6.5.1-5, is used to estimate the radionuclide transfer from volcanic ash to resuspended ash in the air (Assumption 13), and then to estimate the human inhalation dose. Radionuclide concentrations in the critical thickness for surface particle resuspension is a reference concentration that is used for developing the inhalation pathway contribution to BDCFs. For non-cultivated lands, radionuclide leaching is likely to be low because of the limited precipitation and lack of irrigation. Consequently, using the depth of ash on non-cultivated land for determining inhalation dose is a conservative approach.

### 6.5.2 Air Submodel

The air submodel for the volcanic ash scenario has two components: the resuspension of particles from deposited volcanic ash or from a mixture of ash and soil, and the exhalation of radon gas from radium-contaminated volcanic ash. Because groundwater is uncontaminated in the volcanic ash scenario, radionuclide transfer into indoor air from evaporative coolers is not

considered. This submodel also does not consider $^{14}C$ in the air because it is not a radionuclide considered important to the TSPA-LA in the volcanic ash scenario (Section 6.1.3).

#### 6.5.2.1 Resuspension of Volcanic Ash or a Mixture of Soil and Ash

As discussed in Section 6.5.1, volcanic ash would settle on cultivated and non-cultivated lands. On cultivated lands, ash would be well mixed with uncontaminated soil to the depth of the surface soil. On non-cultivated lands, volcanic ash would not be mixed with surface soil unless the amount of ash is less than the critical thickness (Section 6.5.1.2). Radionuclide concentrations in the air are estimated separately for the two cases. The mixture of soil and ash on cultivated lands is used for the deposition of resuspended particles onto plant surface (Section 6.5.3), while the volcanic ash or mixture of soil and ash from non-cultivated land is used for the inhalation dose (Section 6.5.6).

For resuspended particles deposited on crops, only particles from the local farm fields or gardens would be deposited on the plants (Assumption 13). Therefore, the submodel is based on the same mass concentration of radionuclides in the surface soil and in the airborne particles

$$Ca_{p,i} = Cs_{m,i}\ S \qquad \text{(Eq. 6.5.2-1)}$$

where

$Ca_{p,i}$ = activity concentration of radionuclide $i$ in the air for crop deposition (Bq/m$^3$)
$S$ = concentration of total resuspended particulates (mass loading) for direct deposition on crops (kg/m$^3$)
and the other parameters are defined in Equation 6.5.1-2.

The mass loading term, $S$, is characteristic of cultivated areas in a dry climate after a volcanic eruption. The value for mass loading likely would be different from the value used in the groundwater scenario (BSC 2003 [DIRS 160965]).

Similar to the groundwater scenario, the enhancement factor, defined as the ratio of airborne particle concentration (Bq/kg) to total surface soil concentration (Bq/kg), is used in the calculation of airborne activity concentrations used to determine the inhalation dose. Although small particles would be picked up and transported by wind more easily than large particles, the smaller particles would not necessarily carry a higher radionuclide activity because spent fuel particles would have a greater density than regular ash particles. Similar to Equation 6.4.2-2, radionuclide concentrations in the air inhaled by the receptor are calculated as

$$Ca_{h,i,n}(d_a,t) = f_{enhance}\ \ Cs_{mc,i}(d_a)\ \ S_n(t) \qquad \text{(Eq. 6.5.2-2)}$$

where

$Ca_{h,i,n}(d_a,t)$ = activity concentration of radionuclide $i$ in the air for environment $n$ at time $t$ and ash thickness $d_a$ (Bq/m$^3$)
$n$ = index of the environments, $n$ = 1 for active outdoors; 2 for inactive outdoors; 3 for active indoors; 4 for asleep indoors; and 5 for away from the contaminated area
$f_{enhance}$ = enhancement factor for the activity concentration of resuspended particles

(dimensionless)

$S_n(t)$ = total average annual mass loading (the concentration of total resuspended particulates in the air) in environment $n$ at time $t$ following a volcanic eruption (kg/m$^3$)

and the other parameters are defined in Equation 6.5.1-3.

Mass loading would be higher for some time after a volcanic eruption because there would be more unconsolidated, fine particles on the soil surface that would be readily resuspended by wind, human activity, or other disturbances. Over time, the ash would be consolidated into the soil or removed by erosion, and mass loading would return to levels experienced before the eruption (i.e., nominal mass loading; Assumption 14). This assumption is based on measurements of mass loading after the eruption of Mount St. Helens and other volcanoes (BSC 2003 [DIRS 160965], Section 6.2 and 6.3). To account for this effect, radionuclide concentrations in the air are separated into two parts. The first part is for the period immediately after the eruption and before ash stabilization. The second part is for the time when mass loading has returned to pre-eruption levels. This second part is ash-thickness dependent but not time dependent. By separating the time and ash thickness components, radionuclide concentrations immediately after the eruption can be evaluated.

The dependence of mass loading on time is expressed as

$$S_n(t) = S_n + S_{v,n}\ f(t) \qquad \text{(Eq. 6.5.2-3)}$$

where

$S_n$ = nominal annual average mass loading (the concentration of total resuspended particulates) in environment $n$ (kg/m$^3$)

$S_{v,n}$ = elevated, post-volcanic ($v$) annual average mass loading (the concentration of total resuspended particulates) in environment $n$, in addition to $S_n$, during the first year following a volcanic eruption (kg/m$^3$)

$f(t)$ = mass loading time function, which described the rate of change in mass loading after a volcanic eruption

and the other parameters are defined in Equation 6.5.2-2.

Mass loading is an important parameter for the inhalation pathway because the radionuclide concentration in air is proportional to mass loading. Mass loading depends on the environment and human activities, and values range from about $1 \times 10^{-8}$ to $1 \times 10^{-5}$ kg/m$^3$ (BSC 2003 [DIRS 160965], Section 6.2). Mass loading in indoor environments is considerably lower than in some outdoor environments. Mass loading distributions for nominal conditions, $S_n$, are the same as in the groundwater scenario (Equation 6.4.2-2); under post-volcanic conditions, $S_{v,n}$, mass loading would be elevated due to the volcanic eruption. The parameter $S_{v,n}$ represents the initial increased mass loading and differs among environments (BSC 2003 [DIRS 160965]). The mass loading time function, $f(t)$, which is expected to rapidly decrease with time (BSC 2003 [DIRS 160965], Section 6.3), will be carried into the TSPA-LA model to evaluate the final dose (Section 6.5.8).

Combining Equations 6.5.1-4, 6.5.2-2, and 6.5.2-3, radionuclide concentrations in the air are calculated in two parts, one steady state and one time-dependent. The ash thickness dependent function, $f(d_a)$ defined in Equation 6.5.1-5, is applied to both parts, as

$$\begin{aligned} Ca_{h,i,n}(d_a,t) &= f_{enhance}\ Cs_{mc,i}\, f(d_a)[S_n + S_{v,n}\ f(t)] \\ &= f_{enhance}\ Cs_{mc,i}\ f(d_a)\ S_n + f_{enhance}\ Cs_{mc,i}\ f(d_a)\, S_{v,n}\ f(t) \\ &= Ca_{h,i,n}\, f(d_a) + Ca_{v,i,n}\, f(d_a)\, f(t) \end{aligned} \qquad \text{(Eq. 6.5.2-4)}$$

where

$Ca_{h,i,n}$ = activity concentration of radionuclide *i* in the air in environment *n*, calculated from the nominal mass loading levels (Bq/m$^3$)

$Ca_{v,i,n}$ = activity concentration of radionuclide *i* in the air in environment *n*, calculated from the post-volcanic mass loading levels (Bq/m$^3$)

and the other parameters are defined in Equations 6.5.1-3, 6.5.2-2, and 6.5.2-3.

### 6.5.2.2 Exhalation of Radon from the Ground Surface

The volcanic ash scenario considers the release of radon from volcanic ash deposited on the ground surface. Because the layer of contaminated volcanic ash is expected to be relatively thin (< 10 cm, Section 5.12), the use of a radon release factor, $f_{m,\ Rn\text{-}222}$ = 0.25 (Bq/m$^3$)/(Bq/kg) (Section 6.4.2.3), is not valid because it is based on a thickness of $^{226}$Ra-contaminated soil that is infinite with respect to radon transport. However, in the case of volcanic ash and soil mixing, the radium concentration in the soil would not be immediately known, and in addition, the assessment of radon release from a limited contaminated source would require a radon diffusion submodel, for which more input data would be needed. Therefore, a simplified method for estimating the radon concentration in the air, using the relationship between the concentration of $^{226}$Ra in the surface soil (Bq/m$^2$), $^{222}$Rn flux density from soil (Bq/(m$^2$ s)), and $^{222}$Rn in the air (Bq/m$^3$) is used. This method is based on a thin layer of $^{226}$Ra on the ground surface and the assumption that all of the $^{222}$Rn is released into the air (Assumption 15).

Based on this assumption, if the $^{226}$Ra concentration on the top of the ground is 1 Bq/m$^2$, then one atom of $^{226}$Ra/m$^2$/sec would decay to $^{222}$Rn. Because all of the $^{222}$Rn would be released into the air, the $^{222}$Rn flux density from soil would be one atom per m$^2$/sec. To convert the number of $^{222}$Rn atoms ($N_{Rn\text{-}222}$) into activity of $^{222}$Rn ($A_{Rn\text{-}222}$), a half-life ($T_{1/2,Rn\text{-}222}$) of 3.8235 d ($3.3 \times 10^5$ sec, Table 6.3-7) is used as

$$A_{Rn-222} = \frac{\ln(2)}{T_{1/2,Rn-222}} N_{Rn-222} = \frac{\ln(2)}{3.3\times10^5\ \text{(sec.)}} \times 1\,\text{(atom)} = 2\times10^{-6}\ \text{(Bq)} \qquad \text{(Eq. 6.5.2-5)}$$

This indicates that one atom of $^{222}$Rn has an activity of about $2 \times 10^{-6}$ Bq. Then, $^{222}$Rn flux density per 1 Bq/m$^2$ of $^{226}$Ra from the ground surface is expressed as

$$FD_{Rn-222} = \frac{1\,(\text{atom/(m}^2\text{ s)})_{\text{Rn-222}}}{1\,(\text{Bq/m}^2)_{\text{Ra-226}}} = 2\times10^{-6}\ \frac{\text{Bq/(m}^2\text{ s)}}{\text{(Bq/m}^2\text{)}} \qquad \text{(Eq. 6.5.2-6)}$$

where

$FD_{Rn\text{-}222}$ = flux density of $^{222}$Rn per unit $^{226}$Ra-activity on the ground surface ((Bq/(m$^2$ sec))/(Bq/m$^2$) = /sec).

Using the ratio of $^{222}$Rn activity concentration in the air to the flux density, $CF_{Rn\text{-}222}$, from a large contaminated area outdoors (which is introduced in the air submodel for the groundwater scenario for calculating the indoor radon concentration; Section 6.4.2.3), the release factor of $^{222}$Rn from $^{226}$Ra surface concentration is estimated as

$$f_{s,Rn-222} = FD_{Rn-222} \times CF_{Rn-222} \qquad \text{(Eq. 6.5.2-7)}$$

where

$f_{s,Rn\text{-}222}$ = ratio of $^{222}$Rn activity concentration in the air to the $^{226}$Ra activity concentration on the ground surface ((Bq/m$^3$)/(Bq/m$^2$) = /m)

$CF_{Rn\text{-}222}$ = ratio of $^{222}$Rn concentration in air to flux density from soil for outdoors ((Bq/m$^3$)/(Bq/(m$^2$ s)) = (sec/m)

and the other parameters are defined in Equation 6.5.2-6.

Using the release factor for $^{222}$Rn ($f_{s,Rn\text{-}222}$) and an equation similar to Equation 6.4.2-5, the activity concentration of radon in air is estimated as

$$\begin{aligned} Ca_{g,\,Rn-222} &= f_{s,Rn-222}\, Cs_{Ra-226} \\ &= FD_{Rn\text{-}222}\, CF_{Rn-222}\, Cs_{Ra-226} \end{aligned} \qquad \text{(Eq. 6.5.2-8)}$$

where

$Ca_{g,Rn\text{-}222}$ = activity concentration of $^{222}$Rn in air (Bq/m$^3$)

$Cs_{Ra\text{-}226}$ = activity concentration of $^{226}$Ra in surface soil (Bq/m$^2$)

and the other parameters are defined in Equation 6.5.2-7.

Using a typical value of $CF_{Rn\text{-}222}$ = 300 sec/m (BSC 2003 [DIRS 160964], Section 6.6.1), the radon release factor is about 0.0006 (Bq/m$^3$)/(Bq/m$^2$). This estimate is an upper bound because all of the radon in the ash is released into the air.

Unlike the groundwater scenario, indoor radon concentrations for the volcanic ash scenario are considered to be the same as the outdoor radon concentration because the initial amount of indoor volcanic ash would be limited. Even if new houses are built on contaminated land, the release of $^{222}$Rn indoors is limited because the thin layer of ash would be removed or mixed with the surface soil during home construction. Because an upper bound value for outdoor concentrations is used, it is not necessary to consider an additional, indoor radon source.

### 6.5.3 Plant Submodel

Under the volcanic ash scenario, ash contaminates surface soil and surface water. The biosphere model does not include permanent surface waters (e.g., rivers, lakes, or reservoirs;

Section 6.3.1.1), and it does not consider surface water contamination. Groundwater could become contaminated if radionuclides from volcanic ash leached into the deep soil, but this process is not considered in the biosphere model. Therefore, the plant submodel for this scenario only considers contaminated soil and air, which contaminate crops by root uptake and dust deposition.

The plant submodel for the volcanic ash scenario is similar to the groundwater scenario. The discussions in Section 6.4.3 on crop type, mechanisms of crop contamination, and radionuclide decay are valid for the volcanic ash scenario. Equations presented in this section are the same as those in Section 6.4.3, except that contaminated water is not considered. The radionuclide concentrations in specific plant foodstuffs are estimated as

$$Cp_{i,j} = Cp_{root\ i,j} + Cp_{dust,i,j} \qquad \text{(Eq. 6.5.3-1)}$$

where

| | | |
|---|---|---|
| $Cp_{i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* (Bq/kg) |
| *j* | = | crop-type index; j = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain (used for both human and animals), and 5 for fresh forage feed (used for beef cattle and dairy cows) |
| $Cp_{root\ i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* contributed from plant root uptake (Bq/kg) |
| $Cp_{dust\ i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* contributed from plant leaf uptake due to the deposition of resuspended particulates on crop surfaces (Bq/kg). |

### 6.5.3.1 Root Uptake

Root uptake is estimated using the same methods as those for the groundwater scenario (Section 6.4.3.1). It is assumed that all plant roots are in the surface soil (to the tilling depth) to maximize radionuclide uptake (Assumption 7). This approach eliminates the need for determining the fraction of roots in a defined thickness of surface soil. Radionuclides taken up by plant roots are internal to the plants and not subject to removal by weathering or food processing. The activity concentration of radionuclides in crops contributed from root uptake is expressed as

$$Cp_{root,i,j} = Cs_{m,i}\ F_{s\rightarrow p,i,j}\ DW_j \qquad \text{(Eq. 6.5.3-2)}$$

where

| | | |
|---|---|---|
| $Cp_{root,i,j}$ | = | activity concentration of radionuclide *i* in crop type *j* contributed from root uptake (Bq/kg wet weight of edible portions of the plant) |
| $Cs_{m,i}$ | = | activity concentration of radionuclide *i* in surface soil (Bq/kg $_{\text{dry soil}}$) |
| $F_{s\rightarrow p,i,j}$ | = | soil-to-plant transfer factor for radionuclide *i* and crop type *j* (Bq/kg $_{\text{dry-plant}}$ per Bq/kg $_{\text{dry-soil}}$) |
| $DW_j$ | = | dry-to-wet weight ratio for edible plant parts (kg $_{\text{dry-plant}}$ /kg $_{\text{wet-plant}}$). |

The activity concentration of radionuclides in surface soil, $Cs_{m,i}$, is calculated using Equation 6.5.1-2. The soil-to-plant transfer factor and the dry-to-wet ratio (Section 6.4.3.1) are expected to be the same for the groundwater and volcanic ash scenarios (BSC 2003 [DIRS 160964], Section 7; BSC 2003 [DIRS 160976], Section 7).

### 6.5.3.2 Uptake from Resuspended Soil

The second mechanism of crop contamination is the deposition of resuspended soil on leaf surfaces. Similar to the groundwater scenario (Section 6.4.3.3), radionuclide concentrations in plant foodstuffs from uptake by foliar interception of airborne particulates are expressed as

$$Cp_{dust,i,j} = \frac{Da_i \, Ra_j \, T_j}{\lambda_w \, Y_j} \left(1 - e^{-\lambda_w \, t_{g,j}}\right) \qquad \text{(Eq. 6.5.3-3)}$$

where

| | | |
|---|---|---|
| $Da_i$ | = | deposition rate of radionuclide *i* in resuspended soil (Bq/(m$^2$ d)). |
| $Ra_j$ | = | interception fraction for resuspended soil (dimensionless) |
| $T_j$ | = | translocation factor (dimensionless) |
| $\lambda_w$ | = | weathering constant (per d), calculated from the weathering half-life ($T_w$ in units of day) by $\lambda_w = \ln(2)/T_w$ |
| $t_{g,j}$ | = | crop growing time (d) |
| $Y_j$ | = | crop biomass or wet yield (kg$_{wet}$/m$^2$) |

and the other parameters are defined in Equation 6.5.3-1.

The translocation factor, weathering constant, crop growing time, and crop biomass are expected to be the same in the groundwater and volcanic ash scenarios (BSC 2003 [DIRS 160964], Section 7; BSC 2003 [DIRS 160976] Section 7). The deposition rate of contaminated resuspended soil, $Da_i$, quantifies the combined effect of contaminant removal from the atmosphere by several processes, such as gravitational settling, diffusion, and turbulent transport. The deposition rate is expressed as

$$Da_i = 8.64 \times 10^4 \, Ca_{p,i} \, V_d \qquad \text{(Eq. 6.5.3-4)}$$

where

| | | |
|---|---|---|
| $Ca_{p,i}$ | = | activity concentration of radionuclide *i* in the air used for evaluation of activity deposition on the crops (Bq/m$^3$). |
| $V_d$ | = | deposition velocity for resuspended soil (m/sec) |
| $8.64 \times 10^4$ | = | unit conversion factor (sec/d). |

Activity concentrations of radionuclides in the air is calculated using Equation 6.5.2-1. The deposition velocity for resuspended soil, $V_d$, is a function of particle size. The value of this parameter is developed considering site-specific conditions in the Yucca Mountain region (BSC 2003 [DIRS 160964] Section 6.2.2).

The interception fraction for resuspended soil, $Ra_j$, quantifies the initial fractional deposition of radionuclides on plant surfaces from dry deposition. This parameter is crop-type dependent and ranges in value from zero to one. Values for this parameter are estimated using an empirical formula as

$$Ra_j = 1.0 - e^{-a_j DB_j} \qquad \text{(Eq. 6.5.3-5)}$$

where

$a_j$ = an empirical factor ($m^2$/kg $_{\text{dry biomass}}$)
$DB_j$ = the dry standing biomass of crop type $j$ (value in units of kg $_{\text{dry weigh}}$/$m^2$)
and the other parameters are defined in Equation 6.5.3-3.

This empirical equation is adopted from the GENII-S model, including the values of the empirical factor. The recommended values of the empirical factor are 2.9 for leafy vegetables, fresh forage feed, and grain, and 3.6 for root and other vegetables plus fruit (Napier et al. 1988 [DIRS 157927], p. 4.69). The empirical formula is modified for this submodel (Section 6.4.3.3).

### 6.5.4 Animal Submodel

The animal product submodel is used to evaluate the accumulation of radionuclides in animal products that later would be consumed by humans. Two pathways are considered for the contamination of animal products: ingestion of contaminated feed and soil. Inhalation of contaminated air is not considered in the submodel because it is much less important than ingestion (Section 7.4.5).

Discussions presented for the groundwater scenario (Section 6.4.4) are valid for the volcanic ash scenario. Also, as mentioned in the plant submodel, only fresh forage is considered as feed for beef cattle and dairy cows, and only stored grain is considered as feed for poultry and laying hens.

Radionuclide decay is not considered in this submodel because the growing time and storage time (time between harvest and consumption) for animal feed are short compared with the half life of the radionuclides of interest. The radionuclide concentration in animal products ($Cd_{i,k}$) is evaluated as

$$Cd_{i,k} = Cd_{feed,i,k} + Cd_{soil,i,k} \qquad \text{(Eq. 6.5.4-1)}$$

where

$Cd_{i,k}$ = activity concentration of radionuclide $i$ in animal product $k$ (Bq/kg $_{\text{fresh weight}}$ or Bq/L $_{\text{milk}}$)
$k$ = animal product index; $k$ = 1 for beef, 2 for poultry, 3 for milk, and 4 for eggs
$Cd_{feed,i,k}$ = activity concentration of radionuclide $i$ in animal product $k$ due to ingestion of contaminated animal feed (Bq/kg or Bq/L)
$Cd_{soil,i,k}$ = activity concentration of radionuclide $i$ in animal product $k$ due to ingestion of contaminated soil (Bq/kg or Bq/L).

#### 6.5.4.1 Animal Feed

The radionuclide concentrations in animal products, resulting from the ingestion of contaminated animal feed, is evaluated as

$$Cd_{feed,i,k} = Fm_{i,k}\ Cp_{i,j}\ Qf_k \qquad \text{(Eq. 6.5.4-2)}$$

where

| | | |
|---|---|---|
| $Fm_{i,k}$ | = | animal intake-to-animal product transfer coefficient for radionuclide *i* and animal product *k* (d/kg $_{\text{fresh weight}}$ or d/L) |
| $Cp_{i,j}$ | = | activity concentration of radionuclide *i* in animal feed *j* (Bq/kg $_{\text{fresh weight}}$) |
| $j$ | = | animal feed index; $j$ = 5 for fresh forage, $j$ = 4 for grain |
| $k$ | = | animal product index; $k$ = 1 for beef, 2 for milk, 3 for poultry, and 4 for eggs |
| $Qf_k$ | = | animal consumption rate of feed (kg $_{\text{fresh weight}}$/d). |

Radionuclide concentrations in animal feed are calculated in the plant submodel (Section 6.5.3). The transfer coefficients for the animal products and animal consumption rates are considered to be the same in the volcanic ash and groundwater scenarios (BSC 2003 [DIRS 160964], Section 7).

#### 6.5.4.2 Animal Soil Ingestion

Animal soil ingestion is an important pathway (Section 7.4.5) because soil is the initial source of contamination in the volcanic ash scenario. To be consistent with the methods used for the contamination of foodstuffs, radionuclide concentrations in the contaminated soil that an animal ingests are calculated for cultivated lands (Equation 6.5.1-2). Radionuclide concentrations in animal products from the ingestion of contaminated soil are evaluated as

$$Cd_{soil\ i,k} = Fm_{i,k}\ Cs_{m,i}\ Qs_k \qquad \text{(Eq. 6.5.4-3)}$$

where

| | | |
|---|---|---|
| $Cs_{m,i}$ | = | activity concentration of radionuclide *i* in contaminated soil under saturation conditions (Bq/kg) |
| $Qs_k$ | = | animal consumption rate of soil (kg/d) |

and the other parameters are defined in Equation 6.5.4-2.

Inadvertent soil ingestion by animals is estimated for mature animals, and the values are animal-type specific. Typical literature values for beef cattle and dairy cows are about 1 kg/d (BSC 2003 [DIRS 160964], Section 6.3).

### 6.5.5 External Exposure Submodel

As in the groundwater scenario, the external exposure submodel for the volcanic ash scenario considers a human receptor exposed only to contaminated soil. Other external exposure pathways, air submersion and water immersion, are excluded because of the low contribution likely from air submersion (Section 7.4.8) and the lack of a contaminated source for water

immersion. Air submersion could be important during a volcanic eruption, but the ERMYN model does not consider any scenarios during a volcanic eruption. Dose from external exposure is calculated as the annual EDE.

#### 6.5.5.1 External Exposure to Contaminated Ground Surface

Under the volcanic ash scenario, a thin layer of contaminated volcanic ash would be deposited on the surface of the ground. It would be improper to use a fixed volumetric source for the volcanic ash because the thickness of the source (i.e., the layer of ash) would be unknown, and it may change through time. To simplify the calculations, it is assumed (Assumption 16) that, regardless of the actual thickness of the ash, all radionuclides are only in a thin layer on the ground, which gives a higher external dose than if radionuclides mix with the soil. The annual external exposure, based on a modification of Equation 6.4.7-1 for the groundwater scenario, is evaluated as

$$D_{ext,i} = EDCs_{soil,i}\, Cs_i \sum_n f_{ext,i,n} \left( \sum_m PP_m \, (3600 \times t_{n,m}) \right) \qquad \text{(Eq. 6.5.5-1)}$$

where

| | | |
|---|---|---|
| $D_{ext,i}$ | = | dose from external exposure to radionuclide *i* in deposited volcanic ash (Sv/yr) |
| $EDCs_{soil,i}$ | = | effective dose coefficient for exposure to a contaminated ground surface for radionuclide *i* (Sv/sec per Bq/m$^2$); calculation of effective dose coefficients for contaminated ground is discussed in Section 6.5.5.2 |
| $Cs_i$ | = | activity concentration of radionuclide *i* in deposited volcanic ash (Bq/m$^2$). |
| $f_{ext,i,n}$ | = | external shielding factor for exposure to radionuclide *i* in the ground at environment *n* (dimensionless). |
| $n$ | = | environment index; $n$ = 1 for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area |
| $m$ | = | population group index; $m$ = 1 for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for non-workers |
| $PP_m$ | = | fraction of total population in population group *m* (population proportion) (dimensionless) |
| $t_{n,m}$ | = | time spent by population group *m* in environment *n* (exposure time) (hr/yr). |
| 3600 | = | unit conversion of hours to seconds; 3,600 (sec/hr). |

Similar to the volumetric source discussed in Section 6.4.7, the short-lived decay products in equilibrium with their long-lived primary radionuclides are considered in the effective dose coefficients for contaminated ground surface. Development of the effective dose coefficients is discussed below. The radionuclide concentration in the surface soil is the source term for this scenario.

The external shielding factor, $f_{ext,i,n}$, accounts for the reduction in external exposure offered by dwellings. Outdoors ($n$ = 1, 2, and 5), there is no shielding reduction and the value of $f_{ext,i,n}$ is

considered to be one. For indoor environments ($n$ = 3 and 4), the shielding factor is radionuclide dependent (e.g., strong gamma-ray emitters would be more penetrating and have a higher factor than would weak gamma emitters). Consequently, values for the shielding factor range from zero to one; however, typical values, even for the most penetrating radiation emissions, do not exceed 0.4. Values for this parameter should be the same as those used in the groundwater scenario, as developed in BSC (2003 [DIRS 161241]).

The external exposure time, $t_{n,m}$, the amount of time spent annually in environment $n$ by population $m$, depends on the life style of the receptor. The fraction of the total population in population group $m$, $PP_m$, is based on Amargosa valley census data (BSC 2003 [DIRS 161241], Section 6.3). The spatial distribution of contamination differs between the two exposure scenarios. Therefore, the fraction of the population that works outside the contaminated area (i.e., commuters) and the time it would take them to leave the area differs, and different values for exposure times and population proportions must be used for the two scenarios.

### 6.5.5.2 Effective Dose Coefficients for Contaminated Ground Surface

Dose coefficients for exposure to a contaminated ground surface are evaluated in BSC (2003 [DIRS 161241], Section 6.5) and are based on the values from FGR-12 (Eckerman and Ryman 1993 [DIRS 107684], Table III.3). Dose contributions from short-lived decay products are combined with those of the long-lived parent radionuclides (Section 6.3.5). Effective dose coefficients (Table 6.5-1) are calculated as the sum of the dose coefficients for a long-lived radionuclide and the short-lived decay products, with consideration of the branching ratios. The calculation is expressed as

$$EDCs_{soil,i} = \sum_{s} DCs_{soil,s} \times BN_s \qquad \text{(Eq. 6.5.5-2)}$$

where

| | | |
|---|---|---|
| $DCs_{soil,s}$ | = | dose coefficient for exposure to a contaminated ground surface for radionuclide s in a decay chain of radionuclide $i$ (Sv/sec per Bq/m$^2$). |
| $s$ | = | index of short-lived radionuclide decay chain under a primary radionuclide $i$ |
| $BN_s$ | = | branching fraction for short-lived radionuclide $s$ in the decay chain of primary radionuclide $i$ (dimensionless) |

the other parameter is defined in Equation 6.4.8.2.

Similar to Table 6.4-2, the values in Table 6.5-1 are for demonstration purposes only. The ERMYN model uses branching fractions and dose coefficients as inputs to calculate the effective dose conversion factors in GoldSim (Section 6.9).

Table 6.5-1. Effective Dose Coefficients for Exposure to Contaminated Ground Surface

| Primary Radionuclide | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Coefficient Value ($DCs_{soil}$) (Sv/sec)/(Bq/m$^2$) | Effective Dose Coefficient ($EDCs_{soil}$) (Sv/sec)/(Bq/m$^2$) |
|---|---|---|---|
| C-14 | - | 1.61E-20 | 1.61E-20 |
| Cl-36 | - | 6.73E-19 | 6.73E-19 |
| Se-79 | - | 2.07E-20 | 2.07E-20 |
| Sr-90D [a] | | 2.84E-19 | 5.60E-18 |
| | Y-90 (64.0 hr) | 5.32E-18 | |
| Tc-99 | - | 7.80E-20 | 7.80E-20 |
| Sn-126D | | 5.47E-17 | 1.96E-15 |
| | Sb-126m (19.0 min) | 1.52E-15 | |
| | Sb-126 (14%, 12.4 d) | 2.78E-15 | |
| I-129 | - | 2.58E-17 | 2.58E-17 |
| Cs-135 | - | 3.33E-20 | 3.33E-20 |
| Cs-137D | | 2.85E-19 | 5.55E-16 |
| | Ba-137m (94.6%, 2.552 min) | 5.86E-16 | |
| Pu-242 | - | 6.67E-19 | 6.67E-19 |
| U-238D | | 5.51E-19 | 3.02E-17 |
| | Th-234 (24.10 d) | 8.32E-18 | |
| | Pa-234m (99.80%, 1.17 min) | 1.53E-17 | |
| | Pa-234 (0.33%, 6.7 hr) | 1.84E-15 | |
| Pu-238 | - | 8.38E-19 | 8.38E-19 |
| U-234 | - | 7.48E-19 | 7.48E-19 |
| Th-230 | - | 7.50E-19 | 7.50E-19 |
| Ra-226D | | 6.44E-18 | 1.66E-15 |
| | Rn-222 (3.8235 d) | 3.95E-19 | |
| | Po-218 (3.05 min) | 8.88E-21 | |
| | Pb-214 (99.98%, 26.8 min) | 2.44E-16 | |
| | At-218 (0.02%, 2 sec) | 4.18E-18 | |
| | Bi-214 (19.9 min) | 1.41E-15 | |
| | Po-214 (99.98%, $1.64 \times 10^{-4}$ sec) | 8.13E-20 | |
| | Tl-210 (0.02%, 1.3 min) | 0.00E+00 | |
| Pb-210D | | 2.48E-18 | 3.54E-18 |
| | Bi-210 (5.012 d) | 1.05E-18 | |
| | Po-210 (138.38 d) | 8.29E-21 | |
| Pu-240 | - | 8.03E-19 | 8.03E-19 |
| U-236 | - | 6.50E-19 | 6.50E-19 |
| Th-232 | - | 5.51E-19 | 5.51E-19 |
| Ra-228D [b] | | 0.00E+00 | 9.28E-16 |
| | Ac-228 (6.13 hr) | 9.28E-16 | |
| U-232 | - | 1.01E-18 | 1.01E-18 |

Table 6.5-1. Effective Dose Coefficients for Exposure to Contaminated Ground Surface (continued)

| Primary Radionuclide | Decay Product [c] (branching fraction if not 100%, half-life) | Dose Coefficient Value ($DCs_{soil}$) (Sv/sec)/(Bq/m$^2$) | Effective Dose Coefficient ($EDCs_{soil}$) (Sv/sec)/(Bq/m$^2$) |
|---|---|---|---|
| Th-228D | | 2.35E-18 | 1.41E-15 |
| | Ra-224 (3.66 d) | 9.57E-18 | |
| | Rn-220 (55.6 sec) | 3.81E-19 | |
| | Po-216 (0.15 sec) | 1.65E-20 | |
| | Pb-212 (10.64 hr) | 1.43E-16 | |
| | Bi-212 (60.55 min) | 1.79E-16 | |
| | Po-212 (64.07%, 0.305 µ-sec) | 0.00E+00 | |
| | Tl-208 (35.93%, 3.07 min) [e] | 2.98E-15 | |
| Am-243D | | 5.35E-17 | 2.17E-16 |
| | Np-239 (2.355 d) | 1.63E-16 | |
| Pu-239 | - | 3.67E-19 | 3.67E-19 |
| U-235D | | 1.48E-16 | 1.67E-16 |
| | Th-231 (25.52 hr) | 1.85E-17 | |
| Pa-231 | - | 4.07E-17 | 4.07E-17 |
| Ac-227D | | 1.57E-19 | 3.87E-16 |
| | Th-227 (98.62%, 18.718 d) | 1.04E-16 | |
| | Fr-223 (1.38%, 21.8 min) | 5.65E-17 | |
| | Ra-223 (11.434 d) | 1.28E-16 | |
| | Rn-219 (3.96 sec) | 5.49E-17 | |
| | Po-215 (1.78 millisec) | 1.74E-19 | |
| | Pb-211 (36.1 min) | 5.08E-17 | |
| | Bi-211 (2.14 min) | 4.58E-17 | |
| | Tl-207 (99.72%, 4.77 min) | 3.76E-18 | |
| | Po-211 (0.28%, 0.516 sec) | 7.61E-18 | |
| Am-241 | - | 2.75E-17 | 2.75E-17 |
| Np-237D | | 2.87E-17 | 2.24E-16 |
| | Pa-233 (27.0 d) | 1.95E-16 | |
| U-233 | - | 7.16E-19 | 7.16E-19 |
| Th-229D | | 8.54E-17 | 3.18E-16 |
| | Ra-225 (14.8 d) | 1.33E-17 | |
| | Ac-225 (10.0 d) | 1.58E-17 | |
| | Fr-221 (4.8 min) | 2.98E-17 | |
| | At-217 (32.3 millisec) | 3.03E-19 | |
| | Bi-213 (45.65 min) | 1.32E-16 | |
| | Po-213 (97.84%, 4.2 µ-sec) | 0.00E+00 | |
| | Tl-209 (2.16%, 2.2 min) | 1.90E-15 | |
| | Pb-209 (3.253 hr) | 3.01E-19 | |

NOTES: DC = dose coefficient.

[a] A "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short-lived (< 180 d) decay product.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Eckerman and Ryman (1993 [DIRS 107684], Table A.1).

[d] Dose coefficient source (BSC 2003 [DIRS 161241], Section 6.5).

[e] Half-life of Tl-210 is taken from Lide and Frederikse (1997 [DIRS 103178], p.11-125).

### 6.5.6 Inhalation Submodel

The inhalation submodel for the volcanic ash scenario is more complicated than that for the groundwater scenario because the input parameters, radionuclide concentrations in air and ground, vary with time and thickness of the ash (Equation 6.5.2-4). The inhalation dose is calculated as the CEDE for the 50-yr committed period resulting from annual intake of radionuclides by inhalation. Two sources of contamination in air are considered: resuspended particles (Section 6.5.2.1) and radon gas (Section 6.5.2.2). The total inhalation dose is the sum of the dose from both sources, which is evaluated as

$$D_{inh,i}(d_a,t) = D_{inh,p,i}(d_a,t) + D_{inh,g,i} \qquad \text{(Eq. 6.5.6-1)}$$

where

| | | |
|---|---|---|
| $D_{inh,i}(d_a, t)$ | = | annual dose from inhalation of radionuclide $i$ for ash thickness $d_a$ at time $t$ (Sv/yr) |
| $D_{inh,p,i}(d_a, t)$ | = | annual dose from inhalation of radionuclide $i$ resulting from exposure to resuspended particles ($p$) for ash thickness $d_a$ at time $t$ (Sv/yr) |
| $D_{inh,g,i}$ | = | annual dose from inhalation of radionuclides resulting from gaseous emission ($g$) of radionuclide $i$ in the ash (Sv/yr). |

#### 6.5.6.1 Inhalation of Resuspended Particles

The inhalation dose is calculated considering specific environments associated with human activities and population groups. For this scenario, there are two components to the radionuclide concentrations in the air, one related to nominal mass loading and one related to post-volcanic, time-dependent, mass loading, both of which depend on ash thickness (Section 6.5.2.1). Therefore, the inhalation dose calculation can be separated into two items and expressed as

$$\begin{aligned} D_{inh,p,i}(d_a,t) &= EDCF_{inh,i} \sum_n Ca_{h,i,n}(d_a,t)\, BR_n \left( \sum_m PP_m\, t_{n,m} \right) \\ &= EDCF_{inh,i} \sum_n Ca_{h,i,n}\, f(d_a)\, BR_n \left( \sum_m PP_m\, t_{n,m} \right) \\ &\quad + EDCF_{inh,i} \sum_n Ca_{v,i,n}\, f(d_a)\, f(t)\, BR_n \left( \sum_m PP_m\, t_{n,m} \right) \\ &= D_{inh,p,i}\, f(d_a) + D_{inh,v,i}\, f(d_a)\, f(t) \end{aligned} \qquad \text{(Eq. 6.5.6-2)}$$

where

| | | |
|---|---|---|
| $D_{inh,p,i}(d_a, t)$ | = | annual dose from inhalation of radionuclide $i$ resulting from exposure to resuspended particles for an ash thickness of $d_a$ at time $t$ (Sv/yr) |
| $EDCF_{inh,i}$ | = | effective dose conversion factor for inhalation of primary radionuclide $i$ (Sv/Bq) |
| $n$ | = | environment index; $n$ = 1 for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the |

| | | |
|---|---|---|
| | | contaminated area |
| $BR_n$ | = | breathing rate for environment $n$ ($m^3$/hr) |
| $m$ | = | population group index; $m$ = 1 for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for non-workers |
| $PP_m$ | = | proportion of population in group $m$ (dimensionless) |
| $t_{n,m}$ | = | time spent by group $m$ in environment $n$ (exposure time) (hr/yr) |
| $D_{inh,p,i}$ | = | annual dose from inhalation of radionuclide $i$ resulting from exposure to nominal mass loading ($p$) after a volcanic eruption (Sv/yr) |
| $D_{inh,v,i}$ | = | annual dose from inhalation of radionuclide $i$ resulting from exposure to post-volcanic mass loading ($v$) in addition to nominal mass loading following a volcanic eruption (Sv/yr) |

and the other parameters are defined in Equation 6.5.2-4.

The effective dose conversion factors for inhalation are discussed in Section 6.4.8.5 and shown in Table 6.4-3. The inhalation exposure time, $t_{n,m}$, is the annual amount of time that population $m$ spends in environment $n$, and depends on the life style of the receptor (BSC 2003 [DIRS 161241], Section 6.3). The breathing rate, $BR_n$, varies with the environment. The fraction of the total population in population group $m$, $PP_m$, is based on Amargosa Valley census data (BSC 2003 [DIRS 161241]).

### 6.5.6.2 Inhalation of Radon Decay Products

The only gaseous radionuclide considered in the submodel is $^{222}$Rn, which would be released from $^{226}$Ra in volcanic ash. Considering an infinitely large contaminated area (Section 6.5.2.2), the radon concentration in the air is estimated using a conversion factor between $^{226}$Ra activity concentration on the top of the ground and $^{222}$Rn activity concentration in air. The indoor $^{222}$Rn concentration is the same as the outdoor $^{222}$Rn concentration (Section 6.5.2.2). Under the volcanic ash scenario, the $^{222}$Rn inhalation dose calculation does not require consideration of elevated indoor concentration of $^{222}$Rn produced as a result of operating an evaporative cooler. Using the radon inhalation dose conversion factor derived in Section 6.4.8.5 (Equation 6.4.8-8), the radon inhalation dose is evaluated as

$$\begin{aligned} D_{inh,g,Rn-222} &= Ca_{g,Rn-222} \sum_n DCF_{inh,Rn-222,n}\, BR_n \left( \sum_m PP_m\, t_{n,m} \right) \\ &= Ca_{g,Rn-222}\, DCF_{inh,Rn-222} \sum_n EF_{Rn-222,n}\, BR_n \left( \sum_m PP_m\, t_{n,m} \right) \end{aligned} \qquad \text{(Eq. 6.5.6-3)}$$

where

| | | |
|---|---|---|
| $D_{inh\ g,Rn-222}$ | = | annual dose from inhalation of $^{222}$Rn decay products (Sv/yr) |
| $DCF_{inh,Rn-222,n}$ | = | dose conversion factor for inhalation of $^{222}$Rn decay products in environment $n$ (Sv/Bq) |
| $DCF_{inh,Rn-222}$ | = | dose conversion factor for inhalation of $^{222}$Rn decay products at 100 percent equilibrium |
| $EF_{Rn-222,\ n}$ | = | equilibrium factor for $^{222}$Rn decay products in environment $n$ (dimensionless) |

and the other parameters are defined in Equations 6.5.2-8 and 6.5.6-2.

The radon inhalation dose contribution is to be added into the BDCF for $^{226}$Ra. By combining Equations 6.5.6-2 and 6.5.6-3, Equation 6.5.6-1 can be rewritten as

$$\begin{aligned} D_{inh,i}(d_a,t) &= D_{inh,p,i}(d_a,t) + D_{inh,g,i} \\ &= D_{inh,v\ i}\, f(d_a)\, f(t) + D_{inh,p,i}\ f(d_a) + D_{inh,g\ i} \end{aligned} \qquad \text{(Eq. 6.5.6-4)}$$

where all parameters are defined in Equations 6.5.6-1, 6.5.6-2, and 6.5.6-3.

### 6.5.7 Ingestion Submodel

Because water is uncontaminated in the volcanic ash scenario, the ingestion submodel only considers contaminated crops (leafy vegetables, other vegetables, fruits, and grain), contaminated animal products (meat, poultry, milk, and eggs), and inadvertent ingestion of contaminated soil. The ingestion dose, analogous to the inhalation dose, is calculated as the CEDE for the 50-yr committed period resulting from the annual intake of radionuclides by ingestion. The contaminated foodstuffs are discussed in the plant (Section 6.5.3) and animal submodels (Section 6.5.4). Contaminated soil, resuspended from cultivated lands (Section 6.5.1) and deposited on crops, is another source of contamination for crops. The total ingestion dose includes contributions from all these sources, and for an individual radionuclide is expressed as

$$D_{ing,i} = D_{ing,p,i} + D_{ing,d,i} + D_{ing,s,i} \qquad \text{(Eq. 6.5.7-1)}$$

where

$D_{ing,i}$ = annual dose from ingestion of radionuclide *i* (Sv/yr)
$D_{ing,p,i}$ = annual dose from ingestion of radionuclide *i* in crops (Sv/yr)
$D_{ing,d,i}$ = annual dose from ingestion of radionuclide *i* in animal products (Sv/yr)
$D_{ing,s,i}$ = annual dose from inadvertent ingestion of radionuclide *i* in surface soil (Sv/yr).

These ingestion pathways are discussed in detail in the following subsections.

#### 6.5.7.1 Ingestion of Crop Foodstuffs

The ingestion of contaminated crops is an important pathway for the volcanic scenario, similar to the groundwater scenario, and includes four types of crop foodstuffs. The storage time from harvest to consumption is not considered because only long-lived radionuclides are of concern in the biosphere model. Annual doses from the ingestion of contaminated crops are evaluated as

$$D_{ing,p,i} = EDCF_{ing,i} \sum_j \left( Cp_{i,j}\, Up_j \right) \qquad \text{(Eq. 6.5.7-2)}$$

where

$D_{ing,p,i}$ = annual dose from ingestion of primary radionuclide *i* in crops (Sv/yr)
$EDCF_{ing,i}$ = effective dose coefficient for ingestion of primary radionuclide *i* (Sv/Bq)
$Cp_{i,j}$ = activity concentration of primary radionuclide *i* in crop type *j* (Bq/kg)

| | | |
|---|---|---|
| $j$ | = | index of crop type, $j$ = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, and 4 for grain |
| $Up_j$ | = | annual consumption rate of locally produced contaminated crop type $j$ (kg/yr). |

The effective dose conversion factors for ingestion are discussed in Section 6.4.9.6 and shown in Table 6.4-4. The activity concentrations of radionuclides in crops are discussed in the plant submodel (Section 6.5.3). The consumption rates used in Equation 6.5.7-2 apply only to locally produced crops (BSC 2003 [DIRS 161241]).

### 6.5.7.2 Ingestion of Animal Products

The ingestion of animal products includes the four animal product pathways used for the groundwater scenario. Similar to crops, the storage time from harvest to consumption is not considered. Annual doses from the ingestion of contaminated animal products are evaluated as

$$D_{ing,d,i} = EDCF_{ing,i} \sum_k \left( Cd_{i,k}\, Ud_k \right) \qquad \text{(Eq. 6.5.7-3)}$$

where

| | | |
|---|---|---|
| $D_{ing,d,i}$ | = | annual dose from ingestion of primary radionuclide $i$ in animal products (Sv/yr) |
| $Cd_{i,k}$ | = | activity concentration of primary radionuclide $i$ in animal product $k$ (Bq/kg) |
| $k$ | = | index of animal products, $k$ = 1 for meat, 2 for poultry, 3 for milk, and 4 for eggs |
| $Ud_k$ | = | annual consumption rate of locally produced animal product $k$ (kg/yr) |

and the other parameters are defined in Equation 6.5.7-2.

The activity concentrations of radionuclides in animal products are discussed in the animal submodel (Section 6.5.4). The consumption rates used in Equation 6.5.7-3 apply only to locally produced animal products; imported animal products are considered to be uncontaminated (BSC 2003 [DIRS 161241], Section 6.4).

### 6.5.7.3 Inadvertent Soil Ingestion

Inadvertent soil ingestion may be an important pathway for the volcanic ash scenario because contaminated ash deposited on the soil surface is the source of contamination. Annual doses from inadvertent ingestion of radionuclides in contaminated soil is evaluated as

$$D_{ing,s,i} = EDCF_{ing,i}\, Cs_{m,i}\, Us \qquad \text{(Eq. 6.5.7-4)}$$

where

| | | |
|---|---|---|
| $D_{ing,s,i}$ | = | annual dose from inadvertent ingestion of primary radionuclide $i$ in the surface soil (Sv/yr) |
| $Cs_{m,i}$ | = | mass-based activity concentration of a primary radionuclide $i$ in the surface soil (Bq/kg) |
| $Us$ | = | annual consumption rate of contaminated soil (kg/yr) |

and the other parameters are defined in Equation 6.5.7-2.

The activity concentration of radionuclides in the surface soil is discussed in the surface soil submodel (Section 6.5.1). Estimates of soil ingestion rates have wide uncertainty distributions, with typical values for adults on the order of several tens to a few hundred milligrams per day (BSC 2003 [DIRS 161241], Section 6.4).

### 6.5.8 All-pathway Dose and BDCFs Calculation

Under the volcanic ash scenario, radionuclides in the ash are the source for all radiation pathways, and all depend linearly on this source. The biosphere contribution to the TSPA-LA for dose assessments is separated from the source. The biosphere contribution has three terms, one that is constant, one that depends on the thickness of the ash, and one that depends on time and the thickness of the ash (Equation 6.5.6-4). The time function is due to the expected decline in mass loading after a volcanic eruption. Because the radionuclide source term is time dependent (due to ash redistribution and radionuclide decay), time-dependent dose calculations will be carried out in the TSPA-LA model rather than in the ERMYN model. In addition, two of the BDCF components depend on ash thickness. Because ash thickness is not an input parameter to the ERMYN model, this dose calculation also will be carried out in the TSPA-LA model. This section provides the method to calculate the final dose based on the BDCFs discussed in the previous sections.

#### 6.5.8.1 All-pathway Dose

The all-pathway annual dose for an individual primary radionuclide, expressed in terms of the TEDE, is the sum of the annual EDE from external exposure and the annual CEDE from the radionuclide intake into the body by ingestion and inhalation, and is evaluated as

$$\begin{aligned} D_{all,i}(d_a,t) &= D_{ext,i} + D_{inh,i}(d_a,t) + D_{ing,i} \\ &= D_{ext,i} + D_{ing,i} + D_{inh,g,i} + D_{inh,v,i} f(d_a) f(t) + D_{inh,p,i} f(d_a) \\ &= D_{all,i} + D_{inh,v,i} f(d_a) f(t) + D_{inh,p,i} f(d_a) \end{aligned} \qquad \text{(Eq. 6.5.8-1)}$$

where

$D_{all,i}(d_a, t)$ = all-pathway annual dose from internal and external exposure to radionuclide $i$ for ash deposited to a depth of $d_a$ at time $t$ (Sv/yr)

$D_{all,i}$ = all-pathway annual dose from external exposure, radon inhalation, and ingestion to radionuclide $i$ (Sv/yr)

and the other parameters are defined in Equations 6.5.5-1, 6.5.6-1, 6.5.6-2, 6.5.6-4, and 6.5.7-1.

#### 6.5.8.2 Biosphere Dose Conversion Factors for the Volcanic Ash Scenario

The radionuclide concentration in the volcanic ash deposited on the surface of the ground is the only source of radionuclide contamination for the volcanic ash scenario. All radiation pathways discussed in the previous sections depend linearly on this source, which is summarized in Table 6.5-2.

Table 6.5-2. Summary of the Biosphere Submodels for the Volcanic Ash Scenario

| Submodel | Quantity Calculated in Submodel | Section | Simplified Equation | Equation Number |
|---|---|---|---|---|
| Soil | Activity concentration of a primary radionuclide on cultivated lands | 6.5.1.1 | $Cs_{m,i} = K1\ Cs_i$ | 6.5.1-2 |
| | Activity concentration of a primary radionuclide on non-cultivated lands | 6.5.1.2 | $Cs_{mc,i} = K2\ Cs_i$ | 6.5.1-3 |
| Air | Activity concentration of a radionuclide in air from soil resuspension | 6.5.2.1 | $Ca_i = K3\ Cs_i$ | 6.5.2-2 |
| | Activity concentration of radon gas in air | 6.5.2.3 | $Ca_{Rn\text{-}222} = K4\ Cs_{Ra\text{-}226}$ | 6.5.2-8 |
| Plant | Activity concentration of a radionuclide in crops from root uptake | 6.5.3.1 | $Cp_i = K5\ Cs_i$ | 6.5.3-2 |
| | Activity concentration of a radionuclide in crops from foliar interception of resuspended soil | 6.5.3.3 | $Cp_i = K6\ Ca_i = K6\ K3\ Cs_i$ | 6.5.3-3<br>6.5.3-4 |
| Animal | Activity concentration of a radionuclide in animal product from animal feed | 6.5.4.1 | $Cd_i = K7\ Cp_I = K8\ Cs_i$ | 6.5.4-2 |
| | Activity concentration of a radionuclide in animal product from soil ingestion | 6.5.4.3 | $Cd_i = K9\ Cs_i$ | 6.5.4-3 |
| External Exposure | External exposure dose | 6.5.5.1 | $D_{ext,\ i} = K10\ Cs_i$ | 6.5.5-1 |
| Inhalation | Inhalation dose from airborne particulates | 6.5.6.1 | $D_{inh,\ i} = K11\ Ca_i = K11\ K3\ Cs_i$ | 6.5.6-2 |
| | Inhalation dose from radon decay products | 6.5.6.2 | $D_{inh,Rn\text{-}222} = K12\ Ca_{Rn\text{-}222}$<br>$= K12\ K4\ Cs_{Ra\text{-}226}$ | 6.5.6-3 |
| Soil | Ingestion dose from crops | 6.5.7.1 | $D_{ing,\ i} = K13\ Cp_i = K14\ Cs_i$ | 6.5.7-2 |
| | Ingestion dose from animal products | 6.5.7.2 | $D_{ing,\ i} = K15\ Cd_i = K16\ Cs_i$ | 6.5.7-3 |
| | Ingestion dose from soil | 6.5.7.3 | $D_{ing,\ i} = K17\ Cs_i$ | 6.5.7-4 |

NOTES: In the simplified equations, the proportionality constants (e.g., K1, K2, …$K_i$) can be derived from the referenced equations. The dose is proportional to the source, $Cs_i$, the activity concentration of radionuclide *i* in surface soil per unit area (Bq/m$^2$). The constants in this table are specific to the volcanic ash scenario and are not the same as the constants in Table 6.4-5.

Because of the need to consider ash thickness and time in the biosphere model, the post-eruption BDCFs for the volcanic ash scenario are calculated as a function of ash thickness and time. In the TSPA-SR, the time dependence is eliminated using conservative transition phase BDCFs (CRWMS M&O 2000 [DIRS 153246]). Alternatively, modeling the BDCFs as a function of ash thickness allows for applying the BDCFs to any ash thickness. Also, the new format for BDCFs allows for incorporating source variation, including ash redistribution, radionuclide decay and ingrowth, and surface erosion.

All of the pathways are linearly proportional to the areal radionuclide concentration in the volcanic ash on the ground (Table 6.5-2). Thus, the biosphere contribution for the dose assessment can be separated from the source. The radionuclide-specific BDCFs are the final products from the ERMYN model, and these will be used in the TSPA-LA model. For the volcanic ash scenario, the radionuclide-specific BDCFs are calculated as

$$
\begin{aligned}
BDCF_i(d_a,t) &= \frac{D_{all,i}(d_a,t)}{Cs_i} \\
&= \frac{D_{all,i}}{Cs_i} + \frac{D_{inh,v,i}}{Cs_i} f(d_a) f(t) + \frac{D_{inh,p,i}}{Cs_i} f(d_a) \qquad \text{(Eq. 6.5.8-2)} \\
&= BDCF_i + \left(BDCF_{inh,v,i} f(t) + BDCF_{inh,p,i}\right) f(d_a)
\end{aligned}
$$

where

| | | |
|---|---|---|
| $BDCF_i(d_a, t)$ | = | BDCF for radionuclide *i* for an ash deposition depth of $d_a$ at time *t* following a volcanic eruption (Sv/yr per Bq/m$^2$) |
| $BDCF_i$ | = | BDCF for radionuclide *i* for external exposure, radon inhalation, and ingestion (Sv/yr per Bq/m$^2$) |
| $BDCF_{inh,v,i}$ | = | BDCF for radionuclide *i* for inhalation of post-volcanic mass loading in addition to nominal mass loading following a volcanic eruption (Sv/yr per Bq/m$^2$) |
| $BDCF_{inh,p,i}$ | = | BDCF for radionuclide *i* for inhalation of nominal mass loading following a volcanic eruption (Sv/yr per Bq/m$^2$) |

and the other parameters are defined in Equations 6.5.1-1 and 6.5.8-1.

For the volcanic ash scenario, three BDCF components are provided to the TSPA-LA model. The first one is for the time-independent component, $BDCF_i$, which includes external exposure, radon inhalation, and ingestion. The second one is for the ash thickness dependent component, $BDCF_{inh,p,i}$, which includes inhalation of resuspension particles at normal condition. The last one is for the ash thickness and time dependent component, $BDCF_{inh,v,i}$, which includes inhalation of resuspended particles under post-volcanic conditions.

### 6.5.8.3 Use of BDCFs in the Total System Performance Assessment Model

Similar to the groundwater scenario, the expected annual dose calculation for the volcanic scenario will be calculated in the TSPA-LA model, where input parameters will include the radionuclide-specific BDCFs, the mass loading decrease function, and the thickness of the volcanic ash. The TSPA-LA code will be used to calculate the time-dependent amount of volcanic ash deposited on the ground. The total annual dose will be the sum of the individual annual doses from radionuclides tracked by the TSPA-LA, including the doses from any short-lived decay products incorporated into the BDCFs (half-life < 180 d). The expected annual dose will be the final output of the TSPA-LA model. This quantity will be used to determine compliance with the individual protection standard, which is one of the performance measures for the repository. The total annual dose, as a function of time and conditional on the occurrence of an eruption, will be calculated using the TSPA-LA model as

$$D_{total}(t) = \sum_i BDCF_i(d_{a,}t) \times Cs_i(t)$$

$$= \sum_i BDCF_i \times Cs_i(t) \qquad \text{(Eq. 6.5.8-3)}$$

$$+ \sum_i \left(BDCF_{inh,v,i}\, f(t) + BDCF_{inh,p,i}\right) f(d_a) \times Cs_i(t)$$

where

$D_{total}(t)$ = time-dependent total annual dose to a defined receptor resulting from the release of radionuclides from the repository including contributions from all radionuclides considered in the TSPA-LA (Sv/yr)

$Cs_i(t)$ = time dependent activity concentration of radionuclide *i* in volcanic ash deposited on the ground (Bq/m$^2$)

and the other parameters are defined in Equation 6.5.8.2.

## 6.6 CONSIDERATION OF MODEL UNCERTAINTY

The ERMYN model is based on the included FEPs, but it includes many assumptions, simplifications, and idealizations, and therefore uncertainties must be considered. Uncertainty in the results of models comes from the conceptual model (e.g., from decisions concerning the inclusion or exclusion of pathways), the mathematical model (e.g., from the use of simplified analytical methods), and the input parameters (e.g., when represented by distributions of parameter values). When models are executed, the conceptual and mathematical model uncertainties are fixed, but if input distributions are used and multiple model simulations are realized, the output will be a range of values that can be used to characterize uncertainty distributions for the output values. The ERMYN model has capabilities for simulating biosphere processes using variable inputs. In this section, uncertainty in the ERMYN model from the conceptual model, mathematical model, and input parameters are discussed.

### 6.6.1 Conceptual Model Uncertainty

Uncertainty generated by the conceptual model comes from decisions regarding FEPs screening, assumptions, and the selection of ACMs, but this uncertainty cannot be quantitatively evaluated. However, if a model is constructed carefully, this uncertainty usually will be unimportant to overall model uncertainty.

**FEPs Screening**–The biosphere model is based on a comprehensive list of the included FEPs; however, screening decisions to include or exclude FEPs could contribute to model uncertainty. Although this uncertainty is not evaluated quantitatively, it is likely that these decisions add little additional uncertainty because all applicable, important FEPs are represented in the conceptual model.

**Human Receptor**–The characteristics of the RMEI are defined by regulation (10 CFR 63.312 [DIRS 156605]). Development of the attributes and behavioral characteristics of the RMEI

involves uncertainties related to site-specific information. These uncertainties are considered in input parameter uncertainty (discussed below), rather than conceptual model uncertainty.

**Consideration of Human Exposure Pathways**–All applicable pathways are considered during development of the conceptual model (Sections 6.3.1 and 6.3.2), and only applicable pathways shown to have little influence on the results are excluded. For example, air submersion and water immersion pathways are not included because numerical comparisons made between dose coefficients and typical exposure times indicate that they are not important when compared with the included pathways (Section 7.4.8). Uncertainty due to ignoring pathways has little affect on overall uncertainty in the ERMYN model results.

**Environmental Transport of Radionuclides**–Interaction matrices (Table 6.3-2, groundwater scenario; Table 6.3-4, volcanic ash scenario; Table 6.3-6, verification) are used to summarize radionuclide transfers between biosphere model components (environmental media). Because applicable, important FEPs are considered in the interaction matrices, it is expected that the important radionuclide transfer mechanisms are considered during development of the ERMYN model. Of the transfer mechanisms considered, only those shown to have little influence on model results (e.g., inhalation of resuspended particles by livestock; see Section 7.4.5) are excluded from the model. Therefore, uncertainty due to omission or exclusion of radionuclide transfer mechanisms should be low.

**Alternative Conceptual Model**–ACMs are discussed in Section 6.3.3. Based on evaluations (Section 7.4), the selected submodels and components are considered more reasonable than the excluded ACMs, and the main uncertainties associated with the ACMs are captured in the ERMYN model. Therefore, screening of ACMs added little uncertainty to the final results.

**Future Conditions**–Regulation 10 CFR 63.305 ([DIRS 156605]) states that the DOE should not project changes in society, the biosphere (other than climate), human biology, and increases or decreases in human knowledge and technology. Therefore, uncertainty due to changes in the lifestyle and biology of the receptor, or conditions in the biosphere other than climate, are not considered in the ERMYN model.

### 6.6.2 Mathematical Model Uncertainty

Uncertainty associated with mathematical models comes from how accurately a conceptual model is represented by the mathematical equations. Selection of the mathematical model used to express a conceptual model is mainly based on the appropriateness of the model representation and on data availability. When data are not available, assumptions and simplifications are used to develop a reasonable mathematical model so that the processes can be quantitatively evaluated. Uncertainty associated with the assumptions and simplifications becomes part of mathematical model uncertainty. Mathematical model uncertainty usually cannot be quantitatively evaluated unless it is included in the input parameters.

Uncertainty for all of the assumptions discussed in Section 5 are summarized in Table 6.6-1. In general, the assumptions do not underestimate radiological consequences. The assumptions tend to be conservative, but not overly conservative, with respect to the implications of compounding conservatism in the ERMYN model results. When an assumption is reasonable, uncertainty

about how the assumption represents reality is expected to be relatively small. However, assumptions are necessary to reduce the numerical requirements of the mathematical model and the details required in the associated input data. The tradeoff between model uncertainty and simplified methods is considered worthwhile if the dose estimates are not substantially underestimated. This section does not quantitatively evaluate uncertainty associated with the assumptions; rather it discusses the qualitative uncertainty due to using the assumptions.

Table 6.6-1. Uncertainty Considerations for All Assumptions Used in the Model

| Assumption | Assumption Description | Uncertainty Consideration | Conclusion |
|---|---|---|---|
| 1 | Radionuclide concentrations in the groundwater are constant | Radionuclide buildup in the soil would eventually reach saturation conditions; however, the time to reach these conditions would depend on the individual radionuclide. See also Assumption 5. | Low uncertainty for most radionuclides, higher uncertainty for radionuclides that take a long time to reach saturation |
| 2 | Short-lived (<180 d) decay products are in equilibrium with the long-live primary radionuclide | For dose assessment of long-lived radionuclides, this assumption has low uncertainty because even if short-lived decay products are not in secular equilibrium, they should be close. In addition, short-lived radionuclides usually contribute little to human dose compared with the long-lived parent radionuclides. | Low uncertainty |
| 3 | Radionuclide concentrations in the air are calculated using an annual average irrigation rate | It is more reasonable to assume crop rotation than to assume single crops are grown forever on a single farm field. By using a distribution for the long-term irrigation input parameter, model uncertainty is considered in input parameter uncertainty. | Input parameters include uncertainty |
| 4 | Harvest removal is compensated by the use of cow manure for fertilizer | These mechanisms are not modeled because of a lack of input data. This assumption is considered conservative. Uncertainty introduced by this assumption is not evaluated quantitatively. | Uncertainty not evaluated mathematically |
| 5 | Radionuclides in surface soil are in steady-state condition | For most radionuclides of interest, it takes less than a few hundred years to reach saturation. For these radionuclides, uncertainty in accumulation is low because the performance assessment time is longer than the time required to reach saturation. However, a few radionuclides take thousands years to reach saturation, and although uncertainty can be estimated for these radionuclides, the ERMYN model results do not include this uncertainty. | Low uncertainty for most radionuclides, higher uncertainty for radionuclides that take a long time to reach saturation throughout the root depth. However, uncertainty would be reduced because buildup in thin top layer of soil (e.g., 3 mm for resuspension) could be more rapid. |
| 6 | Irrigation water initially deposited on the crop leaf surface is subject to weathering deposition | Mathematical evaluation of weathering deposition is not conducted because crops only retain a fraction of the contaminants from irrigation water (Section 7.4.4). This assumption contributes little uncertainty to the results. | Low uncertainty |

Table 6.6-1. Uncertainty Considerations for All Assumptions Used in the Model (continued)

| Assumption | Assumption Description | Uncertainty Consideration | Conclusion |
|---|---|---|---|
| 7 | Crop roots grow in the upper layer of the surface soil (tilling depth), regardless of the actual surface soil depth | When radionuclides reach steady state, the radionuclide concentration is not dependent on surface soil depth. This assumption contributes little uncertainty for saturation conditions. | Low uncertainty |
| 8 | Cows are fed with forage; chickens are fed with grain | Feeds are based on site-specific information. The plant submodel includes variation in radionuclide concentrations in feed, which partially accounts for uncertainty in the types of animal feed. | Input parameters partially include uncertainty |
| 9 | Animal product types (meat, milk, poultry and eggs) are representative | Each animal product type in the ERMYN model may include more than one product. The most common animal products are selected to represent the groups, and variation is incorporated into input parameter uncertainty. | Input parameters include uncertainty |
| 10 | Dose coefficients for exposure to soil that is contaminated to an infinite depth | Differences between dose coefficients for infinite and limited soil depths are compared for two sets of dose coefficients (Eckerman and Ryman 1993 [DIRS 107684], Tables III-6 and III-7). The differences are small (10%), and uncertainty due to this assumption is low. | Low uncertainty |
| 11 | Radionuclide concentrations in indoor air are due only to radionuclides introduced from the use of contaminated water in evaporative coolers | Radionuclide accumulation in indoor air is unlikely because a large volume of air would be circulated. Radionuclide decay is possible, but unlikely because the residence time of the air would be short, even if the evaporative coolers are temporary turned off. Therefore, uncertainty due to this assumption is low. | Low uncertainty |
| 12 | The mixing of volcanic ash and surface soil depends on land use | This assumption allows realistic considerations of volcanic ash mixing with surface soil. Thus, it contributes little uncertainty to the results. | Low uncertainty |
| 13 | Resuspended ash deposited on plants comes from cultivated lands, while ash for human inhalation cones from uncultivated lands | This assumption eliminates considering the mixing of resuspended particles from different lands, as there is no information to evaluate how the mixing occurs. Because inhalation is the predominant pathway, it is conservative to assume that ash is undiluted or only slightly diluted. However, this uncertainty could not be evaluated quantitatively. | Uncertainty not evaluated mathematically |
| 14 | Time dependent mass loading | Mass loading decreases with time after a volcanic eruption, but the specific decrease rate depends on many factors. Uncertainty due to this assumption is accounted for using a distribution function to describe the decrease rate. | Input parameter includes uncertainty |

Table 6.6-1. Uncertainty Considerations for All Assumptions Used in the Model (continued)

| Assumption | Assumption Description | Uncertainty Consideration | Conclusion |
|---|---|---|---|
| 15 | Radon gas is released from volcanic ash on the ground surface | It is conservative to assume that all $^{222}$Rn from $^{226}$Ra is released into the air. However, uncertainty is not evaluated quantitatively because of dynamic changes in the volcanic ash thickness. | Uncertainty not evaluated mathematically |
| 16 | External exposure from volcanic ash on the ground surface | It is conservative to assume that radionuclides in volcanic ash are concentrated on the surface of the ground. However, uncertainty is not evaluated quantitatively because of dynamic changes in the volcanic ash thickness. | Uncertainty not evaluated mathematically |

### 6.6.3 Input Parameter Uncertainty

The mathematical models for the groundwater (Section 6.4) and volcanic ash scenarios (Section 6.5) require many input parameters. Typically, parameter uncertainty is represented by probability distribution functions. General considerations of uncertainty in the input parameters is discussed below, followed by a list of the input parameters and further discussions of the general parameter uncertainty.

**Site-Specific Data**–Wherever possible, site-specific and regional information is used to develop parameter distributions. However, the development of a fully site-specific biosphere model is not possible because of the limited availability of site-specific data. Information from the scientific literature is used when site-specific or regional information is unavailable. Uncertainty in the application of literature data to site-specific conditions is incorporated into the parameter distributions.

**Parameter Distributions**–All ERMYN model input parameters can be represented by probability distributions, but fixed values are used for a few parameters. Discussions of parameter uncertainty represented by distribution functions is presented in Section 6.6.3.2.

**Fixed Parameter Values**–Justification is provided if a fixed value is used for a parameter. In general, fixed values are used for parameters that have little influence on the modeling results or are associated with limited uncertainty and variation. Therefore, parameters with fixed values have relatively minor contributions, and likely add little uncertainty to the final results.

**Parameter Correlation**–For parameters that use distributions, the probability density functions are considered to vary independently unless information indicates that pairs of parameters are correlated. When parameters are correlated, correlation coefficients are developed, although information on parameter correlation is limited. In general, the effect of neglecting covariance is to imprecisely estimate variability in the results. For positively correlated parameters, neglecting correlation typically results in underestimating variation in the ERMYN model results, and for negatively correlated parameters, neglecting correlation typically results in overestimating variation in the results.

### 6.6.3.1 List of Input Parameters

Parameter definitions are given in the sections of this report where parameters are introduced in the submodels. A complete list of input parameters, including their use in the groundwater and volcanic ash scenarios, is provided in Table 6.6-2. The table indicates whether the same or different values of a parameter should be used for current or future climate conditions and to which scenario the parameter applies. These parameters are grouped based on the submodels for the two scenarios. Because of simplifications in the table, the parameter names may not be exactly the same as those used when the parameter is first described. The parameter notations, shown in the third column, are exactly the same as those used in the mathematical equations. The characterization of uncertainty is shown, and either a fixed value or a distribution is given. Further discussion of parameter uncertainty is provided in the following sections. The number of values used in each parameter, array, or matrix (e.g., five types of crops, climate change impacts for many agricultural related parameters, and scenario change impacts for some particle resuspension related parameters) is presented as is a reference back to the section of the report where parameter values are described.

Table 6.6-2. Summary of Parameters Used in the ERMYN Model for the Two Scenarios

| Submodel | Parameter Name | Symbol | Eqn. [a] | Dist. | Array No. [b] | Climate Change [c] | Scenario Change [d] | Ref. [e] |
|---|---|---|---|---|---|---|---|---|
| Surface Soil | Radionuclide concentration in groundwater | $Cw_i$ | 6.4.1-1 | Fixed | 28 | Same | Water | Unit source |
| | Annual irrigation rate | $IR$ | 6.4.1-1 | Dist. | 1x2 | Different | Water | [DIRS 160976] |
| | Radionuclide half-life | $T_{d\,i}$ | 6.4.1-1 | Fixed | 31 | Same | Same | [DIRS 161241] |
| | Surface soil erosion rate | $ER$ | 6.4.1-11 | Dist. | 1 | Same | Water | [DIRS 161239] |
| | Soil bulk density | $\rho$ | 6.4.1-6 | Dist. | 1 | Same | Same | [DIRS 161239] |
| | Surface soil depth | $d$ | 6.4.1-6 | Dist. | 1 | Same | Same | [DIRS 160976] |
| | Soil solid-liquid partition coefficient | $Kd_i$ | 6.4.1-10 | Dist. | 17 | Same | Water | [DIRS 161239] |
| | Overwatering rate | $OW$ | 6.4.1-10 | Dist. | 1x2 | Different | Water | [DIRS 160976] |
| | Volumetric water content | $\theta$ | 6.4.1-10 | Dist. | 1 | Same | Water | [DIRS 161239] |
| | Radionuclide concentration in ash deposited on the ground | $Cs_i$ | 6.5.1-3 | Fixed | 23 | Same | Ash | Unit source |
| | Ash bulk density | $\rho_a$ | 6.5.1-3 | Dist. | 1 | Same | Ash | [DIRS 161239] |
| | Thickness of ash deposited on the ground | $d_a$ | 6.5.1-3 | Dist. | 1 | Same | Ash | TSPA-LA model |
| | Critical thickness for resuspension | $d_c$ | 6.5.1-3 | Dist | 1 | Same | Ash | [DIRS 160964] |

Table 6.6-2. Summary of Parameters Used in the ERMYN Model for the Two Scenarios (continued)

| Submodel | Parameter Name | Symbol | Eqn. [a] | Dist. | Array No. [b] | Climate Change [c] | Scenario Change [d] | Ref. [e] |
|---|---|---|---|---|---|---|---|---|
| Air | Mass loading for crops | $S$ | 6.4.2-1<br>6.5.2-1 | Dist. | 1x2 | Same | Different | [DIRS 160965] |
| | Mass loading for receptor environments at nominal condition | $S_n$ | 6.4.2-2 | Dist. | 5 | Same | Same | [DIRS 160965] |
| | Mass loading for receptor environments at post-volcanic condition | $S_{v,\ n}$ | 6.5.2-3 | Dist. | 5 | Same | Ash | [DIRS 160965] |
| | Resuspension enhancement factor | $f_{enhance,n}$ | 6.4.2-2<br>6.5.2-2 | Dist. | 5x2 | Same | Different | [DIRS 161239] |
| | Fraction of radionuclide from water to air | $f_{evap}$ | 6.4.2-3 | Dist. | 1 | Same | Water | [DIRS 160964] |
| | Water evaporation rate | $M_{water}$ | 6.4.2-3 | Dist. | 1 | Same | Water | [DIRS 160964] |
| | Evaporative cooler air flow rate | $F_{air}$ | 6.4.2-3 | Dist. | 1 | Same | Water | [DIRS 160964] |
| | Radon release factor | $f_{m,\ Rn\text{-}222}$ | 6.4.2-4 | Dist. | 1 | Same | Water | [DIRS 160964] |
| | Interior wall height | $H$ | 6.4.2-5 | Dist. | 1 | Same | Water | [DIRS 160964] |
| | House ventilation rate (for normal or evaporative condition) | $v$ | 6.4.2-5 | Dist | 1x2 | Same | Water | [DIRS 160964] |
| | Fraction of radon from soil entering into the house | $f_{house}$ | 6.4.2-6 | Dist. | 1 | Same | Water | [DIRS 160964] |
| | Ratio of $^{222}$Rn concentration in air to flux density from soil | $CF_{Rn\text{-}222}$ | 6.4.2-7 | Dist. | 1 | Same | Same | [DIRS 160964] |
| Plant | Soil-to-plant transfer factor | $F_{s\rightarrow p,i,j}$ | 6.4.3-2 | Dist. | 16x5 | Same | Same | [DIRS 160964] |
| | Dry-to-wet weight ratio | $DW_j$ | 6.4.3-2 | Dist. | 5 | Same | Same | [DIRS 160976] |
| | Translocation factor | $T_j$ | 6.4.3-3 | Dist./ Fixed | 5 | Same | Same | [DIRS 160964] |
| | Fraction of overhead irrigation | $f_{o,j}$ | 6.4.3-3 | Dist. | 5 | Same | Water | [DIRS 160976] |
| | Weathering half-life | $T_w$ | 6.4.3-3 | Dist. | 1 | Same | Same | [DIRS 160964] |
| | Crop growing time | $t_{g,\ j}$ | 6.4.3-3 | Fixed | 5x2 | Different | Same | [DIRS 160976] |
| | Crop wet yield | $Y_j$ | 6.4.3-3 | Dist. | 5 | Same | Same | [DIRS 160976] |
| | Daily irrigation rate | $IRD_j$ | 6.4.3-4 | Dist. | 5x2 | Different | Water | [DIRS 160976] |
| | Crop dry biomass | $DB_j$ | 6.4.3-5 | Dist. | 5 | Same | Same | [DIRS 160976] |
| | Irrigation amount per application | $IA_j$ | 6.4.3-5 | Dist. | 5x2 | Different | Water | [DIRS 160976] |

Table 6.6-2. Summary of Parameters Used in the ERMYN Model for the Two Scenarios (continued)

| Submodel | Parameter Name | Symbol | Eqn. [a] | Dist. | Array No. [b] | Climate Change [c] | Scenario Change [d] | Ref. [e] |
|---|---|---|---|---|---|---|---|---|
| Plant (continued) | Irrigation intensity | $I$ | 6.4.3-5 | Dist. | 1 | Same | Water | [DIRS 160976] |
| | Dry deposition velocity | $V_d$ | 6.4.3-7 | Dist. | 1 | Same | Same | [DIRS 160964] |
| Animal | Animal product transfer coefficient | $Fm_{i,k}$ | 6.4.4-2 | Dist. | 16x4 | Same | Same | [DIRS 160964] |
| | Animal consumption rate of feed | $Qf_k$ | 6.4.4-2 | Dist. | 4 | Same | Same | [DIRS 160964] |
| | Animal consumption rate of water | $Qw_k$ | 6.4.4-3 | Dist./ Fixed | 4 | Same | Water | [DIRS 160964] |
| | Animal consumption rate of soil | $Qs_k$ | 6.4.4-4 | Dist. | 4 | Same | Same | [DIRS 160964] |
| Fish | Bioaccumulation factor | $BF_i$ | 6.4.5-1 | Dist. | 17 | Same | Water | [DIRS 160964] |
| | Water concentration modifying factor | $MF_i$ | 6.4.5-2 | Dist. | 17x2 | Different | Water | [DIRS 160964] |
| $^{14}C$ | $^{14}C$ emission rate | $\lambda_{a,C-14}$ | 6.4.6-1 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Annual total groundwater usage | $W$ | 6.4.6-3 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Annual average wind speed (for crops or inhalation) | $U$ | 6.4.6-3 | Dist. | 1x2 | Same | Water | [DIRS 160964] |
| | $^{14}C$ mixing height (for crops or inhalation) | $H_{mix}$ | 6.4.6-3 | Fixed | 1x2 | Same | Water | [DIRS 160964] |
| | Fraction of soil-derived carbon in plants | $Fs$ | 6.4.6-4 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Fraction of stable carbon in plant | $Fc_{plant,j}$ | 6.4.6-4 | Fixed | 5 | Same | Water | [DIRS 160964] |
| | Fraction of air-derived carbon in plants | $Fa$ | 6.4.6-5 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Fraction of stable carbon in soil | $fc_{soil}$ | 6.4.6-4 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Concentration of stable carbon in air | $fc_{air}$ | 6.4.6-5 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Concentration of stable carbon in water | $Fc_{water}$ | 6.4.6-7 | Fixed | 1 | Same | Water | [DIRS 160964] |
| | Fraction of stable carbon in animal product | $Fc_{anim,\,k}$ | 6.4.6-7 | Fixed | 4 | Same | Water | [DIRS 160964] |

Table 6.6-2. Summary of Parameters Used in the ERMYN Model for the Two Scenarios (continued)

| Submodel | Parameter Name | Symbol | Eqn. [a] | Dist. | Array No. [b] | Climate Change [c] | Scenario Change [d] | Ref. [e] |
|---|---|---|---|---|---|---|---|---|
| External Exposure | Population proportion | $PP_m$ | 6.4.7-1 | Dist. | 4 | Same | Different | [DIRS 161241] |
| | Exposure time by population group and environment | $t_{n,m}$ | 6.4.7-1 | Dist. | 5x4 | Same | Different | [DIRS 161241] |
| | Building shielding factor | $f_{ext\ i,n}$ | 6.4.7-1 | Fixed | 31 | Same | Same | [DIRS 161241] |
| | Branching fraction | $BN_s$ | 6.4.7-2 | Fixed | 75 | Same | Same | Table 6.3-7 |
| | Dose coefficient for exposure contaminated to an infinite depth | $DCF_{soil\ i}$ | 6.4.7-2 | Fixed | 75 | Same | Water | Section 6.4.7 & [DIRS 161241] |
| | Dose coefficient for exposure to contaminated ground surface | $DC_{soil,\ i}$ | 6.5.5-2 | Fixed | 75 | Same | Ash | Section 6.5.5 & [DIRS 161241] |
| Inhalation | Breathing rate | $BR_n$ | 6.4.8-2 | Fixed | 5 | Same | Same | [DIRS 161241] |
| | Fraction of houses with evaporative coolers | $f_{cooler}$ | 6.4.8-3 | Dist. | 1 | Same | Water | [DIRS 161241] |
| | Evaporative cooler use factor | $f_{use}$ | 6.4.8-3 | Dist. | 1 | Different | Water | [DIRS 161241] |
| | Equilibrium factor for $^{222}$Rn decay products | $EF_{Rn\text{-}222,\ n}$ | 6.4.8-6 | Dist. | 5 | Same | Same | [DIRS 160964] |
| | Dose conversion factor for inhalation of $^{222}$Rn decay products at 100% equilibrium | $DCF_{inh,\ Rn\text{-}222}$ | 6.4.8-6 | Fixed | 1 | Same | Same | Section 6.4.8 & [DIRS 161241] |
| | Dose conversion factor for inhalation | $DCF_{inh,i}$ | 6.4.8-8 | Fixed | 75 | Same | Same | Section 6.4.8 & [DIRS 161241] |
| Ingestion | Consumption rate of water | $Uw$ | 6.4.9-2 | Fixed | 1 | Same | Water | [DIRS 161241] |
| | Consumption rate of locally produced crop foodstuffs | $Up_j$ | 6.4.9-3 | Dist. | 4 | Same | Same | [DIRS 161241] |
| | Consumption rate of locally produced animal products | $Ud_k$ | 6.4.9-4 | Dist. | 4 | Same | Same | [DIRS 161241] |
| | Consumption rate of locally produced fish | $Uf$ | 6.4.9-5 | Dist. | 1 | Same | Water | [DIRS 161241] |
| | Inadvertent soil ingestion rate | $Us$ | 6.4.9-6 | Dist. | 1 | Same | Same | [DIRS 161241] |
| | Dose conversion factor for ingestion | $DCF_{ing,i}$ | 6.4.9-7 | Fixed | 75 | Same | Same | Section 6.4.9 & [DIRS 161241] |

NOTES for Table 6.6-2:

[a] Equation number where the parameter is introduced. The equation for the groundwater scenario is listed unless the parameter is only for the volcanic ash scenario.

[b] The number of values for the parameter, which depends on the radionuclides and elements ($i$ = 31 primary radionuclides included in the ERMYN model; these radionuclides result from total of 75 radionuclides including short-lived radionuclides, 17 elements corresponding to primary radionuclides, 16 elements for transfer factors and coefficients because carbon is a special element), crop types ($j$ = 5 including forage; 4 used for plant ingestion pathways), animal products ($k$ = 4), population groups ($m$ = 4), environments ($n$ = 5), climate conditions ($n$ = 2), and exposure scenarios ($n$ = 2).

[c] Indicates if the parameter values change due to climate conditions, "Same" means the same value is used for different climate conditions, "Different" means different values are used in different climate conditions.

[d] Indicates where the parameter is used. "Same" means it is used in both scenarios with the same value, "Different" means it is used in both scenarios with different values, "Water" means it is used only in the groundwater scenario, and "Ash" means it is used only in the volcanic ash scenario.

[e] Reference number for the reports where the parameter values are developed: BSC (2003 [DIRS 160976]), BSC (2003 [DIRS 161239]), BSC (2003 [DIRS 160965]), BSC (2003 [DIRS 161241]), BSC (2003 [DIRS 160964]).

### 6.6.3.2 Consideration of Parameter Uncertainty

As discussed in the previous section, sources of data for parameter development vary with the input parameter types and the available information. Regulations state that the model must consider the full range of defensible and reasonable parameter distributions (10 CFR 63.114 [DIRS 156605]) and that the DOE must use mean values to represent current diets and life styles (10 CFR 63.305 [DIRS 156605]). This section briefly describes sources of parameter uncertainty and methods used to develop parameter distributions that measure the parameter uncertainty.

Two types of probability distribution functions are considered. The first type is a population distribution, which describes the probability of any reasonable event occurring within the population. If the distribution is statistically normal, it is defined using the mean and standard deviation of a sample from the population. The second type of probability distribution is a distribution of the population mean, which describes the probability of occurrence of any reasonable mean value for the population. For statistically normal distributions, this second type of distribution is defined using the mean and standard error of the mean. Other distributions are considered (e.g., lognormal, uniform, and triangular) if the data are not statistically normal. Because some distributions range from negative infinity to positive infinity, the distributions are truncated to eliminate physically impossible input values and to make the distribution meaningful.

When a parameter is developed based on the mean characteristics of a group, the distribution of the parameter represents variation and uncertainty in the mean value. For normal distributions, such parameters are characterized using the mean as the reasonable estimate and the standard error as a measure of variance or parameter range (the second type described above). Based on the requirements in 10 CFR 63.305 [DIRS 156605], parameters in this category include the diet and life style of the RMEI (e.g., consumption rates and time spent in various environments), which primarily are used in the external exposure, inhalation, and ingestion submodels.

When parameters describe processes or properties of a group, even if the processes or properties are constant over time or space, the distribution is selected to represent the entire range of

variation among individuals within the group. For normal distributions, the distributions are characterized using the mean as a reasonable estimate and the standard deviation as a measure of variance (the first type described above). For many parameters, lognormal distributions better describe the variation, and a geometric mean is used for a reasonable estimate and the geometric standard deviation is used for the variance. Parameters in this category include many environmental transport and agricultural parameters (e.g., transfer factors, irrigation rates, biomass, and dry-wet ratio) that are used in the plant, animal, and fish submodels.

If evidence indicates that a parameter contributes little to overall dose, or if it has little impact on model uncertainty, then a fixed value may be used for the input parameter. Parameters in this category include the transfer of $^{14}C$ among soil, air, crop, and animal product components, which are evaluated in the $^{14}C$ special submodel.

Cumulative distributions, or piece-wise linear distributions, are used for some model input parameters. A cumulative distribution is defined as a set of input values and corresponding cumulative probabilities that is developed based on empirical data points. The probability density function for this type of distribution may contain distinct, irregular peaks.

This section provides a brief summary of parameter uncertainty consideration because every parameter is developed separately based on available information. Details concerning development of the input parameters are presented in the five analysis reports (BSC 2003 [DIRS 160976]; BSC 2003 [DIRS 161239]; BSC 2003 [DIRS 160965]; BSC 2003 [DIRS 161241]; BSC 2003 [DIRS 160964]), as discussed in Section 1 and Figure 1-1.

#### 6.6.3.3 Summary of Parameter Uncertainty

A summary of parameter values and probability distribution functions are presented in Table 6.6-3. The table includes parameter values and uncertainty information taken from the five data analysis reports (Figure 1-1), including the distribution type, the mean or mode, standard deviation or standard error, range (minimum and maximum), and brief notes describing uncertainty considerations. The parameter values in Table 6.6-3 are shown in accordance with the ERMYN model parameters shown in Table 6.6-2. To show parameter values and distributions, parameters with subscript indices in the mathematical model are shown for each individual value in Table 6.6-3. The purpose of the table is to summarize possible model input values that are developed under the current TWP (BSC 2003 [DIRS 163602]). Other parameter distributions may be used with this model if they are within the limits of the model described in Section 8.2.

The parameter values listed in Table 6.6-3 use the same units as the data analysis reports (Figure 1-1). The units may not be the same as those in the equations shown in Sections 6.4 and 6.5. This is not a discrepancy between the model and inputs, as the GoldSim software automatically converts to the proper units.

### 6.6.4 Uncertainty of Model Results

When models that use parameters with distribution functions are realized, parameter values are sampled from the range of possible values. For each realization, the values are fixed for the run to produce one deterministic calculation for the entire model. However, the realized parameter

values change for each realization, and therefore the model results differ for each realization. After many realizations, the results yield a distribution of possible outcomes (i.e., a distribution function), which reflect the possibility of the result in the uncertainty. This simulation method, built into the GoldSim software, includes two sampling methods: Monte Carlo or Latin Hypercube. A detailed description of the software is presented below.

Uncertainty in the ERMYN model results is considered for all of the input parameters that are represented by uncertainty distributions. Uncertainty from conservative assumptions and simplifications cannot be evaluated quantitatively.

Table 6.6-3. Summary of Input Parameter Values and Their Distributions

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Surface Soil | Radionuclide concentration in groundwater | | Fixed | $Bq/m^3$ | 1 | - | - | - | Unit concentration of source for the groundwater scenario. |
| | Annual average irrigation rate | Current climate/ Lower bound monsoon climate | Normal | m/yr | 0.94 | 0.08 | 0.73 | 1.15 | Normal distribution used for long-term averaged annual irrigation. Term of current climate is used for modern interglacial climate (Section 6.1.1.2). Term of future climate is used for glacial transition climate (Section 6.1.1.2). |
| | | Upper bound monsoon climate | | | 0.52 | - | - | - | |
| | | Lower bound future climate | | | 0.88 | - | - | - | |
| | | Upper bound future climate | | | 0.50 | 0.04 | 0.40 | 0.60 | |
| | Radionuclide half-life | | Fixed | yr | See Notes | - | - | - | Values presented in Table 6.3-7 are representative. |
| | Surface soil erosion rate | | Triangular | $kg/(m^2\ yr)$ | 0.49 (mean) 0.19 (mode) | - | 0.19 | 1.1 | Mean given in the source report for deterministic calculation. |
| | Soil bulk density | | Triangular | $kg/m^3$ | 1500 (mean and mode) | - | 1300 | 1700 | |
| | Surface soil depth | | Uniform | m | 0.25 | - | 0.05 | 0.30 | Tilling depth. Mean given in the data source report. |
| | Soil solid-liquid partition coefficient | Carbon | Lognormal | L/kg | 1.8E+01 | 6.0E+00 | - | - | Partition coefficients are correlated with the soil-to-plant transfer factors. The correlation coefficient is -0.8. |
| | | Chlorine | | | 1.4E-01 | 6.0E+00 | - | - | |
| | | Selenium | | | 1.5E+02 | 6.0E+00 | - | - | |
| | | Strontium | | | 2.0E+01 | 5.5E+00 | - | - | |
| | | Technetium | | | 1.4E-01 | 6.0E+00 | - | - | |
| | | Tin | | | 4.5E+02 | 6.0E+00 | - | - | |
| | | Iodine | | | 4.5E+00 | 7.4E+00 | - | - | |
| | | Cesium | | | 4.4E+03 | 3.7E+00 | - | - | |
| | | Lead | | | 1.6E+04 | 4.1E+00 | - | - | |
| | | Radium | | | 3.6E+04 | 2.2E+01 | - | - | |
| | | Actinium | | | 1.5E+03 | 6.0E+00 | - | - | |
| | | Thorium | | | 3.0E+03 | 8.2E+00 | - | - | |
| | | Protactinium | | | 1.8E+03 | 6.0E+00 | - | - | |
| | | Uranium | | | 3.3E+01 | 2.5E+01 | - | - | |
| | | Neptunium | | | 2.5E+01 | 3.3E+00 | - | - | |
| | | Plutonium | | | 1.2E+03 | 3.3E+00 | - | - | |
| | | Americium | | | 2.0E+03 | 1.3E+01 | - | - | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Surface Soil (cont.) | Overwatering rate | Current climate | Cumulative | m/yr | 0.079 | - | 0.009<br>0.030<br>0.045<br>0.076<br>0.128<br>0.233<br>0.275 | 0%<br>19%<br>38%<br>57%<br>76%<br>95%<br>100% | Irrigation water passing through crop root zone. |
| | | Future climate | Cumulative | m/yr | 0.067 | - | 0.004<br>0.02<br>0.047<br>0.072<br>0.104<br>0.15<br>0.177 | 0%<br>19%<br>38%<br>57%<br>76%<br>95%<br>100% | |
| | Volumetric water content | | Uniform | - | 0.23 | - | 0.18 | 0.28 | |
| | Radionuclide concentration in ash deposited on ground surface | | Fixed | $Bq/m^2$ | 1 | - | - | - | Unit concentration of source for the volcanic ash scenario. |
| | Ash bulk density | | Fixed | $kg/m^3$ | 1000 | | | | |
| | Thickness of ash deposited on the ground | | - | - | - | - | - | - | Ash thickness will be calculated in the TSPA-LA model. |
| | Critical thickness for the resuspension | | Uniform | mm | 2 | - | 1 | 3 | Mean calculated from uniform distribution. |
| Air | Mass loading for crops | Nominal | Triangular | $mg/m^3$ | 0.12 | - | 0.025 | 0.200 | |
| | | Post-volcanic | | | 0.24 | - | 0.050 | 0.600 | |
| | Mass loading for receptor environments at nominal condition | Active outdoors | Triangular | $mg/m^3$ | 5.00 | - | 1.000 | 10.000 | Used for the groundwater scenario and for the long time after a volcanic eruption in the volcanic ash scenario. |
| | | Inactive outdoors | | | 0.06 | - | 0.025 | 0.100 | |
| | | Active indoors | | | 0.10 | - | 0.060 | 0.175 | |
| | | Asleep indoors | | | 0.03 | - | 0.010 | 0.050 | |
| | Mass loading for receptor environments at post-volcanic condition | Active outdoors | Triangular | $mg/m^3$ | 2.50 | - | 0.000 | 5.000 | This is additional mass loading for immediately after a volcanic eruption in the volcanic ash scenario. |
| | | Inactive outdoors | | | 0.06 | - | 0.025 | 0.200 | |
| | | Active indoors | | | 0.10 | - | 0.060 | 0.175 | |
| | | Asleep indoors | | | 0.03 | - | 0.010 | 0.060 | |
| | Mass loading function $f(t) = S_0 e^{-\lambda t}$, with constant $\lambda$ value | For initial ash depth < 10 mm | Triangular | /yr | 0.33 | - | 0.2 | 2.0 | This decay function is used in the TSPA-LA model. |
| | | For initial ash depth ≥ 10 mm | | | 0.20 | - | 0.125 | 1.0 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Air | Enhancement factor at nominal condition | Active outdoors | Cumulative | - | 4.0 | - | 2.2<br>4.0<br>6.5 | 0%<br>50%<br>100% | Active outdoors is for disturbed soil, while other environments are for undisturbed soil. Mean taken from 50% value. |
| | | Inactive outdoors | Cumulative | | 0.7 | - | 0.21<br>0.70<br>1.04 | 0%<br>50%<br>100% | |
| | | Active indoors | | | | | | | |
| | | Asleep indoors | | | | | | | |
| | Enhancement factor at post-volcanic condition | Active outdoors | Cumulative | - | 4.4 | - | 2.8<br>4.4<br>8.4 | 0%<br>50%<br>100% | |
| | | Inactive outdoors | Cumulative | | 0.7 | - | 0.21<br>0.70<br>1.04 | 0%<br>50%<br>100% | |
| | | Active indoors | | | | | | | |
| | | Asleep indoors | | | | | | | |
| Air | Fraction of radionuclides from water into air | | Uniform | - | 0.5 | - | 0 | 1 | Mean calculated from uniform distribution. |
| | Water evaporation rate of evaporative cooler | | lognormal | L/hr | 17 | 1.7 | - | - | Water evaporation rate is given as geometric mean and standard deviation. Airflow rate is correlated with water evaporative rate (correlation coefficient = 0.8); mean is 50% value. |
| | Air flow rate of evaporative cooler | | Cumulative | $m^3$/hr | 8300 | - | 1700<br>8300<br>10200 | 0 %<br>50 %<br>100 % | |
| | Radon release factor | | Fixed | ($Bq/m^3$)/ (Bq/kg) | 0.25 | - | - | - | Global average value. |
| | Interior wall height | | Cumulative | m | 2.3 | - | 2.1<br>2.3<br>2.7 | 0 %<br>50 %<br>100 % | Mean taken from 50% value. |
| | House ventilation rate | For regular time | Lognormal | /hr | 1 | 1.1 | 0.35 | 2.9 | |
| | | For evaporative cooler on | Uniform | | 15.5 | - | 1 | 30 | Mean calculated from uniform distribution. |
| | Fraction of radon from soil entering into the house | | Uniform | - | 0.175 | - | 0.10 | 0.25 | Mean calculated from uniform distribution. |
| | Ratio of $^{222}Rn$ concentration in air to flux density from soil | | Fixed | ($Bq\ m^{-3}$)/ ($Bq\ m^{-2}\ sec^{-1}$) | 300 | - | - | - | Global average value. |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Plant | Soil-to-plant transfer factor for leafy vegetables | Chlorine | Lognormal | (Bq/kg $_{plant}$)/(Bq/kg $_{soil}$) | 6.4E+01 | 2.0 | 1.1E+01 | 3.8E+02 | Transfer factors are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 4.6E-02 | 3.8 | 1.4E-03 | 1.4E+00 | |
| | | Strontium | | | 1.7E+00 | 2.0 | 2.9E-01 | 1.0E+01 | |
| | | Technetium | | | 4.6E+01 | 2.6 | 3.8E+00 | 5.5E+02 | |
| | | Tin | | | 3.8E-02 | 2.0 | 6.4E-03 | 2.3E-01 | |
| | | Iodine | | | 2.6E-02 | 9.9 | 7.2E-05 | 9.7E+00 | |
| | | Cesium | | | 1.2E-01 | 2.5 | 1.2E-02 | 1.2E+00 | |
| | | Lead | | | 1.5E-02 | 4.6 | 3.0E-04 | 7.7E-01 | |
| | | Radium | | | 6.8E-02 | 2.7 | 5.1E-03 | 9.2E-01 | |
| | | Actinium | | | 4.3E-03 | 2.0 | 7.2E-04 | 2.6E-02 | |
| | | Thorium | | | 4.3E-03 | 2.8 | 3.2E-04 | 5.9E-02 | |
| | | Protactinium | | | 4.6E-03 | 3.8 | 1.4E-04 | 1.4E-01 | |
| | | Uranium | | | 1.1E-02 | 2.0 | 1.8E-03 | 6.6E-02 | |
| | | Neptunium | | | 5.9E-02 | 4.4 | 1.3E-03 | 2.6E+00 | |
| | | Plutonium | | | 2.9E-04 | 2.0 | 4.9E-05 | 1.7E-03 | |
| | | Americium | | | 1.2E-03 | 2.5 | 1.2E-04 | 1.3E-02 | |
| | Soil-to-plant transfer factor for other vegetables | Chlorine | Lognormal | (Bq/kg $_{plant}$)/(Bq/kg $_{soil}$) | 6.4E+01 | 2.0 | 1.1E+01 | 3.8E+02 | Transfer factors are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 4.6E-02 | 3.8 | 1.4E-03 | 1.4E+00 | |
| | | Strontium | | | 7.9E-01 | 2.0 | 1.4E-01 | 4.5E+00 | |
| | | Technetium | | | 4.4E+00 | 3.7 | 1.5E-01 | 1.2E+02 | |
| | | Tin | | | 1.5E-02 | 3.6 | 5.3E-04 | 4.0E-01 | |
| | | Iodine | | | 3.2E-02 | 4.4 | 7.0E-04 | 1.5E+00 | |
| | | Cesium | | | 5.0E-02 | 2.0 | 8.4E-03 | 3.0E-01 | |
| | | Lead | | | 9.0E-03 | 3.1 | 5.0E-04 | 1.6E-01 | |
| | | Radium | | | 1.2E-02 | 5.3 | 1.6E-04 | 8.6E-01 | |
| | | Actinium | | | 1.1E-03 | 4.9 | 1.8E-05 | 6.6E-02 | |
| | | Thorium | | | 4.4E-04 | 5.6 | 5.3E-06 | 3.6E-02 | |
| | | Protactinium | | | 1.1E-03 | 10.0 | 3.0E-06 | 4.3E-01 | |
| | | Uranium | | | 6.0E-03 | 2.8 | 4.2E-04 | 8.5E-02 | |
| | | Neptunium | | | 3.1E-02 | 4.9 | 5.0E-04 | 1.9E+00 | |
| | | Plutonium | | | 1.9E-04 | 2.0 | 3.3E-05 | 1.1E-03 | |
| | | Americium | | | 4.0E-04 | 2.6 | 3.5E-05 | 4.6E-03 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Soil-to-plant transfer factor for Fruit | Chlorine | Lognormal | (Bq/kg $_{plant}$)/(Bq/kg $_{soil}$) | 6.4E+01 | 2.0 | 1.1E+01 | 3.8E+02 | Transfer factors are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 4.6E-02 | 3.8 | 1.4E-03 | 1.4E+00 | |
| | | Strontium | | | 2.9E-01 | 2.3 | 3.6E-02 | 2.4E+00 | |
| | | Technetium | | | 4.3E+00 | 4.6 | 8.7E-02 | 2.1E+02 | |
| | | Tin | | | 1.5E-02 | 3.6 | 5.3E-04 | 4.0E-01 | |
| | | Iodine | | | 5.7E-02 | 2.8 | 4.1E-03 | 7.9E-01 | |
| | | Cesium | | | 5.6E-02 | 2.8 | 3.8E-03 | 8.1E-01 | |
| | | Lead | | | 1.2E-02 | 3.3 | 5.8E-04 | 2.6E-01 | |
| | | Radium | | | 7.3E-03 | 4.3 | 1.6E-04 | 3.2E-01 | |
| | | Actinium | | | 8.5E-04 | 3.4 | 3.7E-05 | 2.0E-02 | |
| | | Thorium | | | 2.9E-04 | 4.9 | 4.8E-06 | 1.7E-02 | |
| | | Protactinium | | | 1.1E-03 | 10.0 | 3.0E-06 | 4.3E-01 | |
| | | Uranium | | | 6.3E-03 | 2.9 | 3.9E-04 | 1.0E-01 | |
| | | Neptunium | | | 3.4E-02 | 6.9 | 2.3E-04 | 5.0E+00 | |
| | | Plutonium | | | 1.8E-04 | 3.4 | 7.8E-06 | 4.2E-03 | |
| | | Americium | | | 5.4E-04 | 2.3 | 6.5E-05 | 4.5E-03 | |
| | Soil-to-plant transfer factor for grain | Chlorine | Lognormal | (Bq/kg $_{plant}$)/(Bq/kg $_{soil}$) | 2.4E+01 | 8.4 | 1.0E-01 | 5.8E+03 | Transfer factors are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 2.9E-02 | 2.0 | 4.8E-03 | 1.7E-01 | |
| | | Strontium | | | 1.7E-01 | 2.0 | 2.8E-02 | 1.0E+00 | |
| | | Technetium | | | 1.6E+00 | 4.3 | 3.8E-02 | 6.8E+01 | |
| | | Tin | | | 9.2E-03 | 2.0 | 1.5E-03 | 5.5E-02 | |
| | | Iodine | | | 2.5E-02 | 10.0 | 6.6E-05 | 9.4E+00 | |
| | | Cesium | | | 2.0E-02 | 2.2 | 2.7E-03 | 1.6E-01 | |
| | | Lead | | | 5.5E-03 | 2.1 | 8.2E-04 | 3.8E-02 | |
| | | Radium | | | 3.1E-03 | 4.0 | 8.8E-05 | 1.1E-01 | |
| | | Actinium | | | 5.4E-04 | 2.9 | 3.6E-05 | 8.0E-03 | |
| | | Thorium | | | 1.7E-04 | 5.2 | 2.4E-06 | 1.2E-02 | |
| | | Protactinium | | | 9.5E-04 | 7.2 | 5.9E-06 | 1.5E-01 | |
| | | Uranium | | | 1.1E-03 | 3.6 | 4.1E-05 | 3.1E-02 | |
| | | Neptunium | | | 4.4E-03 | 6.9 | 3.1E-05 | 6.3E-01 | |
| | | Plutonium | | | 1.9E-05 | 4.2 | 4.8E-07 | 7.8E-04 | |
| | | Americium | | | 7.5E-05 | 3.2 | 3.8E-06 | 1.5E-03 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Soil-to-plant transfer factor for forage | Chlorine | Lognormal | (Bq/kg $_{plant}$)/(Bq/kg $_{soil}$) | 7.5E+01 | 2.0 | 1.3E+01 | 4.5E+02 | Transfer factors are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 1.5E-01 | 5.5 | 1.9E-03 | 1.3E+01 | |
| | | Strontium | | | 2.1E+00 | 2.1 | 3.2E-01 | 1.3E+01 | |
| | | Technetium | | | 2.7E+01 | 2.7 | 2.1E+00 | 3.5E+02 | |
| | | Tin | | | 1.6E-01 | 5.8 | 1.7E-03 | 1.5E+01 | |
| | | Iodine | | | 4.0E-02 | 10.0 | 1.1E-04 | 1.5E+01 | |
| | | Cesium | | | 1.3E-01 | 3.3 | 6.3E-03 | 2.8E+00 | |
| | | Lead | | | 1.8E-02 | 7.0 | 1.2E-04 | 2.8E+00 | |
| | | Radium | | | 8.2E-02 | 3.0 | 4.9E-03 | 1.4E+00 | |
| | | Actinium | | | 1.7E-02 | 5.4 | 2.2E-04 | 1.3E+00 | |
| | | Thorium | | | 1.0E-02 | 4.2 | 2.5E-04 | 3.9E-01 | |
| | | Protactinium | | | 1.9E-02 | 6.7 | 1.4E-04 | 2.5E+00 | |
| | | Uranium | | | 1.7E-02 | 6.1 | 1.6E-04 | 1.9E+00 | |
| | | Neptunium | | | 5.8E-02 | 5.6 | 6.8E-04 | 4.9E+00 | |
| | | Plutonium | | | 1.0E-03 | 10.0 | 2.7E-06 | 3.9E-01 | |
| | | Americium | | | 2.1E-03 | 10.0 | 5.5E-06 | 7.9E-01 | |
| | Dry-to-wet weight ratio | Leafy vegetables | Cumulative | kg $_{dry}$/kg $_{wet}$ | 0.070 | - | 0.041<br>0.054<br>0.06<br>0.078<br>0.081<br>0.084<br>0.093 | 0%<br>17%<br>33%<br>50%<br>67%<br>83%<br>100% | Means given in the source reports. |
| | | Other vegetables | | | 0.103 | - | 0.035<br>0.063<br>0.078<br>0.08<br>0.103<br>0.122<br>0.24 | 0%<br>17%<br>33%<br>50%<br>67%<br>83%<br>100% | |
| | | Fruit | | | 0.120 | - | 0.062<br>0.084<br>0.102<br>0.155<br>0.194 | 0%<br>25%<br>50%<br>75%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Dry-to-wet weight ratio (cont.) | | Grain | | | 0.903 | - | 0.891<br>0.896<br>0.906<br>0.918 | 0%<br>33%<br>67%<br>100% | |
| | | | Forage | | | 0.220 | - | 0.182<br>0.227<br>0.238 | 0%<br>75%<br>100% | |
| | Translocation factor | | Leafy vegetation | Fixed | - | 1.0 | - | - | - | Mean taken from 50% value. |
| | | | Other vegetation | Cumulative | - | 0.1 | - | 0.05<br>0.10<br>0.30 | 0 %<br>50 %<br>100% | |
| | | | Fruit | | | | | | | |
| | | | Grain | | | | | | | |
| | | | Forage | Fixed | - | 1.0 | - | - | - | |
| | Fraction of overhead irrigation | | Leafy vegetation | Normal | - | 0.75 | 0.10 | 0.49 | 1.0 | |
| | | | Other vegetation | | | 0.75 | 0.10 | 0.49 | 1.0 | |
| | | | Fruit | | | 0.50 | 0.10 | 0.24 | 1.0 | |
| | | | Grain | | | 0.90 | 0.05 | 0.77 | 1.0 | |
| | | | Forage | | | 0.90 | 0.05 | 0.77 | 1.0 | |
| | Weathering half-life | | | Cumulative | d | 14 | - | 5<br>14<br>30 | 0 %<br>50 %<br>100 % | Mean taken from 50% value. |
| | Crop grow-ing time | Current climate | Leafy vegetation | Fixed | d | 75 | - | - | - | |
| | | | Other vegetation | | | 80 | - | - | - | |
| | | | Fruit | | | 160 | - | - | - | |
| | | | Grain | | | 200 | - | - | - | |
| | | | Forage | | | 75 | - | - | - | |
| | | Future climate | Leafy vegetation | Fixed | d | 75 | - | - | - | |
| | | | Other vegetation | | | 100 | - | - | - | |
| | | | Fruit | | | 105 | - | - | - | |
| | | | Grain | | | 185 | - | - | - | |
| | | | Forage | | | 90 | - | - | - | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Crop wet yield | Leafy vegetation | Cumulative | $kg/m^2$ | 3.30 | - | 1.08<br>1.46<br>1.78<br>2.01<br>2.98<br>3.25<br>3.83<br>7.79<br>7.85 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | Means given in the source reports. |
| | | Other vegetation | | | 4.13 | - | 2.8<br>3.37<br>3.56<br>3.64<br>4.92<br>5.15<br>6.61 | 0%<br>5%<br>28%<br>51%<br>72%<br>95%<br>100% | |
| | | Fruit | | | 2.75 | - | 0.73<br>1.51<br>2.67<br>2.92<br>3.00<br>3.63<br>6.89 | 0%<br>5%<br>28%<br>51%<br>72%<br>95%<br>100% | |
| | | Grain | | | 0.59 | - | 0.27<br>0.28<br>0.44<br>0.54<br>1.1<br>1.22 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | Forage | | | 2.14 | - | 0.69<br>1.02<br>1.87<br>5.78<br>6.28 | 0%<br>5%<br>73%<br>95%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Crop dry biomass | Leafy vegetation | Cumulative | $kg/m^2$ | 0.21 | - | 0.10<br>0.13<br>0.14<br>0.15<br>0.16<br>0.18<br>0.30<br>0.42<br>0.50 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | Means given in the source reports. |
| | | Other vegetation | | | 0.43 | - | 0.30<br>0.40<br>0.41<br>0.43<br>0.44<br>0.46<br>0.60 | 0%<br>5%<br>28%<br>51%<br>73%<br>95%<br>100% | |
| | | Fruit | | | 0.62 | - | 0.10<br>0.56<br>0.60<br>0.65<br>0.68<br>1.30 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | Grain | | | 1.13 | - | 0.50<br>0.61<br>0.74<br>1.20<br>1.97<br>2.20 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | Forage | | | 0.48 | - | 0.10<br>0.23<br>0.34<br>1.38<br>1.50 | 0%<br>5%<br>73%<br>95%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Daily irrigation rate | Current climate | Leafy vegetation | Cumulative | mm/d | 5.40 | - | 4.00<br>5.11<br>5.19<br>5.21<br>5.38<br>5.46<br>5.98<br>7.06 | 0%<br>5%<br>20%<br>35%<br>50%<br>80%<br>95%<br>100% | Means given in the source reports. |
| | | | Other vegetation | | | 7.55 | - | 5.00<br>6.05<br>6.65<br>6.85<br>7.62<br>8.19<br>8.32<br>9.18<br>10.83 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | |
| | | | Fruit | | | 7.38 | - | 4.00<br>5.38<br>7.00<br>7.56<br>8.35<br>8.60<br>10.15 | 0%<br>5%<br>28%<br>51%<br>72%<br>95%<br>100% | |
| | | | Grain | | | 4.64 | - | 3.00<br>3.44<br>3.58<br>3.86<br>7.67<br>9.05 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | | Forage | | | 6.54 | - | 5.00<br>5.84<br>6.18<br>9.00<br>10.62 | 0%<br>5%<br>73%<br>95%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Daily irrigation rate (cont.) | Future climate | Leafy vegetation | Cumulative | mm/d | 3.81 | - | 3.00<br>3.34<br>3.51<br>3.86<br>3.92<br>4.02<br>4.18<br>4.93 | 0%<br>5%<br>20%<br>50%<br>65%<br>80%<br>95%<br>100% | Means given in the source reports. |
| | | | Other vegetation | | | 3.84 | - | 2.00<br>2.73<br>3.08<br>3.48<br>4.08<br>4.16<br>4.43<br>4.95<br>5.84 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | |
| | | | Fruit | | | 3.90 | - | 2.00<br>2.51<br>3.48<br>4.33<br>4.38<br>4.79<br>5.65 | 0%<br>5%<br>28%<br>51%<br>72%<br>95%<br>100% | |
| | | | Grain | | | 3.36 | - | 1.00<br>1.99<br>3.42<br>3.93<br>4.11<br>4.85 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | | Forage | | | 4.14 | - | 3.00<br>3.64<br>4.01<br>5.03<br>5.94 | 0%<br>5%<br>73%<br>95%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Irri-gation amt. per appli-cation | Current climate | Leafy vegetation | Cumulative | mm | 14.7 | - | 6.0<br>7.4<br>8.4<br>10.0<br>10.9<br>20.8<br>22.0<br>23.6<br>27.8 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | Means given in the source reports. |
| | | | Other vegetation | | | 25.4 | - | 8.0<br>9.0<br>18.7<br>19.7<br>21.2<br>32.9<br>34.9<br>41.2<br>48.6 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | |
| | | | Fruit | | | 33.9 | - | 5.0<br>6.0<br>30.2<br>35.5<br>48.4<br>49.2<br>58.1 | 0%<br>5%<br>28%<br>51%<br>72%<br>95%<br>100% | |
| | | | Grain | | | 56.8 | - | 43.0<br>48.7<br>50.1<br>50.3<br>77.9<br>91.9 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | | Forage | | | 57.8 | - | 50.0<br>56.5<br>57.5<br>60.2<br>71.0 | 0%<br>5%<br>72%<br>95%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Irri-gation amt. per appli-cation (cont.) | Future climate | Leafy vegetation | Cumulative | mm | 14.6 | - | 7.0<br>7.8<br>8.0<br>9.0<br>10.1<br>19.3<br>22.0<br>26.1<br>30.8 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | Means given in the source reports. |
| | | | Other vegetation | | | 25.0 | - | 10.0<br>11.3<br>14.4<br>17.7<br>20.1<br>34.1<br>37.2<br>40.3<br>47.6 | 0%<br>5%<br>20%<br>35%<br>50%<br>65%<br>80%<br>95%<br>100% | |
| | | | Fruit | | | 34.2 | - | 6.0<br>7.3<br>31.4<br>34.6<br>43.2<br>54.4<br>64.2 | 0%<br>5%<br>28%<br>51%<br>72%<br>95%<br>100% | |
| | | | Grain | | | 51.3 | - | 28.0<br>32.2<br>46.2<br>59.9<br>66.7<br>78.7 | 0%<br>5%<br>35%<br>65%<br>95%<br>100% | |
| | | | Forage | | | 53.5 | - | 43.0<br>48.3<br>52.5<br>61.9<br>73.0 | 0%<br>5%<br>73%<br>95%<br>100% | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Plant (cont.) | Irrigation intensity | | Uniform | cm/hr | 4.25 | - | 1.0 | 7.5 | |
| | Dry deposition velocity | | Cumulative | m/sec | 8E-3 | - | 3E-4<br>1E-3<br>8E-3<br>3E-2<br>3E-1 | 0 %<br>16 %<br>50 %<br>84 %<br>100 % | Mean taken from 50% value. |
| Animal | Animal product transfer coefficients for meat | Chlorine | Lognormal | d/kg | 4.6E-02 | 2.0 | 7.7E-03 | 2.7E-01 | Transfer coefficients are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 8.8E-02 | 5.8 | 9.6E-04 | 8.0E+00 | |
| | | Strontium | | | 1.4E-03 | 4.4 | 3.1E-05 | 6.2E-02 | |
| | | Technetium | | | 1.1E-03 | 7.2 | 6.9E-06 | 1.8E-01 | |
| | | Tin | | | 1.9E-02 | 4.6 | 3.8E-04 | 9.9E-01 | |
| | | Iodine | | | 1.0E-02 | 2.8 | 6.8E-04 | 1.5E-01 | |
| | | Cesium | | | 2.4E-02 | 2.6 | 2.1E-03 | 2.7E-01 | |
| | | Lead | | | 6.3E-04 | 2.6 | 5.4E-05 | 7.5E-03 | |
| | | Radium | | | 8.1E-04 | 2.1 | 1.1E-04 | 5.7E-03 | |
| | | Actinium | | | 7.9E-05 | 8.2 | 3.5E-07 | 1.8E-02 | |
| | | Thorium | | | 1.1E-04 | 10.0 | 2.8E-07 | 4.0E-02 | |
| | | Protactinium | | | 6.6E-05 | 10.0 | 1.8E-07 | 2.5E-02 | |
| | | Uranium | | | 4.8E-04 | 3.0 | 2.9E-05 | 7.8E-03 | |
| | | Neptunium | | | 3.4E-04 | 8.8 | 1.3E-06 | 9.0E-02 | |
| | | Plutonium | | | 1.3E-05 | 10.0 | 3.3E-08 | 4.7E-03 | |
| | | Americium | | | 3.4E-05 | 9.0 | 1.2E-07 | 9.9E-03 | |
| | Animal product transfer coefficients for milk | Chlorine | Lognormal | d/L | 1.8E-02 | 2.0 | 2.9E-03 | 1.0E-01 | Transfer coefficients are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 5.7E-03 | 2.5 | 5.5E-04 | 6.0E-02 | |
| | | Strontium | | | 1.7E-03 | 2.0 | 2.8E-04 | 1.0E-02 | |
| | | Technetium | | | 2.1E-03 | 6.0 | 2.0E-05 | 2.1E-01 | |
| | | Tin | | | 1.1E-03 | 2.0 | 1.8E-04 | 6.3E-03 | |
| | | Iodine | | | 9.1E-03 | 2.0 | 1.5E-03 | 5.4E-02 | |
| | | Cesium | | | 7.7E-03 | 2.0 | 1.3E-03 | 4.6E-02 | |
| | | Lead | | | 1.7E-04 | 3.0 | 1.0E-05 | 2.9E-03 | |
| | | Radium | | | 5.8E-04 | 2.0 | 1.0E-04 | 3.4E-03 | |
| | | Actinium | | | 7.6E-06 | 4.1 | 2.0E-07 | 2.9E-04 | |
| | | Thorium | | | 4.4E-06 | 2.0 | 7.4E-07 | 2.6E-05 | |
| | | Protactinium | | | 4.4E-06 | 2.0 | 7.4E-07 | 2.6E-05 | |
| | | Uranium | | | 4.9E-04 | 2.0 | 8.1E-05 | 2.9E-03 | |
| | | Neptunium | | | 6.3E-06 | 2.0 | 1.0E-06 | 3.9E-05 | |
| | | Plutonium | | | 2.3E-07 | 7.7 | 1.2E-09 | 4.4E-05 | |
| | | Americium | | | 1.6E-06 | 4.2 | 3.9E-08 | 6.3E-05 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Animal (cont.) | Animal product transfer coefficients for poultry | Chlorine | Lognormal | d/kg | 3.0E-02 | 2.0 | 5.0E-03 | 1.8E-01 | Transfer coefficients are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 5.1E+00 | 3.6 | 1.9E-01 | 1.4E+02 | |
| | | Strontium | | | 3.1E-02 | 5.8 | 3.4E-04 | 2.9E+00 | |
| | | Technetium | | | 6.3E-02 | 10.0 | 1.7E-04 | 2.4E+01 | |
| | | Tin | | | 3.5E-02 | 10.0 | 9.4E-05 | 1.3E+01 | |
| | | Iodine | | | 5.5E-02 | 9.7 | 1.6E-04 | 1.9E+01 | |
| | | Cesium | | | 2.6E+00 | 9.8 | 7.2E-03 | 9.3E+02 | |
| | | Lead | | | 2.5E-02 | 10.0 | 6.6E-05 | 9.3E+00 | |
| | | Radium | | | 1.7E-02 | 10.0 | 4.4E-05 | 6.3E+00 | |
| | | Actinium | | | 4.0E-03 | 2.0 | 6.7E-04 | 2.4E-02 | |
| | | Thorium | | | 5.9E-03 | 8.0 | 2.7E-05 | 1.3E+00 | |
| | | Protactinium | | | 3.0E-03 | 2.0 | 5.1E-04 | 1.8E-02 | |
| | | Uranium | | | 2.4E-01 | 10.0 | 6.5E-04 | 9.2E+01 | |
| | | Neptunium | | | 3.6E-03 | 2.0 | 6.0E-04 | 2.1E-02 | |
| | | Plutonium | | | 1.2E-03 | 10.0 | 3.2E-06 | 4.6E-01 | |
| | | Americium | | | 1.8E-03 | 10.0 | 4.8E-06 | 6.7E-01 | |
| | Animal product transfer coefficients for eggs | Chlorine | Lognormal | d/kg | 4.4E-02 | 10.0 | 1.2E-04 | 1.7E+01 | Transfer coefficients are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Selenium | | | 7.3E+00 | 2.0 | 1.2E+00 | 4.4E+01 | |
| | | Strontium | | | 2.7E-01 | 2.0 | 4.5E-02 | 1.6E+00 | |
| | | Technetium | | | 2.4E+00 | 2.0 | 4.0E-01 | 1.4E+01 | |
| | | Tin | | | 8.7E-02 | 10.0 | 2.3E-04 | 3.3E+01 | |
| | | Iodine | | | 2.6E+00 | 2.0 | 4.4E-01 | 1.6E+01 | |
| | | Cesium | | | 5.9E-01 | 2.3 | 7.2E-02 | 4.8E+00 | |
| | | Lead | | | 5.6E-02 | 10.0 | 1.5E-04 | 2.1E+01 | |
| | | Radium | | | 3.9E-04 | 10.0 | 1.0E-06 | 1.5E-01 | |
| | | Actinium | | | 2.9E-03 | 2.3 | 3.4E-04 | 2.5E-02 | |
| | | Thorium | | | 3.5E-03 | 7.3 | 2.0E-05 | 5.9E-01 | |
| | | Protactinium | | | 2.0E-03 | 2.0 | 3.4E-04 | 1.2E-02 | |
| | | Uranium | | | 6.3E-01 | 2.5 | 6.0E-02 | 6.7E+00 | |
| | | Neptunium | | | 3.4E-03 | 2.4 | 3.4E-04 | 3.3E-02 | |
| | | Plutonium | | | 1.7E-03 | 7.4 | 9.7E-06 | 2.9E-01 | |
| | | Americium | | | 4.9E-03 | 2.0 | 8.2E-04 | 2.9E-02 | |
| | Animal consumption rate of feed | Meat | Uniform | kg/d | 48.5 | - | 29 | 68 | Mean calculated from uniform distribution. |
| | | Milk | | | 61.5 | - | 50 | 73 | |
| | | Poultry | | | 0.26 | - | 0.12 | 0.40 | |
| | | Eggs | | | 0.26 | - | 0.12 | 0.40 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Animal (cont.) | Animal consumption rate of water | Meat | Fixed | L/d | 60 | - | - | - | Mean calculated from uniform distribution. |
| | | Milk | Uniform | | 80 | - | 60 | 100 | |
| | | Poultry | Fixed | | 0.5 | - | - | - | |
| | | Eggs | Fixed | | 0.5 | - | - | - | |
| | Animal consumption rate of soil | Meat | Uniform | kg/d | 0.7 | - | 0.4 | 1.0 | Mean calculated from uniform distribution. |
| | | Milk | | | 0.95 | - | 0.8 | 1.1 | |
| | | Poultry | | | 0.02 | - | 0.01 | 0.03 | |
| | | Eggs | | | 0.02 | - | 0.01 | 0.03 | |
| Fish | Bioaccumulation factor | Carbon | Lognormal | L/kg | 4.6E+03 | 3.2 | 2.3E+02 | 9.2E+04 | Bioaccumulation factors are given in geometric mean and geometric standard deviation. The lower and upper bounds are 0.01 and 0.99 percentile values. |
| | | Chlorine | | | 2.2E+02 | 5.6 | 2.6E+00 | 1.9E+04 | |
| | | Selenium | | | 2.3E+02 | 2.0 | 3.9E+01 | 1.2E+03 | |
| | | Strontium | | | 4.6E+01 | 2.0 | 7.8E+00 | 2.8E+02 | |
| | | Technetium | | | 2.0E+01 | 2.0 | 3.3E+00 | 1.2E+02 | |
| | | Tin | | | 2.5E+03 | 2.0 | 4.2E+02 | 1.5E+04 | |
| | | Iodine | | | 4.5E+01 | 2.6 | 3.8E+00 | 5.3E+02 | |
| | | Cesium | | | 3.5E+03 | 2.2 | 4.7E+02 | 2.5E+04 | |
| | | Lead | | | 2.9E+02 | 2.5 | 2.7E+01 | 3.1E+03 | |
| | | Radium | | | 6.7E+01 | 2.2 | 9.2E+00 | 5.0E+02 | |
| | | Actinium | | | 2.9E+01 | 3.0 | 1.7E+00 | 5.0E+02 | |
| | | Thorium | | | 1.1E+02 | 2.5 | 1.0E+01 | 1.2E+03 | |
| | | Protactinium | | | 1.2E+01 | 2.0 | 2.0E+00 | 7.1E+01 | |
| | | Uranium | | | 1.4E+01 | 3.0 | 8.4E-01 | 2.3E+02 | |
| | | Neptunium | | | 3.0E+01 | 2.9 | 1.9E+00 | 4.7E+02 | |
| | | Plutonium | | | 4.1E+01 | 4.7 | 7.9E-01 | 2.2E+03 | |
| | | Americium | | | 5.2E+01 | 2.3 | 5.8E+00 | 4.6E+02 | |
| | Modifying factor for current climate | Carbon | Fixed | - | 1 | - | - | - | Developed based on estimates of water evaporation in fishpond. Mean calculated from uniform distribution. |
| | | Other elements | Uniform | - | 4.15 | - | 2.2 | 6.1 | |
| | Modifying factor for future climate | Carbon | Fixed | - | 1 | - | - | - | |
| | | Other elements | Uniform | - | 2.4 | - | 1.5 | 3.3 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| $^{14}C$ | $^{14}C$ emission rate | | Fixed | /yr | 22 | - | - | - | Fixed value for sandy soil. |
| | Annual total groundwater usage | | Fixed | $m^3$/yr | 3714450 | - | - | - | From 10 CFR 63, contaminated groundwater volume. |
| | Annual average wind speed | For inhalation | Uniform | m/sec | 2.45 | - | 2.1 | 2.8 | Wind speed at 1 m for crops and 2 m for inhalation. |
| | | For crops | | | 1.9 | - | 1.5 | 2.3 | |
| | $^{14}C$ mixing height | For inhalation | Fixed | m | 2 | - | - | - | Fixed values are from RESRAD code. |
| | | For crops | | | 1 | - | - | - | |
| | Fraction of air-derived carbon in plants | | Fixed | - | 0.98 | - | - | - | |
| | Fraction of soil-derived carbon in plants | | Fixed | - | 0.02 | - | - | - | |
| | Fraction of stable carbon in plant | Leafy vegetation | Fixed | - | 0.09 | - | - | - | Fixed values are from RESRAD and GENII/GENII-S codes. |
| | | Other vegetation | | | 0.09 | - | - | - | |
| | | Fruit | | | 0.09 | - | - | - | |
| | | Grain | | | 0.40 | - | - | - | |
| | | Forage | | | 0.09 | - | - | - | |
| | Fraction of stable carbon in soil | | Fixed | - | 0.03 | - | - | - | |
| | Concentration of stable carbon in air | | Fixed | $kg/m^3$ | 1.8E-4 | - | - | - | |
| | Concentration of stable carbon in water | | Fixed | kg/L | 2.0E-5 | - | - | - | |
| | Fraction of stable carbon in animal product | Meat | Fixed | - | 0.24 | - | - | - | |
| | | Milk | | | 0.07 | - | - | - | |
| | | Poultry | | | 0.20 | - | - | - | |
| | | Eggs | | | 0.15 | - | - | - | |
| External Exposure | Population proportion for groundwater scenario | Outdoor workers | Uniform | % | 5.5 | 2.6 | 2.9 | 8.1 | Based on census data. Indoor worker data calculated in the submodel as one minus the sum of the other three percentages. |
| | | Indoor workers | | | 16.1 | Cal'ed | - | - | |
| | | Commuters | | | 39.2 | 5.3 | 33.9 | 44.5 | |
| | | Non-workers | | | 39.2 | 4.8 | 34.4 | 44.0 | |
| | Population proportion for volcanic ash scenario | Outdoor workers | Uniform | % | 5.5 | 2.6 | 2.9 | 10.7 | |
| | | Indoor workers | | | 42.8 | Cal'ed | - | - | |
| | | Commuters | | | 12.5 | 3.8 | 4.9 | 16.3 | |
| | | Non-workers | | | 39.2 | 4.8 | 34.4 | 44.0 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| External Exposure (cont.) | For GW | Exposure time for outdoor workers | Active outdoors | Lognormal | hr/d | 3.1 | 0.2 | 2.6 | 3.7 | Activity time budget, time for active indoors is calculated in the submodel as 24 hr/d minus the sum of times in the other four environments. |
| | | | Inactive outdoors | | | 4.0 | 0.3 | 3.3 | 4.8 | |
| | | | Active indoors | | | 6.6 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 2.0 | 0.4 | 1.2 | 3.3 | |
| | | Exposure time for indoor workers | Active outdoors | Lognormal | hr/d | 0.3 | 0.1 | 0.1 | 0.7 | |
| | | | Inactive outdoors | | | 1.3 | 0.2 | 0.9 | 1.9 | |
| | | | Active indoors | | | 12.1 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 2.0 | 0.4 | 1.2 | 3.3 | |
| | | Exposure time for com-muters | Active outdoors | Lognormal | hr/d | 0.3 | 0.1 | 0.1 | 0.7 | |
| | | | Inactive outdoors | | | 1.4 | 0.2 | 1.0 | 2.0 | |
| | | | Active indoors | | | 6.0 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 8.0 | 0.5 | 6.8 | 9.4 | |
| | | Exposure time for non-workers | Active outdoors | Lognormal | hr/d | 0.3 | 0.1 | 0.1 | 0.7 | |
| | | | Inactive outdoors | | | 1.2 | 0.2 | 0.8 | 1.8 | |
| | | | Active indoors | | | 12.2 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 2.0 | 0.4 | 1.2 | 3.3 | |
| | For VA | Time spent by outdoor workers | Active outdoors | Lognormal | hr/d | 3.1 | 0.2 | 2.6 | 3.7 | Activity time budget, time for active indoors is calculated in the submodel as 24 hr/d minus the sum of times in the other four environments. |
| | | | Inactive outdoors | | | 4.2 | 0.3 | 3.5 | 5.0 | |
| | | | Active indoors | | | 6.4 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 2.0 | 0.4 | 1.2 | 3.3 | |
| | | Time spent by indoor workers | Active outdoors | Lognormal | hr/d | 0.3 | 0.1 | 0.1 | 0.7 | |
| | | | Inactive outdoors | | | 1.5 | 0.2 | 1.1 | 2.1 | |
| | | | Active indoors | | | 11.9 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 2.0 | 0.4 | 1.2 | 3.3 | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|---|
| External Exposure (cont.) | For VA | Time spent by commuters | Active outdoors | Lognormal | hr/d | 0.3 | 0.1 | 0.1 | 0.7 | |
| | | | Inactive outdoors | | | 2.0 | 0.2 | 1.5 | 2.6 | |
| | | | Active indoors | | | 5.1 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 8.3 | 0.6 | 6.9 | 10.0 | |
| | | Time spent by non-workers | Active outdoors | Lognormal | hr/d | 0.3 | 0.1 | 0.1 | 0.7 | |
| | | | Inactive outdoors | | | 1.2 | 0.2 | 0.8 | 1.8 | |
| | | | Active indoors | | | 12.2 | Cal'ed | - | - | |
| | | | Asleep indoors | | | 8.3 | 0.1 | 8.0 | 8.6 | |
| | | | Away from area | | | 2.0 | 0.4 | 1.2 | 3.3 | |
| | Building shielding factor | | C-14 | Fixed | - | 0.2 | - | - | - | External shielding factors developed from literature data. |
| | | | Cl-36 | | | 0.4 | - | - | - | |
| | | | Se-79 | | | 0.1 | - | - | - | |
| | | | Sr-90D | | | 0.4 | - | - | - | |
| | | | Tc-99 | | | 0.2 | - | - | - | |
| | | | Sn-126D | | | 0.4 | - | - | - | |
| | | | I-129 | | | 0.1 | - | - | - | |
| | | | Cs-135 | | | 0.1 | - | - | - | |
| | | | Cs-137D | | | 0.4 | - | - | - | |
| | | | Pu-242 | | | 0.1 | - | - | - | |
| | | | U-238D | | | 0.4 | - | - | - | |
| | | | Pu-238 | | | 0.1 | - | - | - | |
| | | | U-234 | | | 0.2 | - | - | - | |
| | | | Th-230 | | | 0.3 | - | - | - | |
| | | | Ra-226D | | | 0.4 | - | - | - | |
| | | | Pb-210D | | | 0.4 | - | - | - | |
| | | | Pu-240 | | | 0.1 | - | - | - | |
| | | | U-236 | | | 0.1 | - | - | - | |
| | | | Th-232 | | | 0.2 | - | - | - | |
| | | | Ra-228D | | | 0.4 | - | - | - | |
| | | | U-232 | | | 0.3 | - | - | - | |
| | | | Th-228D | | | 0.4 | - | - | - | |
| | | | Am-243D | | | 0.4 | - | - | - | |
| | | | Pu-239 | | | 0.3 | - | - | - | |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| External Exposure (cont.) | Building shielding factor | U-235D | Fixed | - | 0.4 | - | - | - | |
| | | Pa-231 | | | 0.4 | - | - | - | |
| | | Ac-227D | | | 0.4 | - | - | - | |
| | | Am-241 | | | 0.2 | - | - | - | |
| | | Np-237D | | | 0.4 | - | - | - | |
| | | U-233 | | | 0.4 | - | - | - | |
| | | Th-229D | | | 0.4 | - | - | - | |
| | Dose coefficient for exposure contaminated to an infinite depth | | Fixed | (Sv/yr)/(Bq/m$^3$) | See Notes | - | - | - | Based on FGR-12. Values presented in Table 6.4-2. |
| | Dose coefficient for exposure to contaminated ground surface | | Fixed | (Sv/yr)/(Bq/m$^2$) | See Notes | - | - | - | Based on FGR-12. Values presented in Table 6.5-1. |
| | Branching fraction | | Fixed | - | See Notes | - | - | - | Values in Table 6.3-7 are representative. |
| Inhalation | Breathing rate | Active outdoors | Fixed | m$^3$/hr | 1.57 | - | - | - | Developed based on ICRP 66. |
| | | Inactive outdoors | | | 1.08 | - | - | - | |
| | | Active indoors | | | 1.08 | - | - | - | |
| | | Asleep indoors | | | 0.39 | - | - | - | |
| | | Away from area | | | 1.08 | - | - | - | |
| | Dose conversion factor for inhalation | | Fixed | Sv/Bq | See Notes | - | - | - | Based on FGR-11. Values presented in Table 6.4-3. |
| | Fraction of houses with evaporative coolers | | Binomial | - | 0.738 | Sample size = 187 | - | - | Developed from site-specific survey done in Amargosa Valley. Mean calculated from uniform distribution. |
| | Evaporative cooler use factor | Current Climate | Uniform | - | 0.39 | - | 0.32 | 0.46 | |
| | | Future Climate | | | 0.085 | - | 0.03 | 0.14 | |
| | Equilibrium factor for $^{222}$Rn decay products | Outdoors | Uniform | - | 0.6 | - | 0.5 | 0.7 | Mean calculated from uniform distribution. |
| | | Indoors | Uniform | - | 0.4 | - | 0.3 | 0.5 | |
| | Dose conversion factor for inhalation of $^{222}$Rn decay products | | Fixed | Sv/Bq | 1.33E-8 | - | - | - | Based on ICRP-32, see Equation 6.4.8-6. |

Table 6.6-3. Summary of Input Parameter Values and Their Distributions (continued)

| Sub-model | Parameter Name | | Distribution Type | Units | Mean, Mode, Average [a] | SD/SE [a] | Min. [b] | Max. [b] | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| Ingestion | Consumption rate of water | | Fixed | L/d | 2 | - | - | - | Required by 10 CFR 63.312 [DIRS 156605]. |
| | Consumption rate of locally produced crop foodstuffs | Leafy vegetables | Lognormal | kg/yr | 3.78 | 0.88 | - | - | Developed based on site-specific survey. Mean/Mode column represents the mean and SD/SE column represents the standard deviation for lognormal distribution. |
| | | Other vegetables | | | 4.73 | 0.67 | - | - | |
| | | Fruit | | | 12.68 | 1.36 | - | - | |
| | | Grain | | | 0.23 | 0.11 | - | - | |
| | Consumption rate of locally produced animal products | Meat | Lognormal | kg/yr | 2.85 | 0.65 | - | - | |
| | | Milk | | | 4.66 | 1.68 | - | - | |
| | | Poultry | | | 0.42 | 0.13 | - | - | |
| | | Eggs | | | 5.30 | 0.83 | - | - | |
| | Consumption rate of locally produced fish | | Lognormal | kg/yr | 0.23 | 0.10 | - | - | |
| | Inadvertent soil ingestion rate | | Cumulative | mg/d | 100 | - | 50<br>100<br>200 | 0%<br>50%<br>100% | Recommended by the U.S. Environmental Protection Agency. |
| | Dose conversion factor for ingestion | | Fixed | Sv/Bq | See notes | - | - | - | Based on FGR-11. Values presented in Table 6.4-4. |

NOTES: GW = groundwater, SD = standard deviation, SE = standard error.

[a] The "Mean, Mode, Average" column represents the value for a fixed distribution, the mean for a normal or lognormal distribution, the mode for a triangular distribution, or the average value for distributions that do not require a mean, mode, or average, such as uniform distribution or cumulative distribution, in which values in this column are taken from the sources listed below or calculated as the 50th-percentile value. Data in this column are used in model verification (Section 6.10) and model validation (Sections 7.3 and 7.4). "SD/SE" represents the standard deviation or standard error for the described input distribution, such as normal distribution and lognormal distribution. However, for the transfer factors, transfer coefficients, and partition coefficients the "Mean, Mode, Average" represents the geometric mean and SD/SE represents geometric standard deviation for their lognormal distributions.

[b] "Min." represents the lower bounding value, and "Max." represents the upper bounding value for most distribution types, except for cumulative distributions, in which the "Min." column is the value, and the "Max." column is the corresponding accumulative percentage.

[c] Source : BSC (2003 [DIRS 160964]); BSC (2003 [DIRS 161239]); BSC (2003 [DIRS 160976]); BSC (2003 [DIRS 160965]); BSC (2003 [DIRS 161241]).

## 6.7 BIOSPHERE MODEL ENHANCEMENT

The ERMYN model, which is based on the previously used GENII-S model, incorporates several enhancements relative to the older model. The enhancements are discussed in this section. The disposition of included FEPs (Table 6.2-1) within the biosphere model is discussed in Section 6.7.1. The mathematical model (Sections 6.4 and 6.5) could not be implemented using the GENII-S code, used for the TSPA-SR, due to the incorporation of new exposure pathways, and a different model implementation tool is selected to accommodate the changes. In this section, the ERMYN model and the previous model performed with GENII-S (Section 6.7.2) are compared. Justification for building the ERMYN model in GoldSim is presented (Section 6.7.3).

### 6.7.1 Disposition of FEPs within Biosphere Mathematical Model

The FEPs considered in the biosphere conceptual model are discussed in Section 6.3.4. Table 6.7-1 describes how those FEPs are dispositioned in the mathematical model. Many of the FEPs (primarily features) are represented in the input parameters. For these FEPs, the related input parameters are identified and the disposition of the FEP through development and use of the input parameters is described (Table 6.7-1). Other FEPs (primarily events and processes) are incorporated into the equations described in Sections 6.4 and 6.5. For these FEPs, the submodels and equations related to the FEPs are identified, and the associated model parameters are listed. Some parameters address several FEPs, and one FEP may be linked to several parameters. Based on the evaluation, all FEPs considered in the conceptual model (Section 6.3.4) are adequately dispositioned in the ERMYN mathematical model.

Table 6.7-1. Disposition of the Included FEPs Within the Biosphere Mathematical Model

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 1.2.04.07.0A | Ashfall | Soil | Radionuclide concentration in ash deposited on ground surface<br>Ash bulk density | Volcanic ash is the initial source of contamination for the volcanic scenario (Section 6.3.2). |
| | | Air | Mass loading for crops<br>Mass loading for receptor environments<br>Mass loading time function | Initial ashfall depth is considered in development of the mass loading parameters (BSC 2003 [DIRS 160965], Section 6.2 and 6.3). |
| 1.3.01.00.0A | Climate change, global | Soil | Annual irrigation rate<br>Overwatering rate | Separate distributions developed for listed parameters based on current and predicted future climatic conditions (BSC 2003 [DIRS 160976], Sections 6.4, 6.5, 6.7, 6.8 and 6.9; BSC 2003 [DIRS 160964], Sections 6.4 and 6.7; BSC 2003 [DIRS 161241], Sections 6.3.4.2). Separate sets of BDCFs will be developed for current and future climate states. |
| | | Plant | Growing time<br>Irrigation amount per application<br>Daily irrigation rate | |
| | | Fish | Water concentration modifying factor | |
| | | $^{14}C$ | Annual irrigation rate<br>Daily irrigation rate<br>Surface area of irrigated land | |
| | | Inhalation | Evaporative cooler use factor | |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 1.4.07.01.0A | Water management activities | Plant | Fraction of overhead irrigation<br>Irrigation intensity | Distributions for the values of the listed parameters are developed based in part on the types of water distribution and storage systems in Amargosa Valley for crop irrigation (BSC 2003 [DIRS 160976], Sections 6.3 and 6.6) and fish farming (BSC 2003 [DIRS 160964], Section 6.4). |
| | | Fish | Water concentration modifying factor | |
| 1.4.07.02.0A | Wells | Soil, Air, Plant, Animal, Fish, Ingestion | Radionuclide concentration in groundwater | A well is initial source of contaminated groundwater for the groundwater scenario (Section 6.3.1). |
| 2.2.08.11.0A | Groundwater discharge to surface at or near receptor location | Soil, Air, Plant Animal, Fish Ingestion | Radionuclide concentration in groundwater | Conceptual and mathematical models for the groundwater scenario are applicable to surface water flowing from a spring or other discharge point as the source of contaminants (Section 6.3.1). |
| 2.3.02.01.0A | Soil type | Soil | Surface soil depth (tillage depth)<br>Soil and ash bulk density<br>Surface soil erosion rate<br>Volumetric water content | Distributions for listed parameters developed based in part on characteristics of the soil types in northern Amargosa Valley (BSC 2003 [DIRS 160976], Sections 6.6, 6.10 and 6.12; BSC 2003 [DIRS 161239], Sections 6.2, 6.4, 6.6, and 6.7; and (BSC 2003 [DIRS 160964], Section 6.7.1). |
| | | Plant | Irrigation Intensity | |
| | | $^{14}C$ | $^{14}C$ emission rate from soil | |
| 2.3.02.02.0A | Radionuclide accumulation in soils | Soil | Annual irrigation rate<br>Overwatering rate<br>Surface soil depth (tillage depth)<br>Soil solid-liquid partition coefficient<br>Soil bulk density<br>Volumetric water content<br>Surface soil erosion rate<br>Critical thickness for the resuspension | The soil submodel includes the accumulation of radionuclides in the soil from irrigation water (Eq. 6.4.1-2 and associated equations). |
| 2.3.02.03.0A | Soil and sediment transport in the biosphere | Soil | Surface soil erosion rate<br>Soil bulk density<br>Dry deposition velocity<br>Critical thickness for resuspension | The soil submodel includes soil loss and gain on farm fields (groundwater scenario, Eq. 6.4.1-11; volcanic ash scenario, Eq. 6.5.1-4). The ERMYN model does not develop thickness of ash deposited on the ground (Eq. 6.5.1-4). |
| | | Air | Mass loading decrease constant in mass loading time function | Selected distribution based in part on the influence of ash redistribution on changes in mass loading through time (BSC 2003 [DIRS 160965], Section 6.3). |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 2.3.04.01.0A | Surface water transport and mixing | Soil, Air, Plant Animal, Fish Ingestion | Radionuclide concentration in groundwater | The conceptual and mathematical models for the groundwater scenario are applicable to water discharged to the surface, and the subsequent transport of radionuclides in surface water. Mixing is not considered because there are no sources of uncontaminated water in the reference biosphere (Section 6.3.1). |
| 2.3.11.01.0A | Precipitation | Soil | Annual irrigation rate<br>Overwatering rate | Distributions of parameters developed based in part on variation and uncertainty in precipitation for the current and predicted future climate (BSC 2003 [DIRS 160976], Sections 6.5, 6.7, 6.8, and 6.9). |
| | | Plant | Irrigation amount per application<br>Daily irrigation rate | |
| | | $^{14}C$ | Daily irrigation rate<br>Annual irrigation rate | |
| 2.3.11.02.0A | Surface runoff and flooding | Soil | Surface soil erosion rate<br>Soil bulk density | The influence of surface runoff and flooding is included in soil erosion rate (Eq. 6.4.1-11) for the groundwater scenario and ash redistribution in volcanic ash source (Eq. 6.5.1-4) for the volcanic ash scenario. |
| 2.3.13.01.0A | Biosphere characteristics | Soil | Annual irrigation rate<br>Overwatering rate | Distributions of parameters developed based in part on variation and uncertainty in site-specific characteristics of the reference biosphere, such as temperature, wind speed, and evaporation rate (BSC 2003 [DIRS 160976], Sections 6.4, 6.5, 6.6, 6.7, 6.8, and 6.9); BSC 2003 [DIRS 161241], Sections 6.3.4.2; BSC 2003 [DIRS 160964], Sections 6.2.2.1, 6.4.3, 6.5.2, and 6.7.2). Some other biosphere characteristics covered by other FEPs, such as soil type (2.3.02.01.0A) and precipitation (2.3.11.01.0A). |
| | | Air | Water evaporation rate | |
| | | Plant | Dry deposition velocity<br>Daily irrigation rate<br>Irrigation application<br>Irrigation intensity<br>Growing time | |
| | | Fish | Water concentration modifying factor | |
| | | $^{14}C$ | Annual average wind speed | |
| | | Inhalation | Evaporative cooler use factor | |
| 2.4.01.00.0A | Human characteristics (physiology, metabolism) | External exposure | Dose coefficient for exposure to soil contaminated to an infinite depth<br>Dose coefficient for exposure to contaminated ground surface | Physiology and metabolism of the human receptor are considered in developing the listed parameters (BSC 2003 [DIRS 161241], Sections 6.3.3, 6.5.3.1, 6.5.3.2, 6.5.4, and 6.5.5). |
| | | Inhalation | Breathing rate<br>Dose conversion factor for inhalation<br>Dose conversion factor for inhalation of radon decay products | |
| | | Ingestion | Dose conversion factor for ingestion | |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 2.4.04.01.0A | Human lifestyle | Air | Mass loading for receptor environments | Distributions based, in part, on variation and uncertainty of the lifestyles and characteristics of people living in Amargosa Valley (BSC 2003 [DIRS 160965], Sections 6.1 and 6.2; BSC 2003 [DIRS 161241], Sections 6.3 and 6.4). Influence of human lifestyle on external exposure considered (Eq. 6.4.7-1 for the groundwater scenario; Eq. 6.5.5-1 for the volcanic ash scenario). Influences on inhalation pathway considered (Eqs. 6.4.8-2 to 6.4.8-7 for the groundwater scenario; Eqs. 6.5.6-2 and 6.5.6-3 for the volcanic ash scenario). Influences on the ingestion pathway are considered (Eqs. 6.4.9-2 to 6.4.9-6 for the groundwater scenario; Eqs. 6.5.7-2 to 6.5.7-4 for the volcanic ash scenario). |
| | | External exposure | Population proportion<br>Exposure time | |
| | | Inhalation | Population proportion<br>Exposure time<br>Fraction of house with evaporative cooler<br>Evaporative cooler usage factor by climate | |
| | | Ingestion | Consumption rate of water<br>Consumption rate of locally produced crop foodstuffs<br>Consumption rate of locally produced animal products<br>Consumption rate of locally produced fish<br>Inadvertent soil ingestion rate | |
| 2.4.07.00.0A | Dwellings | Air | Water evaporation rate<br>Evaporative cooler air flow rate<br>Interior wall height<br>House ventilation rate | Distributions based in part on uncertainty and variation in the characteristics of types of dwellings in northern Amargosa Valley (BSC 2003 [DIRS 161241], Sections 6.3.4.1, 6.3.4.2, and 6.6; BSC 2003 [DIRS 160964], Sections 6.5 and 6.6.2). |
| | | External exposure | Building shielding factor | |
| | | Inhalation | Fraction of houses with evaporative coolers<br>Evaporative cooler use factor | |
| 2.4.08.00.0A | Wild and natural land and water use | Air | Mass loading for receptor environments | Distributions based in part on uncertainty and variation in the use of wild and natural lands and the rate of consumption of wild game by the receptor (BSC 2003 [DIRS 160965], Sections 6.1 and 6.2; BSC 2003 [DIRS 161241], Sections 6.3.2 and 6.4.2). |
| | | External exposure | Exposure time | |
| | | Ingestion | Annual consumption rate of locally produced animal products | |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 2.4.09.01.0B | Agricultural land use and irrigation | Soil | Annual irrigation rate<br>Overwatering rate | The listed parameters quantify irrigation rates and are developed based in part on variation and uncertainty in cultivated land and water use practices in Amargosa Valley (BSC 2003 [DIRS 160965], Section 6.1 and 6.2; BSC 2003 [DIRS 160976], Sections 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, and 6.9; BSC 2003 [DIRS 161241], Section 6.3.2; BSC 2003 [DIRS 160964], Sections 6.3.2, 6.4.3, and 6.7.2). Agricultural use of water is included in the soil (Eq. 6.4.1-2), plant (Eqs. 6.4.3-3 to 6.4.3-5), animal (Eq. 6.4.4-3), fish (Eq. 6.4.5-2), and $^{14}C$ (Eq. 6.4.6-1) submodels of the groundwater scenario. |
| | | Air | Mass loading for receptor environments<br>Mass loading for crops | |
| | | Plant | Fraction of overhead irrigation<br>Crop growing time<br>Irrigation intensity<br>Irrigation amount per application<br>Daily irrigation rate | |
| | | Animal | Animal consumption rate of water | |
| | | $^{14}C$ | Annual irrigation rate<br>Daily irrigation rate<br>Overwatering rate<br>Surface area of irrigated land | |
| | | Fish | Water concentration modifying factor | |
| 2.4.09.02.0A | Animal farms and fisheries | Animal | Animal consumption rate of feed<br>Animal consumption rate of water<br>Animal consumption rate of soil | Parameters developed based in part on variation and uncertainty in animal and fish farming practices (BSC 2003 [DIRS 160964], Sections 6.3.2, 6.4.3, and 6.4.5) |
| | | Fish | Water concentration modifying factor | |
| 2.4.10.00.0A | Urban and industrial land and water use | Soil | Annual Irrigation rate | Distributions developed based in part on uncertainty and variation in land and water use practices in residential and industrial settings in Amargosa Valley (BSC 2003 [DIRS 160965], Section 6.1 and 6.2; BSC 2003 [DIRS 161241], Section 6.3.2; BSC 2003 [DIRS 160964], Section 6.5). Use of contaminated water in residential and urban environments included in soil (Eq. 6.4.1-2) and air (Eq. 6.4.2-3) submodels of the groundwater scenario. |
| | | Air | Mass loading for receptor environments<br>Water evaporation rate | |
| | | $^{14}C$ | Annual Irrigation rate | |
| | | External exposure | Exposure time | |
| | | Inhalation | Exposure time | |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 3.1.01.01.0A | Radioactive decay and In-growth | Soil, Air, Plant, Animal | Activity concentration of a decay product in soil, air, plants and animal products | Radionuclide decay and ingrowth in surface soils is included in the soil (Eq. 6.4.1-9), external exposure (Eq. 6.4.7-1), inhalation (Eqs. 6.4.8-2 to 6.4.8-7), and ingestion (Eq. 6.4.9-3 to 6.4.9-6) submodels of the groundwater scenario. Also included in the external exposure (Eq. 6.5.5-1), inhalation (Eq. 6.5.6-2 to 6.5.6-4), and ingestion (Eq. 6.5.7-2 to 6.5.7-4) submodels of the volcanic ash scenario. Also included in associated dose conversion factors and dose coefficients (BSC 2003 [DIRS 161241], Section 6.5. |
| | | External exposure | Dose coefficient for exposure contaminated to an infinite depth<br>Dose coefficient for exposure to contaminated ground surface | |
| | | Inhalation | Dose conversion factor for inhalation<br>Dose conversion factor for inhalation of radon decay products | |
| | | Ingestion | Dose conversion factor for ingestion | |
| 3.2.10.00.0A | Atmospheric transport of contaminants | Air | Mass loading for crops<br>Mass loading for receptor environments<br>Soil bulk density<br>Resuspension enhancement factor<br>Fraction of radionuclide transfer from water to air<br>Water evaporation rate<br>Evaporative cooler air flow rate<br>Radon release factor<br>Interior wall height<br>House ventilation rate<br>Fraction of $^{222}$Rn from soil entering the house<br>Ratio of $^{222}$Rn concentration in air to flux density from soil | The process of atmospheric transport is included in the air submodel for the groundwater scenario (Eqs. 6.4.2-1 to 6.4.2-8), the air submodel for the volcanic ash scenario (Eqs. 6.5.2-1 to 6.5.2-8), and the $^{14}$C special submodel for the groundwater scenario (Eq. 6.4.6-2 and 6.4.6-3). |
| | | $^{14}$C | $^{14}$C emission rate<br>Surface area of irrigated land<br>Annual average wind speed<br>$^{14}$C mixing height<br>Concentration of stable carbon in air | |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 3.3.01.00.0A | Contaminated drinking water, foodstuffs and drugs | Ingestion | Consumption rates of locally produced crop foodstuffs<br>Consumption rates of locally produced animal products<br>Consumption rates of locally produced fish<br>Consumption rate of water<br>Inadvertent soil ingestion rate | The listed parameters quantify intake of locally produced food and locally obtained water. Distributions of intake of locally produced food are based on a survey of the people of Amargosa Valley (BSC 2003 [DIRS 161241], Section 6.4). The ingestion submodel includes the intake of food, water, and soil (groundwater scenario, Eqs. 6.4.9-2 to 6.4.9-6; volcanic ash scenario, Eqs. 6.5.7-2 to 6.5.7-4). Calculated radionuclide concentrations in foodstuffs (Sections 6.4.3, 6.4.4, 6.4.5, 6.4.6, 6.5.3, 6.5.4) also address this FEP |
| 3.3.02.01.0A | Plant uptake | Plant | Soil-to-plant transfer factor<br>Dry-to-wet ratio<br>Fraction of overhead irrigation<br>Translocation factor<br>Weathering half-life<br>Crop growing time<br>Crop wet yield<br>Daily irrigation rate<br>Crop dry biomass<br>Irrigation amount per application<br>Irrigation intensity<br>Dry deposition velocity | The process of plant uptake of radionuclides is included in the plant submodel for the groundwater (Eqs. 6.4.3-1 to 6.4.3-8) and volcanic ash scenarios (Eqs. 6.5.3-1 to 6.5.3-5), and in the $^{14}C$ special submodel for the groundwater scenario (Eqs. 6.4.6-4 and 6.4.6-6). |
| | | $^{14}C$ | Soil bulk density<br>Fraction of air-derived carbon in plants<br>Fraction of soil-derived carbon in plants<br>Fraction of stable carbon in crops<br>Fraction of stable carbon in soil<br>Concentration of stable carbon in air | |
| 3.3.02.02.0A | Animal uptake | Animal | Animal product transfer coefficient<br>Animal consumption rate of feed<br>Animal consumption rate of water<br>Animal consumption rate of soil | The animal submodel includes the processes of radionuclide uptake by farm animals (groundwater scenario, Eqs. 6.4.4-1 to 6.4.4-4; volcanic ash scenario, Eqs. 6.5.4-1 to 6.5.4-3), and in the $^{14}C$ special submodel for the groundwater scenario (Eq. 6.4.6-7). |
| | | $^{14}C$ | Fraction of stable carbon in animal product<br>Animal consumption rate of feed<br>Animal consumption rate of water<br>Animal consumption rate of soil<br>Fraction of stable carbon in crops<br>Concentration of stable carbon in water | |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 3.3.02.03.0A | Bio-accumulation | Fish | Bioaccumulation factor<br>Water concentration modifying factor | The fish submodel includes the bioaccumulation of radionuclides in fish (groundwater scenario, Eqs. 6.4.5-1 and 6.4.5-2). The accumulation of radionuclides in farm animals is considered in the animal uptake FEP (3.3.02.02.0A). |
| 3.3.03.01.0A | Contaminated non-food products and exposure | External exposure | See parameter list under FEP 3.3.04.03.0A | The external exposure submodel implicitly considers the FEP because these contaminated products cause external exposure that is no worse than exposure of contaminated soil. |
| 3.3.04.01.0A | Ingestion | Ingestion | Dose conversion factor for ingestion<br>Consumption rate of water<br>Consumption rate of locally produced crop foodstuffs<br>Consumption rate of locally produced animal products<br>Consumption rate of locally produced fish<br>Inadvertent soil ingestion rate | The ingestion submodels include ingestion of contaminated food, drinking water, and contaminated soil (groundwater scenario, Eqs. 6.4.9-1 to 6.4.9-6; volcanic ash scenario, Eqs. 6.5.7-1 to 6.5.7-4). |
| 3.3.04.02.0A | Inhalation | Inhalation | Dose conversion factor for inhalation<br>Breathing rate<br>Exposure time<br>Equilibrium factor for $^{222}$Rn decay products<br>Dose conversion factor for inhalation of $^{222}$Rn decay products<br>Critical thickness for resuspension | The inhalation submodel includes inhalation of contaminated resuspended particles, aerosols from evaporative coolers, $^{14}$C, and radon decay products (groundwater scenario, Eqs. 6.4.8-1 to 6.4.8-7; volcanic ash scenario, Eqs. 6.5.6-1 to 6.5.6-4). |
| 3.3.04.03.0A | External exposure | External exposure | Dose coefficient for exposure contaminated to an infinite depth<br>Dose coefficient for exposure to contaminated ground surface<br>Exposure time<br>Building shielding factor | The external exposure submodel includes external exposure to contaminated materials (groundwater scenario, Eq. 6.4.7-1; volcanic ash scenario, Eq. 6.5.5-1). |
| 3.3.05.01.0A | Radiation doses | External exposure, Inhalation, Ingestion | Dose coefficient for exposure contaminated to an infinite depth<br>Dose coefficient for exposure to contaminated ground surface<br>Dose conversion factor for inhalation<br>Dose conversion factor for ingestion<br>BDCFs | Calculation of the predicted annual dose to the receptor for a unit activity concentration of a radionuclide (i.e., BDCF) is described in Eq. 6.4.10-1 and 6.4.10-2 for the groundwater scenario and 6.5.8.1 and 6.5.8-2 for the volcanic ash scenario. |

Table 6.7-1. Disposition of the included FEPs within the Biosphere Mathematical Model (continued)

| LA FEP Number | FEP Name | Biosphere Submodel [a] | Model Parameters that Address the FEP [b] | Disposition within ERMYN Model |
|---|---|---|---|---|
| 3.3.08.00.0A | Radon and radon daughter exposure | Air, Inhalation | Radon release factor<br>Interior wall height<br>House ventilation rate<br>Fraction of $^{222}$Rn from soil entering the house<br>Ratio of $^{222}$Rn concentration to flux density for outdoors<br>Equilibrium factor for $^{222}$Rn decay products<br>Fraction of radionuclide transfer from water to air | The air submodels include radon concentrations (groundwater scenario, Eqs. 6.4.2-4 to 6.4.2-8; volcanic ash scenario, Eqs. 6.5.2-5 to 6.5.2-8). The inhalation submodel includes the consequences of inhaling radon and the decay products (groundwater scenario, Eqs. 6.4.8-5 to 6.4.8-7; volcanic ash scenario, Eqs. 6.5.6-3 and 6.5.6-4). |

NOTES:

[a] Relationships among submodels shown in Figures 6.3-2 and 6.3-4. Mathematical representations described in Sections 6.4 and 6.5.

[b] Model parameters for each submodel presented in Sections 6.4 and 6.5; also summarized in Section 6.6.

### 6.7.2 Comparison of Biosphere Models

Improvements in the current biosphere model are identified by comparing the ERMYN model with the GENII-S model previously used for the TSPA-SR. Forty items or issues are compared (Table 6.7-2), many of which are new exposure pathways that are not considered in the TSPA-SR (e.g., a radon exposure pathway, inhalation of aerosols from evaporative cooling, and soil ingestion by domestic farm animals).

Table 6.7-2. Comparison of Biosphere Models for the TSPA-LA and TSPA-SR

| No. | Item Compared | GENII-S (TSPA-SR) [a] | ERMYN (TSPA-LA) [b] | Used in TSPA-LA Scenario |
|---|---|---|---|---|
| 1 | Parameter uncertainty | Limited number of probability distribution parameters. | Every parameter can be represented by probability distribution function. | Both |
| 2 | Number of realizations per simulation | Scenario dependent, but typically less than 200 realizations. | High limit on number of realizations (e.g. 5,000 realizations). | Both |
| 3 | Cumulative probability results | Some cumulative probability results calculated incorrectly (reported deficiency; Wasiolek 2002 [DIRS 162977]). | Not considered. | Both |
| 4 | Long-term irrigation rate for cultivated lands | Not considered. | Average irrigation rate includes consideration of crop rotation and changes in the use of cultivated land. | Groundwater |
| 5 | Crop rotation and land use | Not considered; assumed one crop grown indefinitely on each plot of land. | Incorporated using an average irrigation rate. | Groundwater |
| 6 | Average radionuclide concentration in soil | Home lawn irrigation rate used for evaluation of external exposure, inhalation, and soil ingestion. | Calculated using the annual average irrigation rate; used for crop root uptake, external exposure, inhalation, and soil ingestion. | Groundwater |

Table 6.7-2. Comparison of Biosphere Models for the TSPA-LA and TSPA-SR (continued)

| No. | Item Compared | GENII-S (TSPA-SR) [a] | ERMYN (TSPA-LA) [b] | Used in TSPA-LA Scenario |
|---|---|---|---|---|
| 7 | Leaching removal into deep soil | Only represented by a fixed value. | Represented by a probability distribution. | Groundwater |
| 8 | Surface soil erosion | Not considered in GENII-S code, but considered externally. | One of removal mechanisms in surface soil. | Groundwater |
| 9 | Radionuclide accumulation in soil | Fixed leaching rate only and calculated based on multiple irrigation periods. | Equilibrium activity concentration of radionuclides in surface soil. | Groundwater |
| 10 | Harvest removal and use of cow manure as fertilizer | Theoretically includes harvest removal, but the code does not execute this part of the submodel (reported deficiency; Wasiolek 2002 [DIRS 162977]). | The ERMYN model does not include these two mechanisms because they balance out. | Both |
| 11 | Volcanic ash deposited on an cultivated land | Uniformly mixed in soil up to a defined depth. | Ash and surface soil mixed uniformly to tilling depth. Mixture is soil-like. Used for crop root uptake and soil ingestion. | Volcanic Ash |
| 12 | Volcanic ash deposited on an non-cultivated land | Not considered. | Ash mixes with surface soil if ash thickness is less than critical thickness. Mixture is ash-like. Used for inhalation of resuspended soil. | Volcanic Ash |
| 13 | Enhancement factor | Not considered. | Correction for enhancement of airborne activity concentration relative to surface soil. | Both |
| 14 | Mass loading for crops | Not directly used; used a related parameter of resuspension factor. | Parameter, based on farm field conditions, used to calculate direct deposition of particles on crop surface. | Both |
| 15 | Mass loading for inhalation | Used average value. | Environment related, based on human activity, including active outdoors, inactive outdoors, active indoors, asleep indoors, and outside of contaminated area. | Both |
| 16 | Time-dependent mass loading | Not considered. | Includes time function to for decreasing mass loading after a volcanic eruption. | Volcanic Ash |
| 17 | Radionuclide release from evaporative cooler | Not considered. | Includes submodel to calculate radionuclide concentration in indoor air from operation of evaporative coolers. | Groundwater |
| 18 | Radon release from soil into air | Not considered. | Considered based on parameter of radon release factor. | Both |
| 19 | Soil-to-plant transfer factor for fresh forage | Used one transfer factor for leafy vegetables. | Includes parameter value based on literature. | Both |
| 20 | Fraction of overhead irrigation method | Not considered. | Includes parameter to better represent site-specific agricultural practice. | Groundwater |

Table 6.7-2. Comparison of Biosphere Models for the TSPA-LA and TSPA-SR (continued)

| No. | Item Compared | GENII-S (TSPA-SR) [a] | ERMYN (TSPA-LA) [b] | Used in TSPA-LA Scenario |
|---|---|---|---|---|
| 21 | Crop daily irrigation rate | Correlation between annual irrigation rate and duration not addressed. | Includes parameter to eliminate irrigation duration and its correlation with annual irrigation rate. | Groundwater |
| 22 | Irrigation interception fraction | A single value for all crop types. | Includes parameter based on site-specific irrigation practices, including irrigation methods, irrigation frequency, and crop type; crop-type dependent. | Groundwater |
| 23 | Translocation factor and weathering rate | Represented by fixed values. | Represented by probability distribution functions. | Both |
| 24 | Crop yield and biomass | Not used correctly (Sections 6.4.3.3 and 7.3.3.3). | Crop yield represents crop foodstuffs and crop biomass represents the total standing biomass for the interception of irrigation water and particle deposition. | Both |
| 25 | Animal soil ingestion | Not considered. | Included. | Both |
| 26 | $^{14}C$ release from soil in form of gaseous species | Not considered. | Considers release of gaseous species of carbon from soil and subsequent uptake by plant and inhalation by humans. | Groundwater |
| 27 | $^{14}C$ leaching removal constant | Value is fixed in the code; user input not used (reported deficiency; Wasiolek 2002 [DIRS 162977]). | User defined. | Groundwater |
| 28 | $^{14}C$ pathways of external exposure, inhalation, and soil ingestion | Not considered. | Included. | Groundwater |
| 29 | Crop $^{14}C$ uptake | Includes root uptake only. | Submodel differentiated between $^{14}C$ fractions derived from air and soil. | Groundwater |
| 30 | Dose coefficients for exposure to contaminated soil | Dose coefficients for 15-cm contaminated soil are used. | Dose coefficients for infinite depth account for radionuclides removed from surface soil by leaching. | Groundwater |
| 31 | Dose coefficients for exposure to contaminated ground surface | Radionuclides mixed in surface soil; used same method for groundwater scenario. | Dose coefficients for the ground surface are used for thin layer of volcanic ash deposited on the ground. | Volcanic Ash |
| 32 | Indoor external exposure | Not considered. | Considers building shielding factor. | Both |
| 33 | External and inhalation exposure time | A single effective value is used. | Environment specific; based on site-specific information. | Both |
| 34 | Human activity budget | Not considered. | Determines external and inhalation exposure times for receptor. | Both |

Table 6.7-2. Comparison of Biosphere Models for the TSPA-LA and TSPA-SR (continued)

| No. | Item Compared | GENII-S (TSPA-SR) [a] | ERMYN (TSPA-LA) [b] | Used in TSPA-LA Scenario |
|---|---|---|---|---|
| 35 | Dose conversion factors for inhalation | Not consistent with FGR-11. | Taken from FGR-11. | Both |
| 36 | Breathing rate | A fixed average value. | Environment related, based on human activity. | Both |
| 37 | Inhalation dose from aerosols released from evaporative cooler | Not considered. | Considered. | Groundwater |
| 38 | Inhalation dose from radon decay products | Not considered. | Considered. | Both |
| 39 | Dose conversion factors for ingestion | Not consistent with FGR-11. | Taken from FGR-11. | Both |
| 40 | BDCFs for volcanic ash scenario | Several sets of BDCFs calculated. | Three components of BDCF: external and ingestion, long-term inhalation, and short-term inhalation. | Volcanic Ash |

NOTES:

[a] Source: GENII manual (Napier et al. 1988 [DIRS 157927], GENII-S user guide (Leigh et al. 1993 [DIRS 100464]), and BDCFs for TSPA-SR (CRWMS M&O 2001 [DIRS 152536]; CRWMS M&O 2001 [DIRS 152539]).

[b] Source: Sections 6.1 to 6.6.

### 6.7.3 Software Selection

Based on biosphere model comparisons (Table 6.7-2), the new biosphere conceptual model (ERMYN) can not be implemented using the old (GENII-S) code. Existing codes that could be used for the Yucca Mountain biosphere model were examined, but no off-the-shelf computer codes are capable of implementing the ERMYN model (Sections 6.4 and 6.5) or of implementing the uncertainty treatment (Section 6.6). The GoldSim software (GoldSim Technology Group 2002 [DIRS 160643]) can perform probabilistic analyses and can simulate process to address uncertainty. Therefore, the ERMYN model is built using GoldSim.

The GoldSim software supports 13 types of stochastic distributions: uniform, normal, lognormal, triangular, cumulative, discrete, Poisson, beta, gamma, Weibull, binomial, Student's *t*, and boolean distributions. The most frequently used distributions in the ERMYN model are lognormal, normal, uniform, and cumulative distributions.

Only the eight basic elements in the GoldSim environment are used in the ERMYN model (Figure 6.7-1). The Data element is used for the input of fixed data or to combine several stochastic inputs into a data array. Sometimes, a simple calculation is done in the Data element. The Stochastic element is used to input distribution data. The 1-D Table element is used to store all radionuclide-related input parameters so that they can be searched later. The Expression

element, the most frequently used element, is used for all calculations. The Sum element is used for some simple additions. The Data and Expression elements accept data arrays, which are used to simplify calculation expressions. The Selector element is used to select parameter values from a database. The Result element is used to present the final distribution results. The Container box is used to separate submodels and calculation tasks.

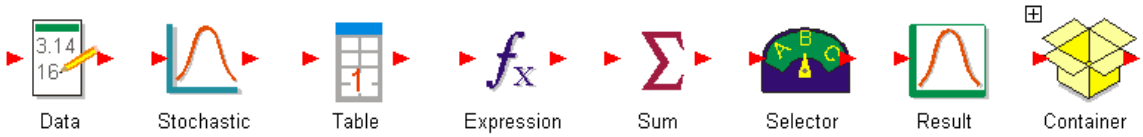



Figure 6.7-1. Basic Elements in the GoldSim Environment

## 6.8 GOLDSIM IMPLEMENTATION OF THE BIOSPHERE MODEL FOR THE GROUNDWATER SCENARIO

As discussed previously, the ERMYN model is implemented using GoldSim stochastic simulation software. The two exposure scenarios are built separately to simplify checking the simulation routines. This section describes the ERMYN groundwater model in GoldSim and shows the overall model algorithm and submodel structures. The GoldSim file (ERMYN_GW.gsm) is part of the model output, which is listed in Attachment I. As discussed in Section 6.4, ERMYN_GW is structured as a series of submodels. Under each submodel, the linkage of GoldSim elements to the submodel input parameters in an equation is tabulated in this section. A color code is used in GoldSim to aid in distinguishing among items displayed on the computer screen. Text descriptions are shown in green. Element names are shown in black for calculated quantities and in blue for input parameters. If the name of a container box is shown in blue, it contains at least one input parameter. The cover page for the ERMYN_GW simulation system for biosphere modeling (Figure 6.8-1) shows the title, the version and other text (green), and one container box, *Biosphere_Model*, which is shown in blue to indicate that it contains at least one input parameter.

The *Biosphere_Model* container holds the submodel containers and the radionuclide data (Figure 6.8-2). GoldSim is an object-oriented graphical program, and the overall model structure looks much like the block diagram of the conceptual model for the groundwater scenario shown in Figure 6.3-2. Each container in GoldSim corresponds to a submodel or to a component model if a container is at a lower level.

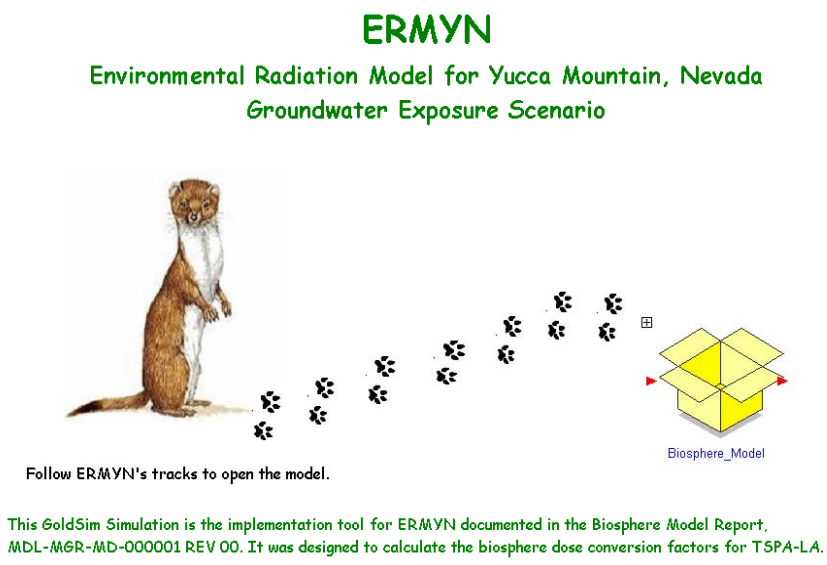



Figure 6.8-1. Cover Page for the ERMYN_GW in GoldSim

Ten containers, including eight submodels ($^{14}C$ does not have a specific box), one result box, and one radionuclide database box are shown in Figure 6.8-2. Each box is discussed in detail in the following subsections. Only two input parameters can be changed at this level: *Radionuclide* and *Water_Source*. *Radionuclide* can be selected only from the data element of *Radionuclide_List* (index $i$ in the equations) that is built in the *Nuclide_Database* container. *Water_Source* is the radionuclide concentration in the groundwater ($Cw_i$ in the equation), which has a default value of 1 Bq/m$^3$. GoldSim can run in deterministic or stochastic modes by adjusting settings in the *MasterClock*. If the stochastic mode is chosen, the number of realizations, the sampling method (Monte Carlo or Latin Hypercube), and a random seed number is set. Because the BDCFs are not a function of time, the time option is disabled for the ERMYN model.

As discussed in Section 6.4, the biosphere model involves radionuclides linearly transported from one media to another. The model algorithm is based on the submodels, in the order discussed in the Section 6.4. The calculated results in one submodel are then used in the next applicable submodel. The arrows in Figure 6.8-2 indicate the relationships and calculation logic flow among submodels.

Many calculations are performed using data vectors to reduce the number of elements. Twelve data arrays are used: primary radionuclides ($i$ = 31), total number of radionuclides ($i$ = 75), pathways ($n$ = 15), plant types ($j$ = 5), crop food types ($j$ = 4), animal product types ($k$ = 4), number of long-lived decay products ($l$ = 3), population groups ($m$ = 4), environments ($n$ = 5), air submodel pathway ($n$ = 4), crop uptake pathway ($n$ = 4), and animal uptake pathway ($n$ = 4). These data sets and submodel pathways are discussed in the mathematical model (Section 6.4).

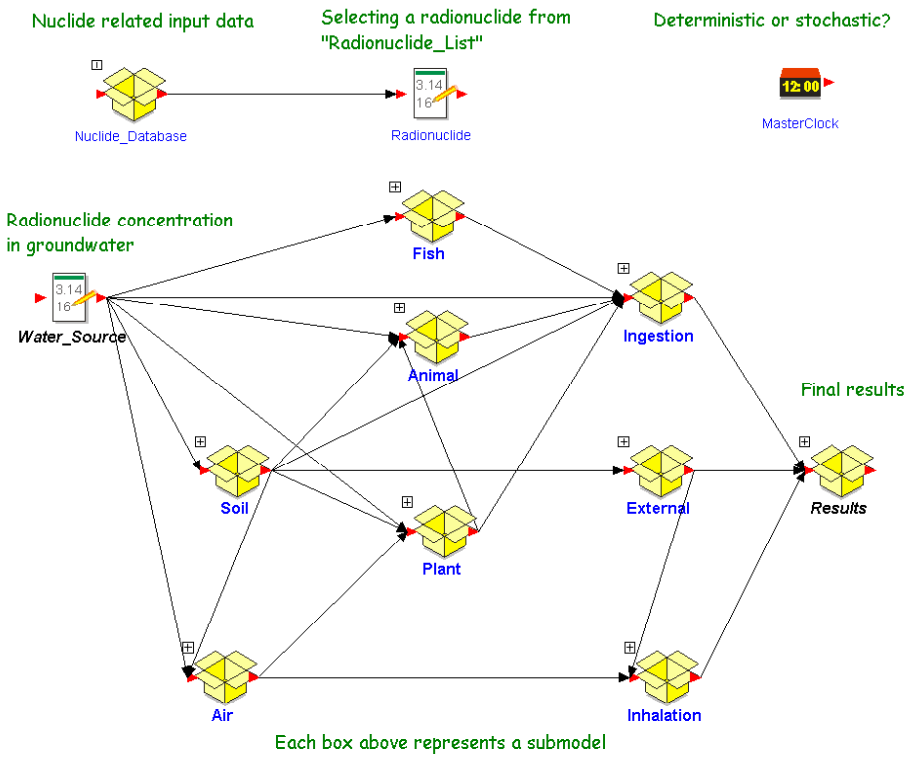



Figure 6.8-2. Graphical Representation of the Groundwater Scenario in GoldSim

### 6.8.1 Nuclide Database

The *Nuclide_Database* container (Figure 6.8-3) includes all radionuclide-related input parameters (under the *Nuclide_Data* container) and their selection in the model (under the *Data_Selection* container). Besides the two containers, there is one data element, *Radionuclide_List*, which includes 31 radionuclides, three more than the number of radionuclides of interest for the TSPA-LA (Table 6.1-1). The three extra radionuclides are $^{228}$Ra, $^{228}$Th, and $^{235}$U. The ERMYN model includes these radionuclides because they are part of decay chains (Table 6.3-7).

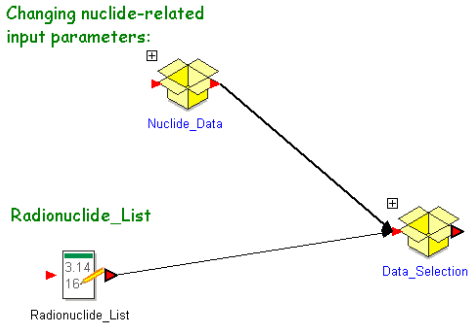



Figure 6.8-3. Nuclide Database Container

The *Nuclide_Data* container includes five sub-containers (element-specific partition coefficients, crop transfer factors, animal product transfer coefficients, fish bioaccumulation factors, and nuclear data). For example, the *Crop_Transfer* container (Figure 6.8-4) includes 80 distribution parameters for 16 elements and 5 plant types. The form of the other three containers (*Animal_Transfer*, *Fish_Transfer*, *Kd_Coefficients*) is similar. The *Nuclear_Data* container includes radionuclide half-lives, branching fractions, external dose coefficients for contaminated soil, and dose conversion factors for inhalation and ingestion. All nuclear input data have fixed values and are in array form.

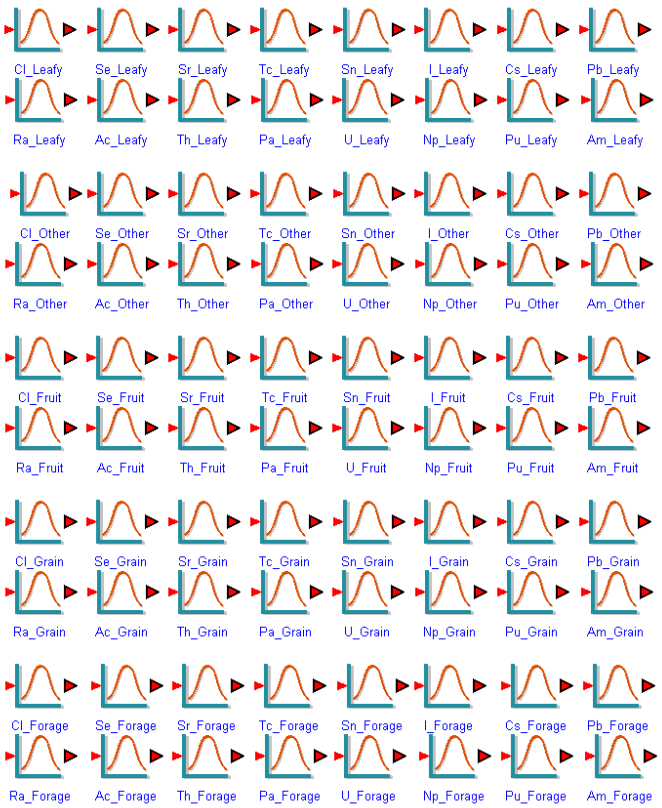



Figure 6.8-4. Input Parameters for Crop Transfer Factors

Within the *Data_Selection* container (Figure 6.8-5), dose coefficients and dose conversion factors of short-lived radionuclides are added to the corresponding primary radionuclides, which are calculated under the *Effective_DCF* (Figure 6.8-6). Three containers determine 15 radionuclide-specific input parameters for the primary radionuclides, the first decay products, and the second decay products (if the primary radionuclide has decay products) (Figure 6.8-5). After a radionuclide is selected for processing through the model, the radionuclide specific input parameters are determined using *Selector* elements (Figure 6.8-7). Parameter names, GoldSim element types, data sources, data types, related mathematical equation numbers, and notations are shown in Table 6.8-1. Information for the decay product containers (*Decay1_Rn* and *Decay2_Rn*) is not tabulated, but it is similar to that shown for the primary radionuclides (Table 6.8-1). The selection of decay products is discussed in Section 6.4.1.2 and Table 6.4-1. After the radionuclide-related input parameters are selected, the values are passed to the appropriate submodels.

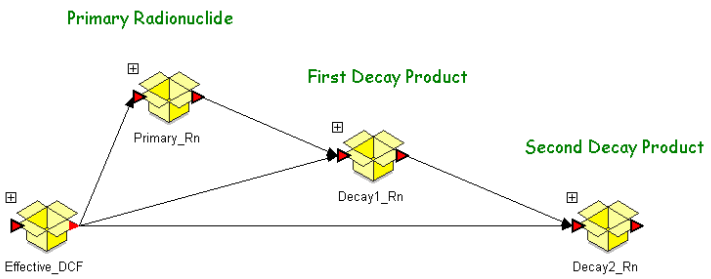



Figure 6.8-5. Radionuclide-Specific Input Parameter Selection

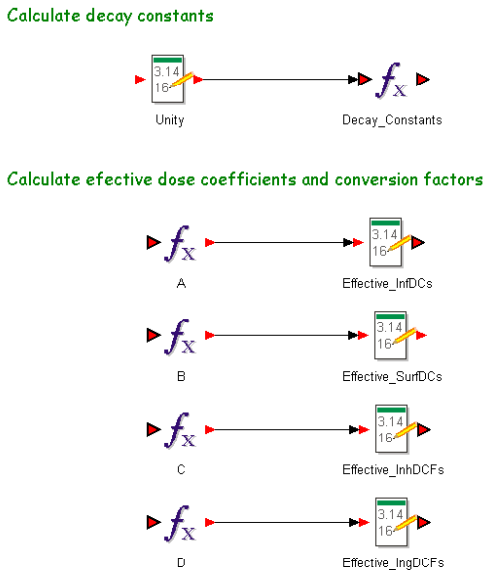



Figure 6.8-6. Calculation of Effective Dose Coefficients and Dose Conversion Factors

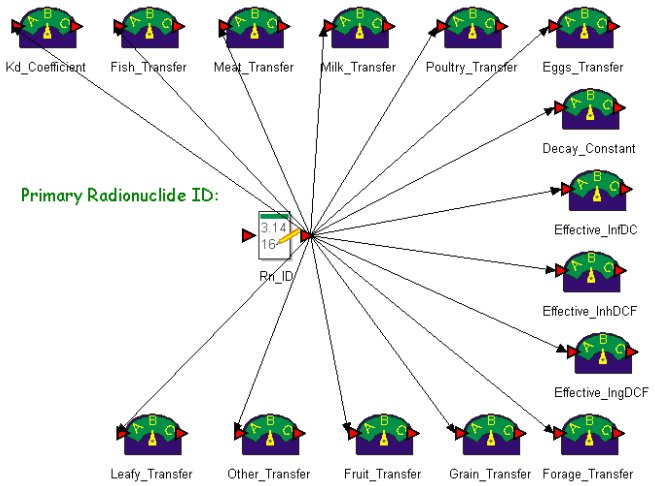



Figure 6.8-7. Primary_Rn Container and Selection of the Second Decay Product

Table 6.8-1. Radionuclide-Related Input Parameters in the Nuclide_Database Container

| First Level Box Name | Second Level Box Name | Parameter or Container Name | Element Type [a] | Data Source [b] | Data Type [c] | Equation | Notation |
|---|---|---|---|---|---|---|---|
| Radionuclide_List | | | Data | Input | Vector(31) | 6.4.1-1 | $i$ |
| Nuclide_ Data | Kd_Coefficients | | Container | Not shown in detail | | | |
| | Crop_Transfers | | | | | | |
| | Animal_Transfers | | | | | | |
| | Fish_Transfers | | | | | | |
| | Nuclear_Data | | | | | | |
| Data_ Selection | Effective _DCF | Unity | Data | - | Vector(31) | - | - |
| | | Decay_Constants | Expression | Cal'ed | Vector(31) | 6.4.1-1 | $\lambda_{d\,i}$ |
| | | A | Expression | Cal'ed | Vector(31) | 6.4.7-2 | $DCF_{soil,i}$ |
| | | B | Expression | Cal'ed | Vector(31) | Not used | - |
| | | C | Expression | Cal'ed | Vector(31) | 6.4.8-8 | $DCF_{inh,i}$ |
| | | D | Expression | Cal'ed | Vector(31) | 6.4.9-7 | $DCF_{ing,i}$ |
| | | Effective_InfDCs | Data | Cal'ed | Vector(31) | 6.4.7-2 | $EDCi_{soil,i}$ |
| | | Effective_SurDCs | Data | Cal'ed | Vector(31) | Not used | - |
| | | Effective_InhDCFs | Data | Cal'ed | Vector(31) | 6.4.8-8 | $EDCF_{inh,i}$ |
| | | Effective_IngDCFs | Data | Cal'ed | Vector(31) | 6.4.9-6 | $EDCF_{ing,i}$ |
| | Primary_ Rn | Rn_ID | Data | Dbase | Scalar | 6.4.1-1 | $i$ |
| | | Decay_Constant | Selector | Dbase | Scalar | 6.4.1-1 | $\lambda_{d\,I}$ |
| | | Effective_InfDC | Selector | Dbase | Scalar | 6.4.7-1 | $EDCi_{soil,i}$ |
| | | Effective_InhDCF | Selector | Dbase | Scalar | 6.4.8-2 | $EDCF_{inh,i}$ |
| | | Effective_IngDCF | Selector | Dbase | Scalar | 6.4.9-2 | $EDCF_{ing,i}$ |
| | | Kd_Coefficient | Selector | Dbase | Scalar | 6.4.1-10 | $Kd_i$ |
| | | Fish_Transfer | Selector | Dbase | Scalar | 6.4.5-1 | $BF_i$ |
| | | Beef_Transfer | Selector | Dbase | Scalar | 6.4.4-2 | $Fm_{i,1}$ |
| | | Poultry_Transfer | Selector | Dbase | Scalar | 6.4.4-2 | $Fm_{i,2}$ |
| | | Milk_Transfer | Selector | Dbase | Scalar | 6.4.4-2 | $Fm_{i,3}$ |
| | | Eggs_Transfer | Selector | Dbase | Scalar | 6.4.4-2 | $Fm_{i,4}$ |
| | | Leafy_Transfer | Selector | Dbase | Scalar | 6.4.3-2 | $F_{s\rightarrow p,i,1}$ |
| | | Other_Transfer | Selector | Dbase | Scalar | 6.4.3-2 | $F_{s\rightarrow p,i,2}$ |
| | | Fruit_Transfer | Selector | Dbase | Scalar | 6.4.3-2 | $F_{s\rightarrow p,i,3}$ |
| | | Grain_Transfer | Selector | Dbase | Scalar | 6.4.3-2 | $F_{s\rightarrow p,i,4}$ |
| | | Forage_Transfer | Selector | Dbase | Scalar | 6.4.3-2 | $F_{s\rightarrow p,i,5}$ |
| | Decay1_Rn | | Container | Not shown in detail | | | |
| | Decay2_Rn | | Container | Not shown in detail | | | |

NOTES: The following notes apply to all GoldSim tables in Section 6.8:

[a] Element type is the GoldSim element type used for inputs, calculations, and other manipulations (Section 6.7.3).

[b] If the data source is "Input," the parameter values are entered in the GoldSim element. If the source is "Dbase," values are taken from a database, or calculated values. If the data source is "Cal'ed," it is a calculated quantity. If the source and the corresponding equation notation are dashes (-), the element is added for GoldSim array calculations.

[c] Data types are scalar (a single value) or array (a set of values). A 1-dimensional array is called a vector, and a 2-dimensional array is called a matrix. The number of values in the array is given in parenthesis.

### 6.8.2 Surface Soil Submodel

The mathematical equations for the surface soil submodel are discussed in Section 6.4.1. The contents of the submodel container are shown in Figure 6.8-8. All GoldSim elements in the surface soil submodel are listed in Table 6.8-2. The submodel includes five lower-level containers. The *SoilModel_Input* container includes all input parameters in the submodel

(Figure 6.8-9), which are all distribution parameters. The *Soil_Conc* container includes calculations of the leaching factor (Equation 6.4.1-10) and the saturation concentration for primary radionuclides (Equation 6.4.1-4). The *Soil_Conc_1* container calculations of includes the soil buildup of the first decay product, while the *Soil_Conc_2* container includes calculations of the buildup of the second decay product. The calculation of decay-product buildup is similar to the calculations for primary radionuclides in the *Soil_Conc* container, but using Equation 6.4.1-9 and radionuclide-specific input parameters. Although the special submodel for $^{14}C$ in the soil is discussed separately (Section 6.4.6), the soil concentration of $^{14}C$ is included in the *C14_Soil* container in the surface soil submodel.

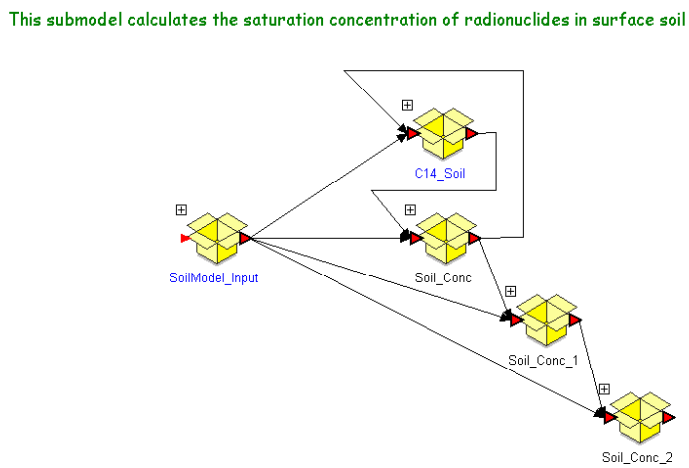



Figure 6.8-8. Soil Submodel Container

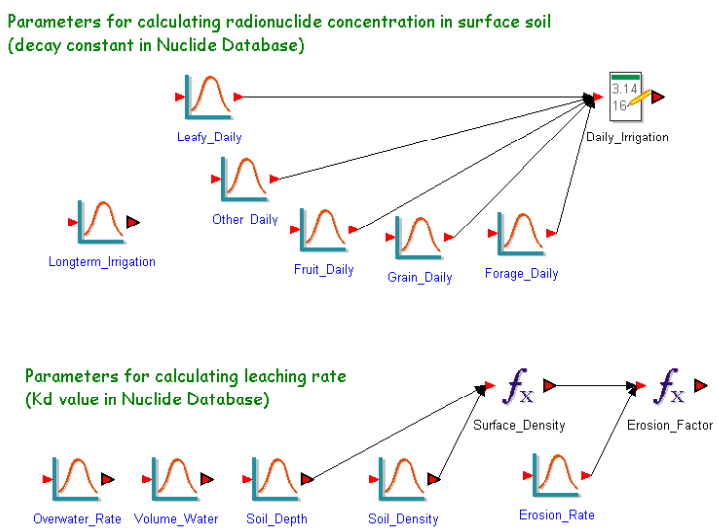



Figure 6.8-9. Input Parameter Container (*SoilModel_Input*) for the Soil Submodel

Table 6.8-2. Parameters in the Surface Soil Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| SoilModel_ Input | Leafy_Daily | Stochastic | Input | Scalar | 6.4.3-4 | $IRD_1$ |
| | Other_Daily | Stochastic | Input | Scalar | 6.4.3-4 | $IRD_2$ |
| | Fruit_Daily | Stochastic | Input | Scalar | 6.4.3-4 | $IRD_3$ |
| | Grain_Daily | Stochastic | Input | Scalar | 6.4.3-4 | $IRD_4$ |
| | Forage_Daily | Stochastic | Input | Scalar | 6.4.3-4 | $IRD_5$ |
| | Daily_Irrigation | Data | Cal'ed | Vector(5) | 6.4.3-4 | $IRD_j$ |
| | Longterm_Irrigation | Stochastic | Input | Scalar | 6.4.1-1 | $IR$ |
| | Overwater_Rate | Stochastic | Input | Scalar | 6.4.1-10 | $OW$ |
| | Volume_Water | Stochastic | Input | Scalar | 6.4.1-10 | $\theta$ |
| | Erosion_Rate | Stochastic | Input | Scalar | 6.4.1-11 | $ER$ |
| | Erosion_Factor | Expression | Cal'ed | Scalar | 6.4.1-11 | $\lambda_e$ |
| | Soil_Depth | Stochastic | Input | Scalar | 6.4.1-6 | $d$ |
| | Soil_Density | Stochastic | Input | Scalar | 6.4.1-6 | $\rho$ |
| | Surface_Density | Expression | Cal'ed | Scalar | 6.4.1-5 | $\rho_s$ |
| C14_Soil | Emission_Factor | Data | Input | Scalar | 6.4.6-1 | $\lambda_{a,C\text{-}14}$ |
| | C14_Zero | Data | - | Vector(5) | - | - |
| | C14Conc_CropSoil | Expression | Cal'ed | Vector(5) | 6.4.6-1 | $Cs_{C\text{-}14,j}$ |
| | C14Conc_InhSoil | Expression | Cal'ed | Scalar | 6.4.6-1 | $Cs_{C\text{-}14,0}$ |
| Soil_Conc | Partition_Coefficient | Data | Dbase | Scalar | 6.4.1-10 | $Kd_i$ |
| | Leaching_Factor | Expression | Cal'ed | Scalar | 6.4.1-10 | $\lambda_{l,i}$ |
| | Decay_Factor | Data | Dbase | Scalar | 6.4.1-1 | $\lambda_{d,i}$ |
| | Effective_Removal | Expression | Cal'ed | Scalar | 6.4.1-3 | $\lambda_{eff,i}$ |
| | Saturated_Conc | Expression | Cal'ed | Scalar | 6.4.1-4 | $Cs_i$ |
| | SatMass_Conc | Expression | Cal'ed | Scalar | 6.4.1-5 | $Cs_{m,i}$ |
| Soil_Conc_1 | Partition_ Coefficient_1 | Data | Dbase | Scalar | 6.4.1-10 | $Kd_1$ |
| | Leaching_Factor_1 | Expression | Cal'ed | Scalar | 6.4.1-10 | $\lambda_{l,1}$ |
| | Decay_Factor_1 | Data | Dbase | Scalar | 6.4.1-1 | $\lambda_{d,1}$ |
| | Effective_Removal_1 | Expression | Cal'ed | Scalar | 6.4.1-3 | $\lambda_{eff,1}$ |
| | Saturated_Conc_1 | Expression | Cal'ed | Scalar | 6.4.1-9 | $Cs_1$ |
| | SatMass_Conc_1 | Expression | Cal'ed | Scalar | 6.4.1-5 | $Cs_{m,1}$ |
| Soil_Conc_2 | Partition_ Coefficient_2 | Data | Dbase | Scalar | 6.4.1-10 | $Kd_2$ |
| | Leaching_Factor_2 | Expression | Cal'ed | Scalar | 6.4.1-10 | $\lambda_{l,2}$ |
| | Decay_Factor_2 | Data | Dbase | Scalar | 6.4.1-1 | $\lambda_{d,2}$ |
| | Effective_Removal_2 | Expression | Cal'ed | Scalar | 6.4.1-3 | $\lambda_{eff,2}$ |
| | Saturated_Conc_2 | Expression | Cal'ed | Scalar | 6.4.1-9 | $Cs_2$ |
| | SatMass_Conc_2 | Expression | Cal'ed | Scalar | 6.4.1-5 | $Cs_{m,2}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.3 Air Submodel

The mathematical equations used for the air submodel are discussed in Section 6.4.2. All parameters in the air submodel are summarized in Table 6.8-3. This submodel includes five lower-level containers (Figure 6.8-10). The *AirModel_Input* container includes two input parameters: mass loading and the enhancement factor (Figure 6.8-11). The *Dust_Air* container calculates radionuclide concentrations in the air due to resuspended particles for direct deposition on crops (Equation 6.4.2-1) and human inhalation (Equation 6.4.2-2). Because particle resuspension is linked to the surface soil, decay product accumulation is considered in this container. The *Radon_Air* container includes calculations related to the release of radon gas from $^{226}$Ra-contaminated soil. Radon-222 is a decay product of the primary radionuclide $^{226}$Ra,

and a decay product of $^{226}$Ra, which is a decay product of $^{230}$Th. The special submodel for $^{14}$C in the air (Section 6.4.6.2) is included in the *C14_Air* container of the air submodel. Radionuclide concentrations in the air due to aerosols from evaporative coolers are calculated in the *Evaporative_Air* container. Because aerosols are released directly from contaminated groundwater, a decay chain due to radionuclide buildup in the soil is not considered.

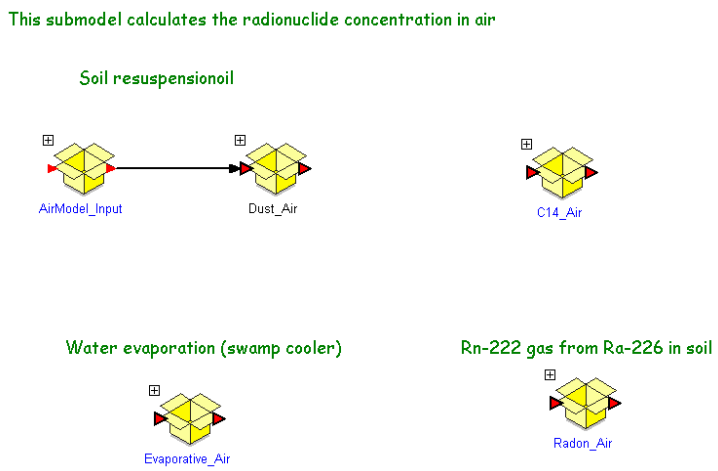



Figure 6.8-10. Air Submodel Container

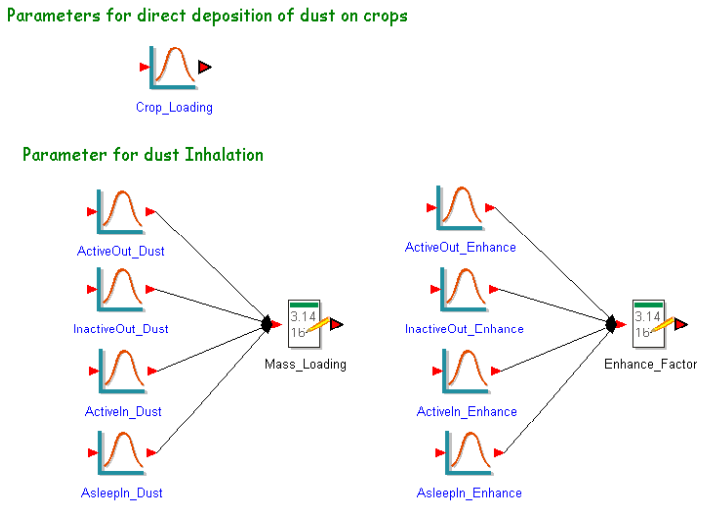



Figure 6.8-11. Input Parameter Container (*AirModel_Input*) for the Air Submodel

Table 6.8-3. Parameters in the Air Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| AirModel_Input | Crop_Loading | Stochastic | Input | Scalar | 6.4.2-1 | $S$ |
| | ActiveOut_Dust | Stochastic | Input | Scalar | 6.4.2-2 | $S_1$ |
| | InactiveOut_Dust | Stochastic | Input | Scalar | 6.4.2-2 | $S_2$ |
| | ActiveIn_Dust | Stochastic | Input | Scalar | 6.4.2-2 | $S_3$ |
| | AsleepIn_Dust | Stochastic | Input | Scalar | 6.4.2-2 | $S_4$ |
| | Mass_Loading | Data | Cal'ed | Vector(5) | 6.4.2-2 | $S_n$ |
| | ActiveOut_Enhance | Stochastic | Input | Scalar | 6.4.2-2 | $f_{enhance,1}$ |
| | InactiveOut_Enhance | Stochastic | Input | Scalar | 6.4.2-2 | $f_{enhance,2}$ |
| | ActiveIn_Enhance | Stochastic | Input | Scalar | 6.4.2-2 | $f_{enhance,3}$ |
| | AsleepIn_Enhance | Stochastic | Input | Scalar | 6.4.2-2 | $f_{enhance,4}$ |
| | Enhance_Factor | Data | Cal'ed | Vector(5) | 6.4.2-2 | $f_{enhance,n}$ |
| Dust_Air | AirConc_Crop | Expression | Cal'ed | Scalar | 6.4.2-1 | $Ca_{p,\ i}$ |
| | AirConc_Crop_1 | Expression | Cal'ed | Scalar | 6.4.2-1 | $Ca_{p,\ 1}$ |
| | AirConc_Crop_2 | Expression | Cal'ed | Scalar | 6.4.2-1 | $Ca_{p,\ 2}$ |
| | AirConc_Inh | Expression | Cal'ed | Vector(5) | 6.4.2-2 | $Ca_{h,\ i,n}$ |
| | AirConc_Inh_1 | Expression | Cal'ed | Vector(5) | 6.4.2-2 | $Ca_{h,\ 1,n}$ |
| | AirConc_Inh_2 | Expression | Cal'ed | Vector(5) | 6.4.2-2 | $Ca_{h,\ 2,n}$ |
| C14_Air | Mixing_Height_Crop | Data | Input | Scalar | 6.4.6-3 | $H_{mix}$ |
| | Wind_Speed_Crop | Stochastic | Input | Scalar | 6.4.6-3 | $U$ |
| | Irrigation_Area | Data | Input | Scalar | 6.4.6-3 | $A$ |
| | Wind_Speed_Inh | Stochastic | Input | Scalar | 6.4.6-3 | $U$ |
| | Mixing_Height_Inh | Data | Input | Scalar | 6.4.6-3 | $H_{mix}$ |
| | C14Conc_Air | Expression | Cal'ed | Scalar | 6.4.6-3 | $Ca_{g,C\text{-}14,}$ |
| | C14_Flux | Expression | Cal'ed | Scalar | 6.4.6-2 | $EVSN_j$ |
| | C14Conc_Inh | Expression | Cal'ed | Scalar | 6.4.6-3 | $Ca_{g.C\text{-}14,0}$ |
| | C14Air_Inh | Data | Cal'ed | Vector(5) | 6.4.6-3 | $Ca_{g,C\text{-}14,j}$ |
| Evaporative_Air | Evap_Fraction | Stochastic | Input | Scalar | 6.4.2-3 | $f_{evap}$ |
| | Water_Usage | Stochastic | Input | Scalar | 6.4.2-3 | $M_{water}$ |
| | Airflow_Rate | Stochastic | Input | Scalar | 6.4.2-3 | $F_{air}$ |
| | AirConc_Evap | Expression | Cal'ed | Scalar | 6.4.2-3 | $Ca_{e,i}$ |
| Radon_ Air | Radon_ConcRatio | Stochastic | Input | Scalar | 6.4.2-4 | $f_{m,\ Rn\text{-}222}$ |
| | AirConc_Radon | Expression | Cal'ed | Scalar | 6.4.2-4 | $Ca_{g,Rn\text{-}222}$ |
| | AirConc_Radon_1 | Expression | Cal'ed | Scalar | 6.4.2-4 | $Ca_{g,Rn\text{-}222}$ |
| | AirConc_Radon_2 | Expression | Cal'ed | Scalar | 6.4.2-4 | $Ca_{g,Rn\text{-}222}$ |
| | Evap_Ventilation | Stochastic | Input | Scalar | 6.4.2-5 | $v_e$ |
| | RnFraction_Indoor | Stochastic | Input | Scalar | 6.4.2-6 | $f_{house}$ |
| | House_Height | Stochastic | Input | Scalar | 6.4.2-5 | $H$ |
| | Radon_FluxRatio | Data | Input | Scalar | 6.4.2-7 | $CF_{Rn\text{-}222}$ |
| | Normal_Ventilation | Stochastic | Input | Scalar | 6.4.2-5 | $v_n$ |
| | Indoor_RnEvap | Expression | Cal'ed | Scalar | 6.4.2-8 | $IF_{e,Rn\text{-}222}$ |
| | Indoor_RnNormal | Expression | Cal'ed | Scalar | 6.4.2-7 | $IF_{n,Rn\text{-}222}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.4 Plant Submodel

Mathematical equations for the plant submodel are discussed in Section 6.4.3. All parameters in the submodel are listed in Table 6.8-4. The contents of the submodel container (Figure 6.8-12) include five lower-level containers. The *PlantModel_Input* container includes many input parameters related to agriculture (Figure 6.8-13). There is one container under the *PlantModel_Input* container, which contains input parameters related to irrigation. Each mechanism of radionuclide transfer into crops is considered separately. The *Water_Uptake* container includes calculations of radionuclide concentrations in crops (Equations 6.4.3-3, 6.4.3-4, and 6.4.3-5) due to foliar interception of contaminated groundwater. One element, the *Intercept_Factor*, combines the interception fractions for the various crops into a vector and checks to determine if the sum exceeds 1.0 (this parameter can not exceed 1.0; Section 6.4.3.2). The *Root_Uptake* container includes calculations of the radionuclide concentrations in crops (Equation 6.4.3-2) due to root uptake of radionuclides. The *Dust_Uptake* container includes calculations of the radionuclide concentrations in crops (Equations 6.4.3-6, 6.4.3-7, and 6.4.3-8) due to the deposition of resuspended contaminated soil. The *C14_Crop* container includes the calculations of transfer of $^{14}C$ into plants (Section 6.4.6.3).

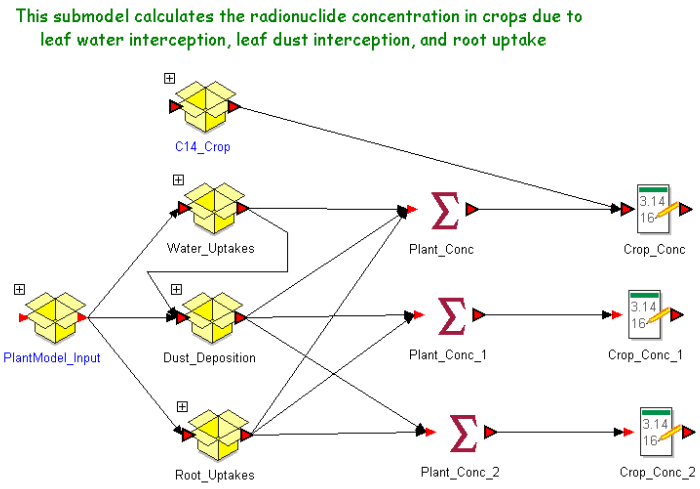



Figure 6.8-12. Plant Submodel Container

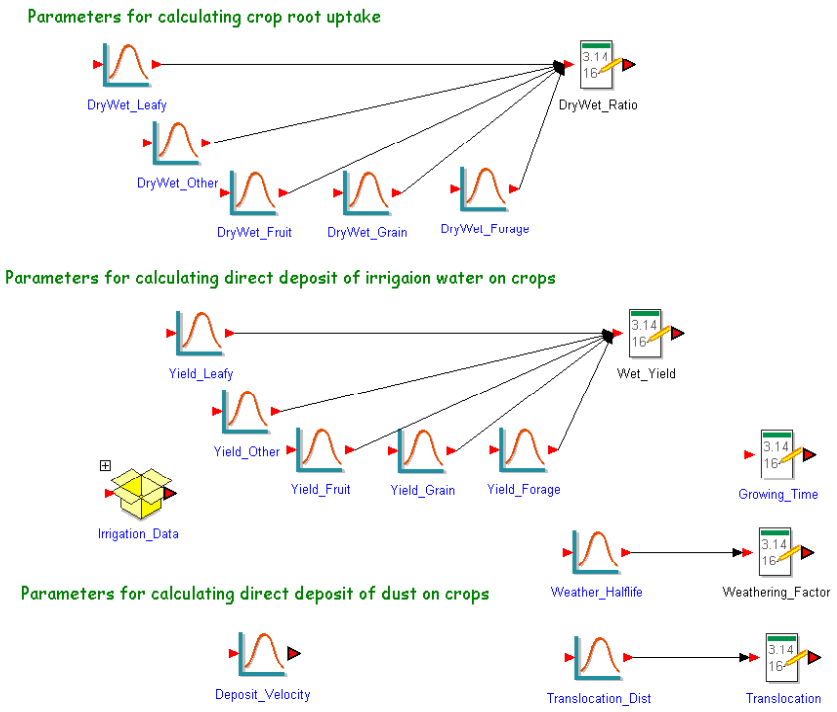



Figure 6.8-13. Input Parameter Container (*PlantModel_Input*) for the Plant Submodel

Table 6.8-4. Parameters in the Plant Submodel

| First Level Name | Second Level Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|---|
| Plant Model_ Input | DryWet_Leafy | | Stochastic | Input | Scalar | 6.4.3-2 | $DW_1$ |
| | DryWet_Other | | Stochastic | Input | Scalar | 6.4.3-2 | $DW_2$ |
| | DryWet_Fruit | | Stochastic | Input | Scalar | 6.4.3-2 | $DW_3$ |
| | DryWet_Grain | | Stochastic | Input | Scalar | 6.4.3-2 | $DW_4$ |
| | DryWet_Forage | | Stochastic | Input | Scalar | 6.4.3-2 | $DW_5$ |
| | DryWet_Ratio | | Data | Cal'ed | Vector(5) | 6.4.3-2 | $DW_j$ |
| | Yield_Leafy | | Stochastic | Input | Scalar | 6.4.3-3 | $Y_1$ |
| | Yield_Other | | Stochastic | Input | Scalar | 6.4.3-3 | $Y_2$ |
| | Yield_Fruit | | Stochastic | Input | Scalar | 6.4.3-3 | $Y_3$ |
| | Yield_Grain | | Stochastic | Input | Scalar | 6.4.3-3 | $Y_4$ |
| | Yield_Forage | | Stochastic | Input | Scalar | 6.4.3-3 | $Y_5$ |
| | Wet_Yield | | Data | Cal'ed | Vector(5) | 6.4.3-3 | $Y_j$ |
| | Growing_Time | | Data | Input | Vector(5) | 6.4.3-3 | $t_{g,j}$ |
| | Weather_Halflife | | Stochastic | input | Scalar | 6.4.3-3 | $T_w$ |
| | Weathering_Factor | | Data | Cal'ed | Scalar | 6.4.3-3 | $\lambda_w$ |
| | Translocation_Dist | | Stochastic | Input | Scalar | 6.4.3-3 | $T_j$ |
| | Translocation | | Data | Input | Vector(5) | 6.4.3-3 | $T_j$ |
| | Deposit_Velocity | | Stochastic | Input | Scalar | 6.4.3-7 | $V_d$ |
| | Irrigation _Data | DryBiom_Leafy | Stochastic | Input | Scalar | 6.4.3-5 | $DB_1$ |
| | | DryBiom_Other | Stochastic | Input | Scalar | 6.4.3-5 | $DB_2$ |
| | | DryBiom_Fruit | Stochastic | Input | Scalar | 6.4.3-5 | $DB_3$ |
| | | DryBiom_Grain | Stochastic | Input | Scalar | 6.4.3-5 | $DB_4$ |
| | | DryBiom_Forage | Stochastic | Input | Scalar | 6.4.3-5 | $DB_5$ |
| | | IrriAmt_Leafy | Stochastic | Input | Scalar | 6.4.3-5 | $IA_1$ |
| | | IrriAmt_Other | Stochastic | Input | Scalar | 6.4.3-5 | $IA_2$ |
| | | IrriAmt_Fruit | Stochastic | Input | Scalar | 6.4.3-5 | $IA_3$ |
| | | IrriAmt_Grain | Stochastic | Input | Scalar | 6.4.3-5 | $IA_4$ |
| | | IrriAmt_Forage | Stochastic | Input | Scalar | 6.4.3-5 | $IA_5$ |
| | | Irrigation_Intensity | Stochastic | Input | Scalar | 6.4.3-5 | $I$ |
| | | Overhead_Leafy | Stochastic | Input | Scalar | 6.4.3-3 | $f_{o,1}$ |
| | | Overhead_Other | Stochastic | Input | Scalar | 6.4.3-3 | $f_{o,2}$ |
| | | Overhead_Fruit | Stochastic | Input | Scalar | 6.4.3-3 | $f_{o,3}$ |
| | | Overhead_Grain | Stochastic | Input | Scalar | 6.4.3-3 | $f_{o,4}$ |
| | | Overhead_Forage | Stochastic | Input | Scalar | 6.4.3-3 | $f_{o,5}$ |
| | | Overhead_Factor | Data | Cal'ed | Vector(5) | 6.4.3-3 | $f_{o,j}$ |
| Water_ Uptakes | ExpGrow_Leafy | | Expression | Cal'ed | Scalar | 6.4.3-3 | $e^{-\lambda w\, tg,1}$ |
| | ExpGrow_Other | | Expression | Cal'ed | Scalar | 6.4.3-3 | $e^{-\lambda w\, tg,2}$ |
| | ExpGrow_Fruit | | Expression | Cal'ed | Scalar | 6.4.3-3 | $e^{-\lambda w\, tg,3}$ |
| | ExpGrow_Grain | | Expression | Cal'ed | Scalar | 6.4.3-3 | $e^{-\lambda w\, tg,4}$ |
| | ExpGrow_Forage | | Expression | Cal'ed | Scalar | 6.4.3-3 | $e^{-\lambda w\, tg,5}$ |
| | Growing_Factors | | Data | Cal'ed | Vector(5) | 6.4.3-3 | $1-e^{-\lambda w\, tg,j}$ |
| | Other_Factor | | Expression | Cal'ed | Vector(5) | 6.4.3-3 | $T_j/(Y_j\lambda_w)(1-e^{-\lambda w\, tg,j})$ |
| | IntFrac_Leafy | | Expression | Cal'ed | Scalar | 6.4.3-3 | $Rw_1$ |
| | IntFrac_Other | | Expression | Cal'ed | Scalar | 6.4.3-3 | $Rw_2$ |
| | IntFrac_Fruit | | Expression | Cal'ed | Scalar | 6.4.3-3 | $Rw_3$ |
| | IntFrac_Grain | | Expression | Cal'ed | Scalar | 6.4.3-3 | $Rw_4$ |
| | IntFrac_Forage | | Expression | Cal'ed | Scalar | 6.4.3-3 | $Rw_5$ |
| | Intercept_Fractor | | Data | Cal'ed | Vector(5) | 6.4.3-3 | $Rw_j$ |
| | Irrigation_Intercept | | Expression | Cal'ed | Vector(5) | 6.4.3-3 | $Dw_{i,j}\, Rw$ |
| | Water_Uptake | | Expression | Cal'ed | Vector(5) | 6.4.3-3 | $Cp_{water\, i,j}$ |

Table 6.8-4. Parameters in the Plant Submodel (continued)

| First Level Name | Second Level Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|---|
| Root_ Uptakes | Transfer_Factor | | Data | Dbase | Vector(5) | 6.4.3-2 | $F_{s \rightarrow p,\, i,j}$ |
| | Transfer_Factor_1 | | Data | Dbase | Vector(5) | 6.4.3-2 | $F_{s \rightarrow p,\, 1,j}$ |
| | Transfer_Factor_2 | | Data | Dbase | Vector(5) | 6.4.3-2 | $F_{s \rightarrow p,\, 2,j}$ |
| | Root_Uptake | | Expression | Cal'ed | Vector(5) | 6.4.3-2 | $Cp_{root,\, i,j}$ |
| | Root_Uptake_1 | | Expression | Cal'ed | Vector(5) | 6.4.3-2 | $Cp_{root,\, 1,j}$ |
| | Root_Uptake_2 | | Expression | Cal'ed | Vector(5) | 6.4.3-2 | $Cp_{root,\, 2,j}$ |
| Dust_ Uptakes | Dust_Factor | | Data | Input | Vector(5) | 6.4.3-8 | $a_j$ |
| | ExpDust_Leafy | | Expression | Cal'ed | Scalar | 6.4.3-8 | $e^{-a_1 DB_1}$ |
| | ExpDust_Other | | Expression | Cal'ed | Scalar | 6.4.3-8 | $e^{-a_2 DB_2}$ |
| | ExpDust_Fruit | | Expression | Cal'ed | Scalar | 6.4.3-8 | $e^{-a_3 DB_3}$ |
| | ExpDust_Grain | | Expression | Cal'ed | Scalar | 6.4.3-8 | $e^{-a_4 DB_4}$ |
| | ExpDust_Forage | | Expression | Cal'ed | Scalar | 6.4.3-8 | $e^{-a_5 DB_5}$ |
| | Dust_Intercept | | Data | Cal'ed | Vector(5) | 6.4.3-8 | $Ra_j$ |
| | Air_Interception | | Expression | Cal'ed | Vector(5) | 6.4.3-6 | $Da_{i,j}\, Ra_j$ |
| | Air_Interception_1 | | Expression | Cal'ed | Vector(5) | 6.4.3-6 | $Da_{1,j}\, Ra_j$ |
| | Air_Interception_2 | | Expression | Cal'ed | Vector(5) | 6.4.3-6 | $Da_{2,j}\, Ra_j$ |
| | Dust_Uptake | | Expression | Cal'ed | Vector(5) | 6.4.3-6 | $Cp_{dust,\, i,j}$ |
| | Dust_Uptake_1 | | Expression | Cal'ed | Vector(5) | 6.4.3-6 | $Cp_{dust,\, 1,j}$ |
| | Dust_Uptake_2 | | Expression | Cal'ed | Vector(5) | 6.4.3-6 | $Cp_{dust,\, 2,j}$ |
| C14_ Crop | Crop_Carbon | | Data | Input | Vector(5) | 6.4.6-6 | $fc_{plant,j}$ |
| | Air_Carbon | | Data | Input | Scalar | 6.4.6-5 | $fc_{air}$ |
| | Soil_Carbon | | Data | Input | Scalar | 6.4.6-4 | $fc_{soil}$ |
| | Cair_Uptake | | Data | Input | Scalar | 6.4.6-6 | $Fa$ |
| | Csoil_Uptake | | Data | Input | Scalar | 6.4.6-6 | $Fs$ |
| | C14Crop_Air | | Expression | Cal'ed | Vector(5) | 6.4.6-6 | $Fa\, Ca_{C\text{-}14} / fc_{air}$ |
| | C14Crop_Soil | | Expression | Cal'ed | Vector(5) | 6.4.6-6 | $Fs\, Cs_{C\text{-}14} / (fc_{soil}\, \rho_s)$ |
| | C14Conc_Crop | | Expression | Cal'ed | Vector(5) | 6.4.6-6 | $Cp_{C\text{-}14,j}$ |
| Plant_Conc | | | Sum | Cal'ed | Vector(5) | 6.4.3-1 | $Cp_{i,j}$ |
| Plant_Conc_1 | | | Sum | Cal'ed | Vector(5) | 6.4.3-1 | $Cp_{1,j}$ |
| Plant_Conc_2 | | | Sum | Cal'ed | Vector(5) | 6.4.3-1 | $Cp_{2,j}$ |
| Crop_Conc | | | Data | Cal'ed | Vector(4) | 6.4.3-1 | $Cp_{i,j}$ |
| Crop_Conc_1 | | | Data | Cal'ed | Vector(4) | 6.4.3-1 | $Cp_{1,j}$ |
| Crop_Conc_2 | | | Data | Cal'ed | Vector(4) | 6.4.3-1 | $Cp_{2,j}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.5 Animal Submodel

The mathematical equations for the animal submodel are discussed in Section 6.4.4. All parameters in the submodel are listed in Table 6.8-5. The contents of the animal submodel container (Figure 6.8-14) include three lower level containers. The *AnimalModel_Input* container includes all animal consumption rates for feed, water, and soil (Figure 6.8-15). The *Animal_Ingestions* container includes three containers for calculating animal uptake from the consumption of contaminated animal feed (Equation 6.4.4-2), contaminated water (Equation 6.4.4-3), and contaminated soil (Equation 6.4.4-4) for four types of animal products. The *C14_Animal* container includes the calculation of $^{14}C$ transfer to animal products (Section 6.4.6.4).

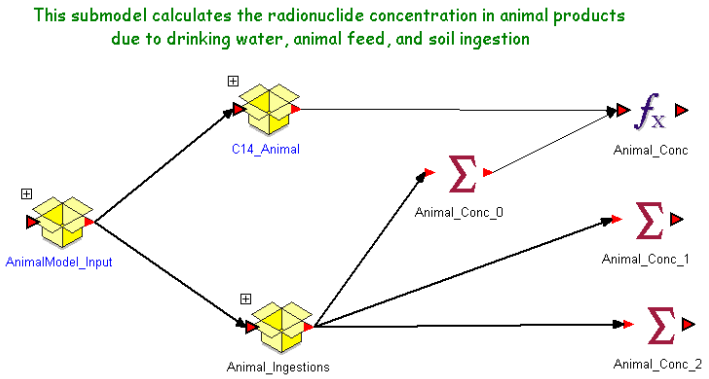



Figure 6.8-14. Animal Submodel Container

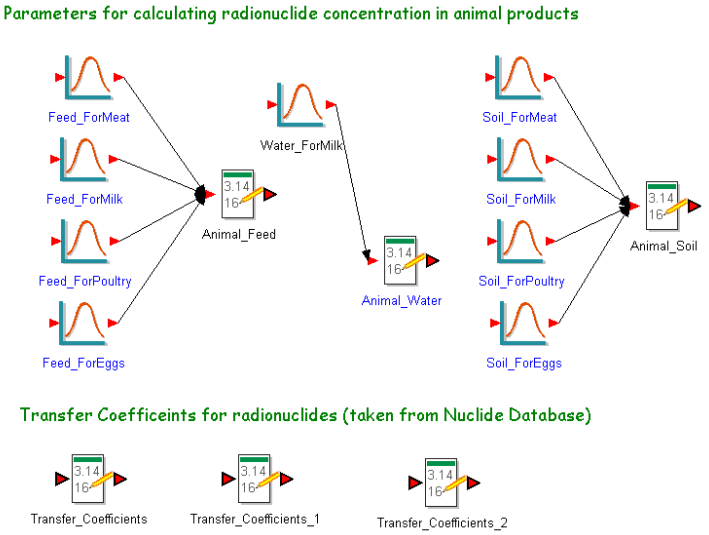



Figure 6.8-15. Input Parameter Container (AnimalModel_Input) for the Animal Submodel

Table 6.8-5. Parameters in the Animal Submodel

| Low Level Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| Animal Model_ Input | Water_ForMilk | Stochastic | Input | Scalar | 6.4.4-3 | $Qw_2$ |
| | Animal_Water | Data | Input | Vector(4) | 6.4.4-3 | $Qw_k$ |
| | Feed_ForMeat | Stochastic | Input | Scalar | 6.4.4-2 | $Qf_1$ |
| | Feed_ForMilk | Stochastic | Input | Scalar | 6.4.4-2 | $Qf_2$ |
| | Feed_ForPoultry | Stochastic | Input | Scalar | 6.4.4-2 | $Qf_3$ |
| | Feed_ForEggs | Stochastic | Input | Scalar | 6.4.4-2 | $Qf_4$ |
| | Animal_Feed | Data | Cal'ed | Vector(4) | 6.4.4-2 | $Qf_k$ |
| | Soil_ForMeat | Stochastic | Input | Scalar | 6.4.4-4 | $Qs_1$ |
| | Soil_ForMilk | Stochastic | Input | Scalar | 6.4.4-4 | $Qs_2$ |
| | Soil_ForPoultry | Stochastic | Input | Scalar | 6.4.4-4 | $Qs_3$ |
| | Soil_ForEggs | Stochastic | Input | Scalar | 6.4.4-4 | $Qs_4$ |
| | Animal_Soil | Data | Cal'ed | Vector(4) | 6.4.4-4 | $Qs_k$ |
| | Transfer_Coefficients | Data | Dbase | Vector(4) | 6.4.4-2 | $Fm_{i,k}$ |
| | Transfer_Coefficients_1 | Data | Dbase | Vector(4) | 6.4.4-2 | $Fm_{1,k}$ |
| | Transfer_Coefficients_2 | Data | Dbase | Vector(4) | 6.4.4-2 | $Fm_{2,k}$ |
| Animal_ Ingestion | Water_Contribution | Expression | Cal'ed | Vector(4) | 6.4.4-3 | $Cd_{water\ i,k}$ |
| | Feed_Conc | Data | Cal'ed | Vector(4) | 6.4.3-1 | $Cp_{i,j}$ |
| | Feed_Conc_1 | Data | Cal'ed | Vector(4) | 6.4.3-1 | $Cp_{1,j}$ |
| | Feed_Conc_2 | Data | Cal'ed | Vector(4) | 6.4.3-1 | $Cp_{2,j}$ |
| | Feed_Contribution | Expression | Cal'ed | Vector(4) | 6.4.4-2 | $Cd_{feed\ i,k}$ |
| | Feed_Contribution_1 | Expression | Cal'ed | Vector(4) | 6.4.4-2 | $Cd_{feed\ 1,k}$ |
| | Feed_Contribution_2 | Expression | Cal'ed | Vector(4) | 6.4.4-2 | $Cd_{feed\ 2,k}$ |
| | Soil_Contribution | Expression | Cal'ed | Vector(4) | 6.4.4-4 | $Cd_{soil\ I,k}$ |
| | Soil_Contribution_1 | Expression | Cal'ed | Vector(4) | 6.4.4-4 | $Cd_{soil\ 1,k}$ |
| | Soil_Contribution_2 | Expression | Cal'ed | Vector(4) | 6.4.4-4 | $Cd_{soil\ 2,k}$ |
| C14_ Animal | Animal_Carbon | Data | Input | Vector(4) | 6.4.6-7 | $fc_{anim,k}$ |
| | C14Conc_Feed | Data | Cal'ed | Vector(4) | 6.4.6-6 | $Cp_{C\text{-}14,j}$ |
| | C14From_Feed | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $Cp_{C\text{-}14,j}\ Qf_k$ |
| | C14From_Water | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $Cw_{C\text{-}14}\ Qw_k$ |
| | C14From_Soil | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $Cs_{C\text{-}14}\ Qs_k$ |
| | Feed_Carbon | Data | Input | Vector(4) | 6.4.6-6 | $fc_{plant,j}$ |
| | CFrom_Feed | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $fc_{plant,j}\ Qf_k$ |
| | Water_Carbon | Data | Input | Scalar | 6.4.6-7 | $fc_{water}$ |
| | Cfrom_Water | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $fc_{water}\ Qw_k$ |
| | Cfrom_Soil | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $fc_{soil}\ Qs_k$ |
| | C14Conc_Animal | Expression | Cal'ed | Vector(4) | 6.4.6-7 | $Cd_{C\text{-}14,k}$ |
| Animal_Conc | | Expression | Cal'ed | Vector(4) | 6.4.4-1 | $Cd_{i,k}$ |
| Animal_Conc_0 | | Sum | Cal'ed | Vector(4) | 6.4.4-1 | $Cd_{i,k}$ |
| Animal_Conc_1 | | Sum | Cal'ed | Vector(4) | 6.4.4-1 | $Cd_{1,k}$ |
| Animal_Conc_2 | | Sum | Cal'ed | Vector(4) | 6.4.4-1 | $Cd_{2,k}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.6 Fish Submodel

The fish submodel (Figure 6.18-16) is described in Section 6.4.5. The fish submodel container includes calculations of activity concentration in the fish. Because $^{14}C$ transport to fish is the same as that for other radionuclides, the $^{14}C$ special submodel is not considered separately. All parameters in the submodel are listed in Table 6.8-6.

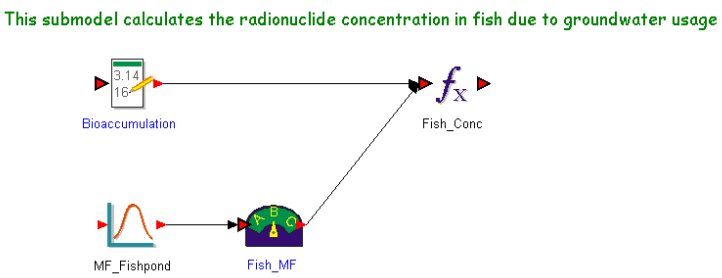



Figure 6.8-16. Fish Submodel Container

Table 6.8-6. Parameters in the Fish Submodel

| Submodel Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| Fish | Bioaccumulation | Data | Dbase | Scalar | 6.4.5-1 | $BF_i$ |
| | MF_Fishpond | Stochastic | Input | Scalar | 6.4.5-2 | $MF_i$ |
| | Fish_MF | Selector | Input | Scalar | 6.4.5-2 | $MF_i$ |
| | Fish_Conc | Expression | Cal'ed | Scalar | 6.4.5-2 | $Cf_i$ |

NOTES: See notes for Table 6.8-1.

### 6.8.7 External Exposure Submodel

The external exposure submodel is discussed in Section 6.4.7. All parameters in the submodel are listed in Table 6.8-7. This submodel includes one lower level container (Figure 6.8-17). The *External_Input* container (Figure 6.8-18) contains all of the external exposure related input parameters for this submodel plus the input data for the population groups and associated time budgets. Model calculation is included in the *External_Model* container. Decay products that build up in the soil as a result of the decay of primary radionuclides are considered in the calculation of external exposure to soil as a result of radionuclide buildup in the soil.

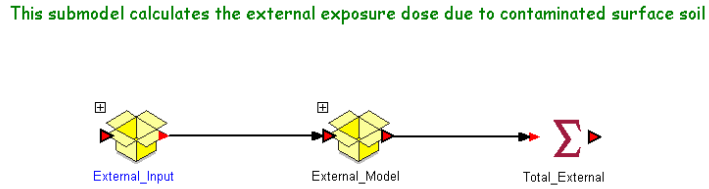



Figure 6.8-17. External Exposure Submodel Container

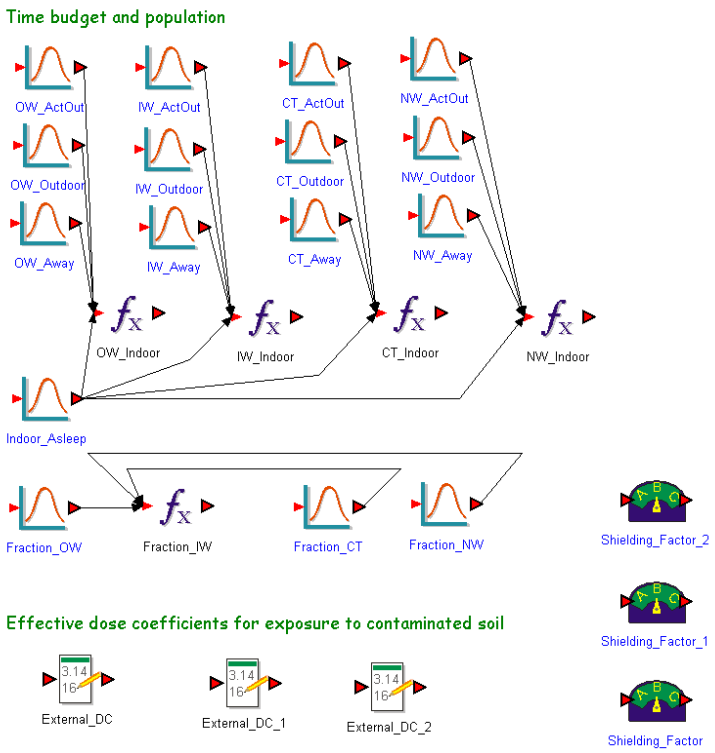



Figure 6.8-18. Input Parameter Container (*External_Input*) for the External Exposure Submodel

Table 6.8-7. Parameters in the External Exposure Submodel

| Low Level Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| External_ Input | OW_ActOut | Stochastic | Input | Scalar | 6.4.7-1 | $t_{1,1}$ |
| | IW_ActOut | Stochastic | Input | Scalar | 6.4.7-1 | $t_{1,2}$ |
| | CT_ActOut | Stochastic | Input | Scalar | 6.4.7-1 | $t_{1,3}$ |
| | NW_ActOut | Stochastic | Input | Scalar | 6.4.7-1 | $t_{1,4}$ |
| | OW_Outdoor | Stochastic | Input | Scalar | 6.4.7-1 | $t_{2,1}$ |
| | IW_Outdoor | Stochastic | Input | Scalar | 6.4.7-1 | $t_{2,2}$ |
| | CT_Outdoor | Stochastic | Input | Scalar | 6.4.7-1 | $t_{2,3}$ |
| | NW_Outdoor | Stochastic | Input | Scalar | 6.4.7-1 | $t_{2,4}$ |
| | OW_Away | Stochastic | Input | Scalar | 6.4.7-1 | $t_{5,1}$ |
| | IW_Away | Stochastic | Input | Scalar | 6.4.7-1 | $t_{5,2}$ |
| | CT_Away | Stochastic | Input | Scalar | 6.4.7-1 | $t_{5,3}$ |
| | NW_Away | Stochastic | Input | Scalar | 6.4.7-1 | $t_{5,4}$ |
| | Indoor_Asleep | Stochastic | Input | Scalar | 6.4.7-1 | $t_{4,m}$ |
| | OW_Indoor | Expression | Cal'ed | Scalar | 6.4.7-1 | $t_{3,1}$ |
| | IW_Indoor | Expression | Cal'ed | Scalar | 6.4.7-1 | $t_{3,2}$ |
| | CT_Indoor | Expression | Cal'ed | Scalar | 6.4.7-1 | $t_{3,3}$ |
| | NW_Indoor | Expression | Cal'ed | Scalar | 6.4.7-1 | $t_{3,4}$ |
| | Fraction_OW | Stochastic | Input | Scalar | 6.4.7-1 | $PP_1$ |
| | Fraction_IW | Expression | Cal'ed | Scalar | 6.4.7-1 | $PP_2$ |
| | Fraction_CT | Stochastic | Input | Scalar | 6.4.7-1 | $PP_3$ |
| | Fraction_NW | Stochastic | Input | Scalar | 6.4.7-1 | $PP_4$ |
| | Shielding_Factor | Data | Input | Scalar | 6.4.7-1 | $f_{ext,i,3/4}$ |
| | Shielding_Factor_1 | Data | Input | Scalar | 6.4.7-1 | $f_{ext,1,3/4}$ |
| | Shielding_Factor_2 | Data | Input | Scalar | 6.4.7-1 | $f_{ext,2,3/4}$ |
| | External_DC | Data | Dbase | Scalar | 6.4.7-1 | $EDCi_{soil,0}$ |
| | External_DC_1 | Data | Dbase | Scalar | 6.4.7-1 | $EDCi_{soil,1}$ |
| | External_DC_2 | Data | Dbase | Scalar | 6.4.7-1 | $EDCi_{soil,2}$ |
| External_ Model | Exposure_times | Data | Cal'ed | Matrix (5,4) | 6.4.7-1 | $t_{n,m}$ |
| | Population | Data | Cal'ed | Vector(4) | 6.4.7-1 | $PP_m$ |
| | Weighted_Time | Expression | Cal'ed | Vector(5) | 6.4.7-1 | $PP_m\ t_{n,m}$ |
| | Weighted_Outdoor | Expression | Cal'ed | Scalar | 6.4.7-1 | $PP_m\ t_{1,m} + PP_m\ t_{2,m}$ |
| | Weighted_Indoor | Expression | Cal'ed | Scalar | 6.4.7-1 | $PP_m\ t_{3,m} + PP_m\ t_{4,m}$ |
| | External_Time | Expression | Cal'ed | Scalar | 6.4.7-1 | $\sum f_{ext,i,n}(\sum PP_m\ t_{n,m})$ |
| | External_Time_1 | Expression | Cal'ed | Scalar | 6.4.7-1 | $\sum f_{ext,1,n}(\sum PP_m\ t_{n,m})$ |
| | External_Time_2 | Expression | Cal'ed | Scalar | 6.4.7-1 | $\sum f_{ext,2,n}(\sum PP_m\ t_{n,m})$ |
| | External_Dose | Expression | Cal'ed | Scalar | 6.4.7-1 | $D_{ext\ 0}$ |
| | External_Dose_1 | Expression | Cal'ed | Scalar | 6.4.7-1 | $D_{ext\ 1}$ |
| | External_Dose_2 | Expression | Cal'ed | Scalar | 6.4.7-1 | $D_{ext\ 2}$ |
| Total_External | | Expression | Cal'ed | Scalar | 6.4.7-1 | $D_{ext\ i}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.8 Inhalation Submodel

The mathematical equations for the inhalation submodel are discussed in Section 6.4.8. All parameters in the submodel are listed in Table 6.8-8. The contents of this submodel container include three lower level containers (Figure 6.8-19). The *Inhalation_Input* container includes all inhalation related input parameters used in this submodel (Figure 6.8-20). The time budget for the receptor is calculated in the external submodel container. The *Dust_Inhalation* container includes the calculations of human inhalation of contaminated resuspended particles. Decay products are considered for resuspended particles in the air as the impact of radionuclide buildup in soil. This container also includes calculations for $^{14}C$ gas inhalation. The *Radon_Inhalation* container includes calculations of the radon inhalation dose due to exhalation of radon gas from $^{226}Ra$-contaminated soil. The dose from inhalation of contaminated aerosols generated from evaporative coolers is calculated in the expression element *Cooler_Inhalation*.

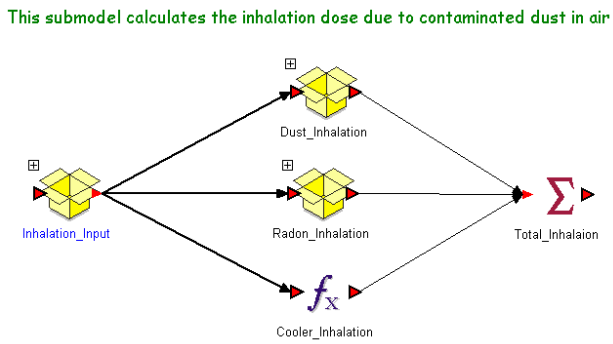



Figure 6.8-19. Inhalation Submodel Container

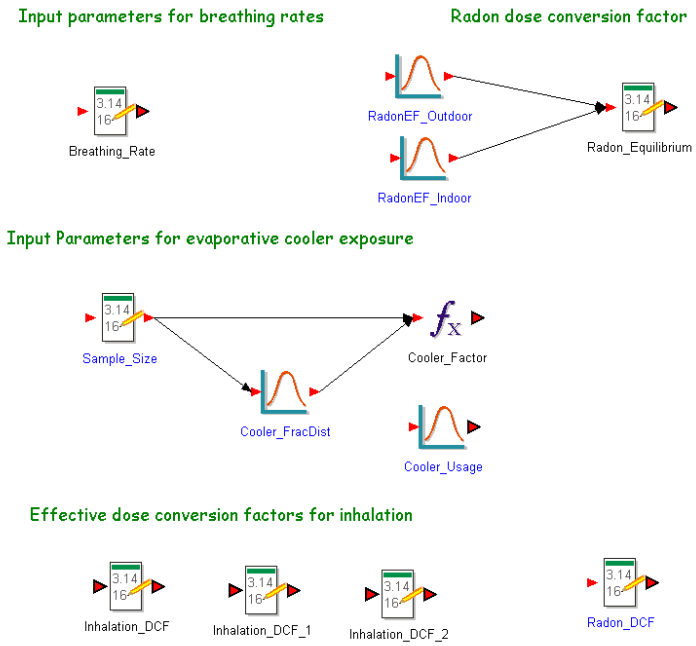



Figure 6.8-20. Input Parameter Container (Inhalation_Input) for the Inhalation Submodel

Table 6.8-8. Parameters in the Inhalation Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| | Breathing_Rate | Data | Input | Vector(5) | 6.4.8-2 | $BR_{n,}$ |
| | Sample_Size | Data | Input | Scalar | 6.4.8-3 | $f_{cooler}$ |
| | Cooler_FacDist | Stochastic | Input | Scalar | 6.4.8-3 | $f_{cooler}$ |
| | Cooler_Factor | Expression | Cal'ed | Scalar | 6.4.8-3 | $f_{cooler}$ |
| | Cooler_Usage | Stochastic | Input | Scalar | 6.4.8-3 | $f_{use}$ |
| | RadonEF_Outdoor | Stochastic | Input | Scalar | 6.4.8-6 | $EF_{Rn\text{-}222,1\&2}$ |
| | RadonET_Indoor | Stochastic | Input | Scalar | 6.4.8-6 | $EF_{Rn\text{-}222,3\&4}$ |
| | Radon_Equilibrium | Data | Cal'ed | Vector(5) | 6.4.8-6 | $EF_{Rn\text{-}222,n}$ |
| | Radon_DCF | Data | Input | Scalar | 6.4.8-6 | $DCF_{inh,Rn\text{-}222}$ |
| | Inhalation_DCF | Data | Dbase | Scalar | 6.4.8-2 | $EDCF_{inh,i}$ |
| | Inhalation_DCF_1 | Data | Dbase | Scalar | 6.4.8-2 | $EDCF_{inh,1}$ |
| | Inhalation_DCF_2 | Data | Dbase | Scalar | 6.4.8-2 | $EDCF_{inh,2}$ |
| Dust_ Inhalation | C14Gas_Inhalation | Expression | Cal'ed | Vector(5) | 6.4.8-4 | $D_{inh,g,C\text{-}14,n}$ |
| | Total_C14 | Sum | Cal'ed | Scalar | 6.4.8-4 | $D_{inh,g,C\text{-}14}$ |
| | Activity_Inhalation | Expression | Cal'ed | Vector(5) | 6.4.8-2 | $D_{inh,p,0,n}$ |
| | Activity_Inhalation_1 | Expression | Cal'ed | Vector(5) | 6.4.8-2 | $D_{inh,p\ 1,n}$ |
| | Activity_Inhalation_2 | Expression | Cal'ed | Vector(5) | 6.4.8-2 | $D_{inh,p\ 2,n}$ |
| | Inhalation_Dose_0 | Sum | Cal'ed | Scalar | 6.4.8-2 | $D_{inh,p,0}$ |
| | Inhalation_Dose | Expression | Cal'ed | Scalar | 6.4.8-2 | $D_{inh,p,0}$ |
| | Inhalation_Dose_1 | Sum | Cal'ed | Scalar | 6.4.8-2 | $D_{inh,p,1}$ |
| | Inhalation_Dose_2 | Sum | Cal'ed | Scalar | 6.4.8-2 | $D_{inh,p,2}$ |
| | Total_Dust | Sum | Cal'ed | Scalar | 6.4.8-2 | $D_{inh,p,i}$ |
| Radon_ Inhalation | Radon_Correction | Data | Cal'ed | Vector(5) | 6.4.8-7<br>6.4.2-7<br>6.4.2-8 | $1$ @ $n=1\&2$<br>$(1- f_{cooler}\, f_{use})\, IF_n + f_{cooler}\, f_{use}\, IF_e$ @ $n=3\&4$<br>$0$ @ $n=5$ |
| | Rn_Inhalation | Expression | Cal'ed | Vector(5) | 6.4.8-7 | $D_{inh,g,Rn\text{-}222,n}$ |
| | Rn_Inhalation_1 | Expression | Cal'ed | Vector(5) | 6.4.8-7 | $D_{inh,g,Rn\text{-}222,n}$ |
| | Rn_Inhalation_2 | Expression | Cal'ed | Vector(5) | 6.4.8-7 | $D_{inh,g,Rn\text{-}222,n}$ |
| | Radon_Dose | Sum | Cal'ed | Scalar | 6.4.8-7 | $D_{inh,g,Rn\text{-}222}$ |
| | Radon_Dose_1 | Sum | Cal'ed | Scalar | 6.4.8-7 | $D_{inh,g,Rn\text{-}222}$ |
| | Radon_Dose_2 | Sum | Cal'ed | Scalar | 6.4.8-7 | $D_{inh,g,Rn\text{-}222}$ |
| | Total_Radon | Sum | Cal'ed | Scalar | 6.4.8-7 | $D_{inh,g,Rn\text{-}222}$ |
| Cooler_Inhalation | | Expression | Cal'ed | Scalar | 6.4.8-3 | $D_{inh,e,i}$ |
| Total_Inhalation | | Sum | Cal'ed | Scalar | 6.4.8-1 | $D_{inh,i}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.9 Ingestion Submodel

The human ingestion pathways includes 11 individual pathways (Section 6.4.9). All parameters in the submodel are listed in Table 6.8-9. This submodel includes two lower level containers (Figure 6.8-21). The *Ingestion_Input* container includes various human foodstuff consumption rates (Figure 6.8-22). The *Ingestion_Model* container includes calculations of the ingestion dose from each foodstuff for primary radionuclides. Contributions from long-lived decay products that accumulate in the soil are calculated if needed. To provide the results of exposure pathway analysis, ingestion dose is presented for individual pathways and radionuclides.

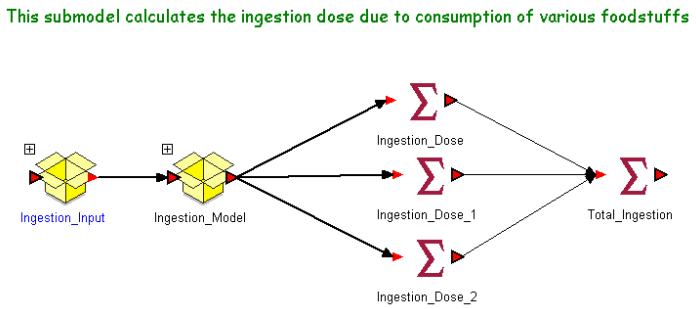



Figure 6.8-21. Ingestion Submodel Container

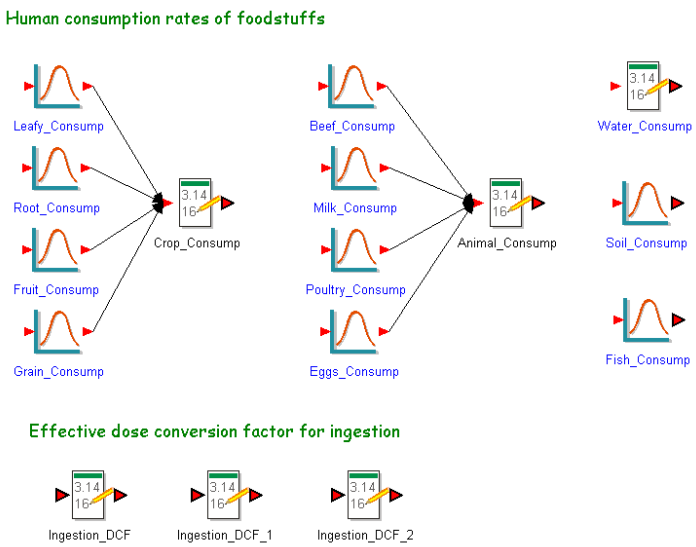



Figure 6.8-22. Input Parameter Container (Ingestion_Input) for the Ingestion Submodel

Table 6.8-9. Parameters in the Ingestion Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| Ingestion_ Input | Leafy_Consump | Stochastic | Input | Scalar | 6.4.9-3 | $Up_1$ |
| | Other_Consump | Stochastic | Input | Scalar | 6.4.9-3 | $Up_2$ |
| | Fruit_Consump | Stochastic | Input | Scalar | 6.4.9-3 | $Up_3$ |
| | Grain_Consump | Stochastic | Input | Scalar | 6.4.9-3 | $Up_4$ |
| | Crop_Consump | Data | Cal'ed | Vector(4) | 6.4.9-3 | $Up_j$ |
| | Beef_Consump | Stochastic | Input | Scalar | 6.4.9-4 | $Ud_1$ |
| | Poultry_Consump | Stochastic | Input | Scalar | 6.4.9-4 | $Ud_2$ |
| | Milk_Consump | Stochastic | Input | Scalar | 6.4.9-4 | $Ud_3$ |
| | Eggs_Consump | Stochastic | Input | Scalar | 6.4.9-4 | $Ud_4$ |
| | Animal_Consump | Data | Cal'ed | Vector(4) | 6.4.9-4 | $Ud_k$ |
| | Water_Consump | Data | Input | Scalar | 6.4.9-2 | $Uw$ |
| | Fish_Consump | Stochastic | Input | Scalar | 6.4.9-5 | $Uf$ |
| | Soil_Consump | Stochastic | Input | Scalar | 6.4.9-6 | $Us$ |
| | Ingestion_DCF | Data | Dbase | Scalar | 6.4.9-2 | $EDCF_{ing,\ 0}$ |
| | Ingestion_DCF_1 | Data | Dbase | Scalar | 6.4.9-2 | $EDCF_{ing,\ 1}$ |
| | Ingestion_DCF_2 | Data | Dbase | Scalar | 6.4.9-2 | $EDCF_{ing,\ 2}$ |
| Ingestion_ Model | Water_Ingestion | Expression | Cal'ed | Scalar | 6.4.9-2 | $D_{ing,w,i}$ |
| | Fish_Ingestion | Expression | Cal'ed | Scalar | 6.4.9-5 | $D_{ing,f,i}$ |
| | Crop_Ingestion | Expression | Cal'ed | Vector(4) | 6.4.9-3 | $D_{ing,p,0}$ |
| | Crop_Ingestion_1 | Expression | Cal'ed | Vector(4) | 6.4.9-3 | $D_{ing,p,1}$ |
| | Crop_Ingestion_2 | Expression | Cal'ed | Vector(4) | 6.4.9-3 | $D_{ing,p,2}$ |
| | Crop_Pathway | Sum | Cal'ed | Vector(4) | 6.4.9-3 | $D_{ing,p,i}$ |
| | Animal_Ingestion | Expression | Cal'ed | Vector(4) | 6.4.9-4 | $D_{ing,d,0}$ |
| | Animal_Ingestion_1 | Expression | Cal'ed | Vector(4) | 6.4.9-4 | $D_{ing,d,1}$ |
| | Animal_Ingestion_2 | Expression | Cal'ed | Vector(4) | 6.4.9-4 | $D_{ing,d,2}$ |
| | Animal_Pathway | Sum | Cal'ed | Vector(4) | 6.4.9-4 | $D_{ing,d,i}$ |
| | Soil_Ingestion | Expression | Cal'ed | Scalar | 6.4.9-6 | $D_{ing,s,0}$ |
| | Soil_Ingestion_1 | Expression | Cal'ed | Scalar | 6.4.9-6 | $D_{ing,s,1}$ |
| | Soil_Ingestion_2 | Expression | Cal'ed | Scalar | 6.4.9-6 | $D_{ing,s,2}$ |
| | Soil_Pathway | Sum | Cal'ed | Scalar | 6.4.9-6 | $D_{ing,s,i}$ |
| Ingestion_Dose | | Sum | Cal'ed | Scalar | 6.4.9-1 | $D_{ing,0}$ |
| Ingestion_Dose_1 | | Sum | Cal'ed | Scalar | 6.4.9-1 | $D_{ing,1}$ |
| Ingestion_Dose_2 | | Sum | Cal'ed | Scalar | 6.4.9-1 | $D_{ing,2}$ |
| Total_ingestion | | Sum | Cal'ed | Scalar | 6.4.9-1 | $D_{ing,i}$ |

NOTES: See notes for Table 6.8-1.

### 6.8.10 BDCF Results

The TEDEs and BDCFs for individual radionuclides are discussed in Section 6.4.10. All parameters in the submodel are listed in Table 6.8-10. The ERMYN GoldSim model calculates the total dose from a radionuclide, the dose from each exposure pathway, the dose from primary radionuclide and the decay products, and the activity concentration of the radionuclide in the environmental media (Figure 6.8-23).

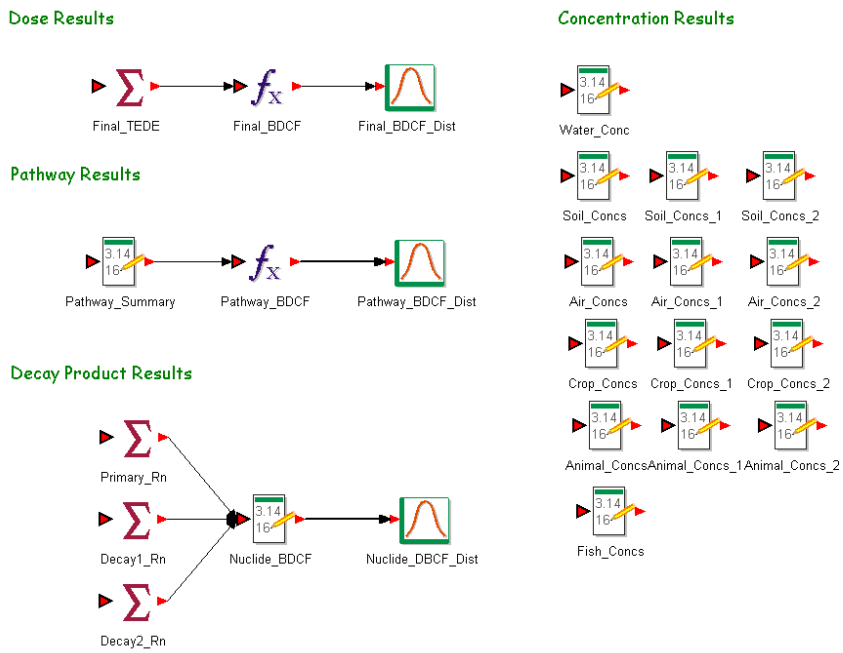



Figure 6.8-23. Final BDCF Result Container

Table 6.8-10. Parameters in the Final BDCF results

| Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|
| Final_TEDE | Sum | Cal'ed | Scalar | 6.4.10-1 | $D_{all,i}$ |
| Final_BDCF | Expression | Cal'ed | Scalar | 6.4.10-2 | $BDCF_i$ |
| Pathway_Summary | Data | Cal'ed | Vector(15) | 6.4.10-3 | $D_{p,i}$ |
| Pathway_BDCF | Expression | Cal'ed | Vector(15) | 6.4.10-4 | $BDCF_{p,i}$ |
| Primary_Rn | Sum | Cal'ed | Scalar | - | - |
| Decay1_Rn | Sum | Cal'ed | Scalar | - | - |
| Decay2_Rn | Sum | Cal'ed | Scalar | - | - |
| Nuclide_BDCF | Data | Cal'ed | Vector(3) | - | - |
| Final_BDCF_Dist | Result | Cal'ed | Scalar | - | - |
| Pathway_BDCF_Dist | Result | Cal'ed | Vector(15) | - | - |
| Nuclide_BDCF_Dist | Result | Cal'ed | Vector(3) | - | - |
| Water_Conc | Data | Cal'ed | Scalar | 6.4.1-1 | $Cw$ |
| Soil_Concs | Data | Cal'ed | Scalar | 6.4.1-5 | $Cs_{m,I}$ |
| Soil_Concs_1 | Data | Cal'ed | Scalar | 6.4.1-9 | $Cs_{m,1}$ |
| Soil_Concs_2 | Data | Cal'ed | Scalar | 6.4.1-9 | $Cs_{m,2}$ |
| Air_Concs | Data | Cal'ed | Matrix(4,5) | 6.4.2-1 | $Ca_i$ |
| Air_Concs_1 | Data | Cal'ed | Matrix(4,5) | 6.4.2-1 | $Ca_1$ |
| Air_Concs_2 | Data | Cal'ed | Matrix(4,5) | 6.4.2-1 | $Ca_2$ |
| Crop_Concs | Data | Cal'ed | Matrix(5,4) | 6.4.3-1 | $Cp_i$ |
| Crop_Concs_1 | Data | Cal'ed | Matrix(5,4) | 6.4.3-1 | $Cp_1$ |
| Crop_Concs_2 | Data | Cal'ed | Matrix(5,4) | 6.4.3-1 | $Cp_2$ |
| Animal_Concs | Data | Cal'ed | Matrix(4,4) | 6.4.4-1 | $Cd_i$ |
| Animal_Concs_1 | Data | Cal'ed | Matrix(4,4) | 6.4.4-1 | $Cd_1$ |
| Animal_Concs_2 | Data | Cal'ed | Matrix(4,4) | 6.4.4-1 | $Cd_2$ |
| Fish_Concs | Data | Cal'ed | Scalar | 6.4.5-1 | $Cf$ |

NOTES: See notes for Table 6.8-1.

## 6.9 GOLDSIM IMPLEMENTATION OF THE BIOSPHERE MODEL FOR THE VOLCANIC ASH SCENARIO

This section describes the ERMYN volcanic ash (ERMYN_VA) simulation and shows the overall model algorithm, submodel structures, input parameters, and calculated results. Many parts of the GoldSim volcanic ash model are similar to those used in the groundwater simulation (ERMYN_GW; Section 6.8). The GoldSim file, ERMYN_VA.gsm, is part of the output, which is listed in Attachment I. Similar to the mathematical model (Section 6.5), the ERMYN_VA is structured as a series of submodels. In each submodel, the linkage of the GoldSim elements to input parameters is tabulated. The description of the ERMYN_VA design is simplified because many parts are the same as those used in the groundwater simulation, ERMYN_GW. As with the ERMYN_GW simulation, there is only one container box (*Biosphere_Model*) on the cover page of the ERMYN_VA simulation (Figure 6.9-1).

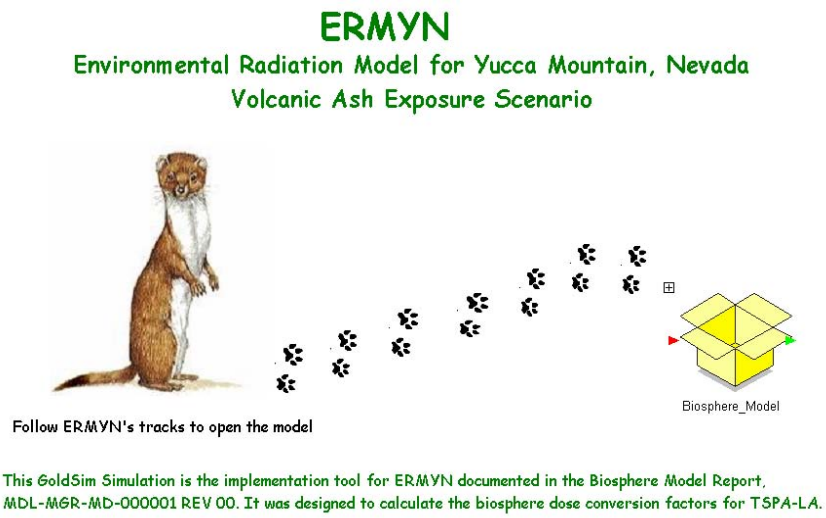



Figure 6.9-1. Cover Page for the ERMYN_VA Simulation in GoldSim

The *Biosphere_Model* container holds the submodel containers and the radionuclide data (Figure 6.9-2). The overall model structure looks much like to the block diagram of the conceptual model for the volcanic ash scenario shown in Figure 6.3-4, and each container in the GoldSim simulation corresponds to a submodel.

Nine containers, including seven submodels, one result box, and one radionuclide database box, are shown in Figure 6.9-2. The fish and $^{14}C$ special submodels are excluded from the volcanic ash scenario. Each box is discussed in detail in the following sections. Only two input parameters can be changed at this level: *Radionuclide* and *Ash_Source*. The *Radionuclide* parameter can only be selected from the data element of *Radionuclide_List* that is built in the *Nuclide_Database* container. *Ash_Source* represents the radionuclide concentration of radionuclides deposited on the ground ($Cs_i$ in the equation), which has a default value of 1 Bq/m$^2$. GoldSim can be run in deterministic and stochastic modes by adjusting settings in the

*MasterClock*. If the stochastic mode is chosen, the number of realizations, the sampling method (Monte Carlo or Latin Hypercube), and the random seed number need to be selected. Because the BDCF is not a function of time, the time option is disabled.

Similar to the ERMYN_GW simulation, many calculations are performed using the data array to reduce the number of GoldSim elements used in the ERMYN model. Thirteen data arrays are used: primary radionuclides ($i$ = 31), total number of radionuclides ($i$ = 75), pathways ($n$ = 15), plant types ($j$ = 5), crop food types ($j$ = 4), animal product types ($k$ = 4), number of decay products ($l$ = 3), population groups ($m$ = 4), environments ($n$ = 5), soil conditions ($n$ = 2), air submodel pathway ($n$ = 4), crop uptake pathway ($n$ = 4), and animal uptake pathway ($n$ = 4). These data sets and submodel pathways are discussed in Section 6.5.

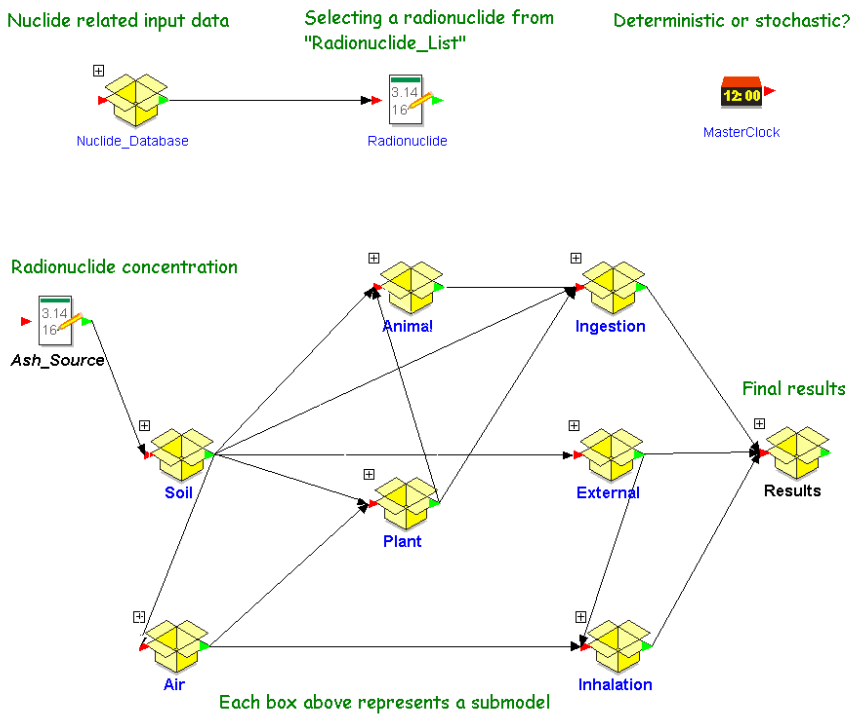



Figure 6.9-2. Biosphere Model for the Volcanic Ash Scenario

### 6.9.1 Nuclide Database

The nuclide database for the volcanic ash scenario is similar to the one used for the groundwater scenario, except that there are no radioactive decay products accumulating in the soil. Thirty-one primary radionuclides are included in the ERMYN_VA (see Section 6.8.1). The *Nuclide_Database* container is the same as that used for the ERMYN_GW (Figure 6.8-3). The *Nuclear_Data* container does not include the *Fish_Transfer* that is used in the groundwater scenario. Only two lower containers are in the *Data_Selection* container. Thirteen radionuclide-specific input parameters are selected using the *Selector* elements (Figure 6.9-3).

All GoldSim elements in this database are presented in Table 6.9-1. This table lists input parameters for each lower level container and their characteristics, including parameter name, GoldSim element type, data source, data types, equation number where the equation is originally defined, and symbol notation.

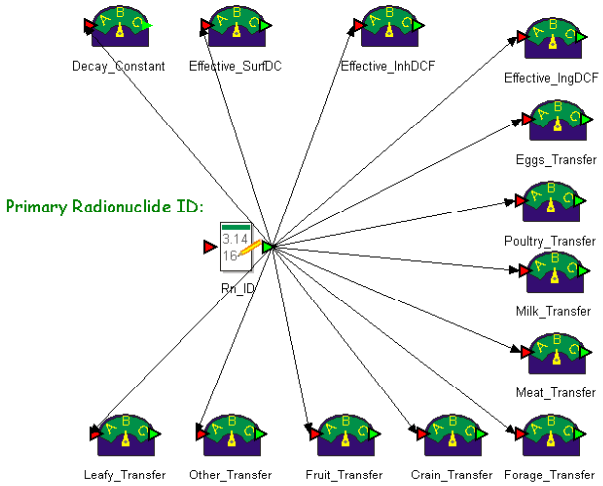



Figure 6.9-3. Nuclide Database Container and Radionuclide List

Table 6.9-1. Radionuclide Related Input Parameters

| First Level Box Name | Second Level Box Name | Parameter or Container Name | Element Type [a] | Data Source [b] | Data Type [c] | Equation | Notation |
|---|---|---|---|---|---|---|---|
| Radionuclide_List | | | Data | Input | Vector(31) | 6.5.1-1 | $i$ |
| Nuclide_ Data | Kd_Coefficients | | Container | Not shown in detail | | | |
| | Crop_Transfers | | | | | | |
| | Animal_Transfers | | | | | | |
| | Nuclear_Data | | | | | | |
| Data_ Selection | Effective _DCF | Unity | Data | - | Vector(31) | - | - |
| | | Decay_Constants | Expression | Cal'ed | Vector(31) | 6.4.1-1 | $\lambda_{d\,i}$ |
| | | A | Expression | Cal'ed | Vector(31) | Not used | - |
| | | B | Expression | Cal'ed | Vector(31) | 6.5.5-2 | $EDCs_{soil,i}$ |
| | | C | Expression | Cal'ed | Vector(31) | 6.4.8-8 | $EDCF_{inh,i}$ |
| | | D | Expression | Cal'ed | Vector(31) | 6.4.9-7 | $EDCF_{ing,i}$ |
| | | Effective_InfDCs | Data | Cal'ed | Vector(31) | Not used | - |
| | | Effective_SurDCs | Data | Cal'ed | Vector(31) | 6.5.5-2 | $EDCs_{soil,i}$ |
| | | Effective_InhDCFs | Data | Cal'ed | Vector(31) | 6.4.8-8 | $EDCF_{inh,i}$ |
| | | Effective_IngDCFs | Data | Cal'ed | Vector(31) | 6.4.9-7 | $EDCF_{ing,i}$ |
| | Primary_ Rn | Decay_Constants | Selector | Dbase | Scalar | 6.4.1-1 | $\lambda_{d\,i}$ |
| | | Effective_SurDC | Selector | Dbase | Scalar | 6.5.5-1 | $EDCs_{soil,i}$ |
| | | Effective_InhDCF | Selector | Dbase | Scalar | 6.5.6-2 | $EDCF_{inh,i}$ |
| | | Effective_IngDCF | Selector | Dbase | Scalar | 6.5.7-2 | $EDCF_{ing,i}$ |
| | | Beef_Transfer | Selector | Dbase | Scalar | 6.5.4-2 | $Fm_{i,1}$ |
| | | Poultry_Transfer | Selector | Dbase | Scalar | 6.5.4-2 | $Fm_{i,2}$ |
| | | Milk_Transfer | Selector | Dbase | Scalar | 6.5.4-2 | $Fm_{i,3}$ |
| | | Eggs_Transfer | Selector | Dbase | Scalar | 6.5.4-2 | $Fm_{i,4}$ |
| | | Leafy_Transfer | Selector | Dbase | Scalar | 6.5.3-2 | $F_{s\rightarrow p,i,1}$ |
| | | Other_Transfer | Selector | Dbase | Scalar | 6.5.3-2 | $F_{s\rightarrow p,i,2}$ |
| | | Fruit_Transfer | Selector | Dbase | Scalar | 6.5.3-2 | $F_{s\rightarrow p,i,3}$ |
| | | Grain_Transfer | Selector | Dbase | Scalar | 6.5.3-2 | $F_{s\rightarrow p,i,4}$ |
| | | Forage_Transfer | Selector | Dbase | Scalar | 6.5.3-2 | $F_{s\rightarrow p,i,5}$ |

NOTES: The following notes apply to all GoldSim tables in Section 6.9:

[a] Element type is the GoldSim element type used for inputs, calculations, and other manipulations (Section 6.7.3).

[b] If the data source is "Input," the parameter values are entered in the GoldSim element. If the source is "Dbase," values are taken from a database, or calculated values. If the data source is "Cal'ed," it is a calculated quantity. If the source and the corresponding equation notation are dashes (-), the element is added for GoldSim array calculations.

[c] Data types are scalar (a single value) or array (a set of values). A 1-dimensional array is called a vector, and a 2-dimensional array is called a matrix. The number of values in the array is given in parenthesis.

### 6.9.2 Surface Soil Submodel

The mathematical equations for the surface soil submodel are discussed in Section 6.5.1. All parameters used in this submodel are listed in Table 6.9-2. The contents of the submodel container are shown in Figure 6.9-4. Only a few GoldSim elements are used for calculating the radionuclide concentrations on cultivated (Equation 6.5.1-2) and non-cultivated lands (Equation 6.5.1-3).

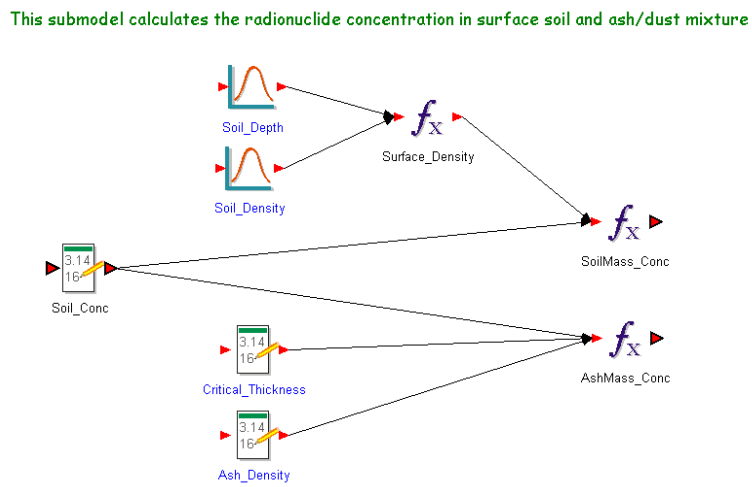



Figure 6.9-4. Surface Soil Submodel Container

Table 6.9-2. Parameters in the Surface Soil Submodel

| Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|
| Soil_Conc | Data | Input | Scalar | 6.5.1-1 | $Cs_i$ |
| Soil_Depth | Stochastic | Input | Scalar | 6.5.1-2 | $d$ |
| Soil_Density | Stochastic | Input | Scalar | 6.5.1-2 | $\rho$ |
| Surface_Density | Expression | Cal'ed | Scalar | 6.5.1-2 | $\rho_s$ |
| SoilMass_Conc | Expression | Cal'ed | Scalar | 6.5.1-2 | $Cs_{m,i}$ |
| Critical_Thickness | Data | Input | Scalar | 6.5.1-3 | $d_c$ |
| Ash_Density | Data | Input | Scalar | 6.5.1-3 | $\rho_a$ |
| AshMass_Conc | Expression | input | Scalar | 6.5.1-3 | $Cs_{mc,i}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.3 Air Submodel

The mathematical equations used for the air submodel are discussed in Section 6.5.2. All parameters used in this submodel are listed in Table 6.9-3. The contents of the submodel container are shown in Figure 6.9-5. One lower level container is included in the submodel. The *AirModel_Input* container calculates the mass loading and enhancement factors that are used for calculating the radionuclide concentration in the air due to resuspended particles. This submodel calculates radionuclide concentrations in the air for crop deposition (Equation 6.5.2-1) and human inhalation (Equation 6.5.2-2). Airborne concentrations of radon gas released from $^{226}$Ra-contaminated soils are calculated using Equation 6.5.2-8.

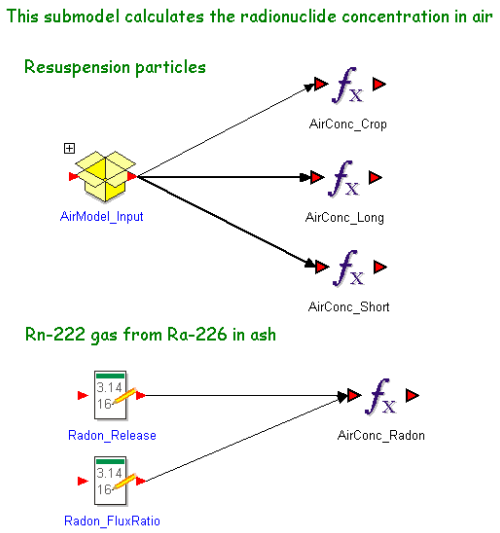



Figure 6.9-5. Air Submodel Container

Table 6.9-3. Parameters in the Air Submodel

| Low Layer Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| AirModel_ Input | Crop_Loading | Stochastic | Input | Scalar | 6.5.2-1 | $S$ |
| | ActiveOut_Dust | Stochastic | Input | Scalar | 6.5.2-3 | $S_1$ |
| | InactiveOut_Dust | Stochastic | Input | Scalar | 6.5.2-3 | $S_2$ |
| | ActiveIn_Dust | Stochastic | Input | Scalar | 6.5.2-3 | $S_3$ |
| | AsleepIn_Dust | Stochastic | Input | Scalar | 6.5.2-3 | $S_4$ |
| | Mass_Loading | Data | Cal'ed | Vector(5) | 6.5.2-3 | $S_n$ |
| | ActiveOut_Ash | Stochastic | Input | Scalar | 6.5.2-3 | $S_{v,1}$ |
| | InactiveOut_Ash | Stochastic | Input | Scalar | 6.5.2-3 | $S_{v,2}$ |
| | ActiveIn_Ash | Stochastic | Input | Scalar | 6.5.2-3 | $S_{v,3}$ |
| | AsleepIn_Ash | Stochastic | Input | Scalar | 6.5.2-3 | $S_{v,4}$ |
| | Ash_Loading | Data | Cal'ed | Vector(5) | 6.5.2-3 | $S_{v,n}$ |
| | ActiveOut_Enhance | Stochastic | Input | Scalar | 6.5.2-2 | $f_{enhance,1}$ |
| | InactiveOut_Enhance | Stochastic | Input | Scalar | 6.5.2-2 | $f_{enhance,2}$ |
| | ActiveIn_Enhance | Stochastic | Input | Scalar | 6.5.2-2 | $f_{enhance,3}$ |
| | AsleepIn_Enhance | Stochastic | Input | Scalar | 6.5.2-2 | $f_{enhance,4}$ |
| | Enhance_Factor | Data | Cal'ed | Vector(5) | 6.5.2-2 | $f_{enhance,n}$ |
| AirConc_Crop | | Expression | Cal'ed | Scalar | 6.5.2-1 | $Ca_{p,i}$ |
| AirConc_Short | | Expression | Cal'ed | Vector(5) | 6.5.2-4 | $Ca_{h,i,n}$ |
| AirConc_Long | | Expression | Cal'ed | Vector(5) | 6.5.2-4 | $Ca_{v,i,n}$ |
| Radon_Release | | Data | Input | Scalar | 6.5.2-6 | $FD_{Rn\text{-}222}$ |
| RnFlux_Ratio | | Data | Input | Scalar | 6.5.2-7 | $CF_{Rn\text{-}222}$ |
| AirConc_Radon | | Expression | Cal'ed | Scalar | 6.5.2-8 | $Ca_{g,Rn\text{-}222}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.4 Plant Submodel

Mathematical equations for the plant submodel are discussed in Section 6.5.3. All parameters used in this submodel are listed in Table 6.9-4. The contents of the submodel container are shown in Figure 6.9-6. This submodel includes two lower level containers. The *Root_Uptake* container (Equation 6.5.3-2) calculates radionuclide concentrations in crops due to contaminated soil. The *Dust_Uptake* container (Equation 6.5.3-3) calculates radionuclide concentrations in crops due to direct deposition of resuspended soil from cultivated lands.

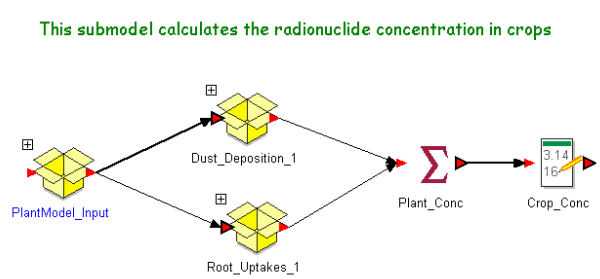



Figure 6.9-6. Plant Submodel Container

Table 6.9-4. Parameters in the Plant Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| PlantModel_ Input | DryWet_Leafy | Stochastic | Input | Scalar | 6.5.3-2 | $DW_1$ |
| | DryWet_Other | Stochastic | Input | Scalar | 6.5.3-2 | $DW_2$ |
| | DryWet_Fruit | Stochastic | Input | Scalar | 6.5.3-2 | $DW_3$ |
| | DryWet_Grain | Stochastic | Input | Scalar | 6.5.3-2 | $DW_4$ |
| | DryWet_Forage | Stochastic | Input | Scalar | 6.5.3-2 | $DW_5$ |
| | DryWet_Ratio | Data | Cal'ed | Vector(5) | 6.5.3-2 | $DW_j$ |
| | Yield_Leafy | Stochastic | Input | Scalar | 6.5.3-3 | $Y_1$ |
| | Yield_Other | Stochastic | Input | Scalar | 6.5.3-3 | $Y_2$ |
| | Yield_Fruit | Stochastic | Input | Scalar | 6.5.3-3 | $Y_3$ |
| | Yield_Grain | Stochastic | Input | Scalar | 6.5.3-3 | $Y_4$ |
| | Yield_Forage | Stochastic | Input | Scalar | 6.5.3-3 | $Y_5$ |
| | Wet_Yield | Data | Cal'ed | Vector(5) | 6.5.3-3 | $Y_j$ |
| | DryBiom_Leafy | Stochastic | Input | Scalar | 6.5.3-5 | $DB_1$ |
| | DryBiom_Other | Stochastic | Input | Scalar | 6.5.3-5 | $DB_2$ |
| | DryBiom_Fruit | Stochastic | Input | Scalar | 6.5.3-5 | $DB_3$ |
| | DryBiom_Grain | Stochastic | Input | Scalar | 6.5.3-5 | $DB_4$ |
| | DryBiom_Forage | Stochastic | Input | Scalar | 6.5.3-5 | $DB_5$ |
| | Deposity_Velocity | Stochastic | Input | Scalar | 6.5.3-4 | $V_d$ |
| | Weather_Halflife | Stochastic | input | Scalar | 6.5.3-3 | $T_w$ |
| | Weathering_Factor | Data | Cal'ed | Scalar | 6.5.3-3 | $\lambda_w$ |
| | Translocation_Dist | Stochastic | Input | Scalar | 6.5.3-3 | $T_j$ |
| | Translocation | Data | Input | Vector(5) | 6.5.3-3 | $T_j$ |
| | Growing_Time | Data | Input | Vector(6) | 6.5.3-3 | $t_{g,j}$ |
| Dust_ Deposition | Dust_Factor | Data | Input | Vector(6) | 6.5.3-5 | $a_j$ |
| | ExpDust_Leafy | Expression | Cal'ed | Scalar | 6.5.3-5 | $e^{-a_1 DB_1}$ |
| | ExpDust_Other | Expression | Cal'ed | Scalar | 6.5.3-5 | $e^{-a_2 DB_2}$ |
| | ExpDust_Fruit | Expression | Cal'ed | Scalar | 6.5.3-5 | $e^{-a_3 DB_3}$ |
| | ExpDust_Grain | Expression | Cal'ed | Scalar | 6.5.3-5 | $e^{-a_4 DB_4}$ |
| | ExpDust_Forage | Expression | Cal'ed | Scalar | 6.5.3-5 | $e^{-a_5 DB_5}$ |
| | Dust_Intercept | Data | Cal'ed | Vector(6) | 6.5.3-5 | $Ra_j$ |
| | ExpGrow_Leafy | Expression | Cal'ed | Scalar | 6.5.3-3 | $e^{-\lambda w\, tg,1}$ |
| | ExpGrow_Other | Expression | Cal'ed | Scalar | 6.5.3-3 | $e^{-\lambda w\, tg,2}$ |
| | ExpGrow_Fruit | Expression | Cal'ed | Scalar | 6.5.3-3 | $e^{-\lambda w\, tg,3}$ |
| | ExpGrow_Grain | Expression | Cal'ed | Scalar | 6.5.3-3 | $e^{-\lambda w\, tg,4}$ |
| | ExpGrow_Forage | Expression | Cal'ed | Scalar | 6.5.3-3 | $e^{-\lambda w\, tg,5}$ |
| | Growing_Factors | Data | Cal'ed | Vector(6) | 6.5.3-3 | $1-e^{-\lambda w\, tg,j}$ |
| | Other_Factor | Expression | Cal'ed | Vector(6) | 6.5.3-3 | $T_j/(Y_j\lambda_w)\,(1-e^{-\lambda w\, tg,j})$ |
| | Air_Interception | Expression | Cal'ed | Vector(6) | 6.5.3-3 | $Ra_j$ |
| | Dust_Uptake | Expression | Cal'ed | Vector(6) | 6.5.3-3 | $Cp_{dust\, i,j}$ |
| Root_ Uptakes | Transfer_Factor | Data | Dbase | Vector(6) | 6.5.3-2 | $F_{s\rightarrow p\, i,j}$ |
| | Root_Uptake | Expression | Cal'ed | Vector(6) | 6.5.3-2 | $Cp_{root\, i,j}$ |
| Plant_Conc | | Expression | Cal'ed | Vector(6) | 6.5.3-1 | $Cp_{i,j}$ |
| Crop_Conc | | Expression | Cal'ed | Vector(4) | 6.5.3-1 | $Cp_{i,j}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.5 Animal Submodel

Mathematical equations for the animal submodel are discussed in Section 6.5.4. All parameters used in this submodel are listed in Table 6.9-5. The animal submodel container includes two lower level containers (Figure 6.9-7). The *AnimalModel_Input* container (Equation 6.5.4-1) includes input parameters for the animal submodel. The *Animal_Ingestion* container calculates radionuclide concentrations in animal products due to the ingestion of contaminated feed (Equation 6.5.4-2) and contaminated soil (Equation 6.5.4-3).

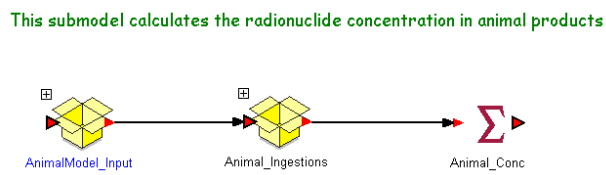



Figure 6.9-7. Animal Submodel Container

Table 6.9-5. Parameters in the Animal Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| Animal Model_ Input | Feed_ForMeat | Stochastic | Input | Scalar | 6.5.4-2 | $Qf_1$ |
| | Feed_ForMilk | Stochastic | Input | Scalar | 6.5.4-2 | $Qf_2$ |
| | Feed_ForPoultry | Stochastic | Input | Scalar | 6.5.4-2 | $Qf_3$ |
| | Feed_ForEggs | Stochastic | Input | Scalar | 6.5.4-2 | $Qf_4$ |
| | Animal_Feed | Data | Cal'ed | Vector(4) | 6.5.4-2 | $Qf_k$ |
| | Soil_ForMeat | Stochastic | Input | Scalar | 6.5.4-3 | $Qs_1$ |
| | Soil_ForMilk | Stochastic | Input | Scalar | 6.5.4-3 | $Qs_2$ |
| | Soil_ForPoultry | Stochastic | Input | Scalar | 6.5.4-3 | $Qs_3$ |
| | Soil_ForEggs | Stochastic | Input | Scalar | 6.5.4-3 | $Qs_4$ |
| | Animal_Soil | Data | Cal'ed | Vector(4) | 6.5.4-3 | $Qs_k$ |
| | Transfer_Coefficients | Data | Dbase | Vector(4) | 6.5.4-2 | $Fm_{i,k}$ |
| Animal_ Ingestions | Feed_Conc | Data | Cal'ed | Vector(4) | 6.5.3-1 | $Cp_{i,j}$ |
| | Feed_Contribution | Expression | Cal'ed | Vector(4) | 6.5.4-2 | $Cd_{feed,i,k}$ |
| | Soil_Contribution | Expression | Cal'ed | Vector(4) | 6.5.4-3 | $Cd_{soil,i,k}$ |
| Animal_Conc | | Expression | Cal'ed | Vector(4) | 6.5.4-1 | $Cd_{i,k}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.6 External Exposure Submodel

Mathematical equations for the external exposure submodel are discussed in Section 6.5.5. All parameters used in this submodel are listed in Table 6.9-6. The external exposure submodel container includes two lower level containers (Figure 6.9-8). The *External_Input* container is used for input data for the population groups and the associated time budgets, and the *External_Model* container calculates the effective external exposure time and the human external radiation dose (Equation 6.5.5-1).

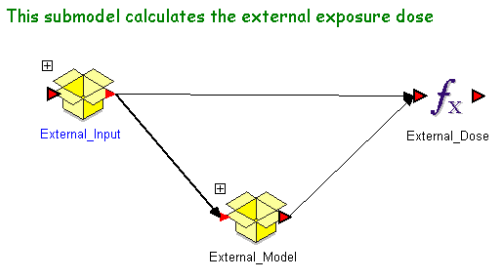



Figure 6.9-8. External Exposure Submodel Container

Table 6.9-6. Parameters in the External Exposure Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| External_ Input | OW_ActOut | Stochastic | Input | Scalar | 6.5.5-1 | $t_{1,1}$ |
| | IW_ActOut | Stochastic | Input | Scalar | 6.5.5-1 | $t_{1,2}$ |
| | CT_ActOut | Stochastic | Input | Scalar | 6.5.5-1 | $t_{1,3}$ |
| | NW_ActOut | Stochastic | Input | Scalar | 6.5.5-1 | $t_{1,4}$ |
| | OW_Outdoor | Stochastic | Input | Scalar | 6.5.5-1 | $t_{2,1}$ |
| | IW_Outdoor | Stochastic | Input | Scalar | 6.5.5-1 | $t_{2,2}$ |
| | CT_Outdoor | Stochastic | Input | Scalar | 6.5.5-1 | $t_{2,3}$ |
| | NW_Outdoor | Stochastic | Input | Scalar | 6.5.5-1 | $t_{2,4}$ |
| | OW_Away | Stochastic | Input | Scalar | 6.5.5-1 | $t_{5,1}$ |
| | IW_Away | Stochastic | Input | Scalar | 6.5.5-1 | $t_{5,2}$ |
| | CT_Away | Stochastic | Input | Scalar | 6.5.5-1 | $t_{5,3}$ |
| | NW_Away | Stochastic | Input | Scalar | 6.5.5-1 | $t_{5,4}$ |
| | Indoor_Asleep | Stochastic | Input | Scalar | 6.5.5-1 | $t_{4,m}$ |
| | OW_Indoor | Expression | Cal'ed | Scalar | 6.5.5-1 | $t_{3,1}$ |
| | IW_Indoor | Expression | Cal'ed | Scalar | 6.5.5-1 | $t_{3,2}$ |
| | CT_Indoor | Expression | Cal'ed | Scalar | 6.5.5-1 | $t_{3,3}$ |
| | NW_Indoor | Expression | Cal'ed | Scalar | 6.5.5-1 | $t_{3,4}$ |
| | Fraction_OW | Stochastic | Input | Scalar | 6.5.5-1 | $PP_1$ |
| | Fraction_IW | Expression | Cal'ed | Scalar | 6.5.5-1 | $PP_2$ |
| | Fraction_CT | Stochastic | Input | Scalar | 6.5.5-1 | $PP_3$ |
| | Fraction_NW | Stochastic | Input | Scalar | 6.5.5-1 | $PP_4$ |
| | Shielding_Factor | Data | Input | Scalar | 6.5.5-1 | $f_{ext,i,3/4}$ |
| | External_DC | Data | Dbase | Scalar | 6.5.5-1 | $EDCs_{soil,i}$ |
| External_ Model | Exposure_times | Data | Cal'ed | Matrix (5,4) | 6.5.5-1 | $t_{n,m}$ |
| | Population | Data | Cal'ed | Vector(4) | 6.5.5-1 | $PP_m$ |
| | Weighted_Time | Expression | Cal'ed | Vector(5) | 6.5.5-1 | $PP_m\ t_{n,m}$ |
| | Weighted_Outdoor | Expression | Cal'ed | Scalar | 6.5.5-1 | $PP_m\ t_{1,m} + PP_m\ t_{2,m}$ |
| | Weighted_Indoor | Expression | Cal'ed | Scalar | 6.5.5-1 | $PP_m\ t_{3,m} + PP_m\ t_{4,m}$ |
| | External_Time | Expression | Cal'ed | Scalar | 6.5.5-1 | $\sum f_{ext,i,n}(\sum PP_m\ t_{n,m})$ |
| External_Dose | | Expression | Cal'ed | Scalar | 6.5.5-1 | $D_{ext,i}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.7 Inhalation Submodel

Mathematical equations for the inhalation submodel are discussed in Section 6.5.6. All parameters used in this submodel are listed in Table 6.9-7. The contents of the inhalation submodel container includes one lower level container (Figure 6.9-9). The *Inhalation_Input* container includes inhalation-related input parameters (e.g., breathing rates and radon data). The time budgets for the receptor is calculated in the *External Submodel* container. Inhalation doses are calculated under normal and post-volcanic conditions (Equation 6.5.6-1). The radon inhalation dose due to exhalation of radon gas from $^{226}$Ra in volcanic ash on the ground is also included in this submodel (Equation 6.5.6-4).

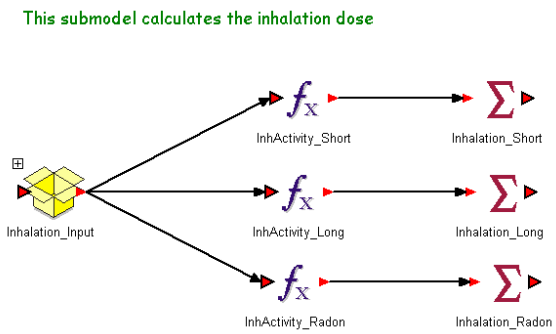



Figure 6.9-9. Inhalation Submodel Container

Table 6.9-7. Parameters in the Inhalation Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| Inhalation_ Input | Breathing_Rate | Data | Input | Vector(5) | 6.5.6-2 | $BR_n$ |
| | RadonEF_Outdoor | Stochastic | Input | Scalar | 6.5.6-3 | $EF_{Rn\text{-}222,1\&2}$ |
| | RadonET_Indoor | Stochastic | Input | Scalar | 6.5.6-3 | $EF_{Rn\text{-}222,3\&4}$ |
| | Radon_Equilibrium | Data | Cal'ed | Vector(5) | 6.5.6-3 | $EF_{Rn\text{-}222,n}$ |
| | Radon_DCF | Data | Input | Scalar | 6.5.6-3 | $DCF_{inh,Rn\text{-}222}$ |
| | Inhalation_DCF | Data | Dbase | Scalar | 6.5.6-2 | $DCF_{inh,i}$ |
| InhActivity_Short | | Expression | Cal'ed | Vector(5) | 6.5.6-2 | $D_{inh,v,i}$ |
| InhActivity_Long | | Expression | Cal'ed | Vector(5) | 6.5.6-2 | $D_{inh,p,i}$ |
| InhActivity_Radon | | Expression | Cal'ed | Vector(5) | 6.5.6-3 | $D_{inh,g,Rn\text{-}222,n}$ |
| Inhalation_Short | | Sum | Cal'ed | Scalar | 6.5.6.4 | $D_{inh,v,i}$ |
| Inhalation_Long | | Sum | Cal'ed | Scalar | 6.5.6.4 | $D_{inh,p,i}$ |
| Inhalation_Radon | | Sum | Cal'ed | Scalar | 6.5.6-3 | $D_{inh,g,Rn\text{-}222}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.8 Ingestion Submodel

Mathematical equations for the human ingestion submodel, which include nine pathways, are discussed in Section 6.5.7. All parameters used in this submodel are listed in Table 6.9-8. The contents of the GoldSim submodel container includes one lower level container (Figure 6.9-10). The *Ingestion_Input* container includes human foodstuff consumption rates. To provide the

results of pathway analysis, the ingestion dose is presented for individual pathways and for total ingestion.

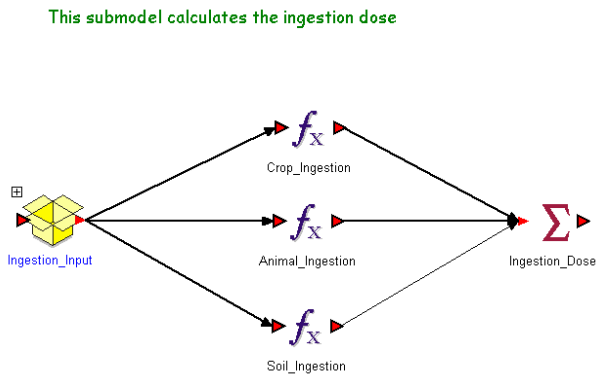



Figure 6.9-10. Ingestion Submodel Container

Table 6.9-8. Parameters in the Ingestion Submodel

| Low Level Box Name | Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|---|
| Ingestion_ Input | Leafy_Consump | Stochastic | Input | Scalar | 6.5.7-2 | $Up_1$ |
| | Other_Consump | Stochastic | Input | Scalar | 6.5.7-2 | $Up_2$ |
| | Fruit_Consump | Stochastic | Input | Scalar | 6.5.7-2 | $Up_3$ |
| | Grain_Consump | Stochastic | Input | Scalar | 6.5.7-2 | $Up_4$ |
| | Crop_Consump | Data | Cal'ed | Vector(4) | 6.5.7-2 | $Up_i$ |
| | Beef_Consump | Stochastic | Input | Scalar | 6.5.7-3 | $Ud_1$ |
| | Poultry_Consump | Stochastic | Input | Scalar | 6.5.7-3 | $Ud_2$ |
| | Milk_Consump | Stochastic | Input | Scalar | 6.5.7-3 | $Ud_3$ |
| | Eggs_Consump | Stochastic | Input | Scalar | 6.5.7-3 | $Ud_4$ |
| | Animal_Consump | Data | Cal'ed | Vector(4) | 6.5.7-3 | $Ud_k$ |
| | Soil_Consump | Stochastic | Input | Scalar | 6.5.7-4 | $Us$ |
| | Ingestion_DCF | Data | Dbase | Scalar | 6.5.7-2 | $EDCF_{ing,i}$ |
| Crop_Ingestion | | Expression | Cal'ed | Vector(4) | 6.5.7-2 | $D_{ing\ p,j}$ |
| Animal_Ingestion | | Expression | Cal'ed | Vector(4) | 6.5.7-3 | $D_{ing\ d,k}$ |
| Soil_Ingestion | | Expression | Cal'ed | Scalar | 6.5.7-4 | $D_{ing\ s}$ |
| Ingestion_Dose | | Sum | Cal'ed | Scalar | 6.5.7-1 | $D_{ing\ 0}$ |

NOTE: See notes for Table 6.9-1.

### 6.9.9 BDCF Results

The TEDE and BDCF for each radionuclide are discussed in Section 6.5.8. All parameters used in this submodel are listed in Table 6.9-9. The BDCF for volcanic ash deposition has three parts. The first part includes external exposure, radon inhalation, and ingestion pathways; the second part includes inhalation of resuspended particles at post-volcanic levels, and the third part includes inhalation of resuspended particles at normal levels. In GoldSim, the pathway results are also calculated (Figure 6.9-11).

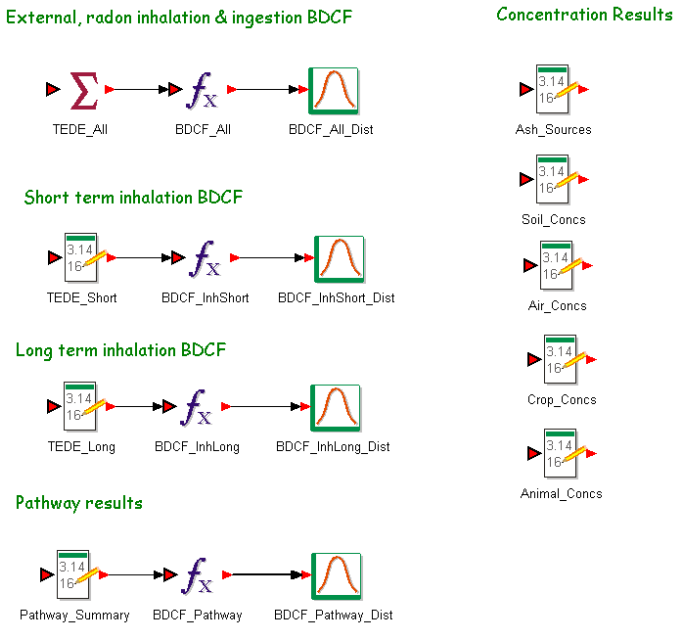



Figure 6.9-11. Final BDCF Result Container

Table 6.9-9. Parameters in the Final BDCF results

| Parameter Name | Element Type | Data Source | Data Type | Equation | Notation |
|---|---|---|---|---|---|
| TEDE_All | Sum | Cal'ed | Scalar | 6.5.8-1 | $D_{all,i}$ |
| BDCF_All | Expression | Cal'ed | Scalar | 6.5.8-2 | $BDCF_i$ |
| TEDE_Short | Data | Cal'ed | Scalar | 6.5.8-1 | $D_{inh,v,i}$ |
| BDCF_InhShort | Expression | Cal'ed | Scalar | 6.5.8-2 | $BDCF_{inh,v,i}$ |
| TEDE_Long | Data | Cal'ed | Scalar | 6.5.8-1 | $D_{inh,v,i}$ |
| BDCF_InhLong | Expression | Cal'ed | Scalar | 6.5.8-2 | $BDCF_{inh,p,i}$ |
| Pathway_Summary | Data | Cal'ed | Vector(12) | 6.4.10-3 | $D_{p,i}$ |
| Pathway_BDCF | Expression | Cal'ed | Vector(12) | 6.4.10-4 | $BDCF_{p,i}$ |
| BDCF_All_Dist | Result | Cal'ed | Scalar | - | - |
| BDCF_InhShort_Dist | Result | Cal'ed | Scalar | - | - |
| BDCF_InhLong_Dist | Result | Cal'ed | Scalar | - | - |
| BDCF_Pathway_Dist | Result | Cal'ed | Vector(12) | - | - |

NOTE: See notes for Table 6.9-1.

## 6.10 VERIFICATION OF THE ERMYN IMPLEMENTATION IN GOLDSIM

Verification of the ERMYN model in GoldSim is carried out by executing the model and comparing the results with results of hand calculations based on the equations described in Sections 6.4 and 6.5. Several test cases are performed to ensure that the ERMYN_GW and ERMYN_VA model is correctly implemented. The test cases are carried out as deterministic runs because stochastic runs are simply sets of many deterministic runs, and the correctness of the stochastic simulation is a property of the GoldSim software.

In addition to verifying the deterministic realization with hand calculations, tests of the stochastic calculations are carried out in which the results of a stochastic realizations are compared with the results of the deterministic realization. This was done to gain confidence that the stochastic results include the deterministic result, which have been verified with hand calculations. Because the sample means of input parameter distributions from some recommended distributions do not match the verification values of the input parameters, the mean of the output from the stochastic realizations is not expected to exactly match the results of the deterministic run. However, the deterministic results are expected be within the range of the output distributions from the stochastic results.

As implemented in GoldSim, the ERMYN model calculates BDCFs for individual radionuclides one at a time. Correlations between BDCFs for primary radionuclides may exist. BDCF correlations are part of the biosphere model results, which are documented and discussed in the two BDCF analysis reports that are shown in Figure 1-1.

### 6.10.1 Verification of the Groundwater Scenario

#### 6.10.1.1 Verification of Deterministic Calculations

Input parameters for verifying the groundwater scenario are taken from the Mean-Mode-Average column in Table 6.6-3. Three radionuclides, $^{239}$Pu, $^{14}$C, and $^{226}$Ra are tested under the groundwater scenario for current climate conditions. For the base case, $^{239}$Pu is selected (Table 6.10-1), $^{14}$C is selected for the $^{14}$C special submodel (Table 6.10-2), and $^{226}$Ra and decay products are selected for the radon dose calculations (Table 6.10-3). In the tables, the hand calculation equations are listed so that the calculations can be reproduced using inputs from Table 6.6-3. In addition, the results from GoldSim are presented with the corresponding GoldSim element names. The results from both methods are the same, indicating that the GoldSim implementation of the ERMYN model (groundwater scenario; Section 6.4) is correct. The GoldSim files described in this section are listed in Attachment I.

The verification results for $^{239}$Pu are presented in Table 6.10-1, in which the verification is presented in the order of each submodel discussed in Section 6.4. The hand-calculated results from the important equations in the biosphere model are presented in the table for comparison with the GoldSim results.

Verification results for $^{14}$C are presented in Table 6.10-2. Because $^{14}$C is a special radionuclide, the model for $^{14}$C (Section 6.6) in the environmental media differs from the model for the other radionuclides. Therefore, the content of this table is different from Table 6.10-1.

Another special radionuclide is $^{226}$Ra. This radionuclide produces a long-lived decay product ($^{210}$Pb) that would accumulate in irrigated soils and produce radon gas. Furthermore, consideration of different radon concentrations indoors and outdoors, the circumstances involving the operation of evaporative coolers, and normal ventilation conditions, made the calculation more complicated. For exposures related to the accumulation of radionuclides in surface soils, the contribution from the $^{210}$Pb decay product is considered (Table 6.10-3).

Table 6.10-1. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 1, $^{239}Pu$)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Soil | Leaching removal constant | | $\lambda_{l,Pu-239}$ | 6.4.1-10 | /yr | 1.76E-04 | Leaching_Factor | 1.76E-04 | Same |
| | Erosion removal constant | | $\lambda_e$ | 6.4.1-11 | /yr | 1.31E-03 | Erosion_Factor | 1.31E-03 | Same |
| | Effective removal constant | | $\lambda_{eff,Pu-239}$ | 6.4.1-3 | /yr | 1.51E-03 | Effective_Removal | 1.51E-03 | Same |
| | Concentration in surface soil | | $Cs_{Pu-239}$ | 6.4.1-4 | $Bq/m^2$ | 622 | Saturated_Conc | 622 | Same |
| | Concentration in soil mass | | $Cs_{m,Pu-239}$ | 6.4.1-5 | Bq/kg | 1.66 | SatMass_Conc | 1.66 | Same |
| Air | Concentration in air for crop | | $Ca_{p,Pu-239}$ | 6.4.2-1 | $Bq/m^3$ | 1.99E-07 | AirConc_Crop | 1.99E-07 | Same |
| | Concentration in air for inhalation | Active outdoors | $Ca_{h,Pu-239,1}$ | 6.4.2-2 | $Bq/m^3$ | 3.32E-05 | AirConc_Inh | 3.32E-05 | Same |
| | | Inactive outdoors | $Ca_{h,Pu-239,2}$ | | | 6.97E-08 | | 6.97E-08 | Same |
| | | Active indoors | $Ca_{h,Pu-239,3}$ | | | 1.16E-07 | | 1.16E-07 | Same |
| | | Asleep indoors | $Ca_{h,Pu-239,4}$ | | | 3.48E-08 | | 3.48E-08 | Same |
| | | Away from area | $Ca_{h,Pu-239,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| | Concentration in air from evaporative cooler | | $Ca_{e,Pu-239}$ | 6.4.2-3 | $Bq/m^3$ | 1.02E-06 | AirConc_Evap | 1.02E-06 | Same |
| Plant | Concentration due to root uptake | Leafy vegetation | $Cp_{root,Pu-239,1}$ | 6.4.3-2 | Bq/kg | 3.37E-05 | Root_Uptake | 3.37E-05 | Same |
| | | Other vegetation | $Cp_{root,Pu-239,2}$ | | | 3.25E-05 | | 3.25E-05 | Same |
| | | Fruit | $Cp_{root,Pu-239,3}$ | | | 3.58E-05 | | 3.58E-05 | Same |
| | | Grain | $Cp_{root,Pu-239,4}$ | | | 2.85E-05 | | 2.85E-05 | Same |
| | | Forage | $Cp_{root,Pu-239,5}$ | | | 3.65E-04 | | 3.65E-04 | Same |
| | Irrigation interception fraction | Leafy vegetation | $Rw_1$ | 6.4.3-5 | - | 0.217 | Intercept_Fractor | 0.217 | Same |
| | | Other vegetation | $Rw_2$ | | | 0.304 | | 0.304 | Same |
| | | Fruit | $Rw_3$ | | | 0.361 | | 0.361 | Same |
| | | Grain | $Rw_4$ | | | 0.472 | | 0.472 | Same |
| | | Forage | $Rw_5$ | | | 0.259 | | 0.259 | Same |
| | Concentration due to water interception | Leafy vegetation | $Cp_{water,Pu-239,1}$ | 6.4.3-3 | Bq/kg | 5.24E-03 | Water_Uptake | 5.24E-03 | Same |
| | | Other vegetation | $Cp_{water,Pu-239,2}$ | | | 8.27E-04 | | 8.27E-04 | Same |
| | | Fruit | $Cp_{water,Pu-239,3}$ | | | 9.78E-04 | | 9.78E-04 | Same |
| | | Grain | $Cp_{water,Pu-239,4}$ | | | 6.74E-03 | | 6.74E-03 | Same |
| | | Forage | $Cp_{water,Pu-239,5}$ | | | 1.40E-02 | | 1.40E-02 | Same |
| | Dust interception fraction | Leafy vegetation | $Ra_1$ | 6.4.3-8 | - | 0.456 | Dust_Intercept | 0.456 | Same |
| | | Other vegetation | $Ra_2$ | | | 0.787 | | 0.787 | Same |
| | | Fruit | $Ra_3$ | | | 0.893 | | 0.893 | Same |
| | | Grain | $Ra_4$ | | | 0.962 | | 0.962 | Same |
| | | Forage | $Ra_5$ | | | 0.751 | | 0.751 | Same |

Table 6.10-1. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 1, $^{239}Pu$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Plant (cont.) | Concentration due to dust interception | Leafy vegetation | $Cp_{dust,Pu-239,1}$ | 6.4.3-6 | Bq/kg | 3.75E-04 | Dust_Uptake | 3.75E-04 | Same |
| | | Other vegetation | $Cp_{dust,Pu-239,2}$ | | | 5.20E-05 | | 5.20E-05 | Same |
| | | Fruit | $Cp_{dust,Pu-239,3}$ | | | 9.02E-05 | | 9.02E-05 | Same |
| | | Grain | $Cp_{dust,Pu-239,4}$ | | | 4.53E-04 | | 4.53E-04 | Same |
| | | Forage | $Cp_{dust,Pu-239,5}$ | | | 9.52E-04 | | 9.52E-04 | Same |
| | Concentration in crops | Leafy vegetation | $Cp_{Pu-239,1}$ | 6.4.3-1 | Bq/kg | 5.65E-03 | Plant_Conc | 5.65E-03 | Same |
| | | Other vegetation | $Cp_{Pu-239,2}$ | | | 9.11E-04 | | 9.11E-04 | Same |
| | | Fruit | $Cp_{Pu-239,3}$ | | | 1.10E-03 | | 1.10E-03 | Same |
| | | Grain | $Cp_{Pu-239,4}$ | | | 7.23E-03 | | 7.23E-03 | Same |
| | | Forage | $Cp_{Pu-239,5}$ | | | 1.53E-02 | | 1.53E-02 | Same |
| Animal | Concentration due to feed | Meat | $Cd_{feed,Pu-239,1}$ | 6.4.4-2 | Bq/kg | 9.68E-06 | Feed_Contribution | 9.68E-06 | Same |
| | | Milk | $Cd_{feed,Pu-239,2}$ | | | 2.17E-07 | | 2.17E-07 | Same |
| | | Poultry | $Cd_{feed,Pu-239,3}$ | | | 2.25E-06 | | 2.25E-06 | Same |
| | | Eggs | $Cd_{feed,Pu-239,4}$ | | | 3.19E-06 | | 3.19E-06 | Same |
| | Concentration due to water | Meat | $Cd_{water,Pu-239,1}$ | 6.4.4-3 | Bq/kg | 7.80E-07 | Water_ Contribution | 7.80E-07 | Same |
| | | Milk | $Cd_{water,Pu-239,2}$ | | | 1.84E-08 | | 1.84E-08 | Same |
| | | Poultry | $Cd_{water,Pu-239,3}$ | | | 6.00E-07 | | 6.00E-07 | Same |
| | | Eggs | $Cd_{water,Pu-239,4}$ | | | 8.50E-07 | | 8.50E-07 | Same |
| | Concentration due to soil | Meat | $Cd_{soil,Pu-239,1}$ | 6.4.4-4 | Bq/kg | 1.51E-05 | Soil_Contribution | 1.51E-05 | Same |
| | | Milk | $Cd_{soil,Pu-239,2}$ | | | 3.62E-07 | | 3.62E-07 | Same |
| | | Poultry | $Cd_{soil,Pu-239,3}$ | | | 3.98E-05 | | 3.98E-05 | Same |
| | | Eggs | $Cd_{soil,Pu-239,4}$ | | | 5.64E-05 | | 5.64E-05 | Same |
| | Concentration in animal products | Meat | $Cd_{Pu-239,1}$ | 6.4.4-1 | Bq/kg | 2.56E-05 | Animal_Conc | 2.56E-05 | Same |
| | | Milk | $Cd_{Pu-239,2}$ | | | 5.98E-07 | | 5.98E-07 | Same |
| | | Poultry | $Cd_{Pu-239,3}$ | | | 4.27E-05 | | 4.27E-05 | Same |
| | | Eggs | $Cd_{Pu-239,4}$ | | | 6.04E-05 | | 6.04E-05 | Same |
| Fish | Concentration in Fish | | $Cf_{Pu-239}$ | 6.4.5-2 | Bq/kg | 0.170 | Fish_Conc | 0.170 | Same |
| External | Environment-specific exposure time | Active outdoors | $\sum(PP_m\ t_{1,m})$ | 6.4.7-1 | hr/d | 0.45 | Weighted_Time | 0.45 | Same |
| | | Inactive outdoors | $\sum(PP_m\ t_{2,m})$ | | | 1.45 | | 1.45 | Same |
| | | Active indoors | $\sum(PP_m\ t_{3,m})$ | | | 9.45 | | 9.45 | Same |
| | | Asleep indoors | $\sum(PP_m\ t_{4,m})$ | | | 8.30 | | 8.30 | Same |
| | | Away from area | $\sum(PP_m\ t_{5,m})$ | | | 4.35 | | 4.35 | Same |
| | Effective exposure time | | $\sum[f_{ext,Pu-239,n}\ \sum(PP_m\ t_{n,m})]$ | 6.4.7-1 | hr/yr | 2639 | External_Time | 2639 | Same |
| | External dose | | $D_{ext,Pu-239}$ | 6.4.7-1 | Sv/yr | 3.74E-11 | Total _External | 3.74E-11 | Same |

Table 6.10-1. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 1, $^{239}Pu$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Inhalation | Inhalation dose for particles | | $D_{inh,p,Pu-239}$ | 6.4.8-2 | Sv/yr | 1.06E-06 | Total_Dust | 1.06E-06 | Same |
| | Inhalation dose from evaporative cooler | | $D_{inh,e,Pu-239}$ | 6.4.8-3 | Sv/yr | 1.68E-07 | Cooler_Inhalation | 1.68E-07 | Same |
| | Inhalation dose | | $D_{inh,Pu-239}$ | 6.4.8-1 | Sv/yr | 1.23E-06 | Total_Inhalation | 1.23E-06 | Same |
| Ingestion | Ingestion dose for water | | $D_{ing,w,Pu-239}$ | 6.4.9-2 | Sv/yr | 6.98E-07 | Water_Ingestion | 6.98E-07 | Same |
| | Ingestion dose for crops | Leafy vegetation | $D_{ing,p,Pu-239,1}$ | 6.4.9-3 | Sv/yr | 2.04E-08 | Crop_Ingestion | 2.04E-08 | Same |
| | | Other vegetation | $D_{ing,p,Pu-239,2}$ | | Sv/yr | 4.12E-09 | | 4.12E-09 | Same |
| | | Fruit | $D_{ing,p,Pu-239,3}$ | | Sv/yr | 1.34E-08 | | 1.34E-08 | Same |
| | | Grain | $D_{ing,p,Pu-239,4}$ | | Sv/yr | 1.59E-09 | | 1.59E-09 | Same |
| | Ingestion dose for animal products | Meat | $D_{ing,d,Pu-239,1}$ | 6.4.9-4 | Sv/yr | 6.96E-11 | Animal_Ingestion | 6.96E-11 | Same |
| | | Milk | $D_{ing,d,Pu-239,2}$ | | Sv/yr | 2.66E-12 | | 2.66E-12 | Same |
| | | Poultry | $D_{ing,d,Pu-239,3}$ | | Sv/yr | 1.71E-11 | | 1.71E-11 | Same |
| | | Eggs | $D_{ing,d,Pu-239,4}$ | | Sv/yr | 3.06E-10 | | 3.06E-10 | Same |
| | Ingestion dose for fish | | $D_{ing,f,Pu-239}$ | 6.4.9-5 | Sv/yr | 3.74E-08 | Fish_Ingestion | 3.74E-08 | Same |
| | Ingestion dose for soil | | $D_{ing,s,Pu-239}$ | 6.4.9-6 | Sv/yr | 5.79E-08 | Soil_Ingestion | 5.79E-08 | Same |
| | Ingestion dose | | $D_{ing,Pu-239}$ | 6.4.9-1 | Sv/yr | 8.34E-07 | Total_Ingestion | 8.34E-07 | Same |
| All Pathway | All-pathway dose | | $D_{all,Pu-239}$ | 6.4.10-1 | Sv/yr | 2.06E-06 | Final_TEDE | 2.06E-06 | Same |
| | BDCF | | $BDCF_{Pu-239}$ | 6.4.10-2 | (rem/yr)/(pCi/L) | 7.63E-03 | Final_BDCF | 7.63E-03 | Same |

NOTES:

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. Calculations performed in Microsoft Excel 97 SR-2. The electronic file, *ERMYN verification.xls*, which contains this calculation in worksheet *GWPu239*, is listed in Attachment I.

[b] The ERMYN model is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _PU239verf.gsm*, for this run is listed in Attachment I.

[c] Comparison of results from Calculated Value (Column 6) and ERMYN_GW Result (Column 8).

Table 6.10-2. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 2, $^{14}C$)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| $^{14}C$/Soil | Leaching removal constant | | $\lambda_{l,C\text{-}14}$ | 6.4.1-10 | /yr | 1.16E-02 | Leaching_Factor | 1.16E-02 | Same |
| | Erosion removal constant | | $\lambda_e$ | 6.4.1-11 | /yr | 1.31E-03 | Erosion_Factor | 1.31E-03 | Same |
| | Effective removal constant | | $\lambda_{eff,C\text{-}14}$ | 6.4.1-3 | /yr | 1.30E-02 | Effective_Removal | 1.30E-02 | Same |
| | Concentration in surface soil | | $Cs_{0,C\text{-}14}$ | 6.4.6-1 | $Bq/m^2$ | 4.27E-02 | C14Conc_InhSoil | 4.27E-02 | Same |
| | Concentration in crop land | Leafy vegetation | $Cs_{1,C\text{-}14}$ | 6.4.6-1 | $Bq/m^2$ | 8.96E-02 | C14Conc_CropSoil | 8.96E-02 | Same |
| | | Other vegetation | $Cs_{2,C\text{-}14}$ | | | 1.25E-01 | | 1.25E-01 | |
| | | Fruit | $Cs_{3,C\text{-}14}$ | | | 1.22E-01 | | 1.22E-01 | |
| | | Grain | $Cs_{4,C\text{-}14}$ | | | 7.70E-02 | | 7.70E-02 | |
| | | Forage | $Cs_{5,C\text{-}14}$ | | | 1.09E-01 | | 1.09E-01 | |
| $^{14}C$/Air | Concentration in air for inhalation | | $Ca_{h,C\text{-}14}$ | 6.4.6-3 | $Bq/m^3$ | 1.21E-05 | C14Conc_Inh | 1.21E-05 | Same |
| | Concentration in air for crops | Leafy vegetation | $Ca_{h,C\text{-}14,1}$ | 6.4.6-3 | $Bq/m^3$ | 6.54E-05 | C14Conc_Air | 6.54E-05 | Same |
| | | Other vegetation | $Ca_{h,C\text{-}14,2}$ | | | 9.14E-05 | | 9.14E-05 | Same |
| | | Fruit | $Ca_{h,C\text{-}14,3}$ | | | 8.93E-05 | | 8.93E-05 | Same |
| | | Grain | $Ca_{h,C\text{-}14,4}$ | | | 5.62E-05 | | 5.62E-05 | Same |
| | | Forage | $Ca_{h,C\text{-}14,5}$ | | | 7.91E-05 | | 7.91E-05 | Same |
| $^{14}C$/Plant | Concentration in crops | Leafy vegetation | $Cp_{C\text{-}14,1}$ | 6.4.6-6 | Bq/kg | 3.20E-02 | C14Conc_Crop | 3.20E-02 | Same |
| | | Other vegetation | $Cp_{C\text{-}14,2}$ | | | 4.48E-02 | | 4.48E-02 | Same |
| | | Fruit | $Cp_{C\text{-}14,3}$ | | | 4.38E-02 | | 4.38E-02 | Same |
| | | Grain | $Cp_{C\text{-}14,4}$ | | | 1.22E-01 | | 1.22E-01 | Same |
| | | Forage | $Cp_{C\text{-}14,5}$ | | | 3.88E-02 | | 3.88E-02 | Same |
| $^{14}C$/ Animal | Concentration in animal product | Meat | $Cd_{C\text{-}14,1}$ | 6.4.6-7 | Bq/kg | 1.06E-01 | C14Conc_Animal | 1.06E-01 | Same |
| | | Milk | $Cd_{C\text{-}14,2}$ | | | 3.10E-02 | | 3.10E-02 | Same |
| | | Poultry | $Cd_{C\text{-}14,3}$ | | | 6.18E-02 | | 6.18E-02 | Same |
| | | Eggs | $Cd_{C\text{-}14,4}$ | | | 4.63E-02 | | 4.63E-02 | Same |
| Fish | Concentration in Fish | | $Cf_{C\text{-}14}$ | 6.4.5-2 | Bq/kg | 4.6 | Fish_Conc | 4.6 | Same |
| External | Environment-specific exposure time | Active outdoors | $\sum(PP_m\ t_{1,m})$ | 6.4.7-1 | hr/d | 0.45 | Weighted_Time | 0.45 | Same |
| | | Inactive outdoors | $\sum(PP_m\ t_{2,m})$ | | | 1.45 | | 1.45 | Same |
| | | Active indoors | $\sum(PP_m\ t_{3,m})$ | | | 9.45 | | 9.45 | Same |
| | | Asleep indoors | $\sum(PP_m\ t_{4,m})$ | | | 8.30 | | 8.30 | Same |
| | | Away from area | $\sum(PP_m\ t_{5,m})$ | | | 4.35 | | 4.35 | Same |
| | Effective exposure time | | $\sum[f_{ext,C\text{-}14,n}\ \sum(PP_m\ t_{n,m})]$ | 6.4.7-1 | hr/yr | 1991 | External_Time | 1991 | Same |
| | External dose | | $D_{ext,C\text{-}14}$ | 6.4.7-1 | Sv/yr | 8.82E-17 | Total _External | 8.82E-17 | Same |
| Inhalation | Inhalation dose for $^{14}C$ gas | | $D_{inh,g,C\text{-}14}$ | 6.4.8-4 | Sv/yr | 4.41E-13 | Total_C14 | 4.41E-13 | Same |
| | Inhalation dose from evaporative cooler | | $D_{inh,e,C\text{-}14}$ | 6.4.8-3 | Sv/yr | 9.20E-15 | Cooler_Inhalation | 9.20E-15 | Same |
| | Inhalation dose | | $D_{inh,C\text{-}14}$ | 6.4.8-1 | Sv/yr | 4.50E-13 | Total_Inhalation | 4.50E-13 | Same |

Table 6.10-2. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 2, $^{14}C$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Ingestion | Ingestion dose for water | | $D_{ing,w,C-14}$ | 6.4.9-2 | Sv/yr | 4.12E-10 | Water_Ingestion | 4.12E-10 | Same |
| | Ingestion dose for crops | Leafy vegetation | $D_{ing,p,C-14,1}$ | 6.4.9-3 | Sv/yr | 6.83E-11 | Crop_Ingestion | 6.83E-11 | Same |
| | | Other vegetation | $D_{ing,p,C-14,2}$ | | Sv/yr | 1.19E-10 | | 1.19E-10 | Same |
| | | Fruit | $D_{ing,p,C-14,3}$ | | Sv/yr | 3.13E-10 | | 3.13E-10 | Same |
| | | Grain | $D_{ing,p,C-14,4}$ | | Sv/yr | 1.59E-11 | | 1.59E-11 | Same |
| | Ingestion dose for animal products | Meat | $D_{ing,d,C-14,1}$ | 6.4.9-4 | Sv/yr | 1.71E-10 | Animal_Ingestion | 1.71E-10 | Same |
| | | Milk | $D_{ing,d,C-14,2}$ | | Sv/yr | 8.15E-11 | | 8.15E-11 | Same |
| | | Poultry | $D_{ing,d,C-14,3}$ | | Sv/yr | 1.46E-11 | | 1.46E-11 | Same |
| | | Eggs | $D_{ing,d,C-14,4}$ | | Sv/yr | 1.38E-10 | | 1.39E-10 | Rounding |
| | Ingestion dose for fish | | $D_{ing,f,C-14}$ | 6.4.9-5 | Sv/yr | 5.97E-10 | Fish_Ingestion | 5.97E-10 | Same |
| | Ingestion dose for soil | | $D_{ing,s,C-14}$ | 6.4.9-6 | Sv/yr | 2.35E-15 | Soil_Ingestion | 2.35E-15 | Same |
| | Ingestion dose | | $D_{ing,C-14}$ | 6.4.9-1 | Sv/yr | 1.93E-09 | Total_Ingestion | 1.93E-09 | Same |
| All Pathway | All-pathway dose | | $D_{all,C-14}$ | 6.4.10-1 | Sv/yr | 1.93E-09 | Final_TEDE | 1.93E-09 | Same |
| | BDCF | | $BDCF_{C-14}$ | 6.4.10-2 | (rem/yr)/(pCi/L) | 7.15E-06 | Final_BDCF | 7.15E-06 | Same |

NOTES:

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. Calculations performed in Microsoft Excel 97 SR-2. The electronic file, *ERMYN verification.xls,* which contains this calculation in worksheet *GWC14*, is listed in Attachment I.

[b] The ERMYN model is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _C14verf.gsm*, for this run is listed in Attachment I.

[c] Comparison of results from Calculated Value (Column 6) and ERMYN_GW Result (Column 8).

Table 6.10-3. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 3, $^{226}Ra$)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Soil | Leaching removal constant | | $\lambda_{l,Ra-226}$ | 6.4.1-10 | /yr | 5.85E-06 | Leaching_Factor | 5.85E-06 | Same |
| | Erosion removal constant | | $\lambda_e$ | 6.4.1-11 | /yr | 1.31E-03 | Erosion_Factor | 1.31E-03 | Same |
| | Effective removal constant | | $\lambda_{eff,Ra-226}$ | 6.4.1-3 | /yr | 1.75E-03 | Effective_Removal | 1.75E-03 | Same |
| | Concentration in surface soil | | $Cs_{Ra-226}$ | 6.4.1-4 | $Bq/m^2$ | 538 | Saturated_Conc | 538 | Same |
| | Concentration in soil mass | | $Cs_{m,Ra-226}$ | 6.4.1-5 | Bq/kg | 1.44 | SatMass_Conc | 1.44 | Same |
| | Leaching removal constant | | $\lambda_{l,Pb-210}$ | 6.4.1-10 | /yr | 1.32E-05 | Leaching_Factor_1 | 1.32E-05 | Same |
| | Effective removal constant | | $\lambda_{eff,Pb-210}$ | 6.4.1-3 | /yr | 3.24E-02 | Effective_Removal_1 | 3.24E-02 | Same |
| | Concentration in surface soil | | $Cs_{Pb-210}$ | 6.4.1-9 | $Bq/m^2$ | 5.17E+02 | Saturated_Conc_1 | 5.17E+02 | Same |
| | Concentration in soil mass | | $Cs_{m,Pb-210}$ | 6.4.1-5 | Bq/kg | 1.38 | SatMass_Conc_1 | 1.38 | Same |
| Air | Concentration in air for crop | | $Ca_{p,Ra-226}$ | 6.4.2-1 | $Bq/m^3$ | 1.72E-07 | AirConc_Crop | 1.72E-07 | Same |
| | Concentration in air for inhalation | Active outdoors | $Ca_{h,Ra-226,1}$ | 6.4.2-2 | $Bq/m^3$ | 2.87E-05 | AirConc_Inh | 2.87E-05 | Same |
| | | Inactive outdoors | $Ca_{h,Ra-226,2}$ | | | 6.03E-08 | | 6.03E-08 | Same |
| | | Active indoors | $Ca_{h,Ra-226,3}$ | | | 1.01E-07 | | 1.01E-07 | Same |
| | | Asleep indoors | $Ca_{h,Ra-226,4}$ | | | 3.02E-08 | | 3.02E-08 | Same |
| | | Away from area | $Ca_{h,Ra-226,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| | Concentration in air from evaporative cooler | | $Ca_{e,Ra-226}$ | 6.4.2-3 | $Bq/m^3$ | 1.02E-06 | AirConc_Evap | 1.02E-06 | Same |
| | Radon concentration in outdoor | | $Ca_{g,Rn-222}$ | 6.4.2-4 | $Bq/m^3$ | 0.359 | AirConc_Radon | 0.359 | Same |
| | Radon indoor factor for normal condition | | $IF_{n,Rn-222}$ | 6.4.2-7 | - | 1.913 | Indoor_RnEvap | 1.913 | Same |
| | Radon indoor factor for evaporative condition | | $IF_{e,Rn-222}$ | 6.4.2-7 | - | 1.059 | Indoor_RnNormal | 1.059 | Same |
| | Concentration in air for crop | | $Ca_{p,Pb-210}$ | 6.4.2-1 | $Bq/m^3$ | 1.65E-07 | AirConc_Crop_1 | 1.65E-07 | Same |
| | Concentration in air for inhalation | Active outdoors | $Ca_{h,Pb-210,1}$ | 6.4.2-2 | $Bq/m^3$ | 2.75E-05 | AirConc_Inh_1 | 2.75E-05 | Same |
| | | Inactive outdoors | $Ca_{h,Pb-210,2}$ | | | 5.79E-08 | | 5.79E-08 | Same |
| | | Active indoors | $Ca_{h,Pb-210,3}$ | | | 9.64E-08 | | 9.64E-08 | Same |
| | | Asleep indoors | $Ca_{h,Pb-210,4}$ | | | 2.89E-08 | | 2.89E-08 | Same |
| | | Away from area | $Ca_{h,Pb-210,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| Plant | Concentration due to root uptake | Leafy vegetation | $Cp_{root,Ra-2261}$ | 6.4.3-2 | Bq/kg | 6.83E-03 | Root_Uptake | 6.83E-03 | Same |
| | | Other vegetation | $Cp_{root,Ra-226,2}$ | | | 1.77E-03 | | 1.77E-03 | Same |
| | | Fruit | $Cp_{root,Ra-226,3}$ | | | 1.26E-03 | | 1.26E-03 | Same |
| | | Grain | $Cp_{root,Ra-226,4}$ | | | 4.02E-03 | | 4.02E-03 | Same |
| | | Forage | $Cp_{root,Ra-226,5}$ | | | 2.59E-02 | | 2.59E-02 | Same |

Table 6.10-3. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 3, $^{226}Ra$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Plant (cont.) | Irrigation interception fraction | Leafy vegetation | $Rw_1$ | 6.4.3-5 | - | 0.217 | Intercept_Fractor | 0.217 | Same |
| | | Other vegetation | $Rw_2$ | | | 0.304 | | 0.304 | Same |
| | | Fruit | $Rw_3$ | | | 0.361 | | 0.361 | Same |
| | | Grain | $Rw_4$ | | | 0.472 | | 0.472 | Same |
| | | Forage | $Rw_5$ | | | 0.259 | | 0.259 | Same |
| | Concentration due to water interception | Leafy vegetation | $Cp_{water,Ra\text{-}226,1}$ | 6.4.3-3 | Bq/kg | 5.24E-03 | Water_Uptake | 5.24E-03 | Same |
| | | Other vegetation | $Cp_{water,Ra\text{-}226,2}$ | | | 8.27E-04 | | 8.27E-04 | Same |
| | | Fruit | $Cp_{water,Ra\text{-}226,3}$ | | | 9.78E-04 | | 9.78E-04 | Same |
| | | Grain | $Cp_{water,Ra\text{-}226,4}$ | | | 6.74E-03 | | 6.74E-03 | Same |
| | | Forage | $Cp_{water,Ra\text{-}226,5}$ | | | 1.40E-02 | | 1.40E-02 | Same |
| | Dust interception fraction | Leafy vegetation | $Ra_1$ | 6.4.3-8 | - | 0.456 | Dust_Intercept | 0.456 | Same |
| | | Other vegetation | $Ra_2$ | | | 0.787 | | 0.787 | Same |
| | | Fruit | $Ra_3$ | | | 0.893 | | 0.893 | Same |
| | | Grain | $Ra_4$ | | | 0.962 | | 0.962 | Same |
| | | Forage | $Ra_5$ | | | 0.751 | | 0.751 | Same |
| | Concentration due to dust interception | Leafy vegetation | $Cp_{dust,Ra\text{-}226,1}$ | 6.4.3-6 | Bq/kg | 3.24E-04 | Dust_Uptake | 3.24E-04 | Same |
| | | Other vegetation | $Cp_{dust,Ra\text{-}226,2}$ | | | 4.50E-05 | | 4.50E-05 | Same |
| | | Fruit | $Cp_{dust,Ra\text{-}226,3}$ | | | 7.81E-05 | | 7.81E-05 | Same |
| | | Grain | $Cp_{dust,Ra\text{-}226,4}$ | | | 3.92E-04 | | 3.92E-04 | Same |
| | | Forage | $Cp_{dust,Ra\text{-}226,5}$ | | | 8.24E-04 | | 8.24E-04 | Same |
| | Concentration in crops | Leafy vegetation | $Cp_{Ra\text{-}226,1}$ | 6.4.3-1 | Bq/kg | 1.24E-02 | Plant_Conc | 1.24E-02 | Same |
| | | Other vegetation | $Cp_{Ra\text{-}226,2}$ | | | 2.65E-03 | | 2.65E-03 | Same |
| | | Fruit | $Cp_{Ra\text{-}226,3}$ | | | 2.31E-03 | | 2.31E-03 | Same |
| | | Grain | $Cp_{Ra\text{-}226,4}$ | | | 1.12E-02 | | 1.12E-02 | Same |
| | | Forage | $Cp_{Ra\text{-}226,5}$ | | | 4.08E-02 | | 4.08E-02 | Same |
| | Concentration due to root uptake | Leafy vegetation | $Cp_{root,Pb\text{-}210,1}$ | 6.4.3-2 | Bq/kg | 1.45E-03 | Root_Uptake_1 | 1.45E-03 | Same |
| | | Other vegetation | $Cp_{root,Pb\text{-}210,2}$ | | | 1.28E-03 | | 1.28E-03 | Same |
| | | Fruit | $Cp_{root,Pb\text{-}210,3}$ | | | 1.98E-03 | | 1.98E-03 | Same |
| | | Grain | $Cp_{root,Pb\text{-}210,4}$ | | | 6.84E-03 | | 6.84E-03 | Same |
| | | Forage | $Cp_{root,Pb\text{-}210,5}$ | | | 5.45E-03 | | 5.45E-03 | Same |
| | Concentration due to dust interception | Leafy vegetation | $Cp_{dust,Pb\text{-}210,1}$ | 6.4.3-6 | Bq/kg | 3.11E-04 | Dust_Uptake_1 | 3.11E-04 | Same |
| | | Other vegetation | $Cp_{dust,Pb\text{-}210,2}$ | | | 4.32E-05 | | 4.32E-05 | Same |
| | | Fruit | $Cp_{dust,Pb\text{-}210,3}$ | | | 7.49E-05 | | 7.49E-05 | Same |
| | | Grain | $Cp_{dust,Pb\text{-}210,4}$ | | | 3.76E-04 | | 3.76E-04 | Same |
| | | Forage | $Cp_{dust,Pb\text{-}210,5}$ | | | 7.90E-04 | | 7.90E-04 | Same |

Table 6.10-3. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 3, $^{226}Ra$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Plant (cont.) | Concentration in crops | Leafy vegetation | $Cp_{Pb\text{-}210,1}$ | 6.4.3-1 | Bq/kg | 1.76E-03 | Plant_Conc_1 | 1.76E-03 | Same |
| | | Other vegetation | $Cp_{Pb\text{-}210,2}$ | | | 1.32E-03 | | 1.32E-03 | Same |
| | | Fruit | $Cp_{Pb\text{-}210,3}$ | | | 2.06E-03 | | 2.06E-03 | Same |
| | | Grain | $Cp_{Pb\text{-}210,4}$ | | | 7.22E-03 | | 7.22E-03 | Same |
| | | Forage | $Cp_{Pb\text{-}210,5}$ | | | 6.24E-03 | | 6.24E-03 | Same |
| Animal | Concentration due to feed | Meat | $Cd_{feed,Ra\text{-}226,1}$ | 6.4.4-2 | Bq/kg | 1.60E-03 | Feed_Contribution | 1.60E-03 | Same |
| | | Milk | $Cd_{feed,Ra\text{-}226,2}$ | | | 1.45E-03 | | 1.45E-03 | Same |
| | | Poultry | $Cd_{feed,Ra\text{-}226,3}$ | | | 4.93E-05 | | 4.93E-05 | Same |
| | | Eggs | $Cd_{feed,Ra\text{-}226,4}$ | | | 1.13E-06 | | 1.13E-06 | Same |
| | Concentration due to water | Meat | $Cd_{water,Ra\text{-}226,1}$ | 6.4.4-3 | Bq/kg | 4.86E-05 | Water_Contribution | 4.86E-05 | Same |
| | | Milk | $Cd_{water,Ra\text{-}226,2}$ | | | 4.64E-05 | | 4.64E-05 | Same |
| | | Poultry | $Cd_{water,Ra\text{-}226,3}$ | | | 8.50E-06 | | 8.50E-06 | Same |
| | | Eggs | $Cd_{water,Ra\text{-}226,4}$ | | | 1.95E-07 | | 1.95E-07 | Same |
| | Concentration due to soil | Meat | $Cd_{soil,Ra\text{-}226,1}$ | 6.4.4-4 | Bq/kg | 8.14E-04 | Soil_Contribution | 8.14E-04 | Same |
| | | Milk | $Cd_{soil,Ra\text{-}226,2}$ | | | 7.91E-04 | | 7.91E-04 | Same |
| | | Poultry | $Cd_{soil,Ra\text{-}226,3}$ | | | 4.88E-04 | | 4.88E-04 | Same |
| | | Eggs | $Cd_{soil,Ra\text{-}226,4}$ | | | 1.12E-05 | | 1.12E-05 | Same |
| | Concentration in animal products | Meat | $Cd_{Ra\text{-}226.1}$ | 6.4.4-1 | Bq/kg | 2.46E-03 | Animal_Conc | 2.46E-03 | Same |
| | | Milk | $Cd_{Ra\text{-}226,2}$ | | | 2.29E-03 | | 2.29E-03 | Same |
| | | Poultry | $Cd_{Ra\text{-}226,3}$ | | | 5.46E-04 | | 5.46E-04 | Same |
| | | Eggs | $Cd_{Ra\text{-}226,4}$ | | | 1.25E-05 | | 1.25E-05 | Same |
| | Concentration due to feed | Meat | $Cd_{feed,Pb\text{-}210,1}$ | 6.4.4-2 | Bq/kg | 1.91E-04 | Feed_ Contribution_1 | 1.91E-04 | Same |
| | | Milk | $Cd_{feed,Pb\text{-}210,2}$ | | | 6.53E-05 | | 6.53E-05 | Same |
| | | Poultry | $Cd_{feed,Pb\text{-}210,3}$ | | | 4.69E-05 | | 4.69E-05 | Same |
| | | Eggs | $Cd_{feed,Pb\text{-}210,4}$ | | | 1.05E-04 | | 1.05E-04 | Same |
| | Concentration due to soil | Meat | $Cd_{soil,Pb\text{-}210,1}$ | 6.4.4-4 | Bq/kg | 6.07E-04 | Soil_Contribution_1 | 6.07E-04 | Same |
| | | Milk | $Cd_{soil,Pb\text{-}210,2}$ | | | 2.22E-04 | | 2.22E-04 | Same |
| | | Poultry | $Cd_{soil,Pb\text{-}210,3}$ | | | 6.89E-04 | | 6.89E-04 | Same |
| | | Eggs | $Cd_{soil,Pb\text{-}210,4}$ | | | 1.54E-03 | | 1.54E-03 | Same |
| | Concentration in animal products | Meat | $Cd_{Pb\text{-}210,1}$ | 6.4.4-1 | Bq/kg | 7.98E-04 | Animal_Conc_1 | 7.98E-04 | Same |
| | | Milk | $Cd_{Pb\text{-}210,2}$ | | | 2.88E-04 | | 2.88E-04 | Same |
| | | Poultry | $Cd_{Pb\text{-}210,3}$ | | | 7.36E-04 | | 7.36E-04 | Same |
| | | Eggs | $Cd_{Pb\text{-}210,4}$ | | | 1.65E-03 | | 1.65E-03 | Same |
| Fish | Concentration in Fish | | $Cf_{Ra\text{-}226}$ | 6.4.5-2 | Bq/kg | 0.278 | Fish_Conc | 0.278 | Same |

Table 6.10-3. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 3, $^{226}Ra$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| External | Environment-specific exposure time | Active outdoors | $\sum(PP_m\ t_{1,m})$ | 6.4.7-1 | hr/d | 0.45 | Weighted_Time | 0.45 | Same |
| | | Inactive outdoors | $\sum(PP_m\ t_{2,m})$ | | | 1.45 | | 1.45 | Same |
| | | Active indoors | $\sum(PP_m\ t_{3,m})$ | | | 9.45 | | 9.45 | Same |
| | | Asleep indoors | $\sum(PP_m\ t_{4,m})$ | | | 8.30 | | 8.30 | Same |
| | | Away from area | $\sum(PP_m\ t_{5,m})$ | | | 4.35 | | 4.35 | Same |
| | Effective exposure time | | $\sum[f_{ext,Ra\text{-}226,n}\ \sum(PP_m\ t_{n,m})]$ | 6.4.7-1 | hr/yr | 3288 | External_Time | 3288 | Same |
| | External dose from Ra-226D | | - | 6.4.7-1 | Sv/yr | 1.53E-06 | External_Dose | 1.53E-06 | Same |
| | Effective exposure time | | $\sum[f_{ext,Pb\text{-}210,n}\ \sum(PP_m\ t_{n,m})]$ | 6.4.7-1 | hr/yr | 3288 | External_Time_1 | 3288 | Same |
| | External dose from Pb-210D | | - | 6.4.7-1 | Sv/yr | 7.99E-10 | External_Dose_1 | 7.99E-10 | Same |
| | Total external dose | | $D_{ext,Ra\text{-}226}$ | 6.4.7-1 | Sv/yr | 1.53E-06 | Total _External | 1.53E-06 | Same |
| Inhalation | Inhalation dose for particles | | $D_{inh,p,Ra\text{-}226}$ | 6.4.8-2 | Sv/yr | 1.84E-08 | Inhalation_Dose | 1.84E-08 | Same |
| | Inhalation dose from evaporative cooler | | $D_{inh,e,Ra\text{-}226}$ | 6.4.8-3 | Sv/yr | 3.36E-09 | Cooler_Inhalation | 3.36E-09 | Same |
| | Inhalation dose from radon | | $D_{inh,g,Rn\text{-}222}$ | 6.4.8-7 | Sv/yr | 1.80E-05 | Total_Radon | 1.80E-05 | Same |
| | Inhalation dose for particles from Pb210D | | - | 6.4.8-2 | Sv/yr | 4.76E-08 | Inhalation_Dose_1 | 4.76E-08 | Same |
| | Total Inhalation dose | | $D_{inh,Ra\text{-}226}$ | 6.4.8-1 | Sv/yr | 1.81E-05 | Total_Inhalation | 1.81E-05 | Same |
| Ingestion | Ingestion dose for water | | $D_{ing,w,Ra\text{-}226}$ | 6.4.9-2 | Sv/yr | 2.62E-07 | Water_Ingestion | 2.62E-07 | Same |
| | Ingestion dose for crops | Leafy vegetation | $D_{ing,p,Ra\text{-}226,1}$ | 6.4.9-3 | Sv/yr | 1.68E-08 | Crop_Ingestion | 1.68E-08 | Same |
| | | Other vegetation | $D_{ing,p,Ra\text{-}226,2}$ | | | 4.48E-09 | | 4.48E-09 | Same |
| | | Fruit | $D_{ing,p,Ra\text{-}226,3}$ | | | 1.05E-08 | | 1.05E-08 | Same |
| | | Grain | $D_{ing,p,Ra\text{-}226,4}$ | | | 9.19E-10 | | 9.19E-10 | Same |
| | Ingestion dose for animal products | Meat | $D_{ing,d,Ra\text{-}226,1}$ | 6.4.9-4 | Sv/yr | 2.52E-09 | Animal_Ingestion | 2.52E-09 | Same |
| | | Milk | $D_{ing,d,Ra\text{-}226,2}$ | | | 3.83E-09 | | 3.83E-09 | Same |
| | | Poultry | $D_{ing,d,Ra\text{-}226,3}$ | | | 8.22E-11 | | 8.22E-11 | Same |
| | | Eggs | $D_{ing,d,Ra\text{-}226,4}$ | | | 2.38E-11 | | 2.38E-11 | Same |
| | Ingestion dose for fish | | $D_{ing,f,Ra\text{-}226}$ | 6.4.9-5 | Sv/yr | 2.29E-08 | Fish_Ingestion | 2.29E-08 | Same |
| | Ingestion dose for soil | | $D_{ing,s,Ra\text{-}226}$ | 6.4.9-6 | Sv/yr | 1.88E-08 | Soil_Ingestion | 1.88E-08 | Same |
| | Ingestion dose from Ra-226 | | - | 6.4.9-1 | Sv/yr | 3.43E-07 | Ingestion_Dose | 3.43E-07 | Same |
| | Ingestion dose for crops | Leafy vegetation | $D_{ing,p,Pb\text{-}210,1}$ | 6.4.9-3 | Sv/yr | 1.31E-08 | Crop_Ingestion_1 | 1.31E-08 | Same |
| | | Other vegetation | $D_{ing,p,Pb\text{-}210,2}$ | | | 1.23E-08 | | 1.23E-08 | Same |
| | | Fruit | $D_{ing,p,Pb\text{-}210,3}$ | | | 5.13E-08 | | 5.13E-08 | Same |
| | | Grain | $D_{ing,p,Pb\text{-}210,4}$ | | | 3.26E-09 | | 3.26E-09 | Same |

Table 6.10-3. Verification of ERMYN Model in GoldSim for the Groundwater Scenario (Case 3, $^{226}Ra$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_GW Result [b] | |
| Ingestion (cont.) | Ingestion dose for animal products | Meat | $D_{ing,d,Pb\text{-}210,1}$ | 6.4.9-4 | Sv/yr | 4.47E-09 | Animal_Ingestion_1 | 4.47E-09 | Same |
| | | Milk | $D_{ing,d,Pb\text{-}210,2}$ | | | 2.64E-09 | | 2.64E-09 | Same |
| | | Poultry | $D_{ing,d,Pb\text{-}210,3}$ | | | 6.07E-10 | | 6.07E-10 | Same |
| | | Eggs | $D_{ing,d,Pb\text{-}210,4}$ | | | 1.72E-08 | | 1.72E-08 | Same |
| | Ingestion dose for soil | | $D_{ing,s,Pb\text{-}210}$ | 6.4.9-6 | Sv/yr | 9.89E-08 | Soil_Ingestion_1 | 9.89E-08 | Same |
| | Ingestion dose from Pb-210 | | - | 6.4.9-1 | Sv/yr | 2.04E-07 | Ingestion_Dose_1 | 2.04E-07 | Same |
| | Total ingestion dose | | $D_{ing,Ra\text{-}226}$ | 6.4.9-1 | Sv/yr | 5.46E-07 | Total_Ingestion | 5.46E-07 | Same |
| All Pathway | All-pathway dose | | $D_{all,Ra\text{-}2226}$ | 6.4.10-1 | Sv/yr | 2.02E-05 | Final_TEDE | 2.02E-05 | Same |
| | BDCF | | $BDCF_{Ra\text{-}226}$ | 6.4.10-2 | (rem/yr)/(pCi/L) | 7.46E-02 | Final_BDCF | 7.46E-02 | Same |

NOTES:

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. Calculations performed in Microsoft Excel 97 SR-2. The electronic file, *ERMYN verification.xls,* which contains this calculation in worksheet *GWRa226*, is listed in Attachment I.

[b] The ERMYN model is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _Ra226verf.gsm*, for this run is listed in Attachment I.

[c] Comparison of results from Calculated Value (Column 6) and ERMYN_GW Result (Column 8).

#### 6.10.1.2 Verification of Stochastic Calculations

To verify the stochastic calculations implemented in the ERMYN model, results from deterministic and stochastic runs are compared for $^{239}$Pu (Table 6.10-4). Differences between the deterministic and stochastic runs are relatively small, within 30 percent. This is because the deterministic inputs ("Mean, Mode, or Average" column in Table 6.6-3) were selected as representative of the parameter distribution used in the stochastic calculations. The deterministic results are within one standard deviation of the stochastic mean values. The stochastic results are considered more realistic.

Table 6.10-4. Results from Deterministic and Stochastic Runs for the Groundwater Scenario

| Parameter | Deterministic Results | Stochastic Results (mean and standard deviation) |
|---|---|---|
| External exposure dose (Sv/yr) | 3.74E-11 | (4.13 ± 2.02)E-11 |
| Inhalation dose (Sv/yr) | 1.23E-06 | (1.52 ± 0.91)E-06 |
| Ingestion dose (Sv/yr) | 8.34E-07 | (9.57 ± 2.29)E-07 |
| BDCF (rem/yr)/(pCi/L) | 7.63E-03 | (9.16 ± 3.59)E-03 |

NOTE: Deterministic calculations done using *ERMYN_GW_Pu239verf.gsm*; stochastic calculations done using *ERMYN_GW_Pu239stoc.gsm*; both listed in Attachment I.

### 6.10.2 Verification of the Volcanic Ash Scenario

#### 6.10.2.1 Verification of Deterministic Calculations

Similar to the groundwater scenario, verification of the implementation of the model for the volcanic ash scenario in GoldSim is performed using reasonable estimates of input values (Table 6.6-3). Two radionuclides, $^{239}$Pu and $^{226}$Ra, are tested for the current climate. For the base case, $^{239}$Pu is selected, and for the radon dose calculations, $^{226}$Ra is selected. The GoldSim files described in this section are listed in Attachment I.

The verification results for $^{239}$Pu are presented in Table 6.10-5, in which the comparison is presented in the order of each submodel discussed in Section 6.5. The hand-calculated results from the important equations in the biosphere model are presented in the table for comparison with the GoldSim results.

Verification results for $^{226}$Ra are presented in Table 6.10-6. The only difference between $^{226}$Ra and $^{239}$Pu is the radon inhalation calculation for $^{226}$Ra. The long-lived decay product, $^{210}$Pb, considered in the groundwater scenario because it accumulates in irrigated soils, is not included in the $^{226}$Ra BDCF for the volcanic ash scenario because it is considered to be a primary radionuclide in the volcanic ash. The results from both methods are the same, indicating that the ERMYN model (volcanic ash scenario; Section 6.5) implementation is correct.

Table 6.10-5. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 1, $^{239}Pu$)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_VA Result [b] | |
| Soil | Concentration in agricultural land | | $Cs_{m,Pu-239}$ | 6.5.1-2 | Bq/kg | 2.67E-03 | SoilMass_Conc | 2.67E-03 | Same |
| | Concentration in non-agricultural land | | $Cs_{mc,Pu-239}$ | 6.5.1-3 | Bq/kg | 5.00E-01 | AshMass_Conc | 5.00E-01 | Same |
| Air | Concentration in air for crop | | $Ca_{p,Pu-239}$ | 6.5.2-1 | Bq/m$^3$ | 6.40E-10 | AirConc_Crop | 6.40E-10 | Same |
| | Concentration in air at nominal condition | Active outdoors | $Ca_{h,Pu-239,1}$ | 6.5.2-4 | Bq/m$^3$ | 1.10E-05 | AirConc_Long | 1.10E-05 | Same |
| | | Inactive outdoors | $Ca_{h,Pu-239,2}$ | | | 2.10E-08 | | 2.10E-08 | Same |
| | | Active indoors | $Ca_{h,Pu-239,3}$ | | | 3.50E-08 | | 3.50E-08 | Same |
| | | Asleep indoors | $Ca_{h,Pu-239,4}$ | | | 1.05E-08 | | 1.05E-08 | Same |
| | | Away from area | $Ca_{h,Pu-239,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| | Concentration in air at post volcanic condition | Active outdoors | $Ca_{v,Pu-239,1}$ | 6.5.2-4 | Bq/m$^3$ | 5.50E-06 | AirConc_Short | 5.50E-06 | Same |
| | | Inactive outdoors | $Ca_{v,Pu-239,2}$ | | | 2.10E-08 | | 2.10E-08 | Same |
| | | Active indoors | $Ca_{v,Pu-239,3}$ | | | 3.50E-08 | | 3.50E-08 | Same |
| | | Asleep indoors | $Ca_{v,Pu-239,4}$ | | | 1.05E-08 | | 1.05E-08 | Same |
| | | Away from area | $Ca_{v,Pu-239,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| Plant | Concentration due to root uptake | Leafy vegetation | $Cp_{root,Pu-239,1}$ | 6.5.3-2 | Bq/kg | 5.41E-08 | Root_Uptake | 5.41E-08 | Same |
| | | Other vegetation | $Cp_{root,Pu-239,2}$ | | | 5.22E-08 | | 5.22E-08 | Same |
| | | Fruit | $Cp_{root,Pu-239,3}$ | | | 5.76E-08 | | 5.76E-08 | Same |
| | | Grain | $Cp_{root,Pu-239,4}$ | | | 4.58E-08 | | 4.58E-08 | Same |
| | | Forage | $Cp_{root,Pu-239,5}$ | | | 5.87E-07 | | 5.87E-07 | Same |
| | Dust interception fraction | Leafy vegetation | $Ra_1$ | 6.5.3-5 | - | 0.456 | Dust_Intercept | 0.456 | Same |
| | | Other vegetation | $Ra_2$ | | | 0.787 | | 0.787 | Same |
| | | Fruit | $Ra_3$ | | | 0.893 | | 0.893 | Same |
| | | Grain | $Ra_4$ | | | 0.962 | | 0.962 | Same |
| | | Forage | $Ra_5$ | | | 0.751 | | 0.751 | Same |
| | Concentration due to dust interception | Leafy vegetation | $Cp_{dust,Pu-239,1}$ | 6.5.3-3 | Bq/kg | 1.20E-06 | Dust_Uptake | 1.20E-06 | Same |
| | | Other vegetation | $Cp_{dust,Pu-239,2}$ | | | 1.67E-07 | | 1.67E-07 | Same |
| | | Fruit | $Cp_{dust,Pu-239,3}$ | | | 2.90E-07 | | 2.90E-07 | Same |
| | | Grain | $Cp_{dust,Pu-239,4}$ | | | 1.46E-06 | | 1.46E-06 | Same |
| | | Forage | $Cp_{dust,Pu-239,5}$ | | | 3.06E-06 | | 3.06E-06 | Same |
| | Concentration in crops | Leafy vegetation | $Cp_{Pu-239,1}$ | 6.5.3-1 | Bq/kg | 1.26E-06 | Plant_Conc | 1.26E-06 | Same |
| | | Other vegetation | $Cp_{Pu-239,2}$ | | | 2.19E-07 | | 2.19E-07 | Same |
| | | Fruit | $Cp_{Pu-239,3}$ | | | 3.48E-07 | | 3.48E-07 | Same |
| | | Grain | $Cp_{Pu-239,4}$ | | | 1.50E-06 | | 1.50E-06 | Same |
| | | Forage | $Cp_{Pu-239,5}$ | | | 3.65E-06 | | 3.65E-06 | Same |

Table 6.10-5. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 1, $^{239}Pu$) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_VA Result [b] | |
| Animal | Concentration due to feed | Meat | $Cd_{feed,Pu-239,1}$ | 6.5.4-2 | Bq/kg | 2.30E-09 | Feed_Contribution | 2.30E-09 | Same |
| | | Milk | $Cd_{feed,Pu-239,2}$ | | | 5.16E-11 | | 5.16E-11 | Same |
| | | Poultry | $Cd_{feed,Pu-239,3}$ | | | 4.69E-10 | | 4.69E-10 | Same |
| | | Eggs | $Cd_{feed,Pu-239,4}$ | | | 6.64E-10 | | 6.64E-10 | Same |
| | Concentration due to soil | Meat | $Cd_{soil,Pu-239,1}$ | 6.5.4-3 | Bq/kg | 2.43E-08 | Soil_Contribution | 2.43E-08 | Same |
| | | Milk | $Cd_{soil,Pu-239,2}$ | | | 5.83E-10 | | 5.83E-10 | Same |
| | | Poultry | $Cd_{soil,Pu-239,3}$ | | | 6.40E-08 | | 6.40E-08 | Same |
| | | Eggs | $Cd_{soil,Pu-239,4}$ | | | 9.07E-08 | | 9.07E-08 | Same |
| | Concentration in animal products | Meat | $Cd_{Pu-239,1}$ | 6.5.4-1 | Bq/kg | 2.66E-08 | Animal_Conc | 2.66E-08 | Same |
| | | Milk | $Cd_{Pu-239,2}$ | | | 6.34E-10 | | 6.34E-10 | Same |
| | | Poultry | $Cd_{Pu-239,3}$ | | | 6.45E-08 | | 6.45E-08 | Same |
| | | Eggs | $Cd_{Pu-239,4}$ | | | 9.13E-08 | | 9.13E-08 | Same |
| External | Environment-specific exposure time | Active outdoors | $\sum(PP_m\ t_{1,m})$ | 6.5.5-1 | hr/d | 0.45 | Weighted_Time | 0.45 | Same |
| | | Inactive outdoors | $\sum(PP_m\ t_{2,m})$ | | | 1.59 | | 1.59 | Same |
| | | Active indoors | $\sum(PP_m\ t_{3,m})$ | | | 10.87 | | 10.87 | Same |
| | | Asleep indoors | $\sum(PP_m\ t_{4,m})$ | | | 8.30 | | 8.30 | Same |
| | | Away from area | $\sum(PP_m\ t_{5,m})$ | | | 2.79 | | 2.79 | Same |
| | Effective exposure time | | $\sum[f_{ext,Pu-239,n}\ \sum(PP_m\ t_{n,m})]$ | 6.5.5-1 | hr/yr | 2848 | External_Time | 2848 | Same |
| | External dose | | $D_{ext,Pu-239}$ | 6.5.5-1 | Sv/yr | 3.76E-12 | Total _External | 3.76E-12 | Same |
| Inhalation | Inhalation dose for long term (at nominal condition) | | $D_{inh,p,Pu-239}$ | 6.5.6-2 | Sv/yr | 3.53E-07 | Inhalation_Long | 3.53E-07 | Same |
| | Inhalation dose for short term (at post-volcanic condition) | | $D_{inh,v,Pu-239}$ | 6.5.6-2 | Sv/yr | 1.86E-07 | Inhalation_Short | 1.86E-07 | Same |
| Ingestion | Ingestion dose for crops | Leafy vegetation | $D_{ing,p,Pu-239,1}$ | 6.5.7-2 | Sv/yr | 4.55E-12 | Crop_Ingestion | 4.55E-12 | Same |
| | | Other vegetation | $D_{ing,p,Pu-239,2}$ | | | 9.92E-13 | | 9.92E-13 | Same |
| | | Fruit | $D_{ing,p,Pu-239,3}$ | | | 4.21E-12 | | 4.21E-12 | Same |
| | | Grain | $D_{ing,p,Pu-239,4}$ | | | 3.30E-13 | | 3.30E-13 | Same |
| | Ingestion dose for animal products | Meat | $D_{ing,d,Pu-239,1}$ | 6.5.7-3 | Sv/yr | 7.24E-14 | Animal_Ingestion | 7.24E-14 | Same |
| | | Milk | $D_{ing,d,Pu-239,2}$ | | | 2.83E-15 | | 2.83E-15 | Same |
| | | Poultry | $D_{ing,d,Pu-239,3}$ | | | 2.59E-14 | | 2.59E-14 | Same |
| | | Eggs | $D_{ing,d,Pu-239,4}$ | | | 4.63E-13 | | 4.63E-13 | Same |
| | Ingestion dose for soil | | $D_{ing,s,Pu-239}$ | 6.5.7-4 | Sv/yr | 9.31E-11 | Soil_Ingestion | 9.31E-11 | Same |
| | Ingestion dose | | $D_{ing,Pu-239}$ | 6.5.7-1 | Sv/yr | 1.04E-10 | Total_Ingestion | 1.04E-10 | Same |

Table 6.10-5. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 1, $^{239}$Pu) (continued)

| Submodel | Parameter in Mathematical Model | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|
| | Parameter Name | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_VA Result [b] | |
| All Pathway | Dose for external, radon and ingestion | $D_{all,Pu\text{-}239}$ | 6.5.8-1 | Sv/yr | 1.08E-10 | TEDE_All | 1.08E-10 | Same |
| | Inhalation dose at post-volcanic condition | $D_{inh,v,Pu\text{-}239}$ | 6.5.8-1 | Sv/yr | 1.86E-07 | TEDE_Short | 1.86E-07 | Same |
| | Inhalation dose at normal condition | $D_{inh,p,Pu\text{-}239}$ | 6.5.8-1 | Sv/yr | 3.53E-07 | TEDE_Long | 3.53E-07 | Same |
| | BDCF for external, radon and ingestion | $BDCF_{Pu\text{-}239}$ | 6.5.8-2 | (rem/yr)/(pCi/m$^2$) | 3.98E-10 | BDCF_All | 3.98E-10 | Same |
| | BDCF for inhalation at post-volcanic condition | $BDCF_{inh,v,Pu\text{-}239}$ | 6.5.8-2 | (rem/yr)/(pCi/m$^2$) | 6.90E-07 | BDCF_InhShort | 6.90E-07 | Same |
| | BDCF for inhalation at normal condition | $BDCF_{inh,p,Pu\text{-}239}$ | 6.5.8-2 | (rem/yr)/(pCi/m$^2$) | 1.30E-06 | BDCF_InhLong | 1.30E-06 | Same |

NOTES:

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. Calculations performed in Microsoft Excel 97 SR-2. The electronic file, *ERMYN verification.xls*, which contains this calculation in worksheet *VAPu239*, is listed in Attachment I.

[b] The ERMYN model is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_VA_PU239verf.gsm*, for this run is listed in Attachment I.

[c] Comparison of results from Calculated Value (Column 6) and ERMYN_GW Result (Column 8).

Table 6.10-6. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 2, Ra-226)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_VA Result [b] | |
| Soil | Concentration in agricultural land | | $Cs_{m,Ra-226}$ | 6.5.1-2 | Bq/kg | 2.67E-03 | SoilMass_Conc | 2.67E-03 | Same |
| | Concentration in non-agricultural land | | $Cs_{mc,Ra-226}$ | 6.5.1-3 | Bq/kg | 5.00E-01 | AshMass_Conc | 5.00E-01 | Same |
| Air | Concentration in air for crop | | $Ca_{p,Ra-226}$ | 6.5.2-1 | Bq/m$^3$ | 6.40E-10 | AirConc_Crop | 6.40E-10 | Same |
| | Concentration in air at nominal condition | Active outdoors | $Ca_{h,Ra-226,1}$ | 6.5.2-4 | Bq/m$^3$ | 1.10E-05 | AirConc_Long | 1.10E-05 | Same |
| | | Inactive outdoors | $Ca_{h,Ra-226,2}$ | | | 2.10E-08 | | 2.10E-08 | Same |
| | | Active indoors | $Ca_{h,Ra-226,3}$ | | | 3.50E-08 | | 3.50E-08 | Same |
| | | Asleep indoors | $Ca_{h,Ra-226,4}$ | | | 1.05E-08 | | 1.05E-08 | Same |
| | | Away from area | $Ca_{h,Ra-226,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| | Concentration in air at post volcanic condition | Active outdoors | $Ca_{v,Ra-226,1}$ | 6.5.2-4 | Bq/m$^3$ | 5.50E-06 | AirConc_Short | 5.50E-06 | Same |
| | | Inactive outdoors | $Ca_{v,Ra-226,2}$ | | | 2.10E-08 | | 2.10E-08 | Same |
| | | Active indoors | $Ca_{v,Ra-226,3}$ | | | 3.50E-08 | | 3.50E-08 | Same |
| | | Asleep indoors | $Ca_{v,Ra-226,4}$ | | | 1.05E-08 | | 1.05E-08 | Same |
| | | Away from area | $Ca_{v,Ra-226,5}$ | | | 0.00E+00 | | 0.00E+00 | Same |
| | Radon concentration in air | | $Ca_{g,Rn-222}$ | 6.5.2-8 | Bq/m$^3$ | 6.00E-04 | AirConc_Radon | 6.00E-04 | Same |
| Plant | Concentration due to root uptake | Leafy vegetation | $Cp_{root,Ra-226,2}$ | 6.5.3-2 | Bq/kg | 1.27E-05 | Root_Uptake | 1.27E-05 | Same |
| | | Other vegetation | $Cp_{root,Ra-226,2}$ | | | 3.30E-06 | | 3.30E-06 | Same |
| | | Fruit | $Cp_{root,Ra-226,3}$ | | | 2.34E-06 | | 2.34E-06 | Same |
| | | Grain | $Cp_{root,Ra-226,4}$ | | | 7.46E-06 | | 7.46E-06 | Same |
| | | Forage | $Cp_{root,Ra-226,5}$ | | | 4.81E-05 | | 4.81E-05 | Same |
| | Dust interception fraction | Leafy vegetation | $Ra_1$ | 6.5.3-5 | - | 0.456 | Dust_Intercept | 0.456 | Same |
| | | Other vegetation | $Ra_2$ | | | 0.787 | | 0.787 | Same |
| | | Fruit | $Ra_3$ | | | 0.893 | | 0.893 | Same |
| | | Grain | $Ra_4$ | | | 0.962 | | 0.962 | Same |
| | | Forage | $Ra_5$ | | | 0.751 | | 0.751 | Same |
| | Concentration due to dust interception | Leafy vegetation | $Cp_{dust,Ra-226,1}$ | 6.5.3-3 | Bq/kg | 1.20E-06 | Dust_Uptake | 1.20E-06 | Same |
| | | Other vegetation | $Cp_{dust,Ra-226,2}$ | | | 1.67E-07 | | 1.67E-07 | Same |
| | | Fruit | $Cp_{dust,Ra-226,3}$ | | | 2.90E-07 | | 2.90E-07 | Same |
| | | Grain | $Cp_{dust,Ra-226,4}$ | | | 1.46E-06 | | 1.46E-06 | Same |
| | | Forage | $Cp_{dust,Ra-226,5}$ | | | 3.06E-06 | | 3.06E-06 | Same |
| | Concentration in crops | Leafy vegetation | $Cp_{Ra-226,1}$ | 6.5.3-1 | Bq/kg | 1.39E-05 | Plant_Conc | 1.39E-05 | Same |
| | | Other vegetation | $Cp_{Ra-226,2}$ | | | 3.46E-06 | | 3.46E-06 | Same |
| | | Fruit | $Cp_{Ra-226,3}$ | | | 2.63E-06 | | 2.63E-06 | Same |
| | | Grain | $Cp_{Ra-226,4}$ | | | 8.92E-06 | | 8.92E-06 | Same |
| | | Forage | $Cp_{Ra-226,5}$ | | | 5.12E-05 | | 5.12E-05 | Same |

Table 6.10-6. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 2, Ra-226) (continued)

| Submodel | Parameter in Mathematical Model | | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|---|
| | Parameter Name | | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_VA Result [b] | |
| Animal | Concentration due to feed | Meat | $Cd_{feed,Ra-226,1}$ | 6.5.4-2 | Bq/kg | 2.01E-06 | Feed_ Contribution | 2.01E-06 | Same |
| | | Milk | $Cd_{feed,Ra-226,2}$ | | | 1.83E-06 | | 1.83E-06 | Same |
| | | Poultry | $Cd_{feed,Ra-226,3}$ | | | 3.94E-08 | | 3.94E-08 | Same |
| | | Eggs | $Cd_{feed,Ra-226,4}$ | | | 9.05E-10 | | 9.05E-10 | Same |
| | Concentration due to soil | Meat | $Cd_{soil,Ra-226,1}$ | 6.5.4-3 | Bq/kg | 1.51E-06 | Soil_Contribution | 1.51E-06 | Same |
| | | Milk | $Cd_{soil,Ra-226,2}$ | | | 1.47E-06 | | 1.47E-06 | Same |
| | | Poultry | $Cd_{soil,Ra-226,3}$ | | | 9.07E-07 | | 9.07E-07 | Same |
| | | Eggs | $Cd_{soil,Ra-226,4}$ | | | 2.08E-08 | | 2.08E-08 | Same |
| | Concentration in animal products | Meat | $Cd_{Ra-226,1}$ | 6.5.4-1 | Bq/kg | 3.52E-06 | Animal_Conc | 3.52E-06 | Same |
| | | Milk | $Cd_{Ra-226,2}$ | | | 3.29E-06 | | 3.29E-06 | Same |
| | | Poultry | $Cd_{Ra-226,3}$ | | | 9.46E-07 | | 9.46E-07 | Same |
| | | Eggs | $Cd_{Ra-226,4}$ | | | 2.17E-08 | | 2.17E-08 | Same |
| External | Environment-specific exposure time | Active outdoors | $\sum(PP_m\ t_{1,m})$ | 6.5.5-1 | hr/d | 0.45 | Weighted_Time | 0.45 | Same |
| | | Inactive outdoors | $\sum(PP_m\ t_{2,m})$ | | | 1.59 | | 1.59 | Same |
| | | Active indoors | $\sum(PP_m\ t_{3,m})$ | | | 10.87 | | 10.87 | Same |
| | | Asleep indoors | $\sum(PP_m\ t_{4,m})$ | | | 8.30 | | 8.30 | Same |
| | | Away from area | $\sum(PP_m\ t_{5,m})$ | | | 2.79 | | 2.79 | Same |
| | Effective exposure time | | $\sum[f_{ext,Ra-226,n}\ \sum(PP_m\ t_{n,m})]$ | 6.5.5-1 | hr/yr | 3548 | External_Time | 3548 | Same |
| | External dose | | $D_{ext,Ra-226}$ | 6.5.5-1 | Sv/yr | 2.12E-08 | Total _External | 2.12E-08 | Same |
| Inhalation | Inhalation dose for long term (at nominal condition) | | $D_{inh,p,Ra-226}$ | 6.5.6-2 | Sv/yr | 7.06E-09 | Inhalation_Long | 7.06E-09 | Same |
| | Inhalation dose for short term (at post-volcanic condition) | | $D_{inh,v,Ra-226}$ | 6.5.6-2 | Sv/yr | 3.74E-09 | Inhalation_Short | 3.74E-09 | Same |
| | Inhalation dose from radon | | $D_{inh,Rn-222}$ | 6.5.6-3 | Sv/yr | 2.17E-08 | Inhalation_Radon | 2.17E-08 | |
| Ingestion | Ingestion dose for crops | Leafy vegetation | $D_{ing,p,Ra-226,1}$ | 6.5.7-2 | Sv/yr | 1.88E-11 | Crop_Ingestion | 1.88E-11 | Same |
| | | Other vegetation | $D_{ing,p,Ra-226,2}$ | | | 5.87E-12 | | 5.87E-12 | Same |
| | | Fruit | $D_{ing,p,Ra-226,3}$ | | | 1.19E-11 | | 1.19E-11 | Same |
| | | Grain | $D_{ing,p,Ra-226,4}$ | | | 7.35E-13 | | 7.35E-13 | Same |
| | Ingestion dose for animal products | Meat | $D_{ing,d,Ra-226,1}$ | 6.5.7-3 | Sv/yr | 3.60E-12 | Animal_Ingestion | 3.60E-12 | Same |
| | | Milk | $D_{ing,d,Ra-226,2}$ | | | 5.50E-12 | | 5.50E-12 | Same |
| | | Poultry | $D_{ing,d,Ra-226,3}$ | | | 1.42E-13 | | 1.42E-13 | Same |
| | | Eggs | $D_{ing,d,Ra-226,4}$ | | | 4.12E-14 | | 4.12E-14 | Same |
| | Ingestion dose for soil | | $D_{ing,s,Ra-226}$ | 6.5.7-4 | Sv/yr | 3.49E-11 | Soil_Ingestion | 3.49E-11 | Same |
| | Ingestion dose | | $D_{ing,Ra-226}$ | 6.5.7-1 | Sv/yr | 8.15E-11 | Total_Ingestion | 8.15E-11 | Same |

Table 6.10-6. Verification of ERMYN Model in GoldSim for the Volcanic Ash Scenario (Case 2, Ra-226) (continued)

| Submodel | Parameter in Mathematical Model | | | | | Parameter in GoldSim | | Notes [c] |
|---|---|---|---|---|---|---|---|---|
| | Parameter Name | Notation in Equation | Equation Number | Units | Calculated Value [a] | Element Name | ERMYN_VA Result [b] | |
| All Pathway | Dose for external, radon and ingestion | $D_{all,Ra\text{-}226}$ | 6.5.8-1 | Sv/yr | 4.30E-08 | TEDE_All | 4.30E-08 | Same |
| | Inhalation dose at post-volcanic condition | $D_{inh,v,Ra\text{-}226}$ | 6.5.8-1 | Sv/yr | 3.74E-09 | TEDE_Short | 3.74E-09 | Same |
| | Inhalation dose at normal condition | $D_{inh,p,Ra\text{-}226}$ | 6.5.8-1 | Sv/yr | 7.06E-09 | TEDE_Long | 7.06E-09 | Same |
| | BDCF for external, radon and ingestion | $BDCF_{Ra\text{-}226}$ | 6.5.8-2 | (rem/yr)/(pCi/m$^2$) | 1.59E-07 | BDCF_All | 1.59E-07 | Same |
| | BDCF for inhalation at post-volcanic condition | $BDCF_{inh,v,Ra\text{-}226}$ | 6.5.8-2 | (rem/yr)/(pCi/m$^2$) | 1.38E-08 | BDCF_InhShort | 1.38E-08 | Same |
| | BDCF for inhalation at normal condition | $BDCF_{inh,p,Ra\text{-}226}$ | 6.5.8-2 | (rem/yr)/(pCi/m$^2$) | 2.61E-08 | BDCF_InhLong | 2.61E-08 | Same |

NOTES:

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. Calculations performed in Microsoft Excel 97 SR-2. The electronic file, *ERMYN verification.xls*, which contains this calculation in worksheet *VARa226*, is listed in Attachment I.

[b] The ERMYN model is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_VA_RA226verf.gsm*, for this run is listed in Attachment I.

[c] Comparison of results from Calculated Value (Column 6) and ERMYN_GW Result (Column 8).

### 6.10.2.2 Verification of Stochastic Calculations

Similar to the groundwater scenario, deterministic and stochastic runs for $^{239}Pu$ are performed using input parameters from Table 6.6-3. The results (Table 6.10-7) reveal small differences between the deterministic and stochastic runs, except for the ingestion dose and BDCF for combined external and ingestion pathways. Unlike the groundwater scenario, in which radionuclide concentrations in the soil depend on the partition coefficient, contaminated ash deposited on the ground is the radionuclide source for the volcanic ash scenario, which results in a relatively small difference between the deterministic and stochastic calculations. For the ingestion pathway, sample means and reasonable estimates for some parameters, such as soil depth and transfer coefficients, are different. As before, differences between the BDCFs calculated using the two methods are not significant because the deterministic results are within the one standard deviation of the stochastic mean values. The stochastic results are considered more realistic.

Table 6.10-7. Results from the Deterministic and Stochastic Runs for the Volcanic Ash Scenario

| Parameter | Deterministic Results | Stochastic Results (mean and standard deviation) |
|---|---|---|
| External dose (Sv/yr) | 3.76E-12 | (3.80 ± 0.07)E-12 |
| Inhalation dose; post-volcanic conditions (Sv/yr) | 1.86E-07 | (2.47 ± 1.49)E-07 |
| Inhalation dose; normal conditions (Sv/yr) | 3.53E-07 | (4.97 ± 3.05)E-07 |
| Ingestion dose (Sv/yr) | 1.04E-10 | (3.30 ± 4.27)E-10 |
| BDCF for external exposure and ingestion (rem/yr)/(pCi/m$^2$) | 3.98E-10 | (1.24 ± 1.58)E-09 |
| BDCF for inhalation; post-volcanic conditions (rem/yr)/(pCi/m$^2$) | 6.90E-07 | (9.12 ± 5.52)E-07 |
| BDCF for inhalation; normal conditions (rem/yr)/(pCi/m$^2$) | 1.30E-06 | (1.84 ± 1.13)E-06 |

NOTE: Deterministic calculations done using *ERMYN_GW_Pu239verf.gsm*; stochastic calculations done using *ERMYN_GW_Pu239stoc.gsm*; both listed in Attachment I.

# 7. MODEL VALIDATION

The ERMYN model is validated to establish confidence that the conceptual (Section 6.3) and mathematical models (Sections 6.4 and 6.5) adequately represent the biosphere systems, processes, and phenomena in the reference biosphere. The model validation approach, including the selection of published biosphere models for the comparison and the validation criteria are discussed in Section 7.1. The conceptual models (Section 7.2) and mathematical models (Section 7.3) are compared to identify similarities and differences. For submodels that differ, numerical comparisons are made (Section 7.4), and the ERMYN submodels are justified. Finally, verification of the ERMYN model implementation in GoldSim is performed by comparing results from the GoldSim implementation with those generated by the GENII-S implementation for the TSPA-SR (Section 7.5). The range of validation for the input parameters is presented in Section 7.6. The conclusions of an external review are presented in Section 7.7.

## 7.1 VALIDATION APPROACH

In this section, the biosphere model validation approach, the selection of published biosphere models and supporting information used for corroboration, and the criteria and level of confidence for the ACMs are discussed.

### 7.1.1 Biosphere Model Validation Approach

The ERMYN model (Section 6) is based on the previous biosphere model, implemented in GENII-S, for the TSPA-SR radiation dose assessments. The current model includes many improvements and modifications to represent site-specific conditions (Section 6.7.2).

As required by the *Models* procedure (AP-SIII.10Q [DIRS 164074]), developed models must be validated to ensure that they are suitable for the intended purpose. The approach to validating the biosphere model is specified in the biosphere TWP (BSC 2003 [DIRS 163602], Section 2). The *Scientific Process Guidelines Manual* (BSC 2002 [DIRS 160313], Appendix B) specifies the levels of model importance and validation, and it describes three levels of validation and associated requirements. Although the Guidelines Manual states that the biosphere model only requires Level I validation for the groundwater scenario (BSC 2002 [DIRS 160313], p. B-9), this report validates the ERMYN model to Level II (which includes Level I requirements). There are two reasons for doing this. First, the ERMYN model, which supports the TSPA-LA, is considerably changed from the older biosphere model. Second, Level II validation requirements are more stringent and provide greater confidence in the model. The Guidelines Manual also states that Level III validation is required for biosphere submodels associated with igneous activity, such as soil thickness, removal, and aeolian and fluvial redistribution (BSC 2002 [DIRS 160313], Appendix B). However, these items are part of the radionuclide source term for the volcanic ash scenario, which is not part of the biosphere model.

Level I validation is performed during model development and includes six requirements (BSC 2002 [DIRS 160313], p. B-1), each of which is discussed to verify that appropriate actions were taken in the model description (Section 6):

a) **Evaluate and select input parameters and data**–Input parameters are defined when they first appeared in the mathematical model description. The physical meaning and typical ranges are discussed, but the input parameter values are evaluated and selected in other analysis reports (Figure 1-1).

b) **Formulate defensible assumptions and simplifications**–All assumptions and simplifications are discussed in Section 5. Rationales for the assumptions, and their use in the biosphere model, are given in Section 5.

c) **Ensure consistency with physical principles, such as conservation of mass, energy, and momentum**–All equations are consistent with basic physical principles. Conservation of mass and radionuclides is preserved in the developed equations. Units for the parameters are checked to ensure consistency.

d) **Represent important future state (aleatoric), parameter, and alternative model uncertainties**–Current and future climate states are considered in the ERMYN model, and different data sets will be developed for the two climate states. Uncertainties associated with the conceptual and mathematical models are discussed (Section 6.6). The source of parameter uncertainty is discussed, and a summary of parameter uncertainty distributions is presented (Table 6.6-3).

e) **Ensure simulation conditions have been set up to span the range of intended use and avoid inconsistent output**–The ERMYN model is implemented using GoldSim software, which provides the necessary simulation environment. Most input parameters are entered as distributions representing reasonable ranges. These parameter distributions are incorporated in the ERMYN model using GoldSim. Outputs from model realizations are obtained while sampling over the full range of input parameters. Therefore, the simulated results are consistent with the input ranges and distributions.

f) **Ensure that model predications (performance parameters) adequately represent the range of possible outcomes, consistent with important uncertainties**–Most of the parameters are represented by distributions, and the number of realizations is large enough (e.g., 1,000) to ensure that the input parameters are sampled over the full range of values and that the model outcomes encompass the full range of possible values.

Level II validation requires the Level I activities, plus one additional post-development model validation method (BSC 2002 [DIRS 160313], p. B-2) selected from a list of seven possibilities (AP-SIII.10Q [DIRS 164074], Section 5.4.1c):

1) Corroboration of model results with data acquired from the laboratory, field experiments, analog studies, or other relevant observations, not previously used to develop or calibrate the model

2) Corroboration of results with alternative mathematical models

3) Corroboration with data published in refereed journals or literature

4) Peer Review per AP-2.12Q [DIRS 155892], *Peer Review*

5) Technical review, planned in the applicable TWP, by reviewers independent of the development, checking, and interdisciplinary review of the model documentation (the Responsible Manager/Lead may not participate in this technical review of products for which they are directly responsible)

6) Corroboration of abstraction model results to the results of the validated process model(s) from which the abstraction was derived

7) Corroboration of pre-test model predictions to data collected during the associated testing.

An additional method can be used to gain confidence in the *Models* procedure (AP-SIII.10Q, Section 5.4.1d): Technical review through publication in a refereed professional journal or review by an external agency, documented by the external agency, may be used to demonstrate additional confidence in the model, if publication or review is used in conjunction with one or more of the post-development validation techniques described in Step 5.4.1c.

Because the ERMYN model is complex and requires hundreds of input values (Section 6.6), it would be difficult to collect all input data through field experiments, laboratory experiments, or other testing on site within a limited time frame. Therefore, comparing model results with data from experimental or other testing is not realistic, and validation methods 1 and 7 cannot be used. Accordingly, corroboration of ERMYN model results with alternative mathematical models (validation method 2) is the principal method for validating the model. Alternative mathematical models result from alternative conceptual models or from different mathematical representations of the same conceptual model. Validation methods 3 and 6 also are used for comparing results from the ERMYN model with results from the selected published models and with data from the published literature.

In addition, technical reviews by external agencies can be used to demonstrate additional confidence in models (AP-SIII.10Q, Section 5.4.1d). Technical review activities for the ERMYN model include an international peer review of the previous biosphere model by an IAEA International Review Team (IAEA 2001 [DIRS 155188]), a model validation status review by experts at Lawrence Livermore National Laboratory (BSC 2001 [DIRS 156257]), and a technical review of the ERMYN model performed separately and independently by another expert at Lawrence Livermore National Laboratory (Daniels 2003 [DIRS 163016]). Recommendations from the first two reviews were incorporated in the ERMYN model. The third review, conducted after the ERMYN model was developed, evaluated functions and improvements in the ERMYN model (Section 7.7).

The ERMYN model is validated through corroboration of the conceptual approach, the mathematical representations, and comparison of the results of individual submodels with the results of published biosphere models that have been used elsewhere for dose assessments. This validation approach is stated in the TWP (BSC 2003 [DIRS 163602], p. 20):

> The biosphere model will be validated through corroboration of the conceptual approach, mathematical representation, and the modeling results for each submodel with those of other published biosphere models. If the mathematical

representations from the published models are mathematically equivalent to, and result in, approximately the same numerical values as the one used in the Yucca Mountain biosphere model, the submodel is considered validated. If the mathematical representations from the published models are not equivalent to the one used in the Yucca Mountain model, a numerical comparison will be conducted by using the appropriate input parameter values to exercise the submodels. Corroboration (i.e. numerical similarity) of the submodels will be considered demonstrated if the results of the numerical comparison are within a factor of 2 over the applicable range of input parameters. This factor of 2 was defined in BSC 2002 ([DIRS 160313] p. B-9). If the numerical results differ by more than a factor of 2 from the expected range of input parameters, corroboration will not be assumed and the modeling methods will be evaluated and the selection of a specific submodel will be justified. The justification of the selected submodel will be documented in the model report.

The main step in validation is corroborating each ERMYN submodel with commonly-used published models to ensure that the ERMYN submodels are appropriate. Validation includes the review of the radiation dose assessment context, evaluation of the biosphere conceptual model and ACMs, consideration of scenarios and radiation pathways, comparison of mathematical submodels with published biosphere models, and documentation of ACMs. The selection of applicable, state-of-the-art published biosphere models (i.e., the validation models) for use in validation is described in Section 7.1.2. The implementation of the validation approach is described in detail below.

If the mathematical representations in the ERMYN or validation models include a parameter that is not used in the other, and if that parameter has no influence on the numerical results for the Yucca Mountain scenarios, the mathematical representations are judged to be equivalent, and no further justification or comparison is required. For example, if a validation model has a parameter that is not used in the ERMYN model, but the parameter is multiplicative and equal to 1 for the Yucca Mountain scenarios, the two representations are mathematically equivalent. Similarly, if a parameter used in the ERMYN is not used in the validation models because of assumptions or site-specific conditions, the equations are mathematically equivalent.

If the validation and ERMYN submodels are mathematically different, they are compared numerically using input parameter values from Table 6.6-3 and, if necessary, default or reasonable values for the validation model. Simple comparisons are presented in Section 7.3. Complex comparisons requiring a series of calculations or the use of a spreadsheet are presented in Section 7.4.

If the validation and ERMYN submodels produce different results, but the difference is less than or equal to a factor of two, the numerical results are similar and no further justification is necessary. Therefore, demonstrating numerical similarity validates the item in the ERMYN model. Usually, comparisons are made by evaluating results at the level of submodels or equations in a submodel, which ensures that differences that could substantially influence dose calculations are identified.

If the validation and ERMYN submodels produce different results, and the difference is more than a factor of two, the difference is evaluated to ensure that it is reasonable. Justification for the selected approach is provided, which usually is based on site-specific or realistically predictable conditions, better incorporating uncertainty, or avoiding over- or underestimating dose calculations.

The overall approach for validating the ERMYN model provides confidence that the ERMYN methods are appropriate because they are similar to, or produce results that are similar to, published state-of-the-art environmental radiation models. In cases where the validation and ERMYN submodels produce different results, this approach ensures that the differences are incorporated for valid reasons and that they improve the model.

### 7.1.2 Selection of Supporting Information

The primary information used to validate the ERMYN model is the descriptions of published biosphere models that are used nationally and internationally for environmental radiation dose assessments. Eleven models were reviewed, and although none use exactly the same pathways as the ERMYN model, they all have comparable submodels (Sections 6.4 and 6.5). Five models were selected for validation because they are representative, in common use, and available. The five selected models, referred to as validation models, are:

- **GENII/GENII-S** (Napier et al. 1988 [DIRS 157927]; Leigh et al. 1993 [DIRS 100464])–This generic computer model for assessing radiation doses was developed by the Pacific Northwest and Sandia National Laboratories. The model supports various sources, including contaminated groundwater, contaminated soil, and air dispersion. This model can be used for evaluating individual and population doses, and for chronic and acute releases. The GENII-S model was used to calculate BDCFs for the TSPA-SR, and limitations in GENII-S (Table 6.7-2) are the basis for developing the ERMYN model.

- **BIOMASS ERB2A** (BIOMASS 2000 [DIRS 154522])–This model, designed for groundwater contamination scenarios using various generic exposure pathways, provides systematic methods for performing postclosure radiation dose assessments for geologic repositories. It was developed by the International Atomic Energy Agency Division of Radiation and Waste Safety. This report is one of a series that provides an example reference biosphere with an agricultural well. Useful information includes the assessment context, biosphere identification, and some input parameter values. BIOMASS ERB2A is not Yucca Mountain specific, but details of the mathematical model are useful.

- **EPRI-YM** (Smith et al. 1996 [DIRS 101085])–This model was developed in 1996 by the Electric Power Research Institute to model a groundwater release at Yucca Mountain. It is one of the few published biosphere models for Yucca Mountain. The report provides a method for identifying biosphere FEPs, identifying other dose assessment requirements for a groundwater scenario at Yucca Mountain, and it presents the mathematical model, the selection of input data, and useful site-specific information. A new revision of the EPRI-YM model uses the BIOMASS ERB2A model (EPRI 2002 [DIRS 158069], Section 8).

- **RESRAD** (Yu et al. 2001 [DIRS 159465])–This generic, but comprehensive tool for estimating radiation doses and risks from radioactive materials in the environment was developed by the Argonne National Laboratory. It is designed for soil contamination scenarios and is useful for comparison with the volcanic ash scenario. The methods for evaluating the movement of radionuclides are considered to be among the best, they are widely accepted in the scientific community, and they are widely used by government agencies and institutions (Yu et al. 2001 [DIRS 159465], p. xvii). Although this model uses radionuclide concentrations in the soil as the primary source, it includes using contaminated groundwater (due to soil leaching) for irrigation. Therefore, this model is useful for comparison with the Yucca Mountain scenarios.

- **NCRP-129** (NCRP 1999 [DIRS 155894])–This document, developed by the National Council on Radiation Protection and Measurements, provides screening limits for contaminated surface soil and reviews factors relevant to site-specific studies. Designed for soil contamination scenarios, this model is useful for comparison with the volcanic ash scenario. The screening limits are calculated conservatively so that no further action is needed if radionuclide concentrations are below the limits. Although the methods are simple, they provide bounding limits for estimations.

Six other biosphere models were reviewed, but they are not used for direct comparison with the ERMYN model because they are similar to the validation models, they do not apply to the Yucca Mountain scenarios, or the methods are not commonly used. These documents are:

- **CNWRA 97-009** (LaPlante and Poor 1997 [DIRS 101079])–This document, produced by the Center for Nuclear Waste Regulatory Analyses, provides information and analyses to support the selection of critical groups and reference biospheres for the Yucca Mountain scenarios. Because this model is based on GENII-S, it is not compared with the ERMYN model.

- **NUREG/CR-5512** (Kennedy and Strenge 1992 [DIRS 103776])–This document, produced by the Pacific Northwest Laboratory, provides generic and site-specific estimates of radiation doses for exposure to residual radioactive contamination after the decommissioning of NRC-licensed facilities. Although the document does not directly mention using the GENII model, the methods, input parameters, and default values are similar to those in the GENII manual (Napier et al. 1988 [DIRS 157927]). In addition, the scenario in this model is similar to that used in RESRAD.

- **NUREG/CR-3332** (Till and Meyer 1983 [DIRS 101895])–This NRC document provides systematic methods for performing generic radiological assessments. This document is cited in newer models, including GENII/GENII-S and RESRAD. This model is not compared because it is similar to newer models.

- **NCRP-76** (NCRP 1984 [DIRS 103784])–This document, produced by the National Council on Radiation Protection and Measurements, provides systematic methods for performing generic radiological assessments. This document is cited in newer models, including GENII/GENII-S and RESRAD, and is not compared because it is similar to newer models.

- **BIOTRAC** (Zach et al. 1996 [DIRS 103831])–This document, produced by Atomic Energy of Canada Limited, Witeshell Laboratories, describes the Canadian biosphere model for assessing the radiological consequences of radioactive waste disposal. This model was developed in association with an environmental impact statement for a postclosure assessment case. The Canadian biosphere is considerably different from Yucca Mountain, so this model is not used in the comparisons.

- **Swedish Biosphere Model** (Karlsson et al. 2001 [DIRS 159470])–This document, produced by the Swedish Nuclear Fuel and Waste Management Company, describes a site-specific biosphere model for a Swedish geological repository. Several release scenarios are considered, including a groundwater release, but not a volcanic ash exposure scenario. Because this model is similar to BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522]), it is not used in the comparisons.

### 7.1.3 Criteria and Level of Confidence

The ERMYN model incorporates the requirements of 10 CFR Part 63 [DIRS 156605], which established the characteristics of the reference biosphere (10 CFR 63.305) and the RMEI (10 CFR 63.312). The results of the ERMYN model will be used to demonstrate compliance with the postclosure individual protection standard (10 CFR 63.311 [DIRS 156605]). Therefore, the ERMYN model will be used in demonstrating compliance with the Individual Protection Standards of 10 CFR Part 63 [DIRS 156605].

The output of the biosphere model will have a direct impact on the results of the TSPA-LA dose calculations because the total (all radionuclides) dose will be calculated as the sum of the products of radionuclide-specific BDCFs and the concentration of individual radionuclides in the source. Variation due to uncertainty in the BDCFs had a small impact on previous dose calculations for the groundwater scenario (CRWMS M&O 2000 [DIRS 153246], p. 5-20), at least in part because BDCF distributions were narrow relative to the distribution of radionuclide concentrations in the groundwater.

Based on the TWP (BSC 2003 [DIRS 163602], Section 2), the biosphere model is validated to a level of confidence commensurate with Level II validation (BSC 2002 [DIRS 160313], p. B-9). This conclusion is based on the facts below.

The ERMYN model deals with a specific environment, is not extrapolated over large distances, and generally does not depend on time. For some radionuclides, however, the surface soil submodel includes long periods of time by assuming constant land use (with irrigation and attendant leaching). This exception only applies to radionuclides with high solid-to-liquid partition coefficients, which would inhibit radionuclide accumulation. Rather than employ a potentially extremely conservative steady-state (long time) solution for the concentration of radionuclides in soil, parameters are developed that allow evolution, build-up, and the incorporation of additional loss mechanisms. Parameters developed for this submodel incorporate long time frames using parameter value distributions for the rates of accumulation and depletion, which address uncertainty in the parameter values.

Overall uncertainty in the ERMYN model is due to uncertainties in the conceptual representation, mathematical representation, and parameter values in each component submodel. Uncertainty associated with each submodel, which is quantified and propagated through the biosphere model, is due to uncertainty in the input parameters. A typical range of BDCF values, due to uncertainty in the input parameter values, is about one order of magnitude (CRWMS M&O 2001 [DIRS 152536]; CRWMS M&O 2001 [DIRS 152539]). This range is relatively low compared with other TSPA components, and it indicates that variation in the overall dose, which is many orders of magnitude, dwarfs variability in the BDCF values (CRWMS M&O 2001 [DIRS 153246], Section 5). Uncertainty in the ERMYN model is evaluated through submodel comparisons.

The level of confidence necessary for the ERMYN model is based on guidance in the TWP for Level II validation (BSC 2002 [DIRS 163602], Section 2), which states that a submodel is considered valid if it is consistent with submodels used and documented in other national or international dose assessment programs, and not using an alternative submodel can be justified based on an explanation of the differences between it and the selected submodel. The biosphere model is valid if the model includes all of the applicable radionuclide transport processes and radiation dose pathways and if each of the corresponding submodels is validated using the methods and criteria listed above.

## 7.2 COMPARISON OF BIOSPHERE CONCEPTUAL MODELS

The biosphere conceptual models for the groundwater (Section 6.3.1) and volcanic ash scenarios (Section 6.3.2) are based on site-specific biosphere FEPs summarized in Section 6.2 and further discussed in Sections 6.3.4 and 6.7.1. To validate the ERMYN model, the biosphere conceptual model, assessment context, scenarios, submodels, and pathways are examined and compared with the validation models. This section documents the results of the comparisons.

### 7.2.1 Review of Biosphere Assessment Context

The assessment context is the general overview of the modeling problem, and the principal consideration in justifying a particular assessment approach is that it is suitable for the intended purpose. Among the five validation models (Section 7.1.2), only two are specific for a groundwater scenario and a geological repository: BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522]) and EPRI-YM (Smith et al. 1996 [DIRS 101085]). The authors of these models provide details of the conceptual models, including the biosphere system identification, justification, and description. GENII-S, RESRAD, and NCRP-129 are generic models that do not have a specific assessment context and therefore are not compared in this section.

Nine aspects of the assessment context for the ERMYN model (groundwater scenario) are compared with those from the BIOMASS ERB2A and EPRI-YM models (Table 7.2-1). The comparison indicates that while the purpose of the models differ, they have many identical or equivalent aspects, and the only major difference is the lower amount of locally produced foodstuffs in the ERMYN model (Societal Assumption). In the BIOMASS ERB2A and EPRI-YM models, most foodstuffs are locally produced. However, consumption rates for locally produced food in the ERMYN model are based on a site-specific survey, which shows

that only a small percentage of the Amargosa population are farmers, that the population imports most of their food, and that agricultural production is limited to a few crops.

The assessment endpoint for the ERMYN model is a TEDE based on the ICRP-26/30 dosimetric methodology (10 CFR 63.2 [DIRS 156605]). Therefore, the human dosimetric model and the corresponding dose conversion factors and dose coefficients should be compatible with this methodology (e.g., Eckerman et al. 1988 [DIRS 101069]; Eckerman and Ryman 1993 [DIRS 107684]), even though this is an older method than is used in the BIOMASS and EPRI-YM models.

Table 7.2-1. Assessment Context for the ERMYN, BIOMASS ERB2A, and EPRI-YM Biosphere Models for Groundwater Contamination

| Issue | ERMYN [a] | BIOMASS ERB2A [b] | EPRI-YM [c] | Comparison |
|---|---|---|---|---|
| Assessment Purpose | Develop dose assessment capability for the TSPA-LA model. | Develop reference biosphere modeling capabilities for an agricultural well scenario. | Develop biosphere model to facilitate independent dose assessment for the Yucca Mountain repository. | ERMYN and EPRI are equivalent; BIOMASS is different. |
| Assessment Endpoint | BDCF based on TEDE for RMEI. | Annual individual effective dose for critical groups. | Annual individual effective dose to members of hypothetical critical groups. | All three are equivalent: ERMYN uses TEDE from ICRP 30 (ICRP 1979 [DIRS 110386]; ICRP 1980 [DIRS 110351]; ICRP 1981 [DIRS 110352]) for the RMEI; BIOMASS and EPRI use effective dose from ICRP 72 (ICRP 1996 [DIRS 152446]) for critical groups. |
| Assessment Philosophy | All parameters are developed based on a reasonable, but conservative approach; “equitable” if possible, “cautious” when unsure. | “Equitable” except for definition of the critical group, which should invoke a “cautious” approach. | “Cautious” for critical groups, “equitable” for other aspects. | All three are equivalent: BIOMASS and EPRI are cautious for human receptor; while ERMYN is equitable for human receptor. |
| Repository Type | Deep repository for long-lived solid radioactive waste. | Deep repository for long-lived solid radioactive waste. | Deep repository for long-lived solid radioactive waste. | All three are the same. |
| Site Context | Specific to the Amargosa Valley; groundwater use, limited climate change. | Generic inland repository; aquifer at accessible depth, no biosphere change. | Vicinity of Yucca Mountain; groundwater use, present climate. | All three are equivalent: ERMYN and EPRI are site-specific; BIOMASS is generic. |
| Geosphere-Biosphere Interface | A well from which contaminated groundwater is pumped; used for drinking, agriculture, and domestic purposes. | Well intruding into aquifer plume with pumping at a rate consistent with domestic and agricultural use. | A deep well sunk into aquifer adjacent to the repository footprint. | All three are the same. |

Table 7.2-1. Assessment Context for the ERMYN, BIOMASS ERB2A, and EPRI-YM Biosphere Models for Groundwater Contamination (continued)

| Issue | ERMYN [a] | BIOMASS ERB2A [b] | EPRI-YM [c] | Comparison |
|---|---|---|---|---|
| Source Term | Constant unit concentration for each radionuclide (Bq/m$^3$ or pCi/L). | Constant unit concentration for each radionuclide (Bq/m$^3$). | Constant radionuclide flux from the well (mol/yr), which can be converted to (Bq/m$^3$). | All three are the same. |
| Societal Assumptions | Current lifestyle of Amargosa Valley residents; rural community, vegetable garden, farm animals, and fish ponds. Small fraction of foodstuffs locally produced. | Agricultural community, using modern cultivation and animal husbandry practices. Community capable of producing a high proportion of the total diet of most foodstuffs. | All foods assumed to be produced locally using modern farming practices, consistent with the modern well abstraction technology. | The three differ: ERMYN uses site-specific data; BIOMASS and EPRI assume all foodstuffs locally produced. |
| Time Frame | Up to 10,000 yrs, up to 1 million yrs. | Up to 1 million yrs. | Up to 1 million yrs. | All three are the same. |

Sources:

[a] This report.

[b] BIOMASS (2000 [DIRS 154522]).

[c] Smith et al. (1996 [DIRS 101085]).

The human receptor for the ERMYN model is the RMEI (10 CFR 63.312 [DIRS 156605]), although the model can be used for other receptors. In the BIOMASS and EPRI-YM models, the human receptor is the critical group. In BIOMASS ERB2A, several groups are considered in finding the most highly exposed critical group.

Two assessment philosophies, cautious and equitable, are used in the biosphere models. The cautious assessment philosophy is based on the assumption that the disposal of radioactive waste represents an involuntary risk from a man-made source from which future generations will derive no benefit (Smith et al. 1996 [DIRS 101085], Section 3.2.1). This assessment philosophy is applied to the critical groups in the BIOMASS and EPRI-YM models. In the ERMYN model, parameters for which there is a lack of information (e.g., translocation factor) are developed based on the cautious assessment philosophy. The equitable assessment philosophy is based on the assumption that radioactive waste disposal constitutes a health risk to present and future generations, and that this health risk is similar to other risks that society chooses to tolerate (Smith et al. 1996 [DIRS 101085], Section 3.2.2). In the ERMYN model, the equitable assessment philosophy is applied to developing input parameters for which there is sufficient information.

The three biosphere models are all specific to a deep geologic repository with a possible radionuclide release through groundwater contamination. Although groundwater transport is not the focus of these studies, an agricultural well pumping contaminated groundwater is the interface between the geosphere and biosphere. A source term of unit concentration of a radionuclide in the groundwater is used to evaluate the biosphere contribution. This indicates that the approach of separating the source term and biosphere contribution is reasonable and acceptable.

### 7.2.2 Consideration of Scenarios, Submodels, and Pathways

The exposure scenarios in the ERMYN model arise from radionuclide releases in groundwater and volcanic ash. For the groundwater exposure scenario, groundwater is the only source of water for people living in the Amargosa Valley. Other dose assessment models (BIOMASS ERB2A and EPRI-YM) consider this scenario (Section 7.2.1). The validation models do not include a volcanic ash exposure scenario. The RESRAD and NCRP-129 models include onsite soil contamination, which is similar to the volcanic ash deposited scenario, and these two models are compared with the ERMYN model for that scenario.

The biosphere conceptual model is based on selected biosphere components (i.e., FEPs), which are the fundamental elements of the submodels. Radionuclide transfer interaction matrices are used in the specific biosphere models (BIOMASS ERB2A and EPRI-YM), and are all similar. The generic biosphere models (GENII-S, RESRAD, and NCRP-129) do not use an interaction matrix, but present their conceptual models. However, their mathematical models are similar to those that use the interaction matrix. Typical biosphere components include groundwater, surface soil, air, plants, animals, fish, and human receptors. Some models, developed for wetter environments, include surface water, sediments, deep soil, and the saturated zone (i.e., aquifers). These components are not used in the ERMYN because they are not present in the arid Yucca Mountain region.

The human exposure pathways and the associated submodels for the five validation models and the two Yucca Mountain models (TSPA-SR and TSPA-LA) are compared (Table 7.2-2). The results of this comparison indicate that the ERMYN model includes all but three of the pathways in the other models. Justification for excluding air submersion and water immersion are given in Section 7.4.8. The ingestion of animal offal is excluded because there is no indication of animal offal in the diet of Amargosa residents. All seven models include most of the exposure pathways, although some pathways are only used in a few models. Detailed comparisons of the ERMYN submodels with the submodels in the validation models are described in the next section.

Table 7.2-2. Pathways and Submodels in Seven Biosphere Models

| Pathway | | Submodel | ERMYN | YMP-SR | GENII-S | BIO-MASS | EPRI-YM | RES-RAD | NCRP-129 |
|---|---|---|---|---|---|---|---|---|---|
| External exposure | Contaminated soil | Soil, External | X | X | X | X | X | X | X |
| | Air submersion | | - | - | X | - | - | - | - |
| | Water immersion | | - | - | X | X | - | - | - |
| Inhalation dose | Resuspended soil (air dust) | Air, Inhalation | X | X | X | X | X | X | X |
| | Radioactive gas ($^{14}C$, $^{222}Rn$) | | X | - | - | - | - | X | X |
| | Water evaporation | | X | - | - | X | - | - | - |
| Ingestion dose | Soil | Soil, Ingestion | X | X | X | X | X | X | X |
| | Drinking water | Ingestion | X | X | X | X | X | X | - |
| | Leafy vegetables | Plant, Ingestion | X | X | X | X | X | X | X |
| | Root vegetables | | X | X | X | X | X | X | X |
| | Fruit | | X | X | X | - | X | - | X |
| | Grain | | X | X | X | X | X | - | X |
| | Fresh feed for cows | Plant | X | X | X | X | X | X | X |
| | Stored feed for birds | | X | X | X | - | X | - | - |
| | Meat | Animal, Ingestion | X | X | X | X | X | X | X |
| | Milk | | X | X | X | X | X | X | X |
| | Offal | | - | - | - | X | X | - | - |
| | Poultry | | X | X | X | - | X | - | - |
| | Eggs | | X | X | X | - | X | - | - |
| | Fish | Fish, Ingestion | X | X | X | X | X | X | - |
| Total Dose | All | All | X | X | X | X | X | X | X |

Source: This table is from Section 6 of this report, CRWMS M&O (2001 [DIRS 152539]), Napier et al. (1988 [DIRS 157927]), BIOMASS (2000 [DIRS 154522]), Smith et al. (1996 [DIRS 101085]), Yu et al. (2001 [DIRS 159465]), and NCRP (1999 [DIRS 155894]).

## 7.3 COMPARISON OF BIOSPHERE MATHEMATICAL SUBMODELS

To validate the ERMYN model, details of the mathematical representations of the biosphere processes in the ERMYN model are compared with similar representations in the validation models (Section 7.1.2). Detailed comparisons, given in the following sections, begin with a summary table (Table 7.3-1) that lists all items compared. For each submodel, the comparison focuses on the core part of the submodels (Sections 6.4 and 6.5). Equation derivations and simple calculations (e.g., unit conversion and summations) are excluded.

Table 7.3-1. Summary of Mathematical Model Comparisons

| Submodel | Table | Item Compared | Equation | Comparison Result |
|---|---|---|---|---|
| Soil | 7.3-2 | Radionuclide concentration in surface soil | 6.4.1-2, 6.4.1-4, 6.4.1-9 | All models use a method equivalent to the ERMYN model. |
| | 7.3-3 | Removal coefficients for surface soil | 6.4.1-10, 6.4.1-11 | Same as above. |
| Air | 7.3-4 | Soil resuspension in air submodel | 6.4.2-1, 6.4.2-2, 6.5.2-1, 6.5.2-2 | Same as above. |
| | 7.3-5 | Radon release from radium contaminated soil | 6.4.2-4, 6.4.2-7, 6.5.2-8 | Only RESRAD and NCRP-129 include the radon pathway. The ERMYN uses the NCRP-129 method, which differs from the RESRAD method. |
| | 7.3-6 | Radionuclide concentration indoors from the operation of evaporative coolers | 6.4.2-3 | No validation models include this pathway. |
| Plant | 7.3-7 | Crop contamination due to root uptake | 6.4.3-2, 6.5.3-2 | All models use the same method as the ERMYN model. |
| | 7.3-8 | Direct deposition on crop leaf surfaces due to interception of irrigation water | 6.4.3-3 | All models except BIOMASS ERB2A use the same method as the ERMYN model. |
| | 7.3-9 | Irrigation deposition rate | 6.4.3-4 | Same as above. |
| | 7.3-10 | Interception fraction of irrigation | 6.4.3-5 | All models use a fixed value independent of irrigation practices. |
| | 7.3-11 | Direct deposition on leaf surfaces due to interception of resuspended soil | 6.4.3-6, 6.5.3-3 | The ERMYN model uses the same method as GENII-S and RESRAD. EPRI-YM, BIOMASS ERB2A, and NCRP-129 use a different method. |
| | 7.3-12 | Dust deposition rate | 6.4.3-7, 6.5.3-4 | Same as above. |
| | 7.3-13 | Interception fraction for resuspended soil | 6.4.3-8, 6.5.3-5 | Same as above. |
| Animal | 7.3-14 | Animal product contamination due to animal feed | 6.4.4-2, 6.5.4-2 | Same as above. |
| | 7.3-15 | Animal product contamination due to drinking water | 6.4.4-3 | Same as above. |
| | 7.3-16 | Animal product contamination due to soil ingestion | 6.4.4-4, 6.5.4-3 | All models except GENII-S use this process. |
| | 7.3-17 | Animal product contamination due to dust inhalation | - | This process is only included in the BIOMASS ERB2A model. |
| Fish | 7.3-18 | Fish contamination due to fishpond water | 6.4.5-1, 6.4.5-2 | All models use the same method as the ERMYN, except for not including evaporation of fishpond water. |
| $^{14}C$ | 7.3-19 | $^{14}C$ special submodel for soil contamination | 6.4.6-1 | ERMYN and RESRAD use the same method; GENII-S and BIOMASS ERB2A use different methods; EPRI-YM and NCRP-129 did not include $^{14}C$. |
| | 7.3-20 | $^{14}C$ special submodel for air contamination | 6.4.6-3 | Same as above. |
| | 7.3-21 | $^{14}C$ special submodel for plant contamination | 6.4.6-6 | Same as above. |
| | 7.3-22 | $^{14}C$ special submodel for animal product contamination | 6.4.6-7 | Same as above. |
| External | 7.3-23 | External exposure to contaminated soil | 6.4.7-1, 6.5.5-1 | All models use the same method as the ERMYN, except for not using exposure time budgets. Few models consider air submersion and water immersion. |

Table 7.3-1. Summary of Mathematical Model Comparisons (continued)

| Submodel | Table | Item Compared | Equation | Comparison Result |
|---|---|---|---|---|
| Inhalation | 7.3-24 | Inhalation dose | 6.4.8-2, 6.4.8-3, 6.4.8-4, 6.4.8-7, 6.5.6-2, 6.5.6-3 | All models use the same method as the ERMYN for air particle inhalation, except that exposure time budgets are not included. Few validation models use radon and $^{14}C$ gas inhalation pathways, and none include evaporative coolers. |
| Ingestion | 7.3-25 | Water ingestion | 6.4.9-2 | All models use the same method as the ERMYN, but the number of ingestion pathways differs among models. |
| | 7.3-26 | Crop ingestion | 6.4.9-3, 6.5.7-2 | Same as above. |
| | 7.3-27 | Animal product ingestion | 6.4.9-4, 6.5.7-3 | Same as above. |
| | 7.3-28 | Fish ingestion | 6.4.9-5 | Same as above. |
| | 7.3-29 | Soil ingestion | 6.4.9-6, 6.5.7-4 | Same as above. |

### 7.3.1 Comparison of Surface Soil Submodels

The surface soil submodels for the groundwater (Section 6.4.1) and volcanic ash (Section 6.5.1) scenarios are different because they have different radionuclide source terms. Under the groundwater scenario, long-term irrigation causes radionuclide buildup in the soil. In contrast, ash deposited on the ground contaminates the surface soil during a single volcanic eruption, but radionuclides do not build up in the surface soil. Therefore, separate comparisons are presented for each scenario.

#### 7.3.1.1 Comparison of Surface Soil Submodels for the Groundwater Scenario

For the groundwater scenario, two items in the surface soil submodel are compared: calculations of radionuclide concentrations in the soil (Table 7.3-2) and removal coefficients (Table 7.3-3). The conversion of radionuclide concentrations in the surface soil to concentrations in the soil mass (Equations 6.4.1-5 and 6.4.1-6) are based on the fundamental relationship between mass and volume, which does not require further comparison and validation.

GENII-S, BIOMASS ERB2A, and EPRI-YM address groundwater contamination and include radionuclide buildup in the soil, although saturation conditions are not used directly in the dose calculations of some models. The EPRI-YM model does not present mathematical equations or solutions for long-term radionuclide buildup in the surface soil, so it is excluded from the comparison. For the RESRAD model, soil contamination is the primary source term, and although it includes irrigation, this is a secondary source calculated from radionuclide removal in the surface soil. Contaminated irrigation water is not a radionuclide source in the NCRP-129 model.

Calculations of soil concentration of radionuclides in the ERMYN (Equation 6.4.1-1) and BIOMASS models (BIOMASS 2000 [DIRS 154522], Equation 8) are based on similar

differential equations and similar initial conditions for the long-term irrigation source. The analytical solution of the differential equation (Equation 6.4.1-2) gives radionuclide concentrations in the surface soil at any time. The GENII-S model does not use the same analytical solution; it uses a numerical method that gives results similar to the analytical solution (Table 7.3-2). A comparison of the treatment of decay products in the ERMYN and GENII-S models is presented in Section 7.4.2.2. The BIOMASS model documentation (BIOMASS 2000 [DIRS 154522]) does not describe the treatment of long-lived decay products in surface soils. Results of the comparison indicate that the calculations of radionuclide concentrations in the soil in the ERMYN, GENII-S, and BIOMASS models are equivalent. The only other differences in the ERMYN, GENII-S, and BIOMASS models for calculating soil concentrations involve calculating removal coefficients (Tables 7.3-2 and 7.3-3).

The methods for calculating removal coefficients are the same in the ERMYN, GENII-S, BIOMASS, and EPRI-YM models, with two exceptions (Table 7.3-3). First, the GENII-S model does not directly include removal by erosion, but because this process can be included in the leaching removal constant by replacing it with an effective removal coefficient, the mathematical approaches are equivalent. Second, the GENII-S and BIOMASS models include harvest removal in calculating radionuclide concentrations in the soil. The ERMYN model does not use a harvest removal factor (Equation 6.4.1.2) because fertilization with animal manure compensates for harvest removal (Assumption 4). Based on this assumption, the mathematical expressions are equivalent.

Because the mathematical representations are the same or give equivalent results, the soil submodel for the groundwater scenario is considered validated

#### 7.3.1.2 Comparison of Surface Soil Submodels for the Volcanic Ash Scenario

GENII-S, RESRAD, and NCRP-129 include soil contamination in a manner applicable to the volcanic ash scenario. The radionuclide source term for these models are in units of $Bq/m^3$ or Bq/kg in soil. Because the source term in the ERMYN model is in units of $Bq/m^2$, it is converted to radionuclide concentration per mass of soil (Bq/kg) based on the depth of the surface soil on cultivated lands (Equation 6.5.1-2) or the critical thickness for ash resuspension on non-cultivated lands (Equation 6.5.1-3). The conversion is based on the fundamental relationship between mass and volume, it is the same in all three models, and it does not require further comparison.

Environmental radiation dose assessments for scenarios similar to the volcanic ash scenario have not been documented in the published literature. Therefore, the approach described in Assumption 12 (the mixing of ash and soil on non-cultivated lands, and the dependence of resuspended soil radionuclide concentrations on ash depth) is unique to the ERMYN model. This approach is expressed in Equations 6.5.1-3 through 6.5.1-5 (Section 6.5.1). The influence of ash depth on activity concentrations in soil is expressed as the ratio of the critical thickness to the actual thickness for ash depths greater than the critical thickness. Because the critical thickness is about 1 to 3 mm (BSC 2003 [DIRS 160964]), it is possible that the depth of ash initially deposited at the location of the receptor would be at least twice that of the critical thickness, this method could result in a difference of more than a factor of two. Additional justification for selecting this method is required for validation.

The justification for this approach is provided in Assumption 12 (Section 5.12). If the volcanic ash deposit is thin (less than the critical thickness), all volcanic ash is readily resuspended; while if volcanic ash deposit is thick (more than critical thickness), only a fraction of the volcanic ash is readily resuspended. This method is reasonable because it uses the same radionuclide concentration in volcanic ash (in volume or mass) as that in resuspended ash particles, and it eliminates overestimating airborne concentrations, which occurs if all deposited radionuclides ($Bq/m^2$) are considered to be within the critical thickness. Based on the above comparison and this justification, the soil submodel for the volcanic scenario is validated.

Table 7.3-2. Comparison of Radionuclide Concentration in Surface Soil

| Document | Mathematical Model | Comparison with the ERMYN Model (Equations 6.4.1-1, 6.4.1-2, 6.4.1-4, and 6.4.1-9) | Reference |
|---|---|---|---|
| GENII-S | $$Cs_1 = \frac{25.4\ Cw_i\ I}{\lambda_l}\left(1 - e^{-\lambda_l t}\right)$$ where<br>• $Cs_1$ = radionuclide activity concentration in soil per unit area after one year of irrigation (Ci/m$^2$)<br>• $Cw_l$ = radionuclide activity concentration in water (Ci/L)<br>• $I$ = crop irrigation rate (in/yr)<br>• 25.4 = unit conversion factor (L/(in. m$^2$))<br>• $\lambda_l$ = leaching coefficient (/yr)<br>• $t$ = time period, yr.<br><br>GENII-S includes radionuclide buildup in the soil using the prior irrigation time with leaching and radionuclide decay. The radionuclide concentration in the soil after $N$ yrs of irrigation is calculated by summing incremental changes in the activity concentration:<br>$$Cs_i = Cs_1 \sum_{n=1}^{N} e^{-\lambda_l n} \times e^{-\lambda_N n} = Cs_1 \sum_{n=1}^{N} e^{-(\lambda_l + \lambda_N)\ n}$$ where<br>• $Cs_l$ = radionuclide concentration in the soil per unit area after $N$ yrs of irrigation (Ci/m$^2$)<br>• $\lambda_N$ = radionuclide decay constant (/yr)<br>• $n$ = number of yrs (yr)<br>• $N$ = total number of years (yr).<br><br>GENII-S also includes harvest removal, which is calculated at the end of each year as:<br>$$Cs' = Cs_1 - C_{crop}\ Y$$<br>• $Cs'$ = soil activity concentration after harvest removal; used in calculations for the next year (Ci/m$^2$)<br>• $C_{crop}$ = crop radionuclide activity concentration (Ci/kg)<br>• $Y$ = crop yield (kg/m$^2$) | • GENII-S includes removal by leaching and decay, but not erosion, although erosion can be combined with the leaching removal constant.<br>• GENII-S calculates long-term radionuclide buildup in the soil by combining single-year net contributions with the number of prior irrigation years. This method is equivalent to the analytical solution (Eq. 6.4.1-1) because the sum of the exponential terms, $\sum[\exp(-\lambda)]$ can be represented by the expression $[1-\exp(-\lambda N)]/[1-\exp(-\lambda)]$.<br>• Although the GENII-S code shows that harvest removal is included, the calculation does not indicate that it is actually subtracted (Wasiolek 2002 [DIRS 162977]).<br><br>The two approaches are different, but the result is the same. In the GENII-S model for the TSPA-SR, BDCFs are calculated at several irrigation time periods to find the saturation condition (CRWMS M&O 2001 [DIRS 153207]). The ERMYN model calculates only the saturation condition. The ERMYN model also calculates the saturation concentration for long-lived decay products that are also primary radionuclides (Equation 6.4.1-9). The GENII/GENII-S manual does not provide the analytical equations for its calculation, but it calculates activity concentration in the soil for the long-lived decay products at a specific time. A comparison is performed (Section 7.4.2) for the equilibrium status of the long-lived decay products between GENII-S and ERMYN models. | Napier et al. 1988 [DIRS 157927], p. 4.57, Eq. 4.6.2. Calculation methods for radionuclide soil buildup, harvest removal, radionuclide decay, and ingrowth are from the GENII-S source code, which is part of the GENII-S software package (SNL 1998 [DIRS 117076]). |

Table 7.3-2. Comparison of Radionuclide Concentration in Surface Soil (continued)

| Document | Mathematical Model | Comparison with the ERMYN Model (Equations 6.4.1-1, 6.4.1-2, 6.4.1-4, and 6.4.1-9) | Reference |
|---|---|---|---|
| BIOMASS ERB2A | $$C_s = \frac{V_{irr}\, C_w}{\lambda_t}\left(1 - e^{-\lambda_t t}\right)$$ • $C_s$ = radionuclide activity concentration in the surface soil (Bq $m^{-2}$)<br>• $V_{irr}$ = irrigation rate, $m^3$/yr, applied to 1-$m^2$ area, which is equivalent to units of m/yr<br>• $C_w$ = radionuclide concentration in groundwater (Bq/$m^3$)<br>• $\lambda_t$ = total removal constant, per yr, expressed as $$\lambda_t = \lambda_N + \lambda_{1C} + \lambda_{1I}$$ • $\lambda_N$ = radionuclide decay constant (/yr)<br>• $\lambda_{1I}$ = infiltration removal rate (/yr)<br>• $\lambda_{1C}$ = cropping removal rate (/yr). $$\lambda_{1C} = \frac{\sum_{crop} \frac{1}{4}\left(CF_{crop} + S_{crop}\right) Y_{crop}}{\left(1 - \theta_t\right) \rho\, d}$$ • $CF_{crop}$ = concentration factor from root uptake (Bq/kg $_{\text{fresh weight of crop}}$ per Bq/kg $_{\text{dry weight of soil}}$)<br>• $S_{crop}$ = soil contamination on crops (kg $_{\text{dry weight soil}}$ /kg $_{\text{fresh weight of crop}}$)<br>• $Y_{crop}$ = wet weight biomass of crops at harvest, obtained from the unit area irrigated (kg/yr)<br>• $\theta_t$ = total porosity of the cultivated soil compartment (dimensionless)<br>• $d$ = thickness of the cultivated soil compartment (m)<br>• $\rho$ = dry grain density of the cultivated soil compartment (kg/$m^3$)<br>• $t$ = total number of years for soil accumulation (yr). After a sufficient time, soil concentration reaches a saturated stage. | BIOMASS ERB2A includes leaching, harvest removal (cropping), and decay removal. It also gives the method for erosion removal. Harvest removal calculations are based on root uptake and external contamination, but not leaf uptake due to interception of irrigation, which may be the major contributor for most radionuclides.<br><br>BIOMASS ERB2A uses equilibrium conditions for dose calculations (BIOMASS 2000 [DIRS 154522], pp. 60 and 61, Tables 22 to 25); therefore, it is the same as the ERMYN model.<br><br>BIOMASS ERB2A is the same as the ERMYN model except that it includes harvest removal and excludes the buildup of long-lived decay products in surface soils.<br><br>BIOMASS ERB2A does not describe the treatment of long-lived decay products accumulation in surface soils. | BIOMASS 2000 [DIRS 154522], p. 33, Eq. 7 and 8. The differential equation in Eq. 8 had inconsistent units for the source term. It is modified using irrigation rate as m/yr and surface soil concentration as Bq/$m^2$. Assumes a constant radionuclide concentration in groundwater over the time of interest. |
| EPRI-YM | Equation for calculating radionuclide concentrations in the surface soil is not given in the document. | N/A | Smith et al. 1996 [DIRS 101085], Section 5. |
| RESRAD | Soil contamination, irrigation is a secondary source. | N/A | Yu et al. 2001 [DIRS 159465]. |
| NCRP-129 | Not included in the model. | N/A | NCRP 1999 [DIRS 155894]. |

Table 7.3-3. Comparison of Removal Coefficients for Surface Soil

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.1-10, and 6.4.1-11) | Reference |
|---|---|---|---|
| GENII-S | $$\lambda_l = \frac{P + I - E}{d\,\theta\left(1 + \frac{\rho}{\theta} K_d\right)}$$ • $\lambda_l$ = leaching coefficient (/yr)<br>• $P$ = precipitation rate (cm/yr)<br>• $I$ = irrigation rate (cm/yr)<br>• $E$ = evapotranspiration rate (cm/yr)<br>• $d$ = depth of surface soil (cm)<br>• $\theta$ = volumetric water content of soil (dimensionless)<br>• $\rho$ = soil bulk density (g/cm$^3$)<br>• $K_d$ = surface soil solid-liquid partition coefficient (mL/g). | The formula shown in the GENII manual (Eq. 4.6.3) is incorrect (CRWMS M&O 2001 [DIRS 152517]). A modified leaching coefficient equation is used in the TSPA-SR. The formula presented here is the modified one, which is the equation used in the ERMYN model, with the input parameter of overwatering rate (*OW*) replacing the equivalent one (*P* + *I* - *E*). | Napier et al. 1988 [DIRS 157927]. The leaching coefficient is a GENII-S input parameter. It is calculated using the equation documented in CRWMS M&O (2001 [DIRS 152517], p. 25) for the TSPA-SR. The equation in GENII (Napier et al. 1988 [DIRS 157927], p. 4.58, Eq. 4.6.3) is not used. |

Table 7.3-3. Comparison of Removal Coefficients for Surface Soil (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.1-10, and 6.4.1-11) | Reference |
|---|---|---|---|
| BIOMASS ERB2A | **Infiltration**<br>$$\lambda_{1I} = \frac{I}{R\,\theta\,d}$$<br>where<br>• $\lambda_{1I}$ = rate coefficient for the transfer of radionuclides out of cultivated soil due to infiltration (/yr)<br>• $I$ = annual infiltration or recharge rate (m/yr)<br>• $\theta$ = water filled porosity of the cultivated soil compartment (dimensionless)<br>• $d$ = thickness of the cultivated soil compartment (m)<br>• $R$ = retardation coefficient for the cultivated soil compartment (dimensionless), which is calculated as<br>$$R = 1 + \frac{(1-\theta_t)\rho}{\theta} K_d$$<br>where<br>• $\theta_t$ = total porosity of the cultivated soil compartment (dimensionless)<br>• $\rho$ = dry grain density of the cultivated soil compartment (kg/m$^3$)<br>• $K_d$ = sorption coefficient for the cultivated soil compartment (m$^3$/kg).<br><br>**Erosion**<br>$$\lambda_{1E} = \frac{E}{d}$$<br>where<br>• $\lambda_{1E}$ = rate coefficient for the transfer of radionuclides from cultivated soil to sinks (i.e., out of system) by erosion (/yr)<br>• $E$ = erosion rate for the soil compartment (m/yr)<br>• $d$ = thickness of the cultivated soil compartment (m). | The leaching rate equation is the same as the ERMYN model with the following equivalent parameters:<br>• The overwatering rate (OW) in the ERMYN model is equivalent to annual infiltration ($I$) in BIOMASS ERB2A<br>• The soil bulk density ($\rho$) in the ERMYN model is equivalent to the cultivated soil density (1 - $\theta_t$)($\rho$) in BIOMASS ERB2A | BIOMASS 2000 [DIRS 154522], pp. 32 and 33, Eqs. 4 to 6. |

Table 7.3-3. Comparison of Removal Coefficients for Surface Soil (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.1-10, and 6.4.1-11) | Reference |
|---|---|---|---|
| EPRI-YM | EPRI-YM uses the same method as BIOMASS ERB2A. Equations are the same, but parameter names may differ from those used in BIOMASS. | EPRI-YM is the same as BIOMASS. | Smith et al. 1996 [DIRS 101085], Eqs 5.2, 5.3, and 5.5. |
| RESRAD | RESRAD uses contaminated soil as initial source, which can be removed from surface soils to deep soil, and eventually to the groundwater. | N/A | Yu et al. 2001 [DIRS 159465]. |
| NCRP-129 | Not included in the model. | N/A | NCRP 1999 [DIRS 155894]. |

### 7.3.2 Validation of the Air Submodel

Particle resuspension is included in the air submodel for both scenarios (Sections 6.4.2.1 and 6.5.2.1), and both scenarios include exhalation of radon from radium-contaminated soil (Sections 6.4.2.3 and 6.5.2.2). The groundwater scenario also includes aerosols from evaporative coolers (Section 6.4.2.2) and the release of $^{14}C$ gas into the air. Particle resuspension from surface soils, radon from radium-contaminated soil, and contaminated aerosols from evaporative coolers are validated in the following sections, and $^{14}C$ gas in the air is validated in Section 7.3.6.

#### 7.3.2.1 Particle Resuspension from Surface Soil

Particle resuspension from surface soils is treated similarly for both scenarios, as both use an enhancement factor and environment-specific mass loading. The volcanic ash scenario also includes time dependent mass loading during the transition period. Radionuclide concentrations in the air are calculated differently for direct deposition on crops (Equations 6.4.2-1 and 6.5.2-1) and human inhalation (Equations 6.4.2-2 and 6.5.2-2). Mass loading for calculating human inhalation exposure depends on specific environments with different levels of activity.

All five validation models include particle resuspension from surface soils, and the core parts of the submodels are the same (Table 7.3-4) because each is based on a mass loading factor and each assumes that the resuspended particles and the surface soil have the same radionuclide concentration per unit mass. The differences between the validation models and the ERMYN model (Table 7.3-4) are:

- BIOMASS includes a retardation coefficient that accounts for radionuclides by the proportion held in soil water. Typical values for the retardation coefficient are much larger than 1 for most radionuclides (based on the retardation coefficient calculation in Table 7.3-3 for BIOMASS ERB2A and input parameters in Table 6.6-3), so the part of the equation with the retardation factor, (R-1)/R, is about equal to one. However, $^{99}Tc$ and $^{36}Tc$ have low partition coefficient ($K_d$) values (0.14 L/kg; Table 6.6-3), which results in a lower retardation coefficient ($R$ = 1.5) and causes the retardation factor to be about 0.33, which differs by more than a factor of two. Excluding this coefficient from the ERMYN model is justified because, although soil water is not resuspended into the air with soil particles, radionuclides in soil water do not disappear when the water evaporates, and they could attach to soil particles that later become resuspended. Therefore, using this factor could underestimate radionuclide concentrations in the air, and the retardation coefficient is excluded to avoid underestimating doses for low partition coefficient radionuclides. However, because these radionuclides do not accumulate in the soil to a large degree, the contribution from these radionuclides to the inhalation dose is relatively low.

- RESRAD includes an area factor to account for the portion of contaminated land. For the groundwater scenario, the total area contaminated by long-term irrigation would be larger because of land use rotation. In the volcanic ash scenario, contaminated ash would be deposited over the entire Amargosa Valley. Thus, the area factor would be about one for both cases and the two methods are mathematically equivalent.

- RESRAD includes a cover-and-depth factor to account for the effects of burying radioactive waste. For the Yucca Mountain scenarios, all radionuclides are in the surface soil, and this factor would be set at one, so the methods are mathematically equivalent.

- None of the validation models use environment-specific mass loading. The ERMYN model uses this method to account for differences in mass loading among, and uncertainty within, various environments. A numerical comparison of the ERMYN and validation model methods is presented in Section 7.4.9. The difference in total activity inhaled per day calculated by the two methods is less than a factor of two (Table 7.4-19), and therefore the two methods are numerically similar.

- The enhancement factor in the ERMYN model (Equations 6.4.2-2 and 6.5.2-2) is also used in NCRP-129. This factor is included in the calculations of activity concentrations in air inhaled by the receptor to account for differences in activity concentrations between large and small resuspended particles. This is an environment-specific parameter with an average value of about four for the active outdoor environment, and an average of less than one for all other environments used in the ERMYN model (Table 6.6-3). Because the average amount of time spent in the active outdoor environment by the RMEI is less than 1 hr/d (Tables 6.6-3 and 7.4-19), the time-weighted enhancement factor for all environments is about one or less. Including the enhancement factor causes a difference in the calculation of airborne activity concentrations by a factor of less than two, and therefore the two methods are numerically similar.

- None of the validation models address mass loading as a function of time. The ERMYN model includes a time function to account for the decrease in mass loading after a volcanic eruption (Equation 6.5.2-2), which avoids overestimating the inhalation dose. Concentrations of resuspended particles during the first year after a volcanic eruption that deposits a thin layer of ash at the location of the receptor likely would not be more than twice as high as those prior to the eruption (BSC 2003 [160965], Section 6.2). For example, average annual concentrations of total suspended particles one year after the eruption of Mount St. Helens at six sites with less than 1 mm to about 10 mm of deposited ash were from about 0 to 90 percent higher than the year prior to the eruption (BSC 2003 [DIRS 160965], Table 6.2.2-1). However, if a large quantity of ash is deposited at the location of the receptor, concentrations in some environments could more than double the mass loading and change airborne concentrations by more than a factor of two. If the submodel does not include the mass loading time function, airborne concentrations remain at high levels throughout the period of calculation. Therefore, the addition of the time function could result in a difference of two or more for some conditions, and an evaluation and justification are needed to validate this portion of the submodel. Concentrations of airborne particles after volcanic eruptions decrease toward per-eruption levels within a relatively short time. For example, concentrations of total suspended particles at six sites in Washington returned to pre-eruption levels within three to eight months after the eruption of Mount St. Helens, and concentrations decreased after other eruptions at similar rates (BSC 2003 [DIRS 160965], Section 6.3). The decrease results from consolidation of ash particles, incorporation of ash into the soil, and removal of ash by residents and natural processes. These processes also would occur in the Yucca Mountain region, although possibly at a different rate (BSC 2003 [DIRS 160965], Section 6.3). Omitting the mass loading time function results in

overestimating airborne activity concentrations during the long period following a volcanic eruption for which doses will be calculated. Because the time function is based on measurement data, because the processes that cause the changes also would occur in the Yucca Mountain region, and because omission of the function results in an invalid overestimation of concentrations, this portion of the air submodel is valid for the volcanic ash scenario.

Based on above discussions, it is concluded that the calculations of particle resuspension from surface soil in the air submodel are mathematically equivalent, numerically similar, or the approach is justified because it includes site-specific or realistically predictable conditions, and therefore this portion of the ERMYN air submodel is validated.

Table 7.3-4. Soil Resuspension in the Air Submodel

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.2-1, 6.4.2-2, 6.5.2-1, and 6.5.2-2) | Reference |
|---|---|---|---|
| GENII-S | $$Ca_i = Cs_i\ M$$ • $Ca_i$ = radionuclide concentration in the air (Ci/m$^3$)<br>• $Cs_I$ = radionuclide activity concentration in soil (Ci/m$^2$)<br>• $M$ = resuspension factor (/m), calculated as $$M = \frac{S}{\rho_s}$$ • $S$ = mass loading, or concentration of total resuspended particles (kg/m$^3$)<br>• $\rho_s$ = surface soil density (kg/m$^2$). | The GENII-S model uses average mass loading, which is the same as mass loading for crops in the ERMYN model (Equations 6.4.2-1 and 6.5.2-1).<br><br>Particle resuspension for inhalation in the ERMYN model uses an enhancement factor and environment-specific mass loading (Eqs. 6.4.2-2 and 6.5.2-2). It also uses time dependent mass loading during the transition period after a volcanic eruption (Eq. 6.5.2-3). | Napier et al. 1988 [DIRS 157927], p. 4.63, Eq. 4.7.2, and p. 4.64, Eq. 4.7.3b. |
| BIOMASS ERB2A | $$C_{airs} = \frac{C_s}{(1-\theta_t)\,\rho}\,\frac{R-1}{R}\,dust_s$$ • $C_{airs}$ = radionuclide concentration in the air above cultivated soils (Bq/m$^3$)<br>• $C_s$ = radionuclide concentration in cultivated soils (Bq/m$^3$)<br>• $\theta_t$ = total porosity of the cultivated soil compartment (dimensionless)<br>• $\rho$ = dry grain density of the cultivated soil compartment (kg/m$^3$)<br>• $R$ = retardation coefficient for cultivated soils (dimensionless)<br>• $dust_s$ = soil derived dust level in the air above cultivated soils (kg/m$^3$). | BIOMASS is equivalent to the GENII-S based on:<br>• The $S$ term in GENII-S is equivalent to the $dust_s$ term in the BIOMASS model<br>• The $C_s$ / $\rho_s$ term in GENII-S is equivalent to the $C_s$ / [(1-$\theta_t$) $\rho$] term in BIOMASS<br>• BIOMASS uses a retardation coefficient ($R$) (defined in Table 7.3-3) which causes the activity concentrations in the air to be element specific. Because $R$ is much larger than 1 for most radionuclides, ($R$ – 1) / $R$ is close to 1 for most radionuclides (see the retardation coefficient calculations in Table 7.3-3). | BIOMASS 2000 [DIRS 154522], p. 36, Eq. 14. |
| EPRI-YM | $$C_{airs} = \frac{C_{sed}}{(1-\theta_{us})\,\rho_{gsed}}\,dust_{sed}$$ • $C_{airs}$ = radionuclide concentration in the air (Bq/m$^3$)<br>• $C_{sed}$ = radionuclide concentration in sediments or soils (Bq/m$^3$)<br>• $\theta_{us}$ = total porosity of the sediment or soil compartment (dimensionless)<br>• $\rho_{gsed}$ = grain density of the sediment or soil compartment (kg/m$^3$)<br>• $dust_{sed}$ = dust level associated with sediments or soils (kg/m$^3$). | EPRI-YM is similar to ERMYN. | Smith et al. 1996 [DIRS 101085], p. 5-14 Eq. 5.16. |

Table 7.3-4. Soil Resuspension in the Air Submodel (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.2-1, 6.4.2-2, 6.5.2-1, and 6.5.2-2) | Reference |
|---|---|---|---|
| RESRAD | $$C_a = ASR_2\ FA_2\ FCD_2(t)\,S(t)$$<br>• $C_a$ = radionuclide concentration in the air (pCi/m$^3$)<br>• $S(t)$ = time-dependent radionuclide concentration in soil mass (pCi/g)<br>• $FA_2$ = area factor (dimensionless)<br>• $FCD_2$ = cover and depth factor (dimensionless)<br>• $ASR_2$ = average mass loading of contaminated airborne soil particles (g/m$^3$). | RESRAD uses an area factor and a cover-and-depth factor. These two factors are used for underground contaminants with a limited area and depth of contamination, which is not used in the ERMYN model. Without these two factors, RESRAD is the same as GENII-S. | Yu et al. 2001 [DIRS 159465], p. B-6, Eq. B.1. Only the parts of the equation applicable to activity concentrations in the air are shown. |
| NCRP-129 | **Method 1: Mass Loading**<br>$$C_{air} = E_f \times S \times M$$<br>• $E_f$ = enhancement factor, the ratio of airborne particle concentration (Bq/kg) to total surface soil concentration (Bq/kg)<br>• $S$ = total surface soil concentration (Bq/kg)<br>• $M$ = total resuspended particulate concentration (mass loading; kg/m$^3$).<br><br>**Method 2: Resuspension Factor**<br>$$C_{air} = S_f \times D$$<br>• $S_f$ = resuspension factor (/m)<br>• $D$ = total decay-corrected soil deposition (inventory; Bq/m$^2$)<br>$$D = \rho\, S\, h_e$$<br>• ρ = soil bulk density (kg/m$^3$); suggests a typical value of 1,600 kg/m$^3$<br>• $h_e$ = effective depth of deposition (m); suggests a value of 5 ± 1.5 cm).<br><br>**Method 3: Mass Loading Derived Resuspension Factors**<br><br>Uses Method 2 to calculate air concentration, but combines Methods 1 and 2 to determine the resuspension factor<br>$$S_f = \frac{E_f \times M}{\rho \times h_e}$$<br>• Parameters defined in Methods 1 and 2. | Method 1 is the same as the ERMYN model. Methods 2 and 3, suggested in NCRP-129, are not often used due to lack of input data, such as the resuspension factor and the effective depth of deposition. | NCRP 1999 [DIRS 155894], pp. 64 to 71, Eqs. 4.3 to 4.13. |

### 7.3.2.2 Radon from Radium-Contaminated Soil

The ERMYN air submodel includes the release of radon from radium-contaminated soil for both exposure scenarios. Under the groundwater scenario, radon concentrations are calculated separately for outdoor air (released from surface soil) and indoor air (based on the outdoor radon and radon in the soil under the foundation of a house; Section 6.4.2.3). For the volcanic ash scenario, the same calculation is used for indoor and outdoor air because there would be no contaminated ash under existing buildings or it would be removed or covered during construction of new buildings. Among the five validation models, RESRAD includes indoor and outdoor radon, NCRP-129 only includes outdoor radon, and the other three validation models do not include radon. RESRAD uses relatively sophisticated radon methods that includes radon emanation from the soil and diffusion in the air.

The indoor air radon calculation for the groundwater scenario (Section 6.4.2.3) is similar to that used in the RESRAD model (Table 7.3-5) with the following exceptions:

- RESRAD uses a radon decay constant that is ignored in the ERMYN model because the typical house ventilation rate (0.5/hr) is larger than the radon decay constant (0.0076/hr).

- RESRAD uses an indoor area factor to account for partially-contaminated house foundations, which does not apply to the Yucca Mountain scenarios.

- The indoor radon flux parameter in the RESRAD model is not defined as proportional to the outdoor radon flux.

Therefore, the indoor air radon calculations in the RESRAD model are mathematically equivalent to those in the ERMYN model.

The NCRP-129 model uses a simple radon release factor, which the ERMYN model uses to determine outdoor radon concentrations for the groundwater scenario (Equation 6.4.2-4). The ERMYN model uses a similar method to determine indoor and outdoor concentrations for the volcanic ash scenario (Equation 6.5.2-8) using a modified release factor (Section 6.5.2). This is different from RESRAD, and therefore the methods are compared numerically (Section 7.4.3.1 and Appendix B). The general differential equation and the boundary conditions given in RESRAD are solved using the ERMYN model parameter values or RESRAD default parameter values if the parameters are not used in the ERMYN model. Using RESRAD, the $^{222}$Rn release factor for volumetric $^{226}$Ra in the soil is 0.19 (Bq/m$^3$)/(Bq/kg) (Section 7.4.3.1 and Table II-1), which is similar to the value of 0.25 (Bq/m$^3$)/(Bq/kg) from the ERMYN model groundwater scenario (Section 6.4.2.3). For the volcanic scenario, RESRAD produces a $^{222}$Rn release factor of 0.0005 (Bq/m$^3$)/(Bq/m$^2$) using a radon emanation coefficient of 1 (Section 7.4.3.1). This is similar to the value of 0.0006 (Bq/m$^3$)/(Bq/m$^2$) from the ERMYN volcanic scenario (Section 6.5.2.2). Because the $^{222}$Rn release factors calculated using the RESRAD and ERMYN methods differ by less than a factor of two, the two methods are numerically similar.

Based on these considerations, the radon calculations are mathematically equivalent or numerically similar, and therefore the ERMYN model methods are validated.

Table 7.3-5. Comparison of Radon Release from Radium Contaminated Soil

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.2-4, and 6.4.2-7) | Reference |
|---|---|---|---|
| GENII-S | Not included. | N/A | Napier et al. 1988 [DIRS 157927]. |
| BIOMASS ERB2A | Not included. | N/A | BIOMASS 2000 [DIRS 154522], Section 7. |
| EPRI-YM | Not included. | N/A | Smith et al. 1996 [DIRS 101085], Section 5.2. |
| RESRAD | The RESRAD radon model for outdoor air (Yu et al. 2001 [DIRS 159465], Section C.2 and C.3, Eq. 1 to Eq. 9) is complicated and includes a radon diffusion equation. The mathematical equations are not shown here.<br><br>Radon model for indoors<br>$$C_i = \frac{\left(\frac{J_i F_{ai}}{H} + \nu C_o\right)}{(\lambda + \nu)}$$<br>• $C_i$ = indoor radon concentration (Bq/m$^3$)<br>• $J_I$ = radon flux from the floor of a house built on a contaminated area (Bq/(m$^2$ sec))<br>• $F_{ai}$ = indoor area factor<br>• $H$ = ceiling height for a single story house<br>• $C_o$ = outdoor radon concentration (Bq/m$^3$)<br>• $\lambda$ = decay constant of radon (/sec)<br>• $\nu$ = ventilation rate of the house (/sec). | The RESRAD submodel for radon concentrations in outdoor air requires site-specific information, such as the diffusion coefficient for radon in the soil and the radon emanation coefficient, which are not available.<br><br>For radon concentrations in indoor air, RESRAD is the same as ERMYN (Eq 6.4.2-7), with the following approximation and equivalent quantities:<br>• The value of $\nu$ is much larger than $\lambda$; typical house ventilation rates are about 0.5/hr, while the radon decay constant is 0.0076/hr.<br>• The indoor radon flux is a fraction of the outdoor flux, $J_I = f_{house}\, J_o$, and the ratio of radon concentration to flux ($C_o/J_o$) could be observed in the natural environment.<br>• The indoor area factor, the fraction of the foundation area that is built on contaminated soil, is 100%. | Yu et al. 2001 [DIRS 159465], Appendix C. |
| NCRP-129 | $$f_{m,Rn-222} = \frac{Ca_{g\ Rn-222}}{Cs_{m,Ra-226}}$$<br>Based on the average $^{226}$Ra concentration measured in soil of 40 Bq/kg, and an average outdoor air radon gas concentration of 10 Bq/m$^3$,<br>$f_{m,Rn-222}$ = 0.25 Bq/m$^3$/Bq/kg | For the groundwater scenario, the radon release factor (or the ratio of average outdoor radon in the air to $^{226}$Ra in the soil) used in NCRP-129 is used in the ERMYN model for calculating outdoor radon concentration (Eq 6.4.2-4).<br>For the volcanic ash scenario, the radon release factor is defined as the ratio of the average airborne radon concentration to the concentration of $^{226}$Ra in the soil. This method is linked to the ratio of average outdoor airborne radon to the average outdoor radon flux density from radium contaminated soil. | NCRP 1999 [DIRS 155894], Section 4.3.6. |

#### 7.3.2.3 Contaminated Aerosols from the Operation of Evaporative Cooler

Evaporative coolers operated using contaminated water would generate contaminated aerosols, and air submodel for the groundwater scenario includes this pathway (Section 6.4.2.2). Calculations of radionuclide concentrations in the air are based on the operating characteristics of evaporative coolers (typical rates for water use and airflow) and the conservation of mass (water and radionuclides).

None of the validation models includes the evaporative cooler exposure pathway. Therefore, the ERMYN method is validated by comparing it with a different mathematical model. Radionuclide concentrations in indoor air can be estimated by accounting for evaporation in terms of the difference in absolute humidity between indoor and outdoor air. Based on physical principles, a fraction of the radionuclides in the contaminated water would be released into the indoor air with the water vapor from the evaporative cooler. The evaporation process would create a difference between the absolute humidity in the indoor and outdoor air. This alternative method is presented in Table 7.3-6 based on known absolute humidities for indoor and outdoor air. Relative humidity can also be used for this because absolute humidity can be determined if the temperature and relative humidity are known. A numerical comparison of the results from the two approaches is documented in Section 7.4.3.2, and the activity concentrations differ by a factor of two (Table 7.4-8). Therefore, the two methods of calculating aerosol concentrations are numerically similar, and this portion of the submodel is validated.

Table 7.3-6. Comparison of Radionuclide Concentration in Indoor Air from the Operation of an Evaporative Cooler

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.2-3) | Reference |
|---|---|---|---|
| | $$Ca = \frac{f_{evap}\,(D_{in} - D_{out})\;Cw}{\rho_w}$$ • $Ca$ = indoor radionuclide concentration (Bq/m$^3$)<br>• $f_{evap}$ = fraction of radionuclide from water to air<br>• $D_{in}$ = absolute indoor humidity (kg/m$^3$)<br>• $D_{out}$ = absolute outdoor humidity (in inlet air) (kg/m$^3$)<br>• $\rho_w$ = water density (kg/m$^3$)<br>• $Cw$ = radionuclide concentration in water (Bq/m$^3$) | The fundamentals of the two methods are the same, but the ERMYN model includes the amount of water used by the evaporative cooler as the amount of water vapor in the air. This ACM considers differences between absolute indoor and outdoor humidity, which is from water used by evaporative coolers. | This method is based on physical principles. |

### 7.3.3 Validation of the Plant Submodel

The plant submodel is used in the groundwater (Section 6.4.3) and volcanic ash scenarios (Section 6.5.3). All five validation models use plant submodels to calculate radionuclide concentrations in crops or human foodstuffs. The ERMYN model includes all radionuclide transfer mechanisms considered in the validation models, including absorption through roots (both scenarios), direct deposition of contaminated water (groundwater scenario only), and soil or ash (both scenarios) on above-ground plant parts. These three aspects of the plant submodel are validated separately in the following sections. Because each aspect of plant submodel is mathematically equivalent, numerically similar, or the approach is justified because it includes site-specific or realistically predictable conditions, the ERMYN plant submodel is validated.

#### 7.3.3.1 Root Uptake

All validation models use similar methods for crop root uptake (Table 7.3-7), with the following differences:

- GENII-S model divides the root zone into two compartments to separately account for deep soil contamination as an initial source of contaminants. However, the contamination in both Yucca Mountain scenarios is on the soil surface, and the ERMYN model assumes that all roots are in the surface soil (Assumption 7). Thus, if used, the GENII-S parameters "deep soil concentration" and "root penetration factor" would be zero in the ERMYN model, making the two methods mathematically equivalent.

- GENII-S includes a parameter for residual soil concentration from deposition in previous years. This parameter accounts for radionuclide accumulation in the soil, which approaches zero as radionuclides reach saturation conditions, which the ERMYN model assumes (Assumption 5). Thus, the methods are mathematically equivalent.

- ERMYN includes the parameter dry-to-wet ratio because the transfer factors used in Equations 6.4.3-2 and 6.5.3-2 are based on dry plant weight. None of the validation models directly use a dry-to-wet ratio because their transfer factors are in units of wet plant weight. Thus, the methods are mathematically equivalent.

- BIOMASS includes a parameter for the fraction of internal contamination retained after food processing. The default value for this parameter is one (i.e., no loss during processing), and processing losses are not included in the ERMYN model; therefore, the methods are mathematically equivalent.

- RESRAD uses an area factor to account for the portion of contaminated land. Under the groundwater scenario, the total area contaminated by long-term irrigation would be large because of land use rotation. Under the volcanic ash scenario, contaminated ash would be deposited over the entire Amargosa Valley. Thus, the area factor would be one for both scenarios, and this calculation is mathematically equivalent to the ERMYN model.

- RESRAD includes a cover-and-depth factor to account for the effects of burying radioactive waste. Because all radionuclides are in the surface soil for the ERMYN scenarios, this factor would be set at one. Therefore, this calculation is mathematically equivalent to the ERMYN.

Thus, the crop root uptake portion of the ERMYN plant submodel is mathematically equivalent to the five validation models, and therefore it is validated.

Table 7.3-7. Comparison of Crop Contamination due to Root Uptake

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.3-2, and 6.5.3.2) | Reference |
|---|---|---|---|
| GENII-S | $$Cr_{ip} = [Cd_i\ R_{p2} + (\frac{Cs_i}{P} + \mathrm{Cb_i})R_{p1}]\ Bv_{ip}$$<br>• $Cr_{ip}$ = plant concentration from root uptake for radionuclide *i* and plant type *p* (Ci/kg)<br>• $Bv_{ip}$ = soil-to-plant transfer factor for radionuclide *i* and plant type *p* (dimensionless)<br>• $Cb_i$ = residual soil concentration from previous years deposition of radionuclide *i* (pCi/kg)<br>• *Csi* = area soil concentration for radionuclide *i* (Ci/m$^2$)<br>• $Cd_i$ = deep soil concentration for radionuclide *i* (Ci/kg)<br>• *P* = effective soil density in the plow layer (kg/m$^2$)<br>• $R_{p1}$ = root penetration factor for surface soil (dimensionless)<br>• $R_{p2}$ = root penetration factor for deep soil (dimensionless). | GENII-S is similar to ERMYN with following approximations and simplifications:<br>• Deep soil is not contaminated ($Cd_i$ = 0), and all crop roots are in the surface soil ($R_{p1}$ = 1, and $R_{ps}$ = 0) (Assumption 7)<br>• Residual soil concentrations from previous years ($Cb_i$) are at the saturated condition in surface soils (Assumption 5)<br>• The GENII-S equation does not include the dry-to-wet ratio, but it could be considered as the soil-to-plant transfer factor ($Bv_{ip}$) based on the wet weight, or $Bv_{ip} = F_{s\rightarrow p}\ DW$, in the ERMYN model. | Napier et al. 1988 [DIRS 157927], p. 4.67, Eq. 4.7.7. |
| BIOMASS ERB2A | $$C_{crop,root} = \frac{F_{p2}\ CF_{crop}\ C_s}{(1-\theta_t)\ \rho}$$<br>• $C_{crop,root}$ = plant root uptake (Bq/kg $_{\text{wet plant}}$)<br>• $C_s$ = radionuclide concentration in soil (Bq/m$^3$)<br>• $\theta_t$ = total soil porosity (dimensionless)<br>• $\rho$ = dry grain density of soil (kg/m$^3$)<br>• $CF_{crop}$ = concentration factor from root uptake for crops (Bq/kg $_{\text{wet plant}}$ per pCi/kg $_{\text{dry soil}}$)<br>• $F_{p2}$ = fraction of internal contamination associated with edible parts of the plant at harvest that is retained after food processing (dimensionless). | BIOMASS ERB2A is the same as ERMYN, except for internal contamination losses due to food processing. Because the default value is 1, the two submodels are the same with the following equivalent parameters:<br>• $C_s$ / [(1 - $\theta_t$) $\rho$] in BIOMASS ERB2A is equivalent to $C_s$ / $\rho_s$ in ERMYN<br>• $CF_{crop}$ in BIOMASS ERB2A is equivalent to $F_{s\rightarrow p}\ DW$ in ERMYN. | BIOMASS 2000 [DIRS 154522], p. 35, Eq. 11. |
| RESRAD | $$E_{p1} = S(0)\ FA_p\ FCD_{p1}\ B_{jv}$$<br>• $E_{p1}$ = plant root uptake (Bq/g $_{\text{wet plant}}$)<br>• $S(0)$ = initial radionuclide concentration in soil (Bq/g $_{\text{dry soil}}$)<br>• $FA_p$ = area factor (dimensionless)<br>• $FCD_{p1}$ = cover-and-depth factor (dimensionless)<br>• $B_{jv}$ = vegetable-soil transfer factor for root uptake (Bq/g $_{\text{wet plant}}$ per Bq/g $_{\text{dry soil}}$). | RESRAD is designed for soil contamination. The equation shown at left is modified to eliminate radionuclide and time dependence, and other subscripts are simplified to reflect root uptake. Two parameters, the area factor and the cover-and-depth factor, are used for underground contaminants with limited area and depth, which is not used in the ERMYN model.<br><br>RESRAD uses the same equation as the ERMYN with the following equivalent parameter:<br>• $B_{i,j}$ in RESRAD is equivalent to $F_{s\rightarrow p}\ DW$ in ERMYN. | Yu et al. 2001 [DIRS 159465], Eq. 3.11, Eqs. D.1 and D.8. |

Table 7.3-7. Comparison of Crop Contamination due to Root Uptake (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.3-2, and 6.5.3.2) | Reference |
|---|---|---|---|
| EPRI-YM | $$C_{crop,root} = \frac{CF_{crop}\, C_{us}}{(1-\theta_{us})\, \rho_{gus}}$$ • $C_{crop,root}$ = plant root uptake (Bq/kg $_{\text{wet plant}}$)<br>• $C_{us}$ = radionuclide concentration in the upper soil compartment (Bq/m$^3$)<br>• $\theta_{us}$ = total porosity in the upper soil compartment (dimensionless)<br>• $\rho_{gus}$ = grain density of the upper soil compartment (kg/m$^3$)<br>• $CF_{crop}$ = concentration factor for crops (Bq/kg $_{\text{fresh weight of crop}}$ per pCi/kg $_{\text{dry weight of soil}}$). | EPRI-YM uses the same equation as BIOMASS ERB2A, except for the fraction of contaminant retained after food processing ($F_{p2}$). Thus, it is the same as the ERMYN. | Smith et al. 1996 [DIRS 101085], p. 5-8, Eq. 5.9. |
| NCRP-129 | $$C_{i,root} = S \times B_v$$ • $C_{i,\,root}$ = concentration in a given type of vegetation due to root uptake (Bq/kg $_{\text{wet plant}}$)<br>• $S$ = radionuclide concentration in the surface soil (Bq/kg $_{\text{dry soil}}$)<br>• $B_v$ = an empirically determined soil-to-vegetation transfer factor for roots, usually expressed as Bq/kg $_{\text{wet vegetation}}$). | NCRP-129 uses the same equation as RESRAD, except for no area factor, and no cover-and-depth factor. Thus, it is the same as the ERMYN model. | NCRP 1999 [DIRS 155894], Section 5.1, Eq. 5.2, p. 92. |

#### 7.3.3.2 Uptake from Irrigation Water

Four of the five validation models, GENII-S, BIOMASS ERB2A, EPRI-YM, and RESRAD, include crop uptake from contaminated irrigation water as a result of direct deposition on leaf surfaces. NCRP-129, which applies only to a soil contamination scenario, does not address this process. The BIOMASS ERB2A and EPRI-YM methods for calculating concentrations in fresh forage (animal feed) are different from those used to calculate concentrations in other crops. These methods are not shown in the comparison (Table 7.3-8) because they are based on cattle fed in pastures, which differs from the farming methods in the Amargosa Valley. The methods these two models use for calculating concentrations in human foodstuffs are compared in Table 7.3-8. The two components for calculating radionuclide uptake, the irrigation deposition rate (Table 7.3-9) and the interception fraction due to irrigation water intercepted by leaf surfaces (Table 7.3-10), are compared separately. Based on the comparisons, the calculations are mathematically equivalent, numerically similar, or have differences that result from model improvements and site-specific conditions, and this portion of the ERMYN plant submodel is validated.

**Radionuclides in Crops**–Among these four validation models, GENII-S and RESRAD use methods similar to the ERMYN model. The BIOMASS ERB2A method includes more transfer processes, is conceptually different from the ERMYN method, and is an ACM (Section 6.3.3). The numerical comparison is described below and in Section 7.4.4.1. The EPRI-YM equation has an error that allows the total activity in the crops to exceed activity in the originally intercepted irrigation water if the fraction of external contamination ($F_{crop}$) is zero. Therefore, the EPRI-YM approach is not valid and is not directly considered here. Differences between the ERMYN and the validation models are:

- None of the validation models use a parameter for the fraction of overhead irrigation (Equation 6.4.3-3). Values of this parameter, ranging from 0 to 1, can be lower than 0.5 for crops such as fruits that normally are drip irrigated (BSC 2003 [DIRS 160976], Section 6.3). Values of 0.5 or lower result in activity concentrations due to irrigation deposition that differ by a factor of two or more, and this portion of the submodel must be further justified. There are three basic methods for irrigating field crops, orchards, and gardens: surface (i.e., flood), drip, and sprinkler irrigation. Of these, only sprinkling directly deposits radionuclides on plant surfaces. Irrigation methods differ among crop types. Drip irrigation often is used on orchard and gardens, and overhead sprinklers and surface irrigation often are used on fields (BSC 2003 [DIRS 160976], Section 6.3). In the Amargosa Valley in 1997, about 85 percent of field crops were irrigated with overhead sprinklers and all of the fruit and nut crops were irrigated with drip systems (BSC 2003 [DIRS 160976], Table 6.3-1). There is little information about the preferred methods of irrigating gardens in the Amargosa Valley; therefore, there is uncertainty in the proportion of crops that would be contaminated by overhead irrigation. The fraction of overhead irrigation is a justifiable improvement to the ERMYN model because it allows for considering site-specific differences in irrigation methods among crop types, accounts for uncertainty in irrigation methods use, and prevents overestimating contamination via this pathway by avoiding the assumption that all crops are irrigated with sprinkler systems. Therefore, using this parameter in the ERMYN plant submodel is justified.

- GENII-S includes parameters that account for radioactive decay during the time from harvest to consumption (holdup time and decay constant). The holdup time generally is days to weeks for fresh produce, which is short relative to radioactive decay rates for the long-lived radionuclides in the ERMYN model (Table 6.3-7). Thus, the exponential factor in GENII-S, which includes the holdup time and decay constant, approaches one, and the methods are mathematically equivalent.

The BIOMASS ERB2A method includes two translocation processes: translocation from external plant surfaces into the plant tissues ($F_{abs}$) and translocation from plant tissues into the edible portion of the crop ($F_{trans}$). It also includes internal ($F_{p2}$) and external ($F_{p3}$) losses due to food processing. Furthermore, it considers that weathering losses occur only during the interval between the last irrigation and harvest ($T$) rather than over the entire growing period. Because frequent irrigation is required during the entire growing season in southern Nevada (BSC 2003 [DIRS 160976], Section 6.5), this consideration is invalid for the ERMYN model. In addition, several parameters used in the BIOMASS ERB2A model, such as the interval time ($T$) and the absorption fraction ($F_{abs}$), are not commonly used in environmental radiation models and therefore are hard to quantify. The BIOMASS and ERMYN methods are numerical compared using input values from Table 6.6-3 and, where necessary, default values from the BIOMASS model (Section 7.4.4.1), and the results differ by a factor of two (Table 7.4-9). Thus, the methods are numerically similar.

**Irrigation Deposition Rate**–The irrigation deposition rate (Equation 6.4.3-4) is used to calculate the direct deposition rate of radionuclides due to application of irrigation water for crops. The ERMYN model and the applicable validation models calculate the deposition rate by multiplying the water concentration by an irrigation rate. The structure of the equations and the input parameters differ in the following ways:

- GENII-S uses an annual irrigation rate divided by the number of months crops are irrigated. The ERMYN model instead uses a daily irrigation rate to eliminate the correlation between irrigation rates and growing season lengths. These terms are mathematically equivalent because they both represent the rate of irrigation application per unit time during the growing season.

- RESRAD uses a factor ($F1$) for the proportion of irrigation water that is contaminated. This value equals one in the ERMYN model because contaminated groundwater is the only source of irrigation water. Thus, the portion of the RESRAD equation with this factor and the associated ratio of surface water concentration to soil concentration ($WSR_2$) becomes one, making the methods mathematically equivalent.

- BIOMASS ERB2A, EPRI-YM, and RESRAD use an annual irrigation rate, without considering the length of the growing season, to determine the average deposition rate. When converted to an annualized rate per day (as is done when divided by the weathering factor in Equation 6.4.3-4), rates based on irrigating over an entire year result in lower deposition rates than rates based on the growing season. This difference is greater than a factor of two for all crops with a growing season of less than six months, and the following evaluation and justification are provided to validate this portion of the submodel. Many of the crops commonly grown in farms and gardens in the Amargosa Valley have growing

seasons of less than 4 months, and no crops types are irrigated all year (BSC 2003 [DIRS 160976], Section 6.4). Using an annual irrigation rate for these crops results in underestimating radionuclide deposition because a rate divided over an entire year would be lower than a rate divided over the growing season. The method in the ERMYN model is used to match the site-specific gardening and agricultural practices in the Amargosa Valley and to avoid underestimating the irrigation deposition rate. Thus, this portion of the submodel is justified.

**Interception Fraction**–The ERMYN method for calculating the proportion of radionuclides in irrigation water intercepted by crops differs from the method in the five validation models, which all include the interception fraction as a single parameter. Default values for the fraction range from 0.05 to 0.3 (Table 7.3-10). In contrast, the ERMYN model uses an empirical equation from Hoffman et al. (1989 [DIRS 124110]) for calculating the interception faction. This equation is based on the interception of $^{7}$Be (i.e., beryllium-7), which has a high interception fraction (Section 6.4.3.2). Inputs to this equation are crop biomass, irrigation amount applied per application, and irrigation intensity. The first two inputs differ among crops, so different distributions are calculated for each crop type.

To compare these methods numerically, interception fractions are calculated using average values for each crop type, and the interception fraction values range from 0.24 for leafy vegetables to 0.51 for grains (Table 7.4-10). Some of the values differ by more than a factor of two from the default values used in the validation models, so an evaluation and justification for the ERMYN model method is provided. The primary reason the empirical equation is used in the ERMYN model is to incorporate variation and uncertainty in irrigation rates and the types of crops grown in the Amargosa Valley. Hoffman et al. (1989 [DIRS 124110]) show that the proportion of radionuclides intercepted differs depending on the size of plants (i.e., aboveground biomass), the rate at which water is applied, the amount of water applied, and the charge carried by the chemical element. Therefore, a single value per crop type is not adequate because there are a substantial number of crops per crop type grown in the Amargosa Valley (BSC 2003 [DIRS 160976], Section 7 and Appendix A). The ERMYN method accounts for differences in irrigation requirements and growth forms of the crops. It also accounts for differences resulting from climate change.

Although experiments indicated that the interception fraction depends on the charge carried by the chemical element (Hoffman et al. 1989 [DIRS 124110]), there is not enough information to calculate radionuclide-specific interception fraction values. Therefore, conservative empirical constants based on the $^{7}$Be results are used in the ERMYN model (Section 6.4.3.2).

The simulated irrigation conditions used by Hoffman et al. (amount of rain = 1 to 30 mm; rain intensity = 2 to 12 cm/hr) generally are comparable with irrigation practices in the Amargosa Valley (Table 6.6-3), except that the amount of irrigation per application for grain and forage (about 55 mm) is higher than the simulated amount of rain. However, the equation is relatively insensitive to the irrigation amount. For example, changing the irrigation application from 15 to 65 mm (and holding the other factors constant at average values) changes the interception fraction from 0.34 to 0.23 (BSC 2003 [DIRS 160976], Section 6.7). The dry biomass of crops in the Amargosa Valley (Table 6.6-3) is generally higher than the experimental conditions used to develop the equation (Hoffman et al. 1989 [DIRS 124110]). However, the interception fraction

asymptotes to one at relatively low values of dry biomass (BSC 2003 [DIRS 160976], Figure 6.1-1), so the equation is insensitive to larger biomass values. Thus, the method is applicable to the site-specific input values in the ERMYN model.

Anspaugh (1987 [DIRS 123696]) reviewed the literature on the retention of radionuclides deposited on crop surfaces. In general, the interception fractions in that report are within the range of average values calculated using the ERMYN method (Table 7.4-10). However, a few of the reviewed studies reported interception fractions higher than the mean values shown in Table 7.4-10 (e.g., greater than 0.7). The amount of rainfall or irrigation applied in these studies was only a fraction of a millimeter per wetting event. Because the irrigation applications in Table 7.4-10 are higher (mean of 15 to 58 mm; Table 6.6-3), the calculated interception fractions (Equation 6.4.3-5) are expected to be lower than the levels obtained experimentally using low application rates.

In summary, the empirical method in the ERMYN model for calculating the irrigation interception fraction incorporates variation and uncertainty in the fraction resulting from differences among crops and in irrigation practices in the Amargosa Valley. The ERMYN method is applicable to the site-specific conditions and is relatively insensitive to input values outside the range of experimental values. The average values calculated using site-specific inputs are similar to values reported in the literature. This method therefore is reasonable, and this portion of the submodel is justified.

Table 7.3-8. Comparison of Direct Deposition on Leaf Surfaces Due to the Interception of Irrigation Water

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-3) | Reference |
|---|---|---|---|
| GENII-S | $$Cl_{ip} = \frac{Du_i \; r \, Tv_p}{\lambda_{e,i} \; Y_p} \left(1 - e^{-\lambda_{e,i} \; te_p}\right) e^{-\lambda_i \; th_p}$$ • $Cl_{ip}$ = concentration of radionuclide *i* in the vegetable for pathway *p* from deposition on leaves (Ci/kg)<br>• $Du_i$ = deposition rate from air or water onto farmland (Ci/m$^2$/sec), calculated in Table 7.3-9<br>• *r* = fraction of initial deposition retained on the crop (dimensionless), used values shown in Table 7.3-10<br>• $Tv_p$ = translocation factor from crop surfaces to the edible crop parts (dimensionless)<br>• $\lambda_{e,i}$ = effective weathering and decay constant (/sec)<br>• $\lambda_i$ = decay constant (/sec)<br>• $te_p$ = duration of the growing period for plant type *p* (sec)<br>• $th_p$ = time between harvest and consumption for crop type *p* (sec)<br>• $Y_p$ = yield of crop type *p* (kg/m$^2$). | Holdup time is not used in ERMYN, as it only uses radioactive decay, which is not important for long-lived radionuclides (Section 6.3.1.5). The fraction of overhead irrigation is used in the ERMYN model to consider other irrigation methods used in Amargosa Valley. | Napier et al. 1988 [DIRS 157927], p. 4.67, Eq. 4.7.6. |
| RESRAD | $$FWR_{j34k} = \frac{I_{rr} \; f_r' T_{jvk}}{\lambda_w \; Y_{vk}} \left(1 - e^{-\lambda_w \; t_{ek}}\right)$$ • $FWR_{j34k}$ = plant-food/water concentration ratio (m$^3$/kg)<br>• $I_{rr}$ = deposition rate from air or water onto farmland (m/yr)<br>• $f_r'$ = fraction of deposited radionuclide retained on vegetation<br>• $T_{jvk}$ = foliage-to-food radionuclide transfer coefficient for the *j*th principal radionuclide and *k*th food class (dimensionless)<br>• $\lambda_{wi}$ = weathering removal constant for vegetation (/yr)<br>• $t_{ek}$ = time of exposure of the *k*th food class to contamination during the growing season (yr)<br>• $Y_{vk}$ = wet-weight crop yield for the *k*th food class (kg/m$^2$). | RESRAD calculates the plant-food/water concentration ratio (m$^3$/kg). The radionuclide concentrations in plants are calculated by using this value multiplying the water concentration (*Cw* – Bq/m$^3$) in the model.<br><br>RESRAD is equivalent to ERMYN, except for the addition of the parameter "fraction of overhead irrigation" to the ERMYN model. | Yu et al. 2001 [DIRS 159465], p. D-14, Eq. D.14. |

Table 7.3-8. Comparison of Direct Deposition on Leaf Surfaces Due to the Interception of Irrigation Water (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-3) | Reference |
|---|---|---|---|
| BIOMASS ERB2A | $$C_{crop,irrig} = I_{crop}\, S \left( \frac{(1-F_{abs})\, e^{-WT}\, F_{p3}}{Y_{crop}} + \frac{F_{abs}\, F_{p2}\, F_{trans}}{Y_{crop}} \right)$$ • $C_{crop,irrig}$ = radionuclide concentration in the edible part of the crop due to irrigation water deposited on crop leaf surface (Bq/kg $_{\text{fresh weight of crop}}$)<br>• $I_{crop}$ = fraction of radionuclides in spray irrigation water initially deposited on standing biomass (dimensionless)<br>• $S$ = irrigation deposition rate (Bq m$^{-2}$ yr$^{-1}$); see Table 7.3-9<br>• $F_{trans}$ = fraction of absorbed activity translocated to edible portions of the plant by the time of harvest (translocation fraction)<br>• $F_{abs}$ = fraction of intercepted radionuclide initially deposited onto plant surfaces absorbed from external surfaces into plant tissues (dimensionless)<br>• $F_{p2}$ = fraction of internal contamination in the edible parts of plants at harvest that is retained after food processing (dimensionless)<br>• $F_{p3}$ = fraction of external contamination from interception retained on edible parts of the plant after food processing (dimensionless)<br>• $W$ = removal (weathering) rate for radionuclides deposited on plant surfaces by irrigation (weathering processes include mechanical weathering, wash-off, and leaf fall) (/yr)<br>• $T$ = interval between irrigation and harvest (yr)<br>• $Y_{crop}$ = wet weight biomass of the crop. | BIOMASS ERB2A uses more transfer processes than the ERMYN, including food processing ($F_{p2}$ and $F_{p3}$), and absorption ($F_{abs}$). It separates internal and external contamination and applies weathering loss to external contamination. As it assumes infrequent irrigation in this model, it uses weathering loss only from the last irrigation to harvest ($T$). The following parameters are equivalent in the two models:<br>• $S$ in BIOMASS is equivalent to $Dw$ in ERMYN<br>• $I_{crop}$ in BIOMASS is equivalent to $Rw$ in ERMYN<br>• $F_{abs} \times F_{trans}$ in BIOMASS is equivalent to $T$ in ERMYN<br>• $Y_{crop}$ in BIOMASS is equivalent to $B$ in ERMYN<br>• $W$ in BIOMASS is equivalent to $\lambda_w$ in ERMYN<br><br>Because BIOMASS ERB2A includes more processes, it is a potential ACM that requires numerical comparison. | BIOMASS 2000 [DIRS 154522], p. 35, Eq. 11. |

Table 7.3-8. Comparison of Direct Deposition on Leaf Surfaces Due to the Interception of Irrigation Water (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-3) | Reference |
|---|---|---|---|
| EPRI-YM | $$C_{crop,irrig} = \mu_{crop}\left(d_{icrop}\, C_{fw}\right)\left(\frac{(1-F_{crop})+F_{trans}}{Y_{crop}\, W_{crop}}\right)$$ • $C_{crop,irrig}$ = radionuclide concentration in crops due to irrigation water deposited on leaf surfaces (Bq/kg $_{\text{fresh weight of crop}}$) • $\mu_{crop}$ = interception factor for irrigation water on crops • $d_{icrop}$ = depth of irrigation water applied to crops (m/yr) • $C_{fw}$ = radionuclide concentration in the freshwater compartment (Bq/m$^3$) • $F_{crop}$ = fraction of external contamination lost due to food processing • $F_{trans}$ = fraction of activity translocated from external to internal surfaces; same as translocation factor • *Wcrop* = removal (weathering) rate of irrigation water from the crop (/yr) • $Y_{crop}$ = yield of the crop (kg/m$^2$). | The EPRI-YM equation has an error that adds the translocation ($F_{trans}$) to the external contamination ($F_{crop}$) factor. For $F_{crop}$ = 0, the total activity in the crop could exceed that originally in intercepted irrigation water. | Smith et al. 1996 [DIRS 101085], p. 5-8, Eq. 5.9. |
| NCRP-129 | Not included in the model. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-9. Comparison of Irrigation Deposition Rate

| **Document** | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-4) | Reference |
|---|---|---|---|
| GENII-S | $$Du_i = \frac{25.4 \times Cw_i \times I}{2.592 \times 10^6\ MY}$$ • $Du_i$ = deposition rate by irrigation (Ci/(m$^2$ sec)) • $I$ = crop irrigation rate (in./yr) • $Cw_I$ = activity concentration of radionuclide in water (Ci/L) • 25.4 = unit conversion factor (L/(in. m$^2$)) • 2.592x10$^6$ = unit conversion factor (sec/month) • $MY$ = irrigation duration (months/yr). | GENII-S uses the duration of irrigation (*MY*) during the crop growing season. In the ERMYN model, this parameter is used in the daily irrigation rate (*IRD*) for crops and is equivalent to (*I* ÷ MY) in GENII-S. The two models are the same, except for different units and notations. | Napier et al. 1988 [DIRS 157927], p. 4.57, Eq. 4.6.2. |
| BIOMASS ERB2A | $$S = V_{irr}\ C_w$$ • $S$ = activity deposition by irrigation (Bq/yr or Bq m$^{-2}$ yr$^{-1}$ depending on the irrigation rate term) • $V_{irr}$ = irrigation rate (m$^3$/yr); this quantity is equivalent to the amount of irrigation water (m) applied to a unit area (m$^2$) per unit time (yr) (m/yr) • $C_w$ = radionuclide concentration in groundwater (Bq/m$^3$). | The irrigation deposition rate in BIOMASS ERB2A is uniformly distributed throughout the year, not just during the growing season, as is used in ERMYN and GENII-S. In addition, a single irrigation rate is applied to all crop types. Most crops do not grow throughout the year, and irrigation should occur only during crop growing season. The difference between annual irrigation rates and daily irrigation rates is not a simple conversion of units because the annual irrigation rate considers the total amount of irrigation in a year and disregards when and how the irrigation occurs. | BIOMASS 2000 [DIRS 154522], p. 32, Eq. 3. |
| RESRAD | $$D = I_{rr}\ [WSR_1\ F1 + WSR_2\ (1\text{-}F1)]\ S(0)$$ • $D$ = radionuclide deposition rate (this parameter is added for comparison) (Bq m$^{-2}$ yr$^{-1}$) • $I_{rr}$ = irrigation rate (m/yr) • $WSR_1$ = ratio of groundwater concentration to the soil concentration of radionuclide (g/L); g/m$^3$ is required for canceling units • $F1$ = groundwater use as a fraction of water from a contaminated source (dimensionless) • $WSR_2$ = ratio of surface water concentration to the soil concentration of radionuclide (g/L); g/m$^3$ is required for canceling units • $S(0)$ = initial radionuclide concentration in soil (Bq/g$_{\text{dry soil}}$). | In the RESRAD document (Yu et al. 2001 [DIRS 159465]), the mathematical representation is based on initial soil contamination, and the source term is discussed in Section 3 of that document, not Appendix D. The equation shown at left is modified to eliminate radionuclide and time dependence. Other subscripts are simplified to reflect irrigation deposition. The terms WSR1 × *S*(0) is equivalent to the calculation of concentrations in groundwater in the ERMYN model. RESRAD is the same as the ERMYN when there is no surface water ($WSR_2$ = 0) and all groundwater is contaminated (*F1* = 1). The unit conversion at left may be different from that shown in the manual because the item compared is not presented directly. Similar to BIOMASS ERB2A, RESRAD does not use irrigation duration, rather it uses an annual rate for the entire year. In addition, a single irrigation rate is used for all crop types. | Yu et al. 2001 [DIRS 159465], Eq. 3.11, Eq. D.14 and D.2. |

Table 7.3-9. Comparison of Irrigation Deposition Rate (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-4) | Reference |
|---|---|---|---|
| EPRI-YM | $S = d_{icorp}\, C_{fw}$<br>• $S$ = radionuclide deposition rate for irrigation (Bq $m^{-2}$ $yr^{-1}$)<br>• $d_{iicorp}$ = depth of irrigation water applied to crops (m/yr)<br>• $C_{fw}$ = radionuclide concentration in the freshwater compartment (Bq/$m^3$). | EPRI-YM is the same as BIOMASS ERB2A. | Smith et al. 1996 [DIRS 101085], p. 5-8. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-10. Comparison of the Intercept Fraction for Irrigation

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-5) | Reference |
|---|---|---|---|
| GENII-S | No mathematical representation for the interception fraction of irrigation in GENII-S. A default value of 0.25 is used for all crop types. | The intercept fraction for irrigation is an important parameter to estimate direct deposition on leaf surfaces due to the interception of irrigation water. A single value is used in most biosphere models. An empirical equation based on experiments conducted by Hoffman et al. (1989 [DIRS 124110]) is used in the ERMYN model because the experiments are applicable to irrigation practices in the Yucca Mountain area and because this equation can be used to develop interception fractions for each crop type. | Napier et al. 1988 [DIRS 157927], p. 4.69. |
| BIOMASS ERB2A | No mathematical representation for the interception fraction of irrigation in BIOMASS ERB2A. A default value of 0.3 is used for all crop types. | | BIOMASS 2000 [DIRS 154522], p. 35, Eq. 11. |
| RESRAD | No mathematical representation for the interception fraction of irrigation in RESRAD. A default value of 0.25 is used for all crop types. | | Yu et al. 2001 [DIRS 159465], Section D.2, Eq. D.9. |
| EPRI-YM | No mathematical representation for the interception fraction of irrigation in EPRI-YM. A value of 0.05 for grain and 0.3 for other crop types is used. | | Smith et al. 1996 [DIRS 101085], p. 5-25. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

#### 7.3.3.3 Uptake from Resuspended Soil

Direct deposition of radionuclides on leaf surfaces due to the interception of resuspended soil is another mechanism by which crops could become contaminated. The ERMYN, GENII-S, and RESRAD models address dust deposition and the subsequent transfer of radionuclides to crops in a manner similar to the interception of irrigation water. The BIOMASS ERB2A, EPRI-YM, and NCRP-129 models address crop surface contamination using a ratio factor (similar to the soil-to-plant transfer factor in the root uptake process). These two approaches are compared mathematically (Table 7-3.11). Two components, the dust deposition rate (Table 7.3-12) and the interception fraction (Table 7.3-13), are compared separately. The results show that the methods are mathematically equivalent, numerically similar, or have differences resulting from model improvements and site-specific conditions, which validates this portion of the ERMYN plant submodel.

**Radionuclides in Crops**–The ERMYN model calculates radionuclide concentrations in plants due to foliar interception of airborne particles (Equations 6.4.3-6 and 6.5.3-3) using a method similar to that used by GENII-S and RESRAD (Table 7.3-11). This method considers the transfer of radionuclides into crops through dust deposition on leaf surfaces, a mechanism similar to the deposition of irrigation water on leaf surfaces. The only difference among these models is that GENII-S includes radioactive decay during the time between harvest and consumption (i.e., holdup time). As explained for water interception, the holdup time is short relative to the decay time of the long-lived radionuclides, and therefore the methods are mathematically equivalent.

BIOMASS ERB2A, EPRI-YM, and NCRP-129 address crop surface contamination using a contamination factor, a method that differs from the ERMYN method and is identified as an ACM (Section 6.3.3). A numerical comparison (Section 7.4.4.3) shows that the activity concentration calculated using the ERMYN method for other vegetables ($3.1 \times 10^{-5}$ Bq/kg; Table 7.4-11) differs by less than a factor of two from the concentration for vegetables and grains using the alternative method ($2.0 \times 10^{-5}$ Bq/kg). In contrast, the ERMYN result for leafy vegetables ($2.2 \times 10^{-4}$ Bq/kg) is an order of magnitude higher than that for the alternative method for vegetables and grains. It is, however, similar to the concentration for forage ($2.0 \times 10^{-4}$ Bq/kg) calculated using the alternative method in BIOMASS, EPRI-YM, and NCRP-129. This is because the ERMYN model uses a high translocation factor for leafy vegetables and forage, whereas the analogous factor in the alternative method (the soil contamination factor) is high only for forage (Section 7.4.4). Because leafy vegetables and forage have similar growth forms (i.e., the consumed portion of the plant, the leaves, are aboveground and directly exposed), the same, high translocation factor should be used for both. Therefore, the alternative method underestimates the radionuclide concentration in leafy vegetables, but the models are numerically similar for the applicable comparison of leafy vegetables to forage. Thus, this portion of the submodel is justified.

**Dust Deposition Rate**–The ERMYN method for calculating the dust deposition rate (Equations 6.4.3-7 and 6.5.3-4) is the same as that in GENII-S and RESRAD, except for the units and associated unit conversion factors (Table 7.3-12). The alternative approach used in the BIOMASS ERB2A, EPRI-YM, and NCRP-129 models does not require calculating the dust deposition rate. The differences between the ERMYN method and the alternative approach to

calculate radionuclide concentrations in plants due to foliar interception of airborne particles are compared above.

**Interception Fraction**–The ERMYN method for calculating the initial fractional deposition of radionuclides on plant surfaces from dry deposition (Equations 6.4.3-8 and 6.5.3-5) is similar to the GENII-S method (Table 7.3-13), with one exception described below. RESRAD uses a fixed value for the interception fraction of resuspended soil, with a default value of 0.25 (Table 7.3-13). Justification is provided below based on a numerical comparison between the RESRAD default value and the calculated values in the ERMYN model. The alternative approach used in the BIOMASS ERB2A, EPRI-YM, and NCRP-129 models does not require a dust interception fraction. Differences between the ERMYN method and the alternative approach for calculating radionuclide concentrations in plants due to foliar interception of airborne particles are already compared.

- The ERMYN and GENII-S models use different measurements of dry biomass for calculating the dust interception fraction. The ERMYN model includes a parameter (dry biomass; Equations 6.4.3-8 and 6.5.3-5) that is defined as the dry weight of aboveground standing biomass. GENII-S calculates dry biomass as the product of crop yield (wet weight) and a dry-to-wet ratio. To evaluate possible differences between these methods, values of the dry biomass parameter are compared to the product of the yield and the dry-to-wet ratio using average parameter values (Table 6.6-3). Dry biomass differed by less than a factor of two for all crop types except grains, which differed by a factor of 2.1 (average dry biomass = 1.13 $kg/m^2$; yield × dry-to-wet ratio = 0.59 $kg/m^2$ × 0.903 = 0.53 $kg/m^2$). Because these two approaches may result in estimates of dry biomass that differ by more than a factor of two, a justification for the ERMYN method is provided. The equation in the ERMYN and GENII-S models was originally developed by Pinder, Ciravolo, and Bowling, as reported by Napier et al. (1988 [DIRS 157927], p. 4.69). This empirical equation requires measurements of dry biomass. Although the GENII manual correctly describes dry biomass as a product of the dry-to-wet biomass ratio and wet standing biomass (Table 7.3-13), the GENII-S code does not require the dry-to-wet biomass ratio as a model input, rather it uses the dry-to-wet ratio for crop products. This is an incorrect method of calculating dry biomass because the dry-to-wet ratios for aboveground biomass and crop products may differ substantially, especially for root crops and crops for which only a small portion of the aboveground biomass is harvested (e.g., grains). In contrast, the ERMYN parameter for dry biomass represents total aboveground, standing-crop biomass. Estimates of the dry biomass parameter in the ERMYN model are based on measurements of crop aboveground dry biomass or on measured ratios of aboveground dry biomass to crop yield (the harvest index; BSC 2003 [DIRS 160976], Section 6.1). Therefore, the ERMYN method is justified because it correctly requires estimates of aboveground dry biomass.

- RESRAD does not calculate the fraction of resuspended particles intercepted by plants; rather, it uses a default value of 0.25 for all crop types. Dust interception fractions calculated using the ERMYN model for average values (Table 6.6-3) range from 0.456 for leafy vegetables to 0.959 for grains (Table 6.10-1). These two approaches produce interception fractions that differ by more than a factor of two, so a justification for the ERMYN method is provided. Field experiments with dry-deposited particles indicate that the interception fraction depends on the deposited materials, particle sizes, and crop types (IAEA 1996 [DIRS

160402], Table I). One experimental result shows that about 96 percent of the deposited $^{212}Pb$ is intercepted by leaves (IAEA 1996 [DIRS 160402], p. 13). Based on the experimental results, a single value of interception fraction for all crop types does not reflect differences among crops, and the default value of 0.25 in the RESRAD model is too low for some crops. Therefore, the method used in the ERMYN is justified.

Table 7.3-11. Comparison of Direct Deposition on Leaf Surface Due to the Interception of Resuspended Soil

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-6, and 6.5.3-3) | Reference |
|---|---|---|---|
| GENII-S | GENII-S uses the same equation as is used for the irrigation interception, except for a different deposition rate, $Du_i$, and interception fraction, $r$ (Table 7.3-8). | GENII-S is similar to the ERMYN. Holdup time is not used in the ERMYN model because the radionuclides of interest are long-lived. | Napier et al. 1988 [DIRS 157927], p. 4.67, Eq. 4.7.6. |
| RESRAD | RESRAD is similar to the equation for irrigation interception, except that irrigation rate, $I_{rr}$, replaces particle deposition velocity, $V_d$, with unit conversions (Table 7.3-8). | RESRAD is the same as the ERMYN. RESRAD calculates a plant-food to air concentration ratio ($m^3$/g). Radionuclide concentrations in plants are calculated using this ratio multiplied by the air concentration (Ca–Bq/$m^3$). | Yu et al. 2001 [DIRS 159465], Eq. D.9 and D.10. |
| BIOMASS ERB2A | BIOMASS does not use dust deposition; instead, it uses a crop soil contamination factor<br>$$C_{crop,dust} = \frac{F_{p1} S_{crop} C_s}{(1-\theta_t)\rho}$$<br>• $C_{crop,dust}$ = dust deposition (Bq/kg $_{\text{wet plant}}$)<br>• $C_s$ = radionuclide concentration in soils (Bq/$m^3$)<br>• $\theta_t$ = total porosity in the soil (dimensionless)<br>• $\rho$ = dry grain density of soil (kg/$m^3$)<br>• $S_{crop}$ = concentration factor from root uptake (Bq/kg $_{\text{wet plant}}$ per pCi/kg $_{\text{dry soil}}$)<br>• $F_{p1}$ = fraction of external soil contamination on edible crop parts retained after food processing, dimensionless). | These three dose assessments use a different method to calculate dust deposition on crops. A crop soil contamination factor, in units of kg $_{\text{dry soil}}$ per kg $_{\text{wet plant}}$ or kg $_{\text{dry plant}}$, is used.<br><br>BIOMASS uses an equation similar to EPRI-YM, except $F_{p1}$ in BIOMASS is equivalent to (1 - $F_{crop}$). NCRP-129 uses a mass soil concentration with no food process losses. These three models use the same method. | BIOMASS 2000 [DIRS 154522], p. 35, Eq. 11. |
| EPRI-YM | EPRI-YM does not use dust deposition; instead, it uses a crop soil contamination factor<br>$$C_{crop,dust} = \frac{(1-F_{crop})\, S_{crop} C_{us}}{(1-\theta_{us})\rho_{gus}}$$<br>• $C_{crop,dust}$ = dust deposition (Bq/kg $_{\text{wet plant}}$)<br>• $F_{crop}$ = fraction of external contamination on the crop lost to food processing<br>• $C_{us}$ = radionuclide concentration in the upper soil compartment (Bq/$m^3$)<br>• $\theta_{us}$ = total porosity in the upper soil compartment (dimensionless)<br>• $\rho_{gus}$ = grain density of the upper soil compartment (kg/$m^3$)<br>• $S_{crop}$ = soil contamination on crops (kg $_{\text{dry weight soil}}$ per kg $_{\text{fresh weight of crop}}$). | | Smith et al. 1996 [DIRS 101085], p. 5-8, Eq. 5.9. |

Table 7.3-11. Comparison of Direct Deposition on Leaf Surface Due to the Interception of Resuspended Soil (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.3-6, and 6.5.3-3) | Reference |
|---|---|---|---|
| NCRP-129 | NCRP-129 does not use dust deposition; instead, is uses transfer factors from soil to vegetation due to soil adhesion for resuspension processes<br>$C_{i,dust} = S \times B_{v'}$<br>• $C_{i,dust}$ = concentration in a crop type due to dust deposition (Bq/kg $_{\text{wet plant}}$)<br>• $S$ = radionuclide concentration in surface soil (Bq/kg $_{\text{dry soil}}$)<br>• $B_{v'}$ = transfer factor for the net effect of all resuspension processes. | | NCRP 1999 [DIRS 155894], p. 92, Eq. 5.2. |

Table 7.3-12. Comparison of the Dust Deposition Rate

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.3-7, and 6.5.3-4) | Reference |
|---|---|---|---|
| GENII-S | $$Du_i = Ca_i \times Vd_i$$ • $Du_i$ = deposition rate for resuspended soil (Ci/(m$^2$ sec)) • $Ca_j$ = air concentration of radionuclide (Ci/m$^3$) • $Vd_i$ = deposition velocity for radionuclide (m/sec). | The GENII-S equation is the same as the ERMYN. | Napier et al. 1988 [DIRS 157927], p. 4.57, Eq. 4.6.1. |
| RESRAD | $$D = 3.16 \times 10^7 \times V_d \times ASR_3 \times S(0)$$ • $D$ = deposition rate for resuspended soil (this parameter is added for the comparison) (Bq/(m$^2$ yr)) • $3.16 \times 10^7$ = unit conversion (sec/yr) • $V_d$ = deposition velocity for radionuclide (m/sec) • $ASR_3$ = air/soil concentration ratio, specified as the average mass loading of airborne contaminated soil particles in a garden during the growing season (g/m$^3$) • $S(0)$ = initial radionuclide concentration in soil (Bq/g $_{\text{dry soil}}$). | RESRAD and ERMYN are the same with the following equivalent quantities: $ASR_3 \times S(0)$ in RESRAD is equivalent to $C_a$, in ERMYN. The unit conversion (to the left) is different from that shown in the manual because the item compared is not presented directly. | Yu et al. 2001 [DIRS 159465], Eq. 3.11, Eq. D.9 and D.10. |
| BIOMASS ERB2A | Dust deposition is not included; instead, it uses a crop soil contamination factor. | Not applicable. | BIOMASS 2000 [DIRS 154522]. |
| EPRI-YM | Dust deposition is not included; instead, it uses a crop soil contamination factor. See the interception fraction for resuspended soil. | | Smith et al. 1996 [DIRS 101085]. |
| NCRP-129 | Dust deposition is not included; instead, it uses transfer factors from soil to vegetation due to soil adhesion for resuspension processes. | | NCRP 1999 [DIRS 155894]. |

Table 7.3-13. Comparison of Interception Fraction for Resuspended Soil

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.3-8, and 6.5.3-5) | Reference |
|---|---|---|---|
| GENII-S | $r = 1.0 - e^{-a\,Y_p\,fd}$<br>• $r$ = interception fraction of resuspended soil deposition (dimensionless)<br>• $a_j$ = empirical factor ($m^2$/kg); 2.9 for leafy vegetables, fresh forage feed, and grain; and 3.6 for root vegetables and fruit<br>• $Y_p$ = standing biomass of growing vegetation (kg $_{\text{wet plant}}$/$m^2$)<br>• $fd$ = dry-to-wet biomass ratio. | The empirical equation for the interception fraction of resuspended soil used in GENII-S is the same as that used in the ERMYN. However, in GENII-S, the dry-to-wet ratio for foodstuff is used for dry-to-wet biomass ratio. These two parameters are different, especially for root vegetables. The ERMYN model uses dry biomass to replace the $Y_p \times fd$ term in GENII-S. The empirical constant, $a_j$, is in the range of valid values from an IAEA review document (IAEA 1996 [DIRS 160402], Section 2.1.2). | Napier et al. 1988 [DIRS 157927], p. 4.69. |
| RESRAD | No mathematical representation for the interception fraction of resuspended soil. A default value of 0.25 is used for all plant types. | The default value is comparable to the results of empirical equation. | Yu et al. 2001 [DIRS 159465], Section D.2, p. D-12. |
| BIOMASS ERB2A | Dust deposition is not included; instead, a crop soil contamination factor is used. A default value of $2 \times 10^{-4}$ kg $_{\text{dry soil}}$ per kg $_{\text{wet plant}}$ is used for leafy vegetables, root vegetables, and grain, and $2 \times 10^{-3}$ is used for fresh forage feed. | Due to differences in the models, numerical comparison of the contribution for direct deposition on crop leaves due to interception of resuspended soil needs to be conducted (Section 7.4.4). | BIOMASS 2000 [DIRS 154522], p. 41, Table 13. |
| EPRI-YM | Dust deposition is not included; instead, a crop soil contamination factor is used. Selected values are $1.3 \times 10^{-4}$ kg $_{\text{dry soil}}$ per kg $_{\text{wet plant}}$ for leafy vegetables and grain, $2.0 \times 10^{-4}$ for root vegetables and fruit, and $8.0 \times 10^{-3}$ for fresh forage feed. | | Smith et al. 1996 [DIRS 101085, p. 5-25. |
| NCRP-129 | Dust deposition is not included; instead, transfer factors from soil to vegetation due to soil adhesion for resuspension processes are used. A value of $1 \times 10^{-4}$ kg $_{\text{dry soil}}$ per kg $_{\text{wet plant}}$ is suggested for cultivated land use. The range is also suggested to be 10 times lower or higher than the recommended value. | | NCRP 1999 [DIRS 155894], p. 104, Table 5.7. |

### 7.3.4 Validation of the Animal Submodel

The animal submodel is used in the groundwater (Section 6.4.4) and volcanic ash (Section 6.5.4) scenarios, except that the drinking water pathway is not included in the volcanic ash scenario. All five validation models use an animal submodel, although some of the models include more contamination processes than others. Each part of the ERMYN animal submodel is validated, as discussed in detail in following four sections. Because the ERMYN animal submodel and the animal submodels in the validation models are mathematically equivalent, numerically similar, or have differences that result from model improvements, the ERMYN animal submodel is validated.

#### 7.3.4.1 Animal Feed

All five validation models use the same method as the ERMYN model for calculating radionuclide concentrations in animal products due to contaminated animal feed (Equations 6.4.4-2 and 6.5.4-2), with two exceptions (Table 7.3-14). First, the GENII-S and NCRP-129 models calculate radionuclide decay during the holdup time between harvest and consumption. The holdup time is short (generally days to weeks for fresh forage; weeks to months for grain) relative to the rate of radioactive decay for long-lived radionuclides (Table 6.3-7). Thus, the exponential factor in the GENII-S and NCRP-129 models, which includes the holdup time and decay constant, approaches one, and the methods are mathematically equivalent. Second, the GENII-S and NCRP-129 models include a parameter for the proportion of contaminated animal feed. In the ERMYN model, this parameter value is assumed to be 100 percent (Assumption 8), and therefore the methods are mathematically equivalent.

#### 7.3.4.2 Drinking Water

The NCRP-129 model does not use contaminated water, but the other four validation models use the same method as the ERMYN model (Equation 6.4.4-3), with two exceptions (Table 7.3-15). First, the GENII-S model includes radionuclide decay during the holdup time between pumping of groundwater and consumption by animals, which is short relative to the rate of radioactive decay for long-lived radionuclides (Table 6.3-7). Thus, the methods are mathematically equivalent. Second, the GENII-S model uses a parameter for the proportion of contaminated water. Because all water is contaminated in the ERMYN model, the value of this parameter is one, and the methods are mathematically equivalent.

#### 7.3.4.3 Soil Ingestion

Three of the validation models (BIOMASS ERB2A, RESRAD, and EPRI-YM) include soil ingestion, and they all use the same method as the ERMYN model (Equations 6.4.4-4 and 6.5.4-3; Table 7.3-16). Therefore, they are mathematically equivalent.

The other two models do not include this process. The omission of this contamination mechanism is an ACM (Section 6.3.3), and a numerical evaluation is conducted to evaluate the importance of soil ingestion to animal product contamination (Section 7.4.5). Omitting soil ingestion by animals results in a difference in radionuclide concentrations in meat by more than a factor of two because this process may account for about 75 percent of the total concentration

(Table 7.4-12). The ERMYN model includes soil ingestion by animals to avoid underestimating the dose from this pathway. Therefore, this addition to the ERMYN animal submodel is justified.

#### 7.3.4.4 Dust Inhalation

The ERMYN model does not include dust inhalation as a mechanism for animal product contamination. Only two of the validation models (BIOMASS ERB2A and EPRI-YM) include this process (Table 7.3-17). Because of a lack of animal data on transfer coefficients for dust inhalation, the two models use human data. Dust inhalation is an ACM (Section 6.3.3, the same ACM as for animal soil ingestion), and the ERMYN and BIOMASS animal submodels are compared to evaluate the importance of this pathway (Section 7.4.5). The two models (which are similar except for this pathway) produce similar estimates of meat concentrations (ERMYN: $2.64 \times 10^{-5}$ Bq/kg; BIOMASS: $2.62 \times 10^{-5}$ Bq/kg), but the contribution from dust inhalation ($3.4 \times 10^{-10}$ Bq/kg) to the total concentration in meat in the BIOMASS model is negligible. Therefore, the methods are numerically similar, and including dust inhalation by animals is unnecessary.

Table 7.3-14. Comparison of Animal Product Contamination Due to Animal Feed

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.4-2, and 6.5.4-2) | Reference |
|---|---|---|---|
| GENII-S | $$Cf_{im} = C_{ip}\ F_{mi}\ f\ Qf\ \exp(-\lambda_i th_m)$$ • $Cf_{im}$ = concentration of radionuclide *i* in animal product *m*, from ingestion of contaminated feed (Ci/kg, Ci/L for milk)<br>• $C_{ip}$ = concentration of radionuclide *i* in feed crop *p* consumed by animals (Ci/ kg)<br>• *f* = fraction of contaminated animal feed (dimensionless)<br>• $F_{mi}$ = transfer coefficient relating daily intake to radionuclide concentrations in edible animal products (d/kg, d/L for milk)<br>• *Qf* = consumption rate of feed by animals (kg/d)<br>• $\lambda_i$ = decay constant (/sec)<br>• $Th_m$ = holdup time between harvest or slaughter and consumption of the animal product (sec). | GENII-S uses a holdup time for animal products to account for radionuclide decay, which can be ignored for long-lived radionuclides. GENII-S also uses a parameter for the fraction of contaminated animal feed, which would be 1.0 in the ERMYN model. Except for these differences, the GENII-S and ERMYN models are the same. | Napier et al. 1988 [DIRS 157927], p. 4.70, Eq. 4.7.11. |
| BIOMASS ERB2A | $$C_{prod,\,fodd} = TF_{proding}\ C_{fodd}\ ING_{fodd}$$ • $C_{prod,\ fodd}$ = radionuclide concentration in an animal product due to ingestion of animal fodder (Bq/kg)<br>• $C_{fodd}$ = radionuclide concentration in animal fodder (Bq/kg $_{\text{fresh weight of fodder}}$)<br>• $TF_{proding}$ = transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$)<br>• $ING_{fodd}$ = consumption rate of fodder by animals (kg $_{\text{fresh weight}}$ /d). | BIOMASS ERB2A and ERMYN use the same method. | BIOMASS 2000 [DIRS 154522], p. 36, Eq. 13. |
| EPRI-YM | EPRI-YM uses the same equation as BIOMASS ERB2A, except for a few notations. | EPRI-YM and ERMYN use the same method. | Smith et al. 1996 [DIRS 101085], p. 5-10, Eq. 5.11. |

Table 7.3-14. Comparison of Animal Product Contamination Due to Animal Feed (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.4-2, and 6.5.4-2) | Reference |
|---|---|---|---|
| RESRAD | $$FSR_{ij,pq}(t) = FQR_{jp} \times FI_{pq} \times QSR_{ij,pq}(t)$$<br>• $FSR_{ij,pq}(t)$ = food/soil concentration ratios for meat and milk<br>• $FQR_{jp}$ = radionuclide transfer factor for meat ($p$ = 4) or milk ($p$ = 5), which is the ratio of the concentration of the $j$th principal radionuclide in meat or milk (in Bq/kg or pCi/kg) to the rate of intake of that radionuclide by farm animals in feed, soil, or water (in Bq/d or pCi/d) (d/kg)<br>• $FI_{pq}$ = daily intake of feed ($q$ = 1, 2, 3, or 4), water ($q$ = 5), or soil ($q$ = 6) by farm animals (kg/d)<br>• $QSR_{ij,pq}(t)$ = feed/soil concentration ratio at time $t$ for meat ($p$ = 4) or milk ($p$ = 5) for the $j$th principal radionuclide and the $q$th sub-pathway (dimensionless) for $q$ = 1 and 2. For $q$ = 3, 4, or 5, it is the ratio of the feed or water concentration of radionuclide $j$ to the initial soil concentration of radionuclide $i$ (dimensionless). For soil intake by farm animals ($q$ = 6), $QSR_{ij,p6}$ = 1. | This equation is for the contamination of all animal products, including feed, soil, and water, which are the same animal pathways used in the ERMYN model. RESRAD and ERMYN are the same, except that the RESRAD equation is based on food/soil concentration ratios. | Yu et al. 2001 [DIRS 159465], p. D-15, Eq. D.15. |
| NCRP-129 | $$C_{milk,meat} = C_{fodder}\ Q_{milk,meat} TQ_{milk,meat}\ F_{milk,meat}$$<br>• $C_{milk,meat}$ = nuclide concentration in animal products (Bq/kg or Bq/L)<br>• $C_{fodder}$ = radionuclide concentration in dry fodder (Bq/kg)<br>• $Q_{milk,meat}$ = average daily intake of dry contaminated feed (kg/d) by animals; $C_{ip}$ = concentration of radionuclide $i$ in feed crop $p$ (Ci/kg)<br>• $TQ_{milk,meat}$ = fraction of locally-grown animal feed<br>• $F_{milk,meat}$ = empirically determined transfer factor representing the equilibrium concentration in meat and milk resulting from a given daily animal intake of a radionuclide (d/kg, or d/L). | NCRP-129 is the same as GENII-S, except that the holdup decay term is not shown here, although it is used in the ingestion submodel (NCRP 1999 [DIRS 155894], p. 91, Eq. 5.1). | NCRP 1999 [DIRS 155894], p. 93, Eq. 5.3. |

Table 7.3-15. Comparison of Animal Product Contamination Due to Drinking Water

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.4-3) | Reference |
|---|---|---|---|
| GENII-S | $$Cw_{im} = Cw_i \; F_{mi} \; fw \, Qw \exp(-\lambda_i th_m)$$ • $Cw_{im}$ = concentration of radionuclide *i* in animal product *m* from animal ingestion of water (Ci/kg, Ci/L for milk)<br>• $Cw_i$ = concentration of radionuclide *i* in water used by animals (Ci/ L)<br>• $fw$ = fraction of contaminated animal water (dimensionless)<br>• $F_{mi}$ = transfer coefficient to relate daily animal intake rate to concentrations in edible animal products (d/kg, d/L for milk)<br>• $Qw$ = consumption rate of water by animals (L/d)<br>• $\lambda_i$ = decay constant (/sec)<br>• $Th_m$ = holdup time between harvest or slaughter and consumption of animal products (sec). | GENII-S uses animal product holdup time for radionuclide decay, which can be ignored for long-lived radionuclides. It also uses the fraction of animal water contaminated. Except for these two differences, GENII-S and ERMYN are the same. | Napier et al. 1988 [DIRS 157927], p. 4.71, Eq. 4.7.12. |
| BIOMASS ERB2A | $$C_{prod,\,fodd} = TF_{proding} \; C_w \; ING_{wa}$$ • $C_{prod,\,fodd}$ = radionuclide concentration in animal products due to ingestion of animal fodder (Bq/kg)<br>• $C_w$ = radionuclide concentrations in groundwater (Bq/kg $_{\text{fresh weight of fodder}}$)<br>• $TF_{proding}$ = transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$)<br>• $ING_{wa}$ = consumption rate of water by animals, kg $_{\text{fresh weight}}$ /d). | BIOMASS ERB2A and ERMYN use the same method. | BIOMASS 2000 [DIRS 154522], p. 36, Eq. 13. |
| EPRI-YM | EPRI-YM used the same equation as BIOMASS ERB2A, except for a few notations. | EPRI-YM and ERMYN use the same method. | Smith et al. 1996 [DIRS 101085], p. 5-10, Eq. 5.11. |
| RESRAD | Mathematical equation shown in Table 7.3-14. | RESRAD is the same as ERMYN, except that the equation is based on food/soil concentration ratios. | Yu et al. 2001 [DIRS 159465], p. D-15, Eq. D.15. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-16. Comparison of Animal Product Contamination Due to Soil Ingestion

| Document | Mathematical Model | Comparison with ERMYN (Equation 6.4.4-4, and 6.5.4-3) | Reference |
|---|---|---|---|
| GENII-S | Not included. | Not applicable. | Napier et al. 1988 [DIRS 157927], Section 4.7.5. |
| BIOMASS ERB2A | $$C_{prod,water} = TF_{proding} \frac{C_s \; ING_{sa}}{(1-\theta_t)\rho + \theta \; \rho_w}$$ • $C_{prod,water}$ = radionuclide concentrations in animal products due to the ingestion of drinking water (Bq/kg)<br>• $TF_{proding}$ = transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$)<br>• $C_s$ = radionuclide concentrations in cultivated soil (Bq/m$^3$)<br>• $ING_{sa}$ = consumption rate of cultivated soil by animals (kg $_{\text{wet weight of soil}}$ /d)<br>• $\theta_t$ = total porosity of the cultivated soil compartment (dimensionless)<br>• $\rho$ = dry grain density of the cultivated soil compartment (kg/m$^3$)<br>• $\theta$ = water filled porosity of the cultivated soil compartment (dimensionless)<br>• $\rho_w$ = density of water (kg/m$^3$) | BIOMASS ERB2A and ERMYN use the same method, except soil concentration requires a unit conversion. | BIOMASS 2000 [DIRS 154522], p. 36, Eq. 13. |
| EPRI-YM | EPRI-YM and BIOMASS ERB2A used the same equation, except for a few notations. | EPRI-YM and ERMYN use the same method. | Smith et al. 1996 [DIRS 101085], p. 5-10, Eq. 5.11. |
| RESRAD | Mathematical equation shown in Table 7.3-14. | RESRAD and ERMYN use the same method, except the equation is derived based on the food/soil concentration ratios. | Yu et al. 2001 [DIRS 159465], p. D-15, Eq. D.15. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999, [DIRS 155894]. |

Table 7.3-17. Comparison of Animal Product Contamination Due to Dust Inhalation

| Document | Mathematical Model | Comparison with the ERMYN (Not considered in ERMYN) | Reference |
|---|---|---|---|
| GENII-S | Not considered. | Not applicable. | Napier et al. 1988 [DIRS 157927], Section 4.7.5. |
| BIOMASS ERB2A | $C_{prod,inh} = TF_{prodinh}\ BR_a\ O_{an}\ C_{airs}$<br>• $C_{prod,inh}$ = radionuclide concentration in animal products due to inhalation of resuspended contaminated soil (Bq/kg$^3$)<br>• $TF_{prodinh}$ = inhalation transfer factor for animal products (d/kg $_{\text{wet weight of soil}}$), which is calculated as<br>$TF_{prodinh} = TF_{proding}\ \frac{f_1(inh)}{f_1(ing)}$<br>• $TF_{proding}$ = transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$)<br>• $f_1(inh)$ = fraction of inhaled activity reaching the body fluid in humans<br>• $f_1(ing)$ = fraction of ingested activity reaching the body fluids in humans<br>• $BR_a$ = animal breathing rate (m$^3$/hr)<br>• $O_{an}$ = occupancy time of animals on cultivated soils (hr/d)<br>• $C_{airs}$ = radionuclide concentrations in the air above cultivated soils (Bq/m$^3$). | BIOMASS ERB2A includes animal inhalation of contaminated dust using a transfer factor for inhalation based on human data (BIOMASS 2000 [DIRS 154522], p. 36, Eq. 13). ERMYN does not include this pathway. A numerical comparison shows that the contribution is small (Section 7.4.4). | BIOMASS 2000 [DIRS 154522], p. 36, Eq. 13. |
| EPRI-YM | EPRI-YM and BIOMASS ERB2A use similar equations and use the same conversion factor for ingestion and inhalation ($CF_{prod} = TF_{proding} = TF_{prodinh}$). | EPRI-YM and ERMYN are similar. | Smith et al. 1996 [DIRS 101085], p. 5-10, Eq. 5.11. |
| RESRAD | Not included. | Not applicable. | Yu et al. 2001 [DIRS 159465], Appendix D. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

### 7.3.5 Validation of the Fish Submodel

Two of the five validation models (GENII-S and RESRAD) use a fish submodel, and both use methods similar to the ERMYN model (Equation 6.4.5-2) with three exceptions (Table 7.3-18):

- GENII-S includes radionuclide decay during the holdup period between harvest and consumption. Holdup time is short (generally days to weeks) relative to the rate of decay for the long-lived radionuclides in the ERMYN model (Table 6.3-7). Thus, the exponential factor in GENII-S that includes the holdup time and decay constant approaches one, making the methods mathematically equivalent.

- RESRAD uses a dietary fraction and a contamination factor in calculating fish contamination. These parameters are incorporated into the fish consumption rate in the ERMYN ingestion submodel; therefore, the methods are mathematically equivalent.

- GENII-S and RESRAD do not include a water concentration modifying factor. Values of that factor depend on the climate and differ among radionuclides. Typical values are 1 for $^{14}C$ and 4.15 for other radionuclides under current climate conditions (Table 6.6-3). Omission of the water concentration modifying factor could result in a difference by more than a factor of two in estimates of radionuclide concentrations in fish. The ERMYN model includes this factor to account for increases in activity concentrations due to evaporation. This addition is necessary because the fish ponds in Amargosa Valley are small, the evaporation rate is high, and the activity concentration likely would increase when additional groundwater is added to compensate for evaporation (Section 6.4.5). This addition is justified because it is based on site-specific conditions in the Amargosa Valley and because it avoids underestimating radionuclide concentrations in fish.

Thus, the fish submodels are mathematically equivalent or the differences are due to model improvements or site-specific conditions, and therefore the ERMYN submodel is validated.

Table 7.3-18. Comparison of Fish Contamination due to Fishpond Water

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.5-2) | Reference |
|---|---|---|---|
| GENII-S | $$Cf_i = Cw_i \; B_{if} \; \exp(-\lambda \times t_p)$$ • $Cf_i$ = concentration of radionuclide *i* in aquatic food type *f* (fish, mollusks, invertebrates, and water plants) (Ci/kg)<br>• $C_w$ = water concentration (Ci/L)<br>• $B_{if}$ = bioaccumulation factor for aquatic food *f* (Ci/kg per Ci/L; L/kg)<br>• $\lambda_i$ = decay constant (/sec)<br>• $t_p$ = decay time (from food harvest to consumption; sec). | The GENII-S model is capable of including more aquatic foods in fresh and salt water, but only freshwater fish are included in the Yucca Mountain biosphere. The GENII-S fish submodel is the same as the ERMYN model, except that the ERMYN model includes a modifying factor for pond water evaporation. | Napier et al. 1988 [DIRS 157927], p. 4.66, Eq. 4.7.5a. |
| BIOMASS ERB2A | Not included. | Not applicable. | BIOMASS 2000 [DIRS 154522], Section 7. |
| EPRI-YM | Not included. | Not applicable. | Smith et al. 1996 [DIRS 101085]. |
| RESRAD | $$ETF_{ij,6}(t) = FR_6 \times \left( \sum DF_{6k} \times FWR_{j6k} \right) \times WSR_{ij,2}(t)$$ • $ETF_{ij,6}(t)$ = environmental transport factor for the aquatic food pathway (fish, crustaceans, and mollusks) (g/yr)<br>• $DF_{6k}$ = dietary factors for annual consumption of fish ($k$ = 1) and crustaceans and mollusks ($k$ = 2) (kg/yr)<br>• $FR_6$ = fraction of contaminated aquatic food (dimensionless)<br>• $FWR_{j6k}$ = fish/water ($k$ = 1) and crustacean-mollusk/water ($k$ = 2) concentration ratios (bioaccumulation factors) (L/kg)<br>• $WSR_{ij,2}(t)$ = ratio of surface water concentration of radionuclide *j* at time *t* to the soil concentration ratio of radionuclide *i* at time 0 (g/L). | RESRAD includes several aquatic food pathways, and it uses a dietary factor and a contamination factor, which are included in the ERMYN consumption rates (ingestion submodel). For the fish pathway, RESRAD and GENII-S are equivalent, except the RESRAD equation is based on a food/soil concentration ratio. | Yu et al. 2001 [DIRS 159465], p. D-18, Eq. D.21. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

### 7.3.6 Validation of the $^{14}C$ Special Submodel

The ERMYN model includes a $^{14}C$ special submodel. Among the five validation models, three (GENII-S, RESRAD, and BIOMASS ERB2A) include $^{14}C$ special submodels. The GENII-S submodel only includes crops, animal products, and fish contamination. The ERMYN, RESRAD, and BIOMASS ERB2A models include these three pathways plus soil and air contamination (which can cause external exposure to contaminated soil, inhalation of contaminated air, and inadvertent soil ingestion). Including soil and air contamination in the ERMYN $^{14}C$ special model is an improvement over the GENII-S model. Comparisons of the methods for calculating $^{14}C$ concentrations in soil, air, plants, and animals are presented below. Concentrations of $^{14}C$ in fish are calculated in the fish submodel (Section 6.4.5).

**Soil Contamination–**In the ERMYN model, the calculation of $^{14}C$ soil contamination resulting from irrigation (Equation 6.4.6-1) is similar to the method used in the soil submodel for other radionuclides (Equation 6.4.1-2). BIOMASS ERB2A is the only validation model that directly calculates $^{14}C$ soil contamination from irrigation water; RESRAD includes soil contamination as the initial source term. The ERMYN and BIOMASS ERB2A models use the same methods, with the following exceptions (Table 7.3-19):

- BIOMASS ERB2A includes the weathering of $^{14}C$ from plants as a soil contamination source. The ERMYN model assumes that all radionuclides in irrigation water eventually are deposited in the soil (Assumption 6). Therefore, the parameters in the BIOMASS ERB2A model for calculating weathering are unnecessary in the ERMYN model, and the methods are mathematically equivalent.

- BIOMASS ERB2A does not include losses of $^{14}C$ due to erosion or radionuclide decay. These loss mechanisms are used in the ERMYN $^{14}C$ submodel to maintain consistency with the soil submodel. The rate of loss from erosion and radionuclide decay is inconsequential compared to the $^{14}C$ emission rate (about 22/yr; Table 6.6-3). Therefore, including losses due erosion and radionuclide decay do not affect the results of the equation, and the methods are mathematically equivalent.

**Air Contamination–**In the air, $^{14}C$ contamination is caused by the release of $^{14}C$ from groundwater-contaminated soil (due to the volatility of $^{14}C$), as almost all $^{14}C$ in the soil is quickly released into the air. The BIOMASS ERB2A and RESRAD models include $^{14}C$ in the air, using methods that are the same as the ERMYN model, with the following exceptions (Table 7.3-20):

- BIOMASS ERB2A and RESRAD include a factor for the proportion of time that the wind blows from the contaminated source to the receptor. In the ERMYN model, the area contaminated by long-term irrigation surrounds the receptor, so this factor would be 1.0. Therefore, these methods are mathematically equivalent.

- BIOMASS ERB2A uses radionuclide concentrations per unit volume ($Bq/m^3$) and includes parameters for the width and volume of the plant canopy. The ERMYN model uses concentrations per unit area and replaces the width and volume parameters with a parameter

for the size of the irrigated area. Thus, the differences are unit conversions, and the methods are mathematically equivalent.

- The calculation of $^{14}C$ flux density from contaminated soil (evasion rate) differs in the RESRAD and ERMYN models because of differences in the source term. The differences are unit conversions (Table 7.3-20), and the methods are mathematically equivalent.

**Plant Contamination–**Plant contamination by $^{14}C$ is included in the GENII-S, RESRAD, and BIOMASS ERB2A models. The ERMYN method (Equation 6.4.6-6) is the same as that used in RESRAD (Table 7.3-21). BIOMASS ERB2A uses a different method that requires additional input parameters, the measurements of which are not available, and the model documentation (BIOMASS 2000 [DIRS 154522]) does not include recommended values. Therefore, a numerical comparison is not possible, and this portion of BIOMASS ERB2A is not used to validate the ERMYN model.

The GENII-S and ERMYN models use substantially different methods for calculating $^{14}C$ plant contamination, so the models are compared numerically (Section 7.4.7). The $^{14}C$ concentration in leafy vegetables calculated using the ERMYN method ($3.2 \times 10^{-2}$ Bq/kg; Table 7.4-13) is about six times higher than the value calculated using the GENII-S method ($5.8 \times 10^{-3}$ Bq/kg). However, using a more appropriate removal rate, the results of the ERMYN and GENII-S models are almost the same (Section 7.4.7). Using the default removal rate, the GENII-S method underestimates $^{14}C$ contamination in plants because it only includes contamination from root uptake, whereas the ERMYN, BIOMASS ERB2A, and RESRAD models include the uptake of $^{14}CO_2$ during photosynthesis. Because of the high emission rate of $^{14}C$ from the soil (Table 6.6-3), uptake of $^{14}C$ via photosynthesis is an important transfer process. Therefore, the ERMYN method is justified because it includes this important transfer process to avoid underestimating dose.

**Animal Contamination–**The GENII-S, RESRAD, and BIOMASS ERB2A models include animal product contamination by $^{14}C$. The ERMYN method (Equation 6.4.6-7) is the same as the RESRAD method (Table 7.3-22). BIOMASS ERB2A uses a different method that requires additional input parameters, the measurements of which are not available, and the model documentation (BIOMASS 2000 [DIRS 154522]) does not include recommended values. Therefore, a numerical comparison is not possible. The GENII-S model is similar to the ERMYN model, except that soil ingestion is not included in GENII-S. As described in Sections 7.3.4 and 7.4.5, ingestion of soil is an important contamination mechanism for animals. Therefore, the method used in the ERMYN model is justified because it avoids underestimating $^{14}C$ concentrations in animals.

Table 7.3-19. Comparison of $^{14}C$ Special Model for Soil Contamination

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-1) | Reference |
|---|---|---|---|
| GENII-S | Not included. | GENII-S does not include $^{14}C$ contamination in the soil. | Napier et al. 1988 [DIRS 157927]. |
| BIOMASS ERB2A | $$C_S = \frac{(C_{SW} + C_{SI})}{D_S}$$ • $C_S$ = concentration of $^{14}C$ in the soil layer (Bq/m$^3$)<br>• $C_{SW}$ = concentration of $^{14}C$ on the soil surface as a result of weathering, Bq m$^{-2}$, which can be estimated as $$C_{SW} = \frac{C_{PS}\lambda_{PSS}}{\lambda_S}$$ • $C_{PS}$ = concentration of $^{14}C$ on plant surfaces, Bq m$^{-2}$<br>• $\lambda_{pss}$ = radionuclide loss by weathering to the soil surface, /yr<br>• $\lambda_S$ = radionuclide loss in the soil root zone, /yr, can be calculated as $$\lambda_S = \lambda_{SA} + \lambda_{SDS}$$ • $\lambda_{SA}$ = radionuclide loss due to degassing (or emission) from the soil surface to the air, /yr<br>• $\lambda_{SDS}$ = radionuclide loss due to infiltration (leaching) to deeper soil, /yr<br>• $D_s$ = depth of the soil layer from which infiltration is considered, in this case the rooting layer, m<br>• $C_{SI}$ = concentration of $^{14}C$ in the soil resulting from irrigation water intercepted by soil, Bq/m$^2$, may be estimated as $$C_{SI} = \frac{C_{IW} R_{IR} f_{IR}}{\lambda_S}$$ • $C_{IW}$ = concentration of $^{14}C$ in irrigation water, Bq/m$^3$<br>• $R_{IR}$ = irrigation rate, m/yr<br>• $f_{IR}$ = intercepted fraction | BIOMASS ERB2A includes $^{14}C$ soil contamination from irrigation and weathering of plant surfaces. This differs from the BIOMASS ERB2A model for all other radionuclides, in which all irrigation water is deposited in the soil (same as Assumption 6). BIOMASS ERB2A uses two loss mechanisms (leaching and emission), but not erosion (which is inconsistent with the regular model in which erosion is limited). BIOMASS ERB2A and ERMYN are similar if it is assumed that the intercepted irrigation water is eventually deposited on the soil. | BIOMASS 2000 [DIRS 154522], Appendix A. |
| EPRI-YM | Not included. | Not applicable. | Smith et al. 1996 [DIRS 101085]. |
| RESRAD | The source term is the concentration of $^{14}C$ in contaminated soil (*Sc*-14), and therefore it is not a calculated value. | Source term in RESRAD. | Yu et al. 2001 [DIRS 159465], Appendix L. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-20. Comparison of $^{14}C$ Special Model for Air Contamination

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-2 and 6.4.6-3) | Reference |
|---|---|---|---|
| GENII-S | Not included. | GENII-S does not include $^{14}C$ contamination in the air. | Napier et al. 1988 [DIRS 157927]). |
| BIOMASS ERB2A | $$C_{SA} = \frac{C_S \lambda_{SA}}{\lambda_A}$$ • $C_{SA}$ = concentration of $^{14}C$ in the canopy due to degassing (Bq/m$^3$)<br>• $C_S$ = concentration of $^{14}C$ on the soil surface (Bq/m$^3$)<br>• $\lambda_{SA}$ = radionuclide loss due to degassing (or emission) from the soil surface to the air (/yr)<br>• $\lambda_A$ = radionuclide loss in the canopy (/yr), calculated as $$\lambda_A = \frac{f \times U \times w_C \times h_c}{v_C}$$ • $f$ = factor to account for the geometry of the contaminated area, varying wind directions<br>• $U$ = average wind speed (m/yr)<br>• $w_c$ = width of the contaminated plant canopy, perpendicular to the wind direction (m)<br>• $h_c$ = assumed height of the canopy layer (m)<br>• $v_c$ = volume of the contaminated plant canopy (m$^3$) | BIOMASS ERB2A and ERMYN are the same, except for the geometry of the contaminated area and the varying wind direction. Because most or all of the area would be contaminated, this parameter is unnecessary in the ERMYN model. The BIOMASS model uses radionuclide concentration in units of Bq/m$^3$, as shown in the equation where $v_c$ is the volume of contaminated plant canopy. In contrast, the ERMYN model uses units of Bq/m$^2$ and an area (A) parameter (Equation 6.6.6-3). | BIOMASS 2000 [DIRS 154522], pp. 69 and 70, Appendix A. |
| EPRI-YM | Not included. | Not applicable. | Smith et al. 1996 [DIRS 101085]. |

Table 7.3-20. Comparison of $^{14}C$ Special Model for Air Contamination (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-2 and 6.4.6-3) | Reference |
|---|---|---|---|
| RESRAD | $$C_{C-14,a} = \frac{3.17\times10^{-8}\times0.5\times EVSN\times\sqrt{A}}{H_{mix}\times U}$$ • $C_{C14,a}$ = average concentration of $^{14}C$ in the air above a contaminated area of finite size (pCi/m$^3$)<br>• 3.17 × 10$^{-8}$ = unit conversion factor (yr/sec)<br>• 0.5 = time fraction for wind blowing towards receptor (dimensionless)<br>• *EVSN* = $^{14}C$ flux (evasion rate) from the contaminated area (pCi/m$^2$-yr)<br>$$EVSN = 10^{-6}\times S_{C-14}\times E_{C-14}\times \rho_b^{(cz)}\times d_{ref}$$ • 106 = unit conversion factor (cm$^3$/m$^3$)<br>• $S_{C-14}$ = concentration of $^{14}C$ in contaminated soil (pCi/g)<br>• $E_{C-14}$ = evasion loss rate constant (22/yr)<br>• $\rho_b^{(cz)}$ = bulk density of the contaminated zone (1.5 g/cm$^3$)<br>• $d_{ref}$ = reference soil depth (0.3 m)<br>• *A* = area of contaminated zone (m$^2$)<br>• *Hmix* = height to which $CO_2$ uniformly mixes (2 m for the human inhalation pathway; 1.0 m for the plant, meat, and milk ingestion pathways)<br>• *U* = annual average wind speed (m/sec). | The ERMYN model uses the RESRAD equation, except that the time fraction for wind blowing toward the receptor is set to 1.0 (Section 6.4.6.2) because the ERMYN model does not need this parameter. Because of different source terms, the $^{14}C$ flux density, *EVSN*, calculations are different in the RESRAD and ERMYN models: $Cs_{C-14}$ (Bq/m$^2$) in ERMYN is equivalent to $10^6 \times S_{c-14} \times \rho_b^{(cz)} \times d_{ref}$ in RESRAD. | Yu et al. 2001 [DIRS 159465], p. L-15, Eq. L.25. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-21. Comparison of C-14 Special Model for Plant Contamination

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-6) | Reference |
|---|---|---|---|
| GENII-S | $$Cc_p = Cw_c\ I\ te_p \frac{0.1}{0.01\,P\,\lambda s_c}[1-\exp(-\lambda s_c\ te_p)]$$<br>• $Cc_p$ = concentration of $^{14}C$ in plant type $p$ (Ci/kg)<br>• $Cw_c$ = concentration of $^{14}C$ in irrigation water (Ci/m$^3$)<br>• $\lambda s_c$ = effective removal rate constant for $^{14}C$ in soil (/sec)<br>• 0.1 = assumed uptake of 10% of plant carbon from soil<br>• 0.01 = average fraction of soil that is carbon<br>• $P$ = surface soil density (kg/m$^2$)<br>• $I$ = irrigation water application rate (m/yr)<br>• $te_p$ = duration of the growing period for plant type $p$ (sec)<br><br>This equation is not used in the GENII-S code. The formula used in the GENII-S code, taken from the source code, is<br>$$Cc_p = \frac{25.4 \times I \times Cw_c}{\rho_s\ \lambda s_c} \times \frac{12}{ID} \times \frac{0.1}{0.01} \times Fc_p$$<br>• $Cc_p$ = concentration of $^{14}C$ in plant type $p$ (pCi/kg)<br>• 25.4 = unit conversion factor (L in.$^{-1}$ m$^{-2}$)<br>• $I$ = irrigation water application rate (in./yr)<br>• $Cw_c$ = concentration of $^{14}C$ in irrigation water (pCi/L)<br>• $\rho_s$ = surface soil density (kg/m$^2$)<br>• $\lambda s_c$ = effective removal rate constant for $^{14}C$ in soil (0.8/yr)<br>• *12* = unit conversion factor (months/yr)<br>• $ID$ = irrigation duration (months/yr)<br>• 0.1 = assumed uptake of 10% of plant carbon from soil<br>• 0.01 = average fraction of soil that is carbon<br>• $Fc_p$ = fraction of carbon in plant; fixed values in GENII-S are 0.09 for fruits, vegetables, and fresh feed; 0.40 for grain and stored feed. | This equation has errors:<br>1) the units conversion is incorrect<br>2) the duration of the growing period, $te_p$ should not be proportional to the concentration of $^{14}C$ in the plants<br>3) the fraction of carbon in plants, $Fc_p$, which is proportional to the $^{14}C$ concentration, is missing.<br>GENII-S considers that $^{14}C$ contamination in plants occurs only through root uptake. Because the $^{14}C$ special model for plant contamination in the GENII-S and ERMYN models are different, a numerical comparison between the GENII-S and ERMYN models is made in Section 7.4.7. | Napier et al. 1988 [DIRS 157927], p. 4.89, Eq. 4.7.32.<br><br>The $^{14}C$ source code is in the GENII-S code (SNL 1998 [DIRS 117076], CANDH subroutine), which is listed in Attachment I, Table I-6. |

Table 7.3-21. Comparison of C-14 Special Model for Plant Contamination (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-6) | Reference |
|---|---|---|---|
| BIOMASS ERB2A | $$C_P = C_{PSP} + C_{SP} + C_{AP}$$<br>• $C_P$ = concentration of $^{14}C$ in plants (Bq/kg$^3$)<br>• $C_{PSP}$ = concentration of $^{14}C$ in plants contributed from plant surfaces (Bq/kg$^3$), estimated as<br>$$C_{PSP} = \frac{C_{PS}\lambda_{PSP} f_{PSP}}{\lambda_C}$$<br>• $\lambda_{PSP}$ = radionuclide loss by translocation into plants (/yr)<br>• $f_{PSP}$ = factor converting surface- (Bq/m$^2$) to mass contamination (Bq/kg)<br>• $\lambda_C$ = radionuclide loss by annual plant cropping (harvest removal) (/yr)<br>• $C_{PS}$ = concentration of $^{14}C$ on plant surfaces (Bq/m$^2$), calculated as<br>$$C_{PS} = \frac{C_{IW} R_{IR}(1 - f_{IR})}{\lambda_{PS}}$$<br>• $C_{IW}$ = concentration of $^{14}C$ in irrigation water (Bq/m$^3$)<br>• $R_{IR}$ = irrigation rate (m/yr)<br>• $f_{IR}$ = intercepted fraction<br>• $\lambda_{PS}$ = sum of radionuclide losses from plants, calculated as<br>$$\lambda_{PS} = \lambda_{PSS} + \lambda_{PSP} + \lambda_{PSA}$$<br>• $\lambda_{PSS}$ = radionuclide loss by weathering to the soil surface (/yr)<br>• $\lambda_{PSA}$ = radionuclide loss from plant surfaces to the atmosphere (/yr), calculated as<br>$$\lambda_{PSA} = \frac{R_{RA}}{C_{CW} D_R}$$<br>• $R_{RA}$ = rate of evasion per unit area of a water body (mol m$^{-2}$ yr$^{-1}$)<br>• $C_{CW}$ = concentration of C in water (mol/m$^3$)<br>• $D_R$ = water depth on the leaf (m). | The BIOMASS ERB2A model includes plant contamination from plant surfaces, soil, and air. This method requires many input parameters that are not given in the document, which makes numerical comparisons impossible. | BIOMASS 2000 [DIRS 154522], Appendix A. |

Table 7.3-21. Comparison of C-14 Special Model for Plant Contamination (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-6) | Reference |
|---|---|---|---|
| BIOMASS ERB2A (cont.) | • $C_{SP}$ = concentration of $^{14}C$ in plants contributed from soil (Bq/kg), estimated as $$C_{SP} = \frac{f_{CP} f_{SP} C_S}{\rho_S f_{CS}}$$ • $f_{CP}$ = fraction of plant mass that is carbon<br>• $f_{SP}$ = fraction of all carbon in plants derived from carbon in soil<br>• $C_S$ = concentration of $^{14}C$ in soil<br>• $\rho_S$ = soil density (kg/m$^3$)<br>• $f_{CS}$ = fraction of soil that is stable carbon<br>• $C_{AP}$ = concentration of $^{14}C$ in plants contributed from the air (Bq/kg), estimated as $$C_{AP} = \frac{f_{CP} f_{AP} C_{SA}}{\rho_P f_{CA}}$$ • $f_{CP}$ = fraction of plant mass that is carbon<br>• $f_{AP}$ = fraction of all carbon in plants derived from $CO_2$ in the air<br>• $C_{SA}$ = concentration of $^{14}C$ in the air<br>• $\rho_p$ = plant density the plant (kg/m$^3$)<br>• $f_{CS}$ = fraction of the air that is stable carbon. | | |
| EPRI-YM | Not included. | Not applicable. | Smith et al. 1996 [DIRS 101085]. |

Table 7.3-21. Comparison of C-14 Special Model for Plant Contamination (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-6) | Reference |
|---|---|---|---|
| RESRAD | $$C_{C-14,v} = C_{C,v}\left[\left(F_a \times \frac{C_{C-14,a}}{C_{C,a}}\right) + \left(1000 \times F_s \times \frac{S_{C-14}}{S_C}\right)\right]$$ • $C_{C\text{-}14,v}$ = concentration of $^{14}C$ in plants (pCi/kg)<br>• $C_{C,v}$ = fraction of stable carbon in plants (dimensionless; 0.4 for grain and non-leafy vegetables; 0.09 for fruits, vegetables, and fodder)<br>• $Fa = C_{C,va} / C_{C,v}$ = fraction of carbon in plants derived from carbon in air (dimensionless; 0.98)<br>• $C_{C,va}$ = fraction of plant mass that is carbon derived from photosynthesis<br>• $C_{C\text{-}14,a}$ = concentration of $^{14}C$ in the air (pCi/m$^3$)<br>• $C_{C,a}$ = concentration of stable carbon in the air ($1.8 \times 10^{-4}$ kg/m$^3$)<br>• 1,000 = unit conversion factor (g/kg)<br>• $Fs = C_{C,vs} / C_{C,v}$ = fraction of carbon in plants derived from carbon in soil (dimensionless; 0.02, $Fs$ = 0 if $Sc$ = 0)<br>• $C_{C,vs}$ = fraction of plant mass that is carbon derived from soil<br>• $S_{C\text{-}14}$ = concentration of $^{14}C$ in soil (pCi/g)<br>• $S_C$ = fraction of the soil that is stable carbon (dimensionless; 0.03). | RESRAD and ERMYN are the same, except for the notations and units for some parameters. | Yu et al. 2001 [DIRS 159465], p. L-20, Eq. L.31. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-22. Comparison of $^{14}C$ Special Model for Animal Product Contamination

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-7) | Reference |
|---|---|---|---|
| GENII-S | $$Cc_m = \frac{Cc_p \times Qf + Cw_c \times Qw}{Fc_f \times Qf + Fc_w \times Qw} \times Fc_m$$ • $Cc_m$ = concentration of $^{14}C$ in animal product *p* (Ci/kg or Ci/L)<br>• $Cc_p$ = concentration of $^{14}C$ in animal feed (Ci/kg)<br>• $Cw_c$ = concentration of $^{14}C$ in irrigation water (Ci/L)<br>• $Qf$ = animal feed consumption rate (kg/d)<br>• $Qw$ = animal water consumption rate (L/d)<br>• $Fc_f$ = fraction of carbon in animal feed (fixed value used in GENII-S, 0.09)<br>• $Fc_w$ = fraction of carbon in animal drinking water (fixed value suggested in GENII manual is $2.0 \times 10^{-5}$ kg/L)<br>• $Fc_m$ = fraction of carbon in animal product (fixed values used in GENII-S are 0.24 for beef, 0.2 for poultry, 0.07 for milk, and 0.15 for eggs).<br>This equation is not used in the GENII-S code. A simpler equation (Napier et al. 1988 [DIRS 157927], Equation 4.7.35, p. 4.89), based on the fact that the carbon content of plants was much higher than that in water ($Fc_f >> Fc_w$), is used in the code $$Cc_m = \frac{Cc_p}{Fc_f} \times Fc_m$$ The parameters are the same as those in the previous equation. This simplification may be inaccurate because it omits the $^{14}C$ source from drinking water ($Cw_c \times Qw$). | GENII-S and ERMYN are equivalent, except that GENII-S does not include soil ingestion by animals, which is similar to the way other radionuclides are treated. | Napier et al. 1988 [DIRS 157927], p. 4.89, Eq. 4.7.34 and Eq. 4.7.35. |
| BIOMASS ERB2A | $$C_{A,C14} = C_{A,C12}\left( f_{A,W}\frac{C_{W,C14}}{C_{W,C12}} + f_{A,S}\frac{C_{S,C14}}{C_{S,C12}} + f_{A,P}\frac{C_{P,C14}}{C_{P,C12}} \right)$$ • $C_{x,C12}$ = fraction of the mass of material that is stable carbon, where X = *A* for animal products, *W* is water, *S* is soil, and *P* is plants (Bq/kg)<br>• $f_{A,X}$ = fraction of carbon derived from medium *X* (water, soil, or plants)<br>• $C_{X,C14}$ = activity concentration of $^{14}C$ on the material, where X = *A* is animal product, *W* is water, *S* is soil, and *P* is plants (Bq/kg). | BIOMASS ERB2A includes $^{14}C$ contamination in animal products through water, soil, and plants, which is the same as the ERMYN, but it uses a different method for calculating radionuclide concentrations in animal products. The values are not given in the document, which makes numerical comparison impossible. | BIOMASS 2000 [DIRS 154522], pp. 70 and 71, Appendix A. |
| EPRI-YM | Not included. | Not applicable. | Smith et al. 1996 [DIRS 101085]. |

Table 7.3-22. Comparison of $^{14}C$ Special Model for Animal Product Contamination (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.6-7) | Reference |
|---|---|---|---|
| RESRAD | $$C_{C14,p} = C_{C,p} \frac{FI_{C-14,p}}{FI_{C,p}}$$ • $C_{C\text{-}14,p}$ = concentration of $^{14}C$ in meat ($p$ = 4) or milk ($p$ = 5) (pCi/kg)<br>• $C_{C,p}$ = fraction of stable carbon in meat (0.24) or milk (0.070) (dimensionless)<br>• $FI_{C\text{-}14,p}$ = intake rate of $^{14}C$ in the diet of beef cattle ($p$ = 4) or dairy cows ($p$ = 5) (pCi/d), calculated as $$FI_{C14,p} = W_{C-14} \times FI_{p5} + FDR_{C-14,p} \times FI_{pq} + S_{C-14} \times FI_{p6}$$ • $W_{C\text{-}14}$ = concentration of $^{14}C$ in water (pCi/L)<br>• $FI_{p5}$ = livestock water intake rate (160 L/d, milk 50/d, beef cattle)<br>• $FDR_{C\text{-}14,p}$ = concentration of $^{14}C$ in livestock feed (pCi/kg)<br>• $FI_{pq}$ = livestock feed intake rate ($p$ = 4, 68 kg/d; $p$ = 5, 55) (kg/d)<br>• $S_{C\text{-}14}$ = concentration of $^{14}C$ in soil (pCi/kg)<br>• $FI_{p6}$ = livestock soil intake rate (0.5 kg/d)<br>• $FI_{C,p}$ = intake rate of stable carbon in the livestock diet (kg/d), calculated as $$FI_{C,p} = W_C \times FI_{p5} + FDR_{C,p} \times FI_{pq} + S_C \times FI_{p6}$$ • $W_C$ = concentration of stable carbon in livestock water ($2.0 \times 10^{-5}$ kg/L)<br>• $FDR_{C,p}$ = concentration of stable carbon in feed (kg/kg)<br>• $S_C$ = fraction of soil that is stable carbon (0.03, dimensionless). | RESRAD and ERMYN are the same, except for notations and units for some parameters. | Yu et al. 2001 [DIRS 159465], p. L-21, Eq. L.33, L.34, and L.36. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

### 7.3.7 Validation of the External Exposure Submodel

The method used to calculate the external exposure dose in the ERMYN model is similar to that used in the validation models (Table 7.3-23). All of the models calculate dose as a product of a radionuclide-specific dose coefficient, radionuclide concentrations in the surface soil, and exposure time. All of the validation models include external exposure to contaminated soil. In addition, the GENII-S model includes air submersion and water immersion, and the BIOMASS ERB2A model includes water immersion (Table 7.2-2). A comparison of dose coefficients for external exposure to contaminated soil, air submersion, and water immersion evaluates the importance of these pathways (Section 7.4.8). The potential doses from air submersion and water immersion are inconsequential compared to soil exposure, and they are excluded from the ERMYN model dose assessments.

There are several differences between the ERMYN methods (Equations 6.4.7-1 and 6.5.5-1) and the validation model methods (Table 7.2-23):

- The ERMYN model uses environment-specific exposure times and shielding factors for five environments and four population groups. The RESRAD and NCRP-129 models use two environments (indoors and outdoors), but the other validation models do not consider different environments. None of the validation models includes differences among population groups. The ERMYN approach accounts for variation in shielding factors among the various environments where a receptor lives, and variation and uncertainty in exposure times among segments of the receptor population. A numerical comparison of inhalation exposure to particulate matter using the ERMYN micro-environmental approach and the single-environment approach used in other models demonstrates that the calculation of exposure rates differ by less than a factor of two (Table 7.4-19). This comparison also is valid for the external exposure submodel because the same values for exposure times and population groups are used for both submodels. Based on this numerical comparison, the ERMYN methods are numerically similar to the validation models.

- The dose coefficients and measurement units differ among models and scenarios because the type of dose coefficient depends on the type and distribution of contaminants. For example, the dose coefficients for exposure to soil contaminated to an infinite depth ($Bq/m^3$) in the ERMYN groundwater scenario (Section 5.10) are similar to those in the BIOMASS ERB2A model. In contrast, dose coefficients for contaminated soil surface ($Bq/m^2$) in the ERMYN volcanic scenario (Section 5.16) are similar to GENII-S. Differences in notations for dose coefficients and associated factors in the ERMYN and validation model equations (e.g., density correction *Ws* in NCRP-129) are required for unit conversion; therefore, the methods are mathematically equivalent.

- The ERMYN, NCRP-129, and RESRAD models include a building shielding factor associated with time spent indoors. In the ERMYN model, this radionuclide-specific parameter accounts for the reduction in external exposure caused by dwellings. The GENII-S, BIOMASS ERB2A, and EPRI-YM models do not differentiate between time spent indoors and outdoors and do not include a shielding factor. However, this factor can be incorporated into exposure time by reducing or excluding time spent indoors, and therefore, the methods are mathematically equivalent. This factor, not used in the previous biosphere

model, is included based on suggestion made during a model validation status review (BSC 2001 [DIRS 156257], Section 6.17.5). Inclusion of this factor is a biosphere model improvement.

- The RESRAD model includes factors for the size and shape of the contaminated area. Under the groundwater scenario, the total area contaminated is large because of long-term irrigation land-use rotation. Under the volcanic ash scenario, contaminated ash would be deposited over the entire Amargosa Valley. Thus, these factors would be about 1.0 for both scenarios and this method is mathematically equivalent to the ERMYN model.

- RESRAD includes a cover-and-depth factor for the effects of burying radioactive waste. For both scenarios in the ERMYN model, all radionuclides are in the surface soil, so this factor would be set at 1.0. Therefore, this method is mathematically equivalent to the ERMYN model.

- The NCRP-129 model includes different exposure rates for children and adults. However, 10 CFR 63.312(e) requires basing the characteristics of the RMEI on an adult, so this factor would equal 1.0, making the methods mathematically equivalent.

Because the mathematical representations are mathematically equivalent or the results are numerically similar, the external exposure submodel is validated.

Table 7.3-23. Comparison of External Exposure to Contaminated Soil

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.7-1 and 6.5.5-1) | Reference |
|---|---|---|---|
| GENII-S | $$Dx_i = ts\, Cs_i\, Ds_i$$ • $Dx_i$ = dose to an individual from exposure to contaminated ground for radionuclide *i* (rem)<br>• $Ds_i$ = external dose conversion factor for exposure to a planar surface contaminated by radionuclide *i* (rem/hr per Ci/m$^2$)<br>• $Cs_i$ = soil concentration of radionuclide *i* (Ci/m$^2$)<br>• *ts* = time of exposure to contaminated ground (hr). | In the GENII-S manual, surface contamination is similar to Equation 6.5.7-1 in ERMYN. The GENII-S code can also use volumetric dose coefficients, which are similar to Equation 6.4.7-1 in ERMYN. The ERMYN also includes a shielding factor and an environment-specific time budget, but GENII-S does not. | Napier et al. 1988 [DIRS 157927], p. 4.84, Eq. 4.7.24. |
| BIOMASS ERB2A | $$D_{exsoil} = O_s\, DC_{exts}\, C_s$$ • $D_{exsoil}$ = individual dose from external irradiation from the soil (Sv/yr)<br>• $DC_{exts}$ = dose factor for external irradiation from the soil (Sv/hr per Bq/m$^3$)<br>• $C_s$ = radionuclide activity concentration in cultivated soil (Bq/m$^3$)<br>• $O_s$ = individual occupancy in the soil compartment (hr/yr). | BIOMASS ERB2A uses a method equivalent to that in the ERMYN (Equation 7.1), except for the lack of a shielding factor and environment-specific time budgets. | BIOMASS 2000 [DIRS 154522], p. 37, Eq. 17. |
| EPRI-YM | $$D_{exsed} = O_{sed}\, D_{exts} \frac{C_{sed}}{(1-\theta_{sed})\rho_{gsed} + \theta_{sedw}\rho_w}$$ • $D_{exsed}$ = individual dose from external irradiation from the soil (Sv/yr)<br>• $O_s$ = individual occupancy on the soil compartment (hr/yr)<br>• $D_{exts}$ = activity to dose conversion factor for external irradiation from sediment or soil (Sv/hr per Bq/kg)<br>• $C_{sed}$ = radionuclide concentration in the sediment or soil compartment (Bq/m$^3$)<br>• $\theta_{sed}$ = total porosity of the sediment or soil compartment<br>• $\rho_{gsed}$ = grain density of the sediment or soil compartment (kg/m$^3$)<br>• $\theta_{sedw}$ = water filled porosity of the sediment or soil compartment (dimensionless)<br>• $\rho_w$ = the density of water (kg/m$^3$). | EPRI-YM uses a method equivalent to BIOMASS ERB2A. The units for dose conversion factors are different (Sv/hr per Bq/kg in EPRI-YM and Sv/hr per Bq/m$^3$ in BIOMASS ERB2A), which changes the form of the equation. | Smith et al. 1996 [DIRS 101085], p. 5-12, Eq. 5.14. |

Table 7.3-23. Comparison of External Exposure to Contaminated Soil (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.7-1 and 6.5.5-1) | Reference |
|---|---|---|---|
| RESRAD | $$ETF_{i1}(t) = FO_1 \times FS_{i1}(t) \times FA_{i1}(t) \times FCD_{i1}(t)$$<br>• $ETF_{i1}(t)$ = environmental transport factor for the external ground radiation pathway<br>• $FS_{i1}(t)$ = shape factor (dimensionless)<br>• $FA_{i1}(t)$ = nuclide-specific area factor (dimensionless)<br>• $FCD_{i1}(t)$ = depth-and-cover factor (dimensionless)<br>• $FO_1$ = occupancy and shielding factor (dimensionless), calculated as<br>$$FO_1 = f_{otd} + (f_{ind} \times F_{sh})$$<br>• $f_{otd}$ = fraction of a year spent outdoors, on site, 0.25 (dimensionless)<br>• $f_{ind}$ = fraction of a year spent indoors, on site, 0.50 (dimensionless)<br>• $F_{sh}$ = indoor shielding factor for external gamma, 0.7 (dimensionless). | The RESRAD model includes several factors, including shape, area, depth, and cover factors that are not in ERMYN. An indoor shielding factor is also used. The equation calculates the environmental transport factor. To convert *ETF* to dose, multiply *ETF* by the effective dose equivalent conversion factor ($DCF_{i1}$ – mrem/yr per pCi/g) and the source term (*S(t)* – pCi/g). | Yu et al. 2001 [DIRS 159465], Appendix A, p. A-7, Eq. A-7. |
| NCRP-129 | $$E_{ext} = Df_{ext} \times [T_{out} + (T_{in} \times SF)] \times (C/A) \times W_s \times S(z,t)$$<br>• $E_{extl}$ = average annual exposure to an exposed individual per unit radionuclide concentration from external radiation (Sv/(Bq/kg))<br>• $Df_{ext}$ = dose factor for a particular radionuclide (Sv/yr per Bq/kg)<br>• *S(z,t)* = radionuclide concentration in the soil, averaged over the 1 yr interval (*t*) for which the dose is calculated (Bq/kg $_{\text{dry soil}}$); varies with depth (*z*) beneath the ground surface<br>• $T_{out}$ = the mean fraction of time spent outdoors on a contaminated site<br>• $T_{in}$ = the mean fraction of time spent indoors in a dwelling on a contaminated site<br>• *SF* = shielding factor or ratio of the dose indoors to the unshielded outdoor dose<br>• *Ws* = density correction due to soil moisture (i.e., the ratio of dry soil density to the actual *in situ* bulk density)<br>• *C/A* = ratio of the external dose to children to that for adults when children are present. | NCRP-129 uses soil density and child-exposure correction factors that are not in ERMYN. $E_{extl}$ should be in units of Sv in the equation when *S(z,t)* is the radionuclide concentration in the soil (in units of Bq/kg). NCRP-129 is equivalent to ERMYN, except that the soil density correction factor and exposure for children are not used in the ERMYN model. | NCRP 1999 [DIRS 155894], p. 34, Eq. 3.1. |

### 7.3.8 Validation of the Inhalation Submodel

The ERMYN model (Equation 6.4.8.2 and 6.5.6.2) and all of the validation models (Table 7.3-24) use the same general approach for calculating the dose from inhalation of particulate matter as the product of radionuclide-specific dose conversion factors, breathing rates, airborne particle concentrations, and exposure times. The ERMYN model also uses this approach for calculating exposure to aerosols generated from operating evaporative coolers (Equation 6.4.8.3), inhalation of $^{14}C$ (Equation 6.4.8-4), and inhalation of radon decay products (Equation 6.4.8-5 and 6.5.6-3). Differences between the ERMYN methods for calculating the inhalation dose for all airborne contaminants and the methods used in the validation models are:

- Four of the five validation models calculate average inhalation exposure using average breathing rates, air concentrations, and inhalation times (Table 7.3-24). Only the NCRP-129 model considers two environments (indoors and outdoors) for these parameters, which is similar to the microenvironment concept in the ERMYN model. The ERMYN model includes five environments and four population groups to incorporate variation and uncertainty in concentrations of radionuclides within the receptor environment and exposure times among segments of the receptor population. A numerical comparison of the ERMYN micro-environment method and the single-environment method evaluates the effects of these differences (Section 7.4.9). Using average values for the single-environment method, the two approaches produce similar results ($1.5 \times 10^{-5}$ versus $1.25 \times 10^{-5}$ Bq/day; Table 7.4-19), and additional validation of this portion of the submodel is not required.

- None of the validation models considers the inhalation dose as a function of time. The inhalation dose for the ERMYN volcanic scenario is treated as a function of time (Equation 6.5.6-2) to account for decreases in mass loading following a volcanic eruption. This approach is evaluated and justified in the validation of the air submodel (Section 7.3.2).

- None of the validation models considers the inhalation dose as a function of ash depth. This is done in the ERMYN volcanic ash scenario (Equation 6.5.6-2) to account for differences in activity concentrations in the air that result from a thin layer of ash or as the ash layer is depleted by erosion (Section 5.12). This approach is evaluated and justified in the validation of the soil submodel (Section 7.3.1).

- None of the validation models include inhalation of aerosols from evaporative coolers. The ERMYN method for calculating this inhalation dose (Equation 6.4.8-3) is similar to the methods in the validation models for particulate matter, except that the ERMYN calculation includes parameters to quantify the proportion of houses with evaporative coolers and the proportion of the year that coolers are used. The calculation of the inhalation dose from radon decay products (Equation 6.4.8-7) includes these factors because of different radon accumulation levels in indoor air when evaporative coolers are tuned on and off. The average cooler use factor may be as low as 0.08 for predicted future climatic conditions (Table 6.6-3); therefore, these factors could result in a difference of more than a factor of two. The ERMYN model includes these parameters because some people in the Amargosa Valley do not use evaporative coolers, and coolers are not operated year-round (DOE 1997 [DIRS 100332]). Excluding these parameters results in overestimating the inhalation dose.

These parameters are justified because they account for site-specific conditions and prevent overestimating dose.

- BIOMASS ERB2A includes the inhalation of aerosols from water sprays, but it does not provide the method for calculating aerosol concentrations, although it does give a default value of $1.0 \times 10^{-11}$ $m^3_{water}/m^3_{air}$ (BIOMASS 2000 [DIRS 154522], Table 13), which corresponds to $1.0 \times 10^{-11}$ $Bq/m^3$ for a unit concentration of contaminated groundwater (1 $Bq/m^3$). This airborne concentration is lower than the typical concentration for resuspended particles ($10^{-5}$ to $10^{-8}$ $Bq/m^3$, Table 6.10-1). In addition, the BIOMASS ERB2A default value for exposure time to aerosols is 36.5 h/yr (BIOMASS 2000 [DIRS 154522], Table 13), which is lower than exposure time to resuspended particles (10.9 hr/day, Table 7.4-19) in the ERMYN model. Therefore, excluding this pathway from the ERMYN model would change the estimated inhalation dose by less than a factor of two, and therefore it does not require further justification.

- RESRAD includes a factor for the size of the contaminated area. Under the groundwater scenario, the total area contaminated is large due to long-term irrigation and land-use rotation. Under the volcanic ash scenario, contaminated ash is deposited over the entire Amargosa Valley. Thus, this factor would be about 1.0 for both scenarios, and the RESRAD and ERMYN methods are mathematically equivalent.

- RESRAD includes a cover-and-depth factor for the effect of burying radioactive waste. Under both ERMYN scenarios, all radionuclides are in the surface soil, so this factor would be 1.0. Therefore, the RESRAD and ERMYN methods are mathematically equivalent.

Because the models are mathematically equivalent or produce similar results, the inhalation submodel is validated.

Table 7.3-24. Comparison of Inhalation Pathway

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.8-2 and 6.5.6-2) | Reference |
|---|---|---|---|
| GENII-S | $$Dn_i = 3.15\times10^7 B\times Ca_i \times f \times Dh_i$$<br>• $Dn_i$ = individual dose from inhalation (rem/yr)<br>• $3.15 \times 10^7$ = the number of seconds per year (sec/yr)<br>• $B$ = breathing rate for exposed individuals ($m^3$/sec)<br>• $Ca_i$ = average air concentration of radionuclide $i$ (Ci/$m^3$)<br>• $f$ = fraction of year exposed to inhalation (dimensionless)<br>• $Dh_i$ = inhalation dose conversion factor for radionuclide $i$ (rem/Ci). | The GENII-S inhalation submodel uses an average breathing rate, air concentration, and annual exposure time. It is simpler than the ERMYN, which uses environment-specific breathing rates and air concentrations, and time budgets for exposure time. | Napier et al. 1988 [DIRS 157927], p. 4.63, Eq. 4.7.1a. |
| BIOMASS ERB2A | $$D_{dust} = DC_{inh}\ C_{airs}\ BR\ \ O_s$$<br>• $D_{dust}$ = individual dose from dust inhalation (Sv/yr)<br>• $DC_{inh}$ = dose coefficient for inhalation (Sv/Bq)<br>• $C_{airs}$ = radionuclide concentration in the air above the cultivated soil compartment (Bq/$m^3$)<br>• $BR$ = breathing rate of humans in the soil compartment ($m^3$/hr)<br>• $O_s$ = individual occupancy in the soil compartment (hr/yr)<br>$$D_{aero} = DC_{inh}\ AIR_{aero}\ BR\ \ O_{aero} C_w$$<br>• $D_{aero}$ = individual dose from the inhalation of aerosols (Sv/yr)<br>• $AIR_{aero}$ = aerosol level in the air in the area affected by aerosol/spray ($m^3$/$m^3$)<br>• $O_{aero}$ = individual occupancy in the area affected by aerosols (hr/yr). | In BIOMASS, the inhalation of dust is the same as in the GENII-S submodel. However, BIOMASS includes the inhalation of aerosols and sprays, which is not important, as discussed in the text. | BIOMASS 2000 [DIRS 154522], p. 38, Eq. 19. |
| EPRI-YM | $$D_{dust} = D_{inh}\ BR_{sed}\ O_{sed}\ C_{airs}$$<br>• $D_{dust}$ = individual dose from dust inhalation (Sv/yr)<br>• $D_{inh}$ = conversion factor for activity to dose for inhalation (Sv/Bq)<br>• $BR_{sed}$ = human breathing rate in the sediment or soil compartment ($m^3$/hr)<br>• $O_{sed}$ = individual occupancy in the sediment or soil compartment (hr/yr)<br>• $C_{airs}$ = radionuclide concentration in the air (Bq/$m^3$) (Table 7.3-4). | The EPRI-YM inhalation submodel is the same as that in the BIOMASS submodel. | Smith et al. 1996 [DIRS 101085], p. 5-14, Eq. 5.16. |
| RESRAD | $$ETF_{i2}(t) = ASR_2 \times\ FA_2 \times FCD_2(t) \times FO_2 \times FI_2$$<br>• $ETF_{i2}(t)$ = environmental transport factor at time $t$ for dust inhalation for the $i$th principle radionuclide (g/yr)<br>• $ASR_2$ = air/soil concentration ratio = average mass loading of airborne contaminated soil particles (g/$m^3$)<br>• $FA_2$ = area factor (dimensionless)<br>• $FCD_2(t)$ = cover-and-depth factor (dimensionless)<br>• $FO_2$ = occupancy factor (dimensionless)<br>• $FI_2$ = annual intake of air ($m^3$/yr). | RESRAD includes several factors, including contaminated soil depth, uncontaminated soil cover, and area contaminated. To convert ETF into dose, ETF is multiplied by the CEDE conversion factor for inhalation ($DCF_{i2}$ – mrem/pCi) and the soil source (S(t) – pCi/g). Without these factors, the RESRAD inhalation submodel is similar to GENII-S. | Yu et al. 2001 [DIRS 159465], p. B-6, Eq. 8.1. |

Table 7.3-24. Comparison of Inhalation Pathway (continued)

| | | | |
|---|---|---|---|
| NCRP-129 | $E_{inh} = Df_{inh} \times C_{air} \times [R_{out} \times T_{out} + (I/O) \times R_{in} \times T_{in}]$<br>• $D_{inh}$ = committed effective dose for inhalation (Sv/yr)<br>• $Df_{inh}$ = inhalation dose factor (Sv/Bq)<br>• $C_{air}$ = average annual outdoor air concentration (Bq/m$^3$)<br>• $R_{out}$ = average breathing rate outdoors (m$^3$/d)<br>• $R_{in}$ = average breathing rate indoors (m$^3$/d)<br>• ($I/O$) = ratio of nuclide concentration in air indoors versus outdoors<br>• $T_{out}$ = time spent outdoors on contaminated land (d/yr)<br>• $T_{in}$ = time spent indoors on contaminated land (d/yr). | The NCRP-129 inhalation submodel uses breathing rates and radionuclide concentrations in the air for indoor and outdoor environments, which is similar to the concept used in the ERMYN for environment-related inhalation.<br>NCRP-129 is similar to ERMYN, except for using fewer human activity and environment categories. | NCRP 1999 [DIRS 155894], p. 64, Eq. 4.2. |

### 7.3.9 Validation of the Ingestion Submodel

The ERMYN and the five validation models use the same methods for calculating ingestion doses, although the number of ingestion pathways differs among the models. All of the models include soil ingestion by humans and use similar methods (Table 7.3-29). All five validation models also use crop (Table 7.3-26) and animal (Table 7.3-27) ingestion pathways. Vegetables, beef, and milk are the most common types of food in the submodels. Water ingestion is included in the ERMYN groundwater water scenario (Equation 6.4.9-2). Among the five validation models, only NCRP-129 excludes the ingestion of drinking water (Table 7.3-25). The ingestion of aquatic foods (e.g., fish) is included in the GENII-S and RESRAD models (Table 7.3-28). Using the same general methods, the ERMYN and the five validation models calculate ingestion doses as the product of radionuclide-specific dose conversion factors, radionuclide concentrations in the ingested media, and ingestion rates. The validation models differ from the ERMYN submodel in the following ways:

- GENII-S and NCRP-129 include radionuclide decay during the holdup time before consumption. The time between harvest or groundwater pumping and consumption is small relative to the half life of long-lived radionuclides (Table 6.3-7). Thus, the terms in the GENII-S and NCRP-129 models that include the holdup time and decay constant approach 1.0, making the methods mathematically equivalent.

- GENII-S and EPRI-YM include factors for the portion of groundwater that is treated or uncontaminated (Table 7.3-25). Because Amargosa Valley groundwater is not treated and all water is contaminated, the percentage of uncontaminated water would be 0.0, and therefore the methods are mathematically equivalent.

- NCRP-129 includes a parameter for the fraction of crop consumption derived from the contaminated site (Table 7.3-26). Because all crops in the Amargosa Valley are contaminated in the ERMYN model, this parameter would be 1.0, and the methods are mathematically equivalent.

- BIOMASS ERB2A includes a water content factor in the estimate of soil density in the soil ingestion dose calculation (Table 7.3-29). This factor is not in the ERMYN model because ingested soil on hands and crops most likely would be dry. The ERMYN model calculates soil density using the dry bulk density of surface soil (Equation 6.4.1-6), which is about 1,500 $kg/m^3$ for soils in the Amargosa Valley (Table 6.6-3). The additional factor in the BIOMASS equation is calculated as the product of the soil volumetric water content (about 0.23; Table 6.6-3) and water density (1,000 $kg/m^3$), or about 230 $kg/m^3$. Including the water content factor would change the estimate of soil density by a factor of less than 1.2. This small difference requires no further justification.

- NCRP-129 uses an occupational exposure modification factor to account for differences in soil ingestion rates among people working in different occupations (Table 7.3-29). Soil ingestion rates in the ERMYN model are based on the occupations and lifestyles of Amargosa Valley residents (BSC 2003 [DIRS 161241], Section 6.4.3). Thus, this parameter is not required in the ERMYN submodel and the methods are mathematically equivalent.

Based on these comparisons, the ERMYN ingestion submodel is supported by the validation models and therefore is validated.

Table 7.3-25. Comparison of Water Ingestion Pathway

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.9-2) | Reference |
|---|---|---|---|
| GENII-S | $$Dw_i = U_w\, Cw_i\, Tf_i \exp(-\lambda_i \times tp)\, Dg_i$$ • $Dw_i$ = individual dose from water ingestion for radionuclide *i* (rem/yr)<br>• $Dg_I$ = ingestion dose conversion factor for radionuclide *i* (rem/Ci)<br>• $U_w$ = individual water intake rate (L/yr)<br>• $Cw_i$ = water concentration of radionuclide *i* (Ci/L)<br>• $Tf_i$ = water treatment purification factor (dimensionless)<br>• $\lambda_i$ = radiological decay constant for radionuclide *i* (/sec)<br>• *tp* = transit time through the water distribution system (sec). | The GENII-S submodel uses decay time, which is negligible for long-lived radionuclides. It also uses a water treatment factor, which is not in the ERMYN because groundwater in the Amargosa Valley is not treated. With these two exceptions, the models are the same. | Napier et al. 1988 [DIRS 157927], p. 4.65, Eq. 4.7.4a. |
| BIOMASS ERB2A | $$D_w = ING_w\, D_{ing}\, C_w$$ • $D_w$ = individual dose from consumption of groundwater ( Sv/yr)<br>• $D_{ing}$ = dose coefficient for ingestion (Sv/Bq)<br>• $ING_w$ = individual consumption rate for groundwater ($m^3$/yr)<br>• $C_w$ = radionuclide activity concentration in groundwater (Bq $m^3$). | The BIOMASS ERB2A water ingestion dose calculations are the same as those in the ERMYN. | BIOMASS 2000 [DIRS 154522], p. 34, Eq. 9. |
| EPRI-YM | $$D_{fw} = ING_{fw}\, D_{ing}\, FF_{fw}\, C_{fw}$$ • $D_{fw}$ = individual dose from consuming drinking water (Sv/yr)<br>• $D_{ing}$ = activity to dose conversion factor for ingestion (Sv/Bq)<br>• $ING_{fw}$ = individual ingestion rate of freshwater ($m^3$/yr)<br>• $FF_{fw}$ = fraction of activity in the filtered freshwater<br>• $C_{fw}$ = radionuclide concentration in the freshwater compartment (Bq/$m^3$). | The EPRI-YM and ERMYN submodels are the same, except that water treatment is included in EPRI-YM, but not in ERMYN. | Smith et al. 1996 [DIRS 101085], p. 5-7, Eq. 5.6. |
| RESRAD | $$H_{E,ip}(t) = DSR_{ij}(t) \times S_i(0)$$ • $H_{E,ip}(t)$ = average annual TEDE received at time *t* by a member of the critical population group from the *i*th principal radionuclide transported through the *p*th environmental pathway together with its associated decay products (mSv/yr or mrem/yr)<br>• $DSR_{ip}(t)$ = dose to soil-concentration ratio for the *i*th principal radionuclide and *p*th environmental pathway ((mSv/yr)/(Bq/g) or (mrem/yr)/(pCi/g))<br>• $S_i(0)$ = initial concentration of the *i*th principal radionuclide in a uniformly contaminated zone (Bq/g or pCi/g). | RESRAD calculates the environmental transport factor for various pathways, then calculates the dose to soil-concentration ratios (*DSR*), then calculates the dose ($H_E$). Although the equation has a different layout, the method is the same as the ERMYN. | Yu et al. 2001 [DIRS 159465], p. 3-10 and 3-11, Eq. 3.6 & 3.9. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-26. Comparison of Crop Ingestion Pathway

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.9-3, and 6.5.7-2) | Reference |
|---|---|---|---|
| GENII-S | $$Dv_i = \sum_{p=1}^{4} \left( U_p \, C_{ip} Dg_i \right)$$ • $Dv_i$ = dose from consumption of contaminated crops (rem/yr)<br>• $Dg_I$ = ingestion dose conversion factor for radionuclide *i* (rem/Ci)<br>• $U_p$ = consumption rate of crop type *p* (leafy, root, grain, or fruit) (kg/yr)<br>• $C_{ip}$ = concentration of radionuclide *i* in crop type *p* at time of consumption (Ci/kg). | GENII-S and ERMYN use the same method to calculate the crop ingestion dose. | Napier et al. 1988 [DIRS 157927], p. 4.69, Eq. 4.7.9. |
| BIOMASS ERB2A | $$D_{crop} = ING_{crop} \, D_{ing} \, \mathrm{C}_{crop}$$ • $D_{crop}$ = individual dose from consumption of crops (Sv/yr)<br>• $ING_{crop}$ = individual consumption rate for crops (kg/yr)<br>• $D_{ing}$ = dose coefficient for ingestion (Sv/Bq)<br>• $C_{crop}$ = radionuclide activity concentration in edible crop parts (Bq/kg). | BIOMASS ERB2A and ERMYN use the same method to calculate the crop ingestion dose. | BIOMASS 2000 [DIRS 154522], p. 34, Eq. 10. |
| EPRI-YM | $$D_{crop} = ING_{crop} \, D_{ing} \, \mathrm{C}_{crop}$$ • $D_{crop}$ = individual dose from consumption of crops (Sv/yr)<br>• $ING_{crop}$ = individual ingestion rate of crops (kg/yr)<br>• $D_{ing}$ = activity to dose conversion factor for ingestion (Sv/Bq)<br>• $C_{crop}$ = radionuclide concentration in crops (Bq/kg). | EPRI-YM and ERMYN are the same. | Smith et al. 1996 [DIRS 101085], p. 5-8, Eq. 5.8. |
| RESRAD | The same equation for water ingestion dose (see Table 7.3-25). | RESRAD calculates the environmental transport factor for various pathways, then calculates the dose to soil-concentration ratios (*DSR*), then calculates the dose ($H_E$). Although the equation has a different layout, the method is the same as the other models. | Yu et al. 2001 [DIRS 159465], p. 3-10 and 3-11, Eq. 3.6 and 3.9. |

Table 7.3-26. Comparison of Crop Ingestion Pathway (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.9-3, and 6.5.7-2) | Reference |
|---|---|---|---|
| NCRP-129 | $$E_{ing} = Df_{ing} \times \sum (C_i \times R_i) \times f_i \times \exp[-\lambda(t - t_0)]$$<br>• $E_{ing}$ = annual committed effective dose from ingestion (Sv/yr)<br>• $Df_{ing}$ = committed effective dose for ingestion that would result from an intake of 1 Bq of this radionuclide (Sv/Bq)<br>• $C_i$ = concentration of a particular radionuclide in foodstuff *i* at harvest (Bq/kg)<br>• $R_i$ = average annual intake of foodstuff *i* (kg)<br>• $f_I$ = fraction of $R_i$ derived from the contaminated site<br>• $Exp[-\lambda(t-t_0)]$ = correction factor to account for radioactive decay between harvest ($t_0$) and ingestion (t). | NCRP-129 uses holding times, which are negligible for long-lived radionuclides. It also uses the fraction of contaminated food consumed, which is incorporated into the consumption rate in the ERMYN model. | NCRP 1999 [DIRS 155894], p. 91, Eq. 5.1. |

Table 7.3-27. Comparison of Animal Product Ingestion Pathway

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.9-4 and 6.5.7-3) | Reference |
|---|---|---|---|
| GENII-S | $$Dm_i = \sum_{m=1}^{4} \left( U_m \, C_{im} Dg_i \right)$$ • $Dm_i$ = individual dose for radionuclide *i* from ingestion of animal product *m* (rem/yr)<br>• $Dg_i$ = dose conversion factor for ingestion (rem/Ci)<br>• $U_m$ = average annual daily consumption rate of animal products (kg/yr or L/yr for milk)<br>• $C_{im}$ = concentration in animal products (Ci/kg or Ci/L for milk). | The original equation (Eq. 4.7.14) in the GENII-S manual has inconsistent units. Modifications are made to the units for the average daily consumption rate and dose. | Napier et al. 1988 [DIRS 157927], p. 4.72, Eq. 4.7.13 and 4.7.14. |
| BIOMASS ERB2A | $$D_{prod} = ING_{prod} \, D_{ing} \, C_{prod}$$ • $D_{prod}$ = individual dose from consuming animal products (Sv/yr)<br>• $ING_{prod}$ = individual consumption rate of animal products (kg/yr)<br>• $D_{ing}$ = dose coefficient for ingestion (Sv/Bq)<br>• $C_{prod}$ = radionuclide concentrations in animal products (Bq/kg). | BIOMASS and ERMYN are the same. | BIOMASS 2000 [DIRS 154522], p. 36, Eq. 12. |
| EPRI-YM | $$D_{prod} = ING_{prod} \, D_{ing} \, C_{prod}$$ • $D_{prod}$ = individual dose from consuming animal products (Sv/yr)<br>• $ING_{prod}$ = individual consumption rate of animal products (kg/yr)<br>• $D_{ing}$ = activity to dose conversion factor for ingestion (Sv/Bq)<br>• $C_{prod}$ = radionuclide concentration in animal products (Bq/kg). | EPRI-YM and ERMYN use the same method. | Smith et al. 1996 [DIRS 101085], p. 5-9, Eq. 5.10. |
| RESRAD | The same equation for water ingestion dose (see Table 7.3-25). | RESRAD calculates the environmental transport factor for various pathways, then calculates the dose to soil-concentration ratios (*DSR*), then calculates the dose ($H_E$). Although the equation has a different layout, the method is the same as the other models. | Yu et al. 2001 [DIRS 159465], p. 3-10, and 3-11, Eq. 3.6 & 3.9. |
| NCRP-129 | The same equation for crop ingestion (see Table 7.4-25). | NCRP-129 model includes holding time, which is negligible for long-lived radionuclides. | NCRP 1999 [DIRS 155894], p. 91, Eq. 5.1. |

Table 7.3-28. Comparison of Fish Ingestion Pathway

| Document | Mathematical Model | Comparison with the ERMYN (Equation 6.4.9-5) | Reference |
|---|---|---|---|
| GENII-S | $$Da_i = \sum_{f=1}^{n} Dg_i \, U_f \, Cf_i \exp(-\lambda_i \, tp)$$ • $Da_i$ = individual dose from aquatic food ingestion for radionuclide *i* (rem/yr)<br>• $Dg_i$ = dose conversion factor for ingestion (rem/Ci)<br>• $n$ = number of aquatic food types ingested<br>• $U_f$ = consumption rate of aquatic food *f* (kg/yr)<br>• $Cf_i$ = activity concentration of radionuclide *i* in aquatic food (Ci/kg)<br>• $\lambda_i$ = radiological decay constant for radionuclide *i* (/sec)<br>• $tp$ = time of transit through the water distribution system (sec). | Units in the manual are not consistent, with $U_f$ in units of kg/d and $Da_i$ in units of rem. A modification is made to be comparable with the ERMYN. GENII-S includes several types of aquatic food and a decay correction. The basic equation is the same as the ERMYN. | Napier et al. 1988 [DIRS 157927], p. 4.66, Eq. 4.7.5a. |
| BIOMASS ERB2A | Not included. | Not applicable. | BIOMASS 2000 [DIRS 154522], Section 7. |
| EPRI-YM | Not included. | Not applicable. | Smith et al. 1996 [DIRS 101085]. |
| RESRAD | The same equation for water ingestion dose (see Table 7.3-25). | RESRAD calculates the environmental transport factor for various pathways, calculates the dose to soil-concentration ratios (*DSR*), and then calculates the dose ($H_E$). Although the equation has a different layout, the method is the same as the other models. | Yu et al. 2001 [DIRS 159465], pp. 3-10 and 3-11, Eq. 3.6 and 3.9. |
| NCRP-129 | Not included. | Not applicable. | NCRP 1999 [DIRS 155894]. |

Table 7.3-29. Comparison of Soil Ingestion Pathway

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.9-6 and 6.5.7-4) | Reference |
|---|---|---|---|
| GENII-S | $$Dd_i = Dg_i \; td \; U_{soil} \frac{Cs_i}{\rho_s}$$ • $Dd_i$ = dose to an individual from inadvertent soil ingestion (rem/yr)<br>• $Dg_i$ = dose conversion factor for ingestion (rem/Ci)<br>• $U_s$ = daily average soil ingestion rate (mg/d)<br>• $td$ = period of exposure to ingestion of soil (d/yr)<br>• $C_s$ = radionuclide activity concentration in the soil per unit area (Ci/m$^2$)<br>• $\rho_s$ = surface soil density (mg/m$^2$). | GENII-S does not calculate the annual dose. A modification is made to be consistent with other components of the dose calculation. GENII-S and ERMYN use the same submodel. | Napier et al. 1988 [DIRS 157927], p. 4.85, Eq. 4.7.25. |
| BIOMASS ERB2A | $$D_{soil} = D_{ing} \; ING_{soil} \frac{C_s}{(1-\theta_t)\,\rho + \theta\,\rho_w}$$ • $D_{soil}$ = individual dose from soil consumption (Sv/yr)<br>• $D_{ing}$ = dose coefficient for ingestion (Sv/Bq)<br>• $ING_{soil}$ = individual consumption rate of soil (kg/yr $_{\text{wet weight}}$)<br>• $C_s$ = radionuclide activity concentration in cultivated soil (Bq/m$^3$)<br>• $\theta_t$ = total porosity of the cultivated soil compartment<br>• $\rho$ = dry grain density of the cultivated soil compartment (kg/m$^3$)<br>• $\theta$ = water filled porosity of the cultivated soil compartment (dimensionless)<br>• $\rho_w$ = density of water (kg/m$^3$). | BIOMASS and ERMYN are equivalent. BIOMASS includes water content in the soil concentration. Because inadvertent soil ingestion by humans is from hands and food, not cultivated soil, the water content should be much lower than cultivated soil. Thus, it is not proper to add water content, which reduces radionuclide concentrations in dry soil. | BIOMASS 2000 [DIRS 154522], p. 37, Eq. 16. |
| EPRI-YM | $$D_{soil} = D_{ing} \; ING_{soil} \frac{C_s}{(1-\theta_t)\,\rho + \theta\,\rho_w}$$ • $D_{sedl}$ = individual dose from soil consumption (Sv/yr)<br>• $D_{ing}$ = activity to dose conversion factor for ingestion (Sv/Bq)<br>• $ING_{soil}$ = individual soil consumption rate (kg/yr)<br>• $C_{sed}$ = radionuclide concentration in the soil compartment (Bq/m$^3$)<br>• $\theta_{sed}$ = total porosity of the soil compartment<br>• $\rho_{gsed}$ = grain density of the soil compartment (kg/m$^3$)<br>• $\theta_{sedw}$ = water filled porosity of the soil compartment<br>• $\rho_w$ = density of water (kg/m$^3$). | EPRI-YM and ERMYN use the same method. | Smith et al. 1996 [DIRS 101085], p. 5-12, Eq. 5.13. |

Table 7.3-29. Comparison of Soil Ingestion Pathway (continued)

| Document | Mathematical Model | Comparison with the ERMYN (Equations 6.4.9-6 and 6.5.7-4) | Reference |
|---|---|---|---|
| RESRAD | $$ETF_{j8}(t) = FSI \times FA_8 \times FCD_8(t) \times FO_8$$<br>• $ETF_{j8}(t)$ = environmental transport factor at time $t$ for soil ingestion for the $i$th principle radionuclide (g/yr)<br>• $FSI$ = annual intake of soil (g/yr)<br>• $FA_8$ = area factor (dimensionless)<br>• $FCD_8(t)$ = cover-and-depth factor (dimensionless)<br>• $FO_8$ = occupancy factor (dimensionless). | RESRAD uses several factors, including depth of the contaminated soil, uncontaminated soil cover, and contaminated area, which are not used in ERMYN model. To convert ETF to dose, ETF is multiplied by the dose coefficients (*DCF* – mrem/pCi) and the source terms (*S(t)* – pCi/g) (Yu et al. 2001 [DIRS 159465], Eq. 3.6 and 3.9). | Yu et al. 2001 [DIRS 159465], p. F-3, Eq. F.2. |
| NCRP-129 | $$E_{soil} = Df_{ing} \times C_{soil} \times I_{soil} \times T \times OF$$<br>• $E_{soil}$ = committed effective dose for soil ingestion (Sv/yr)<br>• $Df_{ing}$ = ingestion dose factor (Sv/Bq)<br>• $C_{soil}$ = average concentration in top 5 cm of soil (Bq/kg)<br>• $I_{soil}$ = average soil ingestion rate during the exposure period (kg/d)<br>• $T$ = exposure duration (d/yr)<br>• $OF$ = occupational exposure modification factor. | NCRP-129 uses an occupational exposure modification factor, which is used for workers. This factor is included in the ERMYN soil consumption rate. Therefore, NCRP-129 and ERMYN use equivalent methods. | NCRP 1999 [DIRS 155894], p. 133, Eq. 5.4. |

## 7.4 NUMERICAL COMPARISON OF MODEL RESULTS

This section describes some of the numerical comparisons conducted to evaluate the assumptions (Section 5) and ACMs (Section 6.3.3), to validate the ERMYN model (Section 7.3), and to determine if the effective dose coefficients and the effective dose conversion factors (Section 6.4) used to consider short-lived decay products are valid.

The model validation criteria for numerical comparisons are specified in the TWP (BSC 2003 [DIRS 163602], p. 20), and implementation of the criteria is described in Section 7.1. In all cases where the ERMYN and the five validation models are not mathematically equivalent, a numerical comparison is required. Simple comparisons are presented in Section 7.3, and complex numerical comparisons are presented in this section. If the difference in the results between the ERMYN and the validation model are within a factor of 2, numerical similarity between the models is demonstrated. If the results differ by more than a factor of 2, further evaluation and justification of the selected method is included in Section 7.3.

To make the model comparisons more realistic, input parameters are selected mainly from the ERMYN model input values (Section 6.6.3), and if possible, the same parameter values are used in all of the comparisons. When parameters are specific to a particular validation model, default values for that model are used.

### 7.4.1 Radionuclide Decay and Ingrowth

This section presents a validation of the methods used for the effective dose coefficients (Section 6.4.7.2), the effective dose conversion factor for inhalation (Section 6.4.8.5), and the effective dose conversion factor for ingestion (Section 6.4.9.6) by comparing the ERMYN model results with those from the RESRAD model (Yu et al. 2001 [DIRS 159465]). This comparison does not involve an ACM (Sections 6.3.3 and 7.3).

As discussed in Section 6.3.5, the ERMYN model assumes that a radionuclide with a half-life of less than 180 d is always in secular equilibrium with the long-lived parent radionuclide (Assumption 2). The half-life cutoff is based on the intended use of the model. From a data file, *RMDLIB.DAT* (Attachment I) in the GENII-S model (SNL 1998 [DIRS 117076]), it can be determined that GENII-S uses a one-hour cutoff for the half-life, as that model is suitable for acute radionuclide releases. Using a high value for the half-life cutoff simplifies the ERMYN model by eliminating many short-lived radionuclide decay chains, while still maintaining the accuracy of the model for a long-term repository dose assessment.

This simplification is used in the RESRAD code, a code widely used by the DOE and DOE contractors, the NRC, U.S. Environmental Protection Agency, and many other organizations (Yu et al. 2001 [DIRS 159465], p. xi). The effective dose coefficients and conversion factors calculated in the ERMYN model (Sections 6.4.7.2, 6.4.8.5 and 6.4.9.6) are compared with the RESRAD values (Tables 7.4-1, 7.4-2 and 7.4-3, respectively). These comparisons indicate that the values derived from the two models are the same, except for small differences due to rounding. The effective dose coefficients for exposure to contaminated ground (Section 6.5.5.2) are not compared because RESRAD does not use this set of dosimetric data, but the method to derive these values is the same as those used for calculating the values compared in this section.

Table 7.4-1. Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth

| Primary Radionuclide | Effective DC [a] (Sv/sec) / ($Bq/m^3$) | Effective DC [b] (mrem/yr) / (pCi/g) | RESRAD DC [c] (mrem/yr) / (pCi/g) | Notes [d] |
|---|---|---|---|---|
| C-14 | 7.20E-23 | 1.35E-05 | 1.34E-05 | Rounding differences |
| Cl-36 | 1.28E-20 | 2.39E-03 | 2.39E-03 | Same |
| Se-79 | 9.96E-23 | 1.86E-05 | 1.86E-05 | Same |
| Sr-90D | 1.32E-19 | 2.47E-02 | 2.46E-02 | Rounding differences |
| Tc-99 | 6.72E-22 | 1.26E-04 | 1.26E-04 | Same |
| Sn-126D | 6.34E-17 | 1.19E+01 | n.a. | Not available in RESRAD |
| I-129 | 6.93E-20 | 1.30E-02 | 1.29E-02 | Rounding differences |
| Cs-135 | 2.05E-22 | 3.83E-05 | 3.83E-05 | Same |
| Cs-137D | 1.83E-17 | 3.42E+00 | 3.41E+00 | Rounding differences |
| Pu-242 | 6.85E-22 | 1.28E-04 | 1.28E-04 | Same |
| U-238D | 8.13E-19 | 1.52E-01 | 1.37E-01 | correction made in RESRAD code 6.1 to be 1.52E-01 |
| Pu-238 | 8.10E-22 | 1.51E-04 | 1.51E-04 | Same |
| U-234 | 2.15E-21 | 4.02E-04 | 4.02E-04 | Same |
| Th-230 | 6.47E-21 | 1.21E-03 | 1.21E-03 | Same |
| Ra-226D | 5.99E-17 | 1.12E+01 | 1.12E+01 | Same |
| Pb-210D | 3.27E-20 | 6.11E-03 | 6.10E-03 | Rounding differences (Pb-210D + Po-210) |
| Pu-240 | 7.85E-22 | 1.47E-04 | 1.47E-04 | Same |
| U-236 | 1.15E-21 | 2.15E-04 | 2.15E-04 | Same |
| Th-232 | 2.79E-21 | 5.21E-04 | 5.21E-04 | Same |
| Ra-228D | 3.20E-17 | 5.98E+00 | 5.98E+00 | Same |
| U-232 | 4.83E-21 | 9.03E-04 | 9.02E-04 | Rounding differences |
| Th-228D | 5.46E-17 | 1.02E+01 | 1.02E+01 | Same |
| Am-243D | 4.79E-18 | 8.96E-01 | 8.95E-01 | Rounding differences |
| Pu-239 | 1.58E-21 | 2.95E-04 | 2.95E-04 | Same |
| U-235D | 4.06E-18 | 7.59E-01 | 7.57E-01 | Rounding differences |
| Pa-231 | 1.02E-18 | 1.91E-01 | 1.91E-01 | Same |
| Ac-227D | 1.08E-17 | 2.02E+00 | 2.01E+00 | Rounding differences |
| Am-241 | 2.34E-19 | 4.38E-02 | 4.37E-02 | Rounding differences |
| Np-237D | 5.88E-18 | 1.10E+00 | 1.10E+00 | Same |
| U-233 | 7.48E-21 | 1.40E-03 | 1.40E-03 | Same |
| Th-229D | 8.55E-18 | 1.60E+00 | 1.60E+00 | Same |

NOTES: DC = dose coefficient.

[a] From Table 6.4-2.

[b] Unit conversion from Column 2 using soil density = 1.6 $g/cm^3$, in order to compare the values with RESRAD values in Column 4

[c] Source: RESRAD (Yu et al. 2001 [DIRS 159465], Table A.1).

[d] Using a conversion factor of $1.87 \times 10^{17}$, ten values differ slightly due to rounding differences.

Table 7.4-2. Effective Equivalent Conversion Factors for Inhalation

| Primary Radionuclide | Inhalation Class [c] | Effective DCF [a] (Sv/Bq) | Effective DCF [b] (mrem/pCi) | RESRAD DCF [c] (mrem/pCi) | Notes |
|---|---|---|---|---|---|
| C-14 | CO2 | 6.36E-12 | 2.35E-08 | 2.35E-08 | Same |
| Cl-36 | W | 5.93E-09 | 2.19E-05 | 2.19E-05 | Same |
| Se-79 | W | 2.66E-09 | 9.84E-06 | 9.84E-06 | Same |
| Sr-90D | D | 6.68E-08 | 2.47E-04 | 2.47E-04 | Same |
| Tc-99 | W | 2.25E-09 | 8.33E-06 | 8.33E-06 | Same |
| Sn-126D | W | 2.74E-08 | 1.53E-03 | n.a. | Not available in RESRAD |
| I-129 | D | 4.69E-08 | 1.74E-04 | 1.74E-04 | Same |
| Cs-135 | D | 1.23E-09 | 4.55E-06 | 4.55E-06 | Same |
| Cs-137D | D | 8.63E-09 | 3.19E-05 | 3.19E-05 | Same |
| Pu-242 | W | 1.11E-04 | 4.11E-01 | 4.11E-01 | Same |
| U-238D | Y | 3.20E-05 | 1.18E-01 | 1.18E-01 | Same |
| Pu-238 | W | 1.06E-04 | 3.92E-01 | 3.92E-01 | Same |
| U-234 | Y | 3.58E-05 | 1.32E-01 | 1.32E-01 | Same |
| Th-230 | W | 8.80E-05 | 3.26E-01 | 3.26E-01 | Same |
| Ra-226D | W | 2.32E-06 | 8.60E-03 | 8.60E-03 | Same |
| Pb-210D | D | 6.26E-06 | 2.32E-02 | 2.32E-02 | Same (Pb-210D + Po-210) |
| Pu-240 | W | 1.16E-04 | 4.29E-01 | 4.29E-01 | Same |
| U-236 | Y | 3.39E-05 | 1.25E-01 | 1.25E-01 | Same |
| Th-232 | W | 4.43E-04 | 1.64E+00 | 1.64E+00 | Same |
| Ra-228D | W | 1.37E-06 | 5.08E-03 | 5.08E-03 | Same |
| U-232 | Y | 1.78E-04 | 6.59E-01 | 6.59E-01 | Same |
| Th-228D | Y | 9.32E-05 | 3.45E-01 | 3.45E-01 | Same |
| Am-243D | W | 1.19E-04 | 4.40E-01 | 4.40E-01 | Same |
| Pu-239 | W | 1.16E-04 | 4.29E-01 | 4.29E-01 | Same |
| U-235D | Y | 3.32E-05 | 1.23E-01 | 1.23E-01 | Same |
| Pa-231 | W | 3.47E-04 | 1.28E+00 | 1.28E+00 | Same |
| Ac-227D | D | 1.82E-03 | 6.72E+00 | 6.72E+00 | Same |
| Am-241 | W | 1.20E-04 | 4.44E-01 | 4.44E-01 | Same |
| Np-237D | W | 1.46E-04 | 5.40E-01 | 5.40E-01 | Same |
| U-233 | Y | 3.66E-05 | 1.35E-01 | 1.35E-01 | Same |
| Th-229D | W | 5.85E-04 | 2.16E+00 | 2.16E+00 | Same |

NOTES: DCF = dose conversion factor.

[a] From Table 6.4-3.

[b] Unit conversion from Column 3.

[c] Source: RESRAD (Yu et al. 2001 [DIRS 159465], Table B.1).

Table 7.4-3. Effective Dose Conversion Factors for Ingestion

| Primary Radionuclide | Ingestion Class [c] | Effective DCF [a] (Sv/Bq) | Effective DCF [b] (mrem/pCi) | RESRAD [c] (mrem/pCi) | Notes |
|---|---|---|---|---|---|
| C-14 | 1.0 | 5.64E-10 | 2.09E-06 | 2.09E-06 | Same |
| Cl-36 | 1.0 | 8.18E-10 | 3.03E-06 | 3.03E-06 | Same |
| Se-79 | 8E-1 | 2.35E-09 | 8.70E-06 | 8.70E-06 | Same |
| Sr-90D | 3E-1 | 4.14E-08 | 1.53E-04 | 1.53E-04 | Same |
| Tc-99 | 8E-1 | 3.95E-10 | 1.46E-06 | 1.46E-06 | Same |
| Sn-126D | 2E-2 | 5.70E-09 | 2.11E-05 | n.a. | Not available in RESRAD |
| I-129 | 1.0 | 7.46E-08 | 2.76E-04 | 2.76E-04 | Same |
| Cs-135 | 1.0 | 1.91E-09 | 7.07E-06 | 7.07E-06 | Same |
| Cs-137D | 1.0 | 1.35E-08 | 5.00E-05 | 5.00E-05 | Same |
| Pu-242 | 1E-3 | 9.08E-07 | 3.36E-03 | 3.36E-03 | Same |
| U-238D | 5E-2 | 7.25E-08 | 2.68E-04 | 2.69E-04 | Rounding difference |
| Pu-238 | 1E-3 | 8.65E-07 | 3.20E-03 | 3.20E-03 | Same |
| U-234 | 5E-2 | 7.66E-08 | 2.83E-04 | 2.83E-04 | Same |
| Th-230 | 2E-4 | 1.48E-07 | 5.48E-04 | 5.48E-04 | Same |
| Ra-226D | 2E-1 | 3.58E-07 | 1.33E-03 | 1.33E-03 | Same |
| Pb-210D | 2E-1 | 1.97E-06 | 7.27E-03 | 7.27E-03 | Same (Pb-210D + Po-210) |
| Pu-240 | 1E-3 | 9.56E-07 | 3.54E-03 | 3.54E-03 | Same |
| U-236 | 5E-2 | 7.26E-08 | 2.69E-04 | 2.69E-04 | Same |
| Th-232 | 2E-4 | 7.38E-07 | 2.73E-03 | 2.73E-03 | Same |
| Ra-228D | 2E-1 | 3.89E-07 | 1.44E-03 | 1.44E-03 | Same |
| U-232 | 5E-2 | 3.54E-07 | 1.31E-03 | 1.31E-03 | Same |
| Th-228D | 2E-4 | 2.18E-07 | 8.08E-04 | 8.08E-04 | Same |
| Am-243D | 1E-3 | 9.80E-07 | 3.63E-03 | 3.63E-03 | Same |
| Pu-239 | 1E-3 | 9.56E-07 | 3.54E-03 | 3.54E-03 | Same |
| U-235D | 5E-2 | 7.23E-08 | 2.67E-04 | 2.67E-04 | Same |
| Pa-231 | 1E-3 | 2.86E-06 | 1.06E-02 | 1.06E-02 | Same |
| Ac-227D | 1E-3 | 3.99E-06 | 1.48E-02 | 1.48E-02 | Same |
| Am-241 | 1E-3 | 9.84E-07 | 3.64E-03 | 3.64E-03 | Same |
| Np-237D | 1E-3 | 1.20E-06 | 4.44E-03 | 4.44E-03 | Same |
| U-233 | 5E-2 | 7.81E-08 | 2.89E-04 | 2.89E-04 | Same |
| Th-229D | 2E-4 | 1.09E-06 | 4.03E-03 | 4.03E-03 | Same |

NOTES: DCF = dose conversion factor.

[a] From Table 6.4-4.

[b] Unit conversion from Column 3.

[c] Source: RESRAD (Yu et al. 2001 [DIRS 159465], Table D.1).

### 7.4.2 Surface Soil Submodel

The surface soil submodel for the groundwater scenario is used to calculate the accumulation of radionuclides in cultivated soils after long-term irrigation. It is assumed that steady-state conditions have been reached, and radionuclide concentrations in the soil are calculated only under steady-state conditions (Assumption 5). An evaluation is conducted (Section 7.4.2.1) to verify that the radionuclides considered would reach steady-state conditions by 10,000 years. Furthermore, in the ERMYN model, decay-chain radionuclides are considered to be in equilibrium (Section 6.4.1.2). Therefore, the radionuclide decay chains in the ERMYN model are compared with those in the GENII-S model to evaluate whether the results are comparable and to ensure that the ERMYN model includes all of the important radionuclides (Section 7.4.2.2).

#### 7.4.2.1 Time Required for a Steady-State Condition

As discussed in Section 6.4.1, the time to reach 95-percent saturation (i.e., the 95-percent saturation time) can be calculated using the effective removal constant. The effective removal factor is controlled mainly by a leaching constant (Equation 6.4.1-10), unless the leaching constant is less than the erosion constant ($1.3 \times 10^{-4}$), which corresponds the partition coefficient about 140 L/kg (Table 7.4-4). The erosion constant, leaching removal constant, effective removal constant, and 95-percent saturation time are calculated (Table 7.4-4) using input parameter values for the expected future climate (Table 6.6-3). Values for future climate conditions are used because of the lower leaching rate and longer time to reach saturation for that climate. Using mean partition coefficients and erosion rates, all radionuclides reach the 95-percent conditions in less than 2,300 years. If uncertainties in the partition coefficients and erosion rates are considered, variation in the leaching constants could be large. However, when the leaching rate is low, erosion is important. Therefore, using the 95-percent saturation condition for radionuclide accumulation in the soil is a valid approach that does not underestimate the radiation dose.

Table 7.4-4. Time to Reach 95-percent Saturation

| Primary Radionuclide | Decay Constant (/yr) | Erosion Constant (/yr) | Partition Coefficient (L/kg) | Calculated Leaching Constant (/yr) | Effective Removal Constant (/yr) | Saturated time @ 95% (yr) |
|---|---|---|---|---|---|---|
| C-14 | 1.21E-04 | 1.31E-03 | 1.8E+01 | 9.8E-03 | 22 [a] | 1 |
| Cl-36 | 2.30E-06 | 1.31E-03 | 1.4E-01 | 6.1E-01 | 6.10E-01 | 5 |
| Se-79 | 1.07E-05 | 1.31E-03 | 1.5E+02 | 1.2E-03 | 2.51E-03 | 1195 |
| Sr-90D | 2.38E-02 | 1.31E-03 | 2.0E+01 | 8.9E-03 | 3.40E-02 | 88 |
| Tc-99 | 3.25E-06 | 1.31E-03 | 1.4E-01 | 6.1E-01 | 6.10E-01 | 5 |
| Sn-126 | 6.93E-06 | 1.31E-03 | 4.5E+02 | 4.0E-04 | 1.71E-03 | 1751 |
| I-129 | 4.41E-08 | 1.31E-03 | 4.5E+00 | 3.8E-02 | 3.97E-02 | 75 |
| Cs-135 | 3.01E-07 | 1.31E-03 | 4.4E+03 | 4.1E-05 | 1.35E-03 | 2223 |
| Cs-137D | 2.31E-02 | 1.31E-03 | 4.4E+03 | 4.1E-05 | 2.45E-02 | 123 |
| Pu-242 | 1.84E-06 | 1.31E-03 | 1.2E+03 | 1.5E-04 | 1.46E-03 | 2056 |
| U-238D | 1.55E-10 | 1.31E-03 | 3.3E+01 | 5.4E-03 | 6.70E-03 | 447 |
| Pu-238 | 7.90E-03 | 1.31E-03 | 1.2E+03 | 1.5E-04 | 9.36E-03 | 320 |
| U-234 | 2.83E-06 | 1.31E-03 | 3.3E+01 | 5.4E-03 | 6.70E-03 | 447 |
| Th-230 | 9.00E-06 | 1.31E-03 | 3.0E+03 | 6.0E-05 | 1.38E-03 | 2178 |
| Ra-226D | 4.33E-04 | 1.31E-03 | 3.6E+04 | 5.0E-06 | 1.74E-03 | 1717 |
| Pb-210D | 3.11E-02 | 1.31E-03 | 1.6E+04 | 1.1E-05 | 3.24E-02 | 92 |
| Pu-240 | 1.06E-04 | 1.31E-03 | 1.2E+03 | 1.5E-04 | 1.56E-03 | 1918 |
| U-236 | 2.96E-08 | 1.31E-03 | 3.3E+01 | 5.4E-03 | 6.70E-03 | 447 |
| Th-232 | 4.93E-11 | 1.31E-03 | 3.0E+03 | 6.0E-05 | 1.37E-03 | 2193 |
| Ra-228D | 1.21E-01 | 1.31E-03 | 3.6E+04 | 5.0E-06 | 1.22E-01 | 25 |
| U-232 | 9.63E-03 | 1.31E-03 | 3.3E+01 | 5.4E-03 | 1.63E-02 | 184 |
| Th-228D | 3.62E-01 | 1.31E-03 | 3.0E+03 | 6.0E-05 | 3.64E-01 | 8 |
| Am-243D | 9.39E-05 | 1.31E-03 | 2.0E+03 | 8.9E-05 | 1.49E-03 | 2011 |
| Pu-239 | 2.88E-05 | 1.31E-03 | 1.2E+03 | 1.5E-04 | 1.48E-03 | 2018 |
| U-235D | 9.85E-10 | 1.31E-03 | 3.3E+01 | 5.4E-03 | 6.70E-03 | 447 |
| Pa-231 | 2.12E-05 | 1.31E-03 | 1.8E+03 | 9.9E-05 | 1.43E-03 | 2099 |
| Ac-227D | 3.18E-02 | 1.31E-03 | 1.5E+03 | 1.2E-04 | 3.33E-02 | 90 |
| Am-241 | 1.60E-03 | 1.31E-03 | 2.0E+03 | 8.9E-05 | 3.00E-03 | 999 |
| Np-237D | 3.24E-07 | 1.31E-03 | 2.5E+01 | 7.1E-03 | 8.41E-03 | 356 |
| U-233 | 4.37E-06 | 1.31E-03 | 3.3E+01 | 5.4E-03 | 6.70E-03 | 447 |
| Th-229D | 9.44E-05 | 1.31E-03 | 3.0E+03 | 6.0E-05 | 1.46E-03 | 2051 |

NOTES: Calculations performed using Microsoft Excel 97 SR-2, and the electronic file, *ERMYN validation.xls*, which is listed in Attachment I. Columns 2 and 4 are from Tables 6.3-7 and 6.6-3, respectively. Column 3 is calculated using Equation 6.4.1-11. Column 5 is calculated using Equation 6.4.1-10. The last two columns are calculated using the method provided in Section 6.4.1.1. All input data are taken from Table 6.6-3.

[a] This value is the $^{14}C$ emission rate (Table 6.6-3).

#### 7.4.2.2 Comparison of Radionuclide Decay Chains in the GENII-S and ERMYN Models

When radionuclide decay and ingrowth are modeled, decay chains often are evaluated to determine where the chains approximately stop, permitting the calculations to be terminated and the computational problem to be simplified. This is especially true for the transuranic radionuclides with long-decay chains. The only decay and ingrowth included in the ERMYN model is related to radionuclide buildup in the soil, where radionuclide decay chains are included in the surface soil submodel (Section 6.4.1.2). In this section, radionuclide decay chains in the GENII-S and ERMYN models are compared to determine if all of the decay products are properly considered.

A data file, *RMDLIB.DAT* (Attachment I), is used in the GENII-S model (SNL 1998 [DIRS 117076]) to control radionuclide decay chains. Part of this data file is shown in the GENII-S manual (Leigh et al. 1993 [DIRS 100464], p. 5-69). Only the high atomic number ($Z \geq 82$) radionuclides are compared. Comparisons are made for each high-Z primary radionuclide and associated decay chain (Table 7.4-5). The comparison indicates that the two models use similar methods to control the decay chains, and therefore the radionuclide decay chains are properly considered in the ERMYN model.

Table 7.4-5. Radionuclide Decay Chains Included in the GENII-S and ERMYN Models

| Primary Radionuclide | GENII-S [a] | ERMYN [b] | Notes |
|---|---|---|---|
| Pu-242 | No decay chain | No decay chain | Same |
| U-238 | Decay chain: Th-234 (Pa-234m) / Pa234 | U-238D | Same |
| Pu-238 | Decay chain: U-234 | No decay chain | Low contribution from ingrowth of U-234 due to long half-life |
| U-234 | No decay chain | Decay chain: Th-230 / Ra-226D / Pb-210D | ERMYN includes the decay chain, which adds a small contribution from the decay products |
| Th-230 | Decay chain: Ra-226 / Rn-222 (Po-218, Pb-214, Bi-214, Po-214) / Pb-210 / Bi-210 / Po-210 | Decay chain: Ra-226D / Pb-210D | Equivalent |
| Ra-226 | Decay chain: Rn-222 (Po-218, Pb-214, Bi-214, Po-214) / Pb-210 / Bi-210 / Po-210 | Decay chain: Ra-226D / Pb-210D | Equivalent |
| Pb-210 | Decay chain: Pb-210 / Bi-210 / Po-210 | Pb-210D | Equivalent |
| Pu-240 | Decay chain: U-236 | No decay chain | Equivalent |
| U-236 | No decay chain | No decay chain | Same |
| Th-232 | Decay chain: Ra-228 / Ac-228 / Th-228 / Ra-224 (Rn-220, Po-216) / Pb-212 / Bi-212 | Decay chain: Ra-228D / Th-228D | Equivalent |
| Ra-228 | Decay chain: Ac-228 / Th-228 / Ra-224 (Rn-220, Po-216) / Pb-212 / Bi-212 | Decay chain: Ra-228D / Th-228D | Equivalent |
| U-232 | Decay chain: Th-228 / Ra-224 (Rn-220, Po-216) / Pb-212 / Bi-212 | Decay chain: Th-228D | Equivalent |
| Th-228 | Decay chain: Ra-224 (Rn-220, Po-216) / Pb-212 / Bi-212 | Th-228D | Equivalent |
| Am-243 | Decay chain: Np-239 / Pu-239 | Decay chain: Am-243D / Pu-239 | Same |
| Pu-239 | No decay chain | No decay chain | Same |
| U-235 | Decay chain: Th-231 / Pa-231 / Ac-227 / Th-227 / Fr-227 / Ra-223 (Rn-129, Po-215, Pb-211, Bi-211, TL-207) | Decay chain: U-235D / Pa-231 / Ac-227D | Equivalent |
| Pa-231 | Decay chain: Ac-227 / Th-227 / Fr-227 / Ra-223 (Rn-129, Po-215, Pb-211, Bi-211, TL-207) | Decay chain: Ac-227D | Equivalent |
| Ac-227 | Decay chain: Th-227 / Fr-227 / Ra-223 (Rn-129, Po-215, Pb-211, Bi-211, TL-207) | Ac-227D | Equivalent |
| Am-241 | Decay chain: Np-237 / Pa-233 | No decay chain | Low contribution from Np-237, due to long half-life |
| Np-237 | Decay chain: Pa-233 | Np-237D | Same |
| U-233 | Decay chain: Th-229 / Ra-225 / Ac-225 (Fr-221, At-217, Bi-213, Po-213, Tl-209, Pb-209) | Decay chain: Th-229D | Equivalent |
| Th-229 | Decay chain: Ra-225 / Ac-225 (Fr-221, At-217, Bi-213, Po-213, Tl-209, Pb-209) | Th-229D | Equivalent |

NOTES:

[a] Decay products in parenthesis are in a secular equilibrium with the parent radionuclides, but the decay chain is considered for those separated by a slash (/). From file RMDLIB.DAT in Attachment I.

[b] "D" indicates that a short half-life (< 180 d) decay product is considered with the primary radionuclide (Section 6.3.5 and Table 6.4-1).

### 7.4.3 Air Submodel

The GENII-S model does not include airborne dose contributions from radon and evaporative coolers. Therefore, the importance of these pathways is evaluated to determine if they warrant inclusion in the ERMYN model. In addition, a numerical comparison of an ACM for calculating the dose contribution from $^{222}$Rn inhalation (ACM 1, Sections 6.3.3 and 7.3.2.2) is documented in this section.

#### 7.4.3.1 Radon Pathway

An evaluation (Table 7.4-6) estimates the contribution of $^{222}$Rn to the total dose from $^{226}$Ra. The information for this evaluation is from the verification calculations (Section 6.10, Tables 6.10-3 and 6.10-6). For the groundwater and volcanic ash scenarios, 89 percent and 50 percent, respectively, of the $^{226}$Ra dose is from $^{222}$Rn inhalation (Table 7.4-6). The ERMYN model includes this pathway because the dose contribution from $^{222}$Rn is high.

Table 7.4-6. Radon Contribution to the Final $^{226}$Ra Dose

| Scenario | Total $^{226}$Ra Including $^{222}$Rn (Sv/yr) | $^{222}$Rn Contribution (Sv/yr) | Ratio (Rn/Ra) |
|---|---|---|---|
| Groundwater [a] | 2.02E-05 | 1.80E-05 | 89.1 % |
| Volcanic Ash [b] | 4.30E-08 [c] | 2.17E-08 | 50.5 % |

NOTES:

[a] Data from Table 6.10-3.

[b] Data from Table 6.10-6.

[c] This value is for all pathways except inhalation, which has two components ($7.06 \times 10^{-9}$ Sv/yr for the nominal condition, and $3.74 \times 10^{-9}$ Sv/yr for the post-volcanic condition) under the volcanic ash scenario (Table 6.10-6).

The methods for assessing dose from $^{222}$Rn inhalation are based on a concentration ratio, or release factor, of the average concentration of $^{222}$Rn in the air (Bq/m$^3$) and the average concentration of $^{226}$Ra in the soil (Bq/kg for groundwater scenario, Sections 6.4.2; Bq/m$^2$ for volcanic ash scenario, Section 6.5.2). The ERMYN method is different from the RESRAD radon diffusion method (Yu et al. 2001 [DIRS 159465], Appendix C; see also Section 7.3.2.2). The RESRAD method is considered an ACM (Section 6.3.3). According to the model validation approach, a numerical comparison between these two methods is required. The detailed analytical solution for radon diffusion is discussed in Attachment II. The general differential equation and the boundary conditions given in RESRAD are solved using the ERMYN model input parameter values or RESRAD default parameter values if the parameters are not included in the ERMYN model. The $^{222}$Rn release factor for volumetric $^{226}$Ra in the soil is 0.19 (Bq/m$^3$)/(Bq/kg) (Table II-1). This value is similar to the ERMYN value, which is 0.25 (Bq/m$^3$)/(Bq/kg) for the groundwater scenario (Section 6.4.2.3).

To compare $^{222}$Rn release factors for the volcanic scenario, the amount of $^{222}$Rn released into air from a thin contaminated layer on the ground surface must be calculated. This calculation is documented in Attachment II, and the results (Table 7.4-7) are taken from Table II-2.

Compared with the selected radon release factor for the volcanic ash scenario, 0.0006 (Bq/m$^3$)/(Bq/m$^2$) (Section 6.5.2.2), the calculated result for a thin layer of contaminated soil, 0.00013 (Bq/m$^3$)/(Bq/m$^2$), is 5 times lower than the selected value. The difference is due to the assumption that all radon released from the soil goes into the air (Assumption 15), which considers the radon emanation coefficient (ε) to equal 1. The default coefficient used in the RESRAD calculation is 0.25 (Table II-1). If a coefficient of 1 is used, the calculated radon release factor is 0.0005 (Bq/m$^3$)/(Bq/m$^2$), which is similar to the value used in the ERMYN model.

In conclusion, the selected radon release factors for the groundwater and volcanic ash scenarios, 0.25 (Bq/m$^3$)/(Bq/kg) and 0.0006 (Bq/m$^3$)/(Bq/m$^2$), respectively, are within a factor of 2 of the RESRAD method for the two scenarios, 0.19 (Bq/m$^3$)/(Bq/kg) and 0.0005 (Bq/m$^3$)/(Bq/m$^2$), respectively. Thus, the radon pathway is important and must be included in the ERMYN model. The selected radon model is simple and valid, and ACM 1 (Section 6.3.3) does not need further consideration for comparable input values.

Table 7.4-7. Radon Release Factors Due to Radium Contaminated Soil

| Depth of Contaminant (m) | Source Exponential Term | Rn-222 Release Factor in Mass (Bq/m$^3$)/(Bq/kg) | Surface Soil Density (kg/m$^2$) | Rn-222 Release Factor in Surface (Bq/m$^3$)/(Bq/m$^2$) |
|---|---|---|---|---|
| 0.003 | 0.0031 | 5.86E-04 | 4.5 | 0.00013 |
| 0.01 | 0.0102 | 1.95E-03 | 15 | 0.00013 |
| 0.02 | 0.0205 | 3.91E-03 | 30 | 0.00013 |
| 0.05 | 0.0512 | 9.76E-03 | 75 | 0.00013 |
| 0.1 | 0.1021 | 1.95E-02 | 150 | 0.00013 |
| 0.2 | 0.2020 | 3.85E-02 | 300 | 0.00013 |
| 0.5 | 0.4716 | 9.00E-02 | 750 | 0.00012 |
| 1 | 0.7716 | 1.47E-01 | 1500 | 0.00010 |
| 2 | 0.9673 | 1.85E-01 | 3000 | 0.00006 |
| 5 | 0.9999 | 1.91E-01 | 7500 | 0.00003 |
| 10 | 1.0000 | 1.91E-01 | 15000 | 0.00001 |

NOTE: This table is taken from Attachment II, Table II-2.

As mentioned in Section 6.4.2.2, $^{222}$Rn released from evaporative coolers is not considered in the air submodel because the amount of radon released from the water would be relatively low compared to that released from radium-saturated soils. The $^{222}$Rn in the groundwater used in evaporative coolers should be in equilibrium with $^{226}$Ra from the repository. Elevated levels of $^{222}$Rn have been reported in groundwater (up to 100,000 Bq/m$^3$; UNSCEAR 2000 [DIRS 158644], p. 102), but the high concentration came from natural rock during groundwater transport. Using typical values given above, the ratio of the $^{222}$Rn concentration in the air to the $^{226}$Ra concentration in the water, which would be the same as the $^{222}$Rn concentration in water due to secular equilibrium, is estimated at a level of $10^{-6}$ (20 L/hr to 8,000 m$^3$/hr). This ratio is lower than a typical value of $10^{-4}$ for radon dissolved in water entering indoor air through de-emanation (UNSCEAR 2000 [DIRS 158644], p. 102). Detailed discussion of the release of $^{222}$Rn from water is given in Section 6.4.2.3.

As mentioned in Section 6.4.2.3, the justification for excluding the radon contributions from evaporative coolers and household water use from the ERMYN model are provided here. Radon concentrations in indoor air resulting from water use can be estimated based on the rates of water use and house ventilation. As mentioned in Section 6.4.2.2, a typical radon release ratio between the concentration of $^{222}$Rn in the air and the concentration of $^{226}$Ra in the water is about $1 \times 10^{-4}$ (Yu et al. 2001 [DIRS 159465], p. C-13). This value can be verified using

$$\frac{Ca_{g,Rn-222}}{Cw_{Ra-226}} = \frac{f_{wa}U_w}{(\lambda_{Rn-222} + v)V} \qquad \text{(Eq. 7.4.3-1)}$$

where

| | | |
|---|---|---|
| $f_{wa}$ | = | transfer efficiency of radon from water to air (dimensionless) |
| $U_w$ | = | household water use rate (L/hr) |
| $\lambda_{Rn-222}$ | = | decay constant of $^{222}$Rn (0.0076/hr) |
| $v$ | = | house ventilation rate (/hr) |
| $V$ | = | volume of the house (L). |

Using typical values suggested in RESRAD, $f_{wa} = 0.55$, $U_w = 9.5$ L/hr for each individual (assuming 4 people in a household), $V = 75{,}000$ L, $v = 1$/hr (when evaporative coolers are not in operation), and $\lambda_{Rn-222} = 0.0076$/hr (Yu et al. 2001 [DIRS 159465], p. C-15), the concentration ratio of $^{222}$Rn in the air to $^{226}$Ra in the water can be calculated as $2.8 \times 10^{-4}$. Equation 7.4.3-1 can also apply to a room, such as a bathroom, where water use would be high. Using values for a shower, $f_{wa} = 0.7$, $U_w = 300$ L/hr, $v \times V = 0.13$ m$^3$/min = 7,800 L/hr (McKone and Bogen 1992 [DIRS 160440], p. 93; McKone and Daniels 1991 [DIRS 160441], p. 50), the ratio for a shower would be 0.027, which is two orders of magnitude higher than that for the house. However, a typical shower lasts for only about 10 min, while a person typically spends more than 8 hrs per day in the house. Therefore, a 10-min shower may cause only twice as much radon exposure as would 8 hrs of home occupancy due to radon released from water use source.

A typical outdoor radon concentration over soil contaminated by the long-term use of irrigation water can be estimated using saturation concentrations of $^{226}$Ra in the soil (Equations 6.4.1-4 and 6.4.1-5) and a $^{222}$Rn release factor (Equation 6.4.2-4). Using typical values ($IR = 1$ m/yr, $\lambda_{eff,Ra-226} = 0.001$/yr, $\rho_s = 250$ kg/m$^2$, and $f_{m,\,Rn-222} = 0.25$ (Bq/m$^3$)/(Bq/kg)), the concentration ratio of $^{222}$Rn in the air to $^{226}$Ra in the contaminated irrigation water would be about 1. This ratio is higher than the ratios for radon dissolved in water entering indoor air ($1 \times 10^{-4}$ to $1 \times 10^{-3}$) and for radon released by evaporative coolers ($10^{-6}$), which are discussed in Section 6.4.2.2. Therefore, it is reasonable to ignore the indoor radon contributions from the use of contaminated household water and evaporative coolers because the radon exposure from contaminated soil is several orders of magnitude higher.

### 7.4.3.2 Evaporative Cooler

The ERMYN model includes radionuclide concentrations in aerosols from evaporative coolers using a submodel based on the mechanical operation of an evaporative cooler (Section 6.4.2.2).

To validate this submodel, it is compared with an alternative method based on the difference between absolute humidities in indoor and outdoor air caused by evaporative coolers (Table 7.3-6).

The results from the two methods differ by a factor of 2 (Table 7.4-8), which meets the validation criteria for numerical similarity and the selected method is valid. It is easier to obtain input values for evaporative coolers than it is to determine the difference in absolute humidities, which depend on temperature and relative humidity. This evaluation indicates that ACM 2 (Section 6.3.3) does not need further consideration, and the chosen method is valid.

Table 7.4-8. Comparison of Evaporative Cooler Model

| Model | ERMYN | | | Alternative | | |
|---|---|---|---|---|---|---|
| Equation | $Ca_e = f_{evap} \frac{M_{water}}{F_{air}} Cw$ | | | $Ca = \frac{f_{evap}\,(D_{in} - D_{out})\;Cw}{\rho_w}$ | | |
| **Parameter** | **Notation** | **Value** | **Units** | **Notation** | **Value** | **Units** |
| Release fraction | $f_{evap}$ | 0.5 | - | $f_{evap}$ | 0.5 | - |
| Concentration in water | $Cw$ | 1 | Bq/m$^3$ | $Cw$ | 1 | Bq/m$^3$ |
| Water evaporation rate | $M_{water}$ | 17 | L/hr | - | - | - |
| Air flow rate | $F_{air}$ | 8,300 | m$^3$/hr | - | - | - |
| Absolute humidity (outdoors) | - | - | - | $D_{out}$ | 4.8 | g/m$^3$ |
| Absolute humidity (indoors) | - | - | - | $D_{in}$ | 8.7 | g/m$^3$ |
| Water density | - | - | - | $\rho_w$ | 1,000 | kg/m$^3$ |
| Concentration in air | $Ca_e$ | 1.0E-6 | Bq/m$^3$ | $Ca_e$ | 2.0E-6 | Bq/m$^3$ |

NOTE: Outdoor absolute humidity is representative of conditions at Yucca Mountain Weather Station #9 (Gate-510; CRWMS M&O 1997 [DIRS 100117] p. A-11), and indoor absolute humidity is based on 24ºC and 40 percent relative humidity. The calculation of absolute humidity from relative humidity and temperature is documented in Attachment III. All other values from the "mean, mode, average" column in Table 6.6-3.

### 7.4.4 Plant Uptake Submodel

Three numerical comparisons (direct deposition of irrigation water on crop surfaces, crop interception fraction for irrigation water, and direct deposition of resuspended soil on crop surfaces) are required to validate the plant submodel (Section 7.3.3), which are described in this section.

#### 7.4.4.1 Direct Deposition of Irrigation Water on Crop Surfaces

The methods in the ERMYN (Section 6.4.3.2) and BIOMASS ERB2A (Section 7.3.3.2) models for calculating concentrations from the direct deposition of irrigation water on crop surfaces are compared (Table 7.4-9). The results indicate that the two methods could differ by a factor of two. Some input parameters in the BIOMASS ERB2A model (e.g., absorption fraction and interval time) are not commonly used in the validation models, but they have a large influence on the results of the model. For example, the absorption fraction, which is 0.5 in BIOMASS ERB2A, is a high value for leaf water absorption. If a lower, perhaps more realistic, value is used (e.g., 0.3), the differences between the two models would be even smaller. The fraction of radionuclides that transfer from irrigation water to crops can be estimated using data in Table 7.4-9. The amount of radioactive material in crops per unit area is small, about

0.03 Bq/m$^2$ (0.015 Bq/kg × 2 kg/m$^2$), while the total amount of radioactive material in irrigation water is larger, 0.45 Bq/m$^2$ (1 Bq/m$^3$ × 0.006 m/d × 75 d).

In conclusion, the two methods are numerically similar. This evaluation shows that ACM 3 (Section 6.3.3) does not need further consideration, and the chosen method is justified.

Table 7.4-9. Comparison of Direct Deposition of Irrigation Water on Crop Surfaces

| **Model** | **ERMYN** [a] | | | **BIOMASS ERB2A** [b] | | |
|---|---|---|---|---|---|---|
| **Equation** | $Cp_w = \frac{Cw\, IRD\, f_o\, Rw\, T}{\lambda_w\, Y}\left(1 - e^{-\lambda_w\, t_{g,}}\right)$ | | | $C_{crop,w} = \frac{I_{crop}\, V_{irr}\, C_w}{Y_{crop}} \times \left[(1 - F_{abs})\, e^{-WT}\, F_{p3} + F_{abs}\, F_{p2}\, F_{trans}\right]$ | | |
| **Parameter** | **Notation** | **Value** | **Units** | **Notation** | **Value** | **Units** |
| Yearly Irrigation Rate | - | - | - | $V_{irr}$ | 0.45 | m/yr |
| Daily irrigation rate | $IRD$ | 0.006 | m/d | - | - | - |
| Concentration | $C_w$ | 1 | Bq/m$^3$ | $C_w$ | 1 | Bq/m$^3$ |
| Absorption fraction | - | - | - | $F_{abs}$ | 0.5 | - |
| Internal wash left | - | - | - | $F_{p2}$ | 1 | - |
| External wash left | - | - | - | $F_{p3}$ | 0.1 | - |
| Translocation | $T$ | 1 | - | $F_{trans}$ | 1 | - |
| Overhead fraction | $f_o$ | 1 | - | - | - | - |
| Interception | $R_w$ | 0.25 | - | $I_{crop}$ | 0.25 | - |
| Weathering | $\lambda_w$ | 0.05 | /d | $W$ | 18 | /yr |
| Wet yield | $Y$ | 2 | kg/m$^2$ | $Y_{crop}$ | 2 | kg/m$^2$/yr |
| Growing time | $tg$ | 75 | d | - | - | - |
| Interval time | - | - | - | $T$ | 0.02 | yr |
| Fraction – weather | $f_w$ | 0.976 | - | - | - | - |
| Fraction – external | - | - | - | $F_{ext}$ | 0.035 | - |
| Fraction – internal | - | - | - | $F_{int}$ | 0.5 | - |
| Leaf water deposition | $Cp_w$ | 1.5E-2 | Bq/kg | $C_{crop,w}$ | 3.0E-2 | Bq/kg |

NOTES: To simplify the equations, the radionuclide and crop-type indices (subscripts) are not shown.

[a] Input values from Table 6.6-3 if available; reasonable values used when there are multiple values per crop type.

[b] Input values are the same as those for the ERMYN model, or default values from BIOMASS ERB2A (BIOMASS 2000, [DIRS 154522], Section 7.4).

### 7.4.4.2 Crop Interception Fraction for Irrigation Water

The crop interception fraction for irrigation is calculated in the ERMYN model using an empirical equation (Equation 6.4.3-5), while all five validation models use a fixed value. Therefore, the models are compared to determine if the results are similar. The calculated results (mean values) for five crop types (Table 7.4-10) range from 0.24 to 0.51, with higher values for crops with more leaf surface (i.e., larger surface area). The results for some of the values differ by more than a factor of two, and an evaluation of the differences and justification for selecting the ERMYN method is presented in Section 7.3.3.2. It is concluded that the selected method is justified, and this part of the ERMYN plant submodel is validated.

Table 7.4-10. Calculated Interception Fraction for Irrigation Water

| Interception Fraction | Notation | Calculated Mean Value |
|---|---|---|
| Leafy vegetables | $Rw_1$ | 0.236 |
| Other vegetables | $Rw_2$ | 0.332 |
| Fruit | $Rw_3$ | 0.394 |
| Grain | $Rw_4$ | 0.514 |
| Forage | $Rw_5$ | 0.282 |

NOTE: Calculated mean values from Table 6.10-1.

### 7.4.4.3 Direct Deposition of Resuspended Soil on Crop Surfaces

The ERMYN (Section 6.4.3.3) and BIOMASS ERB2A (Section 7.3.3.3) models use different methods for calculating crop contamination by direct deposition of resuspended soil on crop surfaces. The BIOMASS ERB2A method is an ACM (Section 6.3.3), and therefore the two methods are compared. The equations presented here are simplified by eliminating radionuclide and crop-type indexes. Input parameter values are taken from Table 6.6-3, except that some default values for unique parameters are taken from the BIOMASS ERB2A model (BIOMASS 2000 [DIRS 154522], Section 7.4). Because the method used in the ERMYN model is sensitive to crop type due to translocation factor values, leafy vegetables and other vegetables are used to calculate radionuclide concentrations in crops from dust deposition (Table 7.4-11). The results of this comparison are evaluated in Section 7.3.3.3. The BIOMASS ERB2A method underestimates radionuclide concentrations in leafy vegetables, but the models are numerically similar for the applicable comparison of leafy vegetables to forage, and therefore the method selected for the ERMYN plant submodel is justified. This evaluation shows that ACM 4 (Section 6.3.3) does not need further consideration.

Table 7.4-11. Comparison of Direct Deposition of Resuspended Soil on Crop Surfaces

| Model | ERMYN [a] | | | | BIOMASS ERB2A [b] | | |
|---|---|---|---|---|---|---|---|
| **Equation** | $Cp_d = \frac{Cs_m S V_d Ra T}{\lambda_w Y}\left(1-e^{-\lambda_w t_g}\right)$ | | | | $C_{crop,d} = \frac{F_{p1} S_{crop} C_s}{(1-\theta_t)\rho}$ | | |
| **Parameter** | **Notation** | **Value for leafy veg.** | **Value for other veg.** | **Units** | **Notation** | **Value** | **Units** |
| Soil volume concentration | - | - | - | - | $Cs$ | 1,500 | Bq/m$^3$ |
| Soil grain density | - | - | - | - | $\rho$ | 2,650 | kg/m$^3$ |
| Total porosity | - | - | - | - | $\theta_t$ | 0.434 [c] | - |
| Soil mass concentration | $Cs_m$ | 1 | 1 | Bq/kg | $Cs_m$ | 1 | Bq/kg |
| Mass loading | $S$ | 1.2E-7 | 1.2E-7 | kg/m$^3$ | - | - | - |
| Deposit velocity | $V_d$ | 0.008 | 0.008 | m/sec | - | - | - |
| External soil left | - | - | - | - | $F_{p1}$ | 0.1 | - |
| Soil contamination | - | - | - | - | $S_{crop}$ | 2.0E-4 (all others)<br>2.0E-3 (forage) | kg/kg |
| Translocation | $T$ | 1 | 0.1 | - | - | - | - |
| Weathering | $\lambda_w$ | 0.05 | 0.05 | /d | - | - | - |
| Wet yield | $Y$ | 3.3 | 4.13 | kg/m$^2$ | - | - | - |
| Growing time | $t_g$ | 75 | 80 | d | - | - | - |
| Air interception [d] | $Ra$ | 0.456 | 0.787 | - | - | - | - |
| Dust deposition | $Cp_d$ | 2.2E-4 | 3.1E-5 | Bq/kg | $C_{crop,d}$ | 2.0E-5 (all others)<br>2.0E-4 (forage) | Bq/kg |

NOTES:

[a] Input values from the "mean, mode, average" column in Table 6.6-3 if available.

[b] Input values are the same as those for the ERMYN model or default values from the BIOMASS ERB2A report (BIOMASS 2000, [DIRS 154522], Section 7.4).

[c] Value from Table 6.6-3 as the ERMYN model has this parameter, although it is not used in this calculation.

[d] Values from Table 6.10-1, "Dust interception fraction."

### 7.4.5 Animal Submodel

Three mechanisms for the contamination of animal products are included in the ERMYN model: animal consumption of contaminated feed, water, and soil (Sections 6.4.4 and 6.5.4). Only two mechanisms, feed and drinking water, are included in the GENII-S model. The BIOMASS ERB2A model includes animal dust inhalation (Section 7.3.4) as an additional mechanism. Animal soil ingestion and animal dust inhalation are identified as ACMs (Section 6.3.3), and the importance of these alternative pathways is evaluated in this section.

This evaluation uses "meat" as an example animal product and $^{239}$Pu as a test radionuclide. The equations are shown in Sections 6.4.3 and 6.4.4, and results from the ERMYN model are taken from Table 6.10-1. The BIOMASS ERB2A model is described in Section 7.3.4, and the equations for calculating radionuclide concentrations in feed and animal products are shown in Table 7.4-12. Because BIOMASS ERB2A uses one irrigation rate for all crops and for soil accumulation, a direct comparison is not meaningful. Thus, radionuclide concentrations in the soil are from the results of the ERMYN model for surface soil submodel, soil grain density is from the default values in the BIOMASS model, and total porosity is calculated to match the soil bulk density in the ERMYN model. The retardation coefficient is calculated from the partition

coefficient and other parameters in the ERMYN model. All other parameter values are from the "mean, mode, average" column in Table 6.6-3 if possible, or default values from BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522], Section 7.4). The calculations (Table 7.4-12) are performed in an Excel spreadsheet, *ERMYN validation.xls*, which is listed in Attachment I.

The two models are equivalent, as the calculated concentrations in meat differ by only a few percent (Table 7.4-12). The ingestion of soil accounts for about 52 to 60 percent of the total concentration in meat for both models (Table 7.4-12), and therefore animal soil ingestion is an important mechanism that must be included in the animal submodel. The inclusion of animal soil ingestion is an improvement in the ERMYN model compared with the previous biosphere model. In contrast, animal inhalation of resuspended soil contributes little to dose (less than 0.01 percent of the meat concentration calculated with the BIOMASS ERB2A model; Table 7.4-12) and is not necessary. This evaluation shows that ACM 5 (Section 6.3.3) does not need further consideration.

Table 7.4-12. Numerical Calculation of Animal Uptake Submodel

| **Model** | **ERMYN [a]** | | | **BIOMASS ERB2A [b]** | | |
|---|---|---|---|---|---|---|
| **Equation** | Equations shown in Section 6.4.3 and 6.4.4, calculations shown in Table 6.10-1. | | | $C_{fodd} = \frac{(CF_{past} + S_{past})C_s}{(1-\theta_t)\rho} + \frac{I_{past}V_{irr}C_w}{SB_{past}W_{past} + 365ING_{fodd}SD}$ <br> $C_{prod} = TF_{proding}\left(C_{fodd}ING_{fodd} + C_w ING_{wa}\right) + \frac{C_s\ ING_{sa}TF_{proding}}{(1-\theta_t)\rho + \theta\ \rho_w} + (BR_a O_{an} C_{air})TF_{prodin}$ | | |
| **Parameter** | **Notation** | **Value** | **Units** | **Notation** | **Value** | **Units** |
| Concentration in soil mass | $Cs_m$ | 1.66 | Bq/kg | $Cs_m$ | 1.66 | Bq/kg |
| Concentration in soil volume | - | - | - | $Cs$ | 2489 | pCi/m$^3$ |
| Retardation coefficient | - | - | - | $R$ | 7827 | - |
| Grain density | - | - | - | $\rho$ | 2.650 | kg/m$^3$ |
| Total porosity | - | - | - | $\theta_t$ | 0.434 | - |
| Mass loading for crops | $S$ | 1.20E-07 | kg/m$^3$ | $Dust_s$ | 1.20E-07 | kg/m$^3$ |
| Concentration in air for crop | $Ca$ | 1.99E-07 | Bq/m$^3$ | $C_{air}$ | 1.99E-07 | Bq/m$^3$ |
| Soil-to-plant transfer factor | $F_{s\rightarrow p\ 5}$ | 1.0E-03 | (dry) | $CF_{past}$ | 2.2E-04 [c] | (wet) |
| Soil contamination on pasture | - | - | - | $S_{past}$ | 2.0E-03 | kg/kg |
| Daily irrigation rate | $IRD_5$ | 6.54 | mm/d | $V_{irr}$ | 2.39 | m/yr |
| Interception fraction for irrigation | $Rw_5$ | 0.259 | - | $I_{past}$ | 0.259 | - |
| Crop wet yield | $Y_5$ | 2.14 | kg/m$^2$ | $SB_{past}$ | 2.14 | kg/m$^2$ |
| Weathering half-live or constant | $Lw$ | 14 | d | $W$ | 18.1 | /yr |
| Animal consumption rate of feed | $Qf_{,1}$ | 75 | kg/d | $ING_{fodd}$ | 48.5 | kg/d |
| Number of animals in the area | - | - | - | $SD$ | 2.0E-04 | - |
| Concentration due to root uptake | $Cp_{,r,5}$ | 3.65E-04 | Bq/kg | $C_{fodd,root}$ | 3.65E-04 | Bq/kg |
| Concentration due to water deposition | $Cp_{,w,5}$ | 1.40E-02 | Bq/kg | $C_{fodd,irri}$ | 1.59E-02 | Bq/kg |
| Concentration due to dust deposition | $Cp_{,d,5}$ | 9.52E-04 | Bq/kg | $C_{fodd,dust}$ | 3.32E-03 | Bq/kg |

Table 7.4-12. Numerical Calculation of Animal Uptake Submodel (continued)

| Model | ERMYN [a] | | | BIOMASS ERB2A [b] | | |
|---|---|---|---|---|---|---|
| Concentration in crops | $Cp_5$ | 1.53E-02 | Bq/kg | $C_{fodd}$ | 1.96E-02 | Bq/kg |
| Animal consumption rate of feed | $Qf_{,1}$ | 48.5 | kg/d | $ING_{fodd}$ | 48.5 | kg/d |
| Animal consumption rate of water | $Qw_{,1}$ | 60 | L/d | $ING_{wa}$ | 0.06 | $m^3$/d |
| Animal consumption rate of soil | $Qs_{,1}$ | 0.7 | kg/d | $ING_{soil}$ | 0.7 | kg/d |
| Animal product transfer coefficient | $Fm_1$ | 1.30E-05 | d/kg | $TF_{proding}$ | 1.30E-05 | d/kg |
| Water density | - | - | - | $\rho_w$ | 1000 | kg/$m^3$ |
| Volumetric water content | - | - | - | $\theta$ | 0.23 | - |
| Animal breathing rate | - | - | - | $BR_a$ | 5.4 | $m^3$/hr |
| Animal occupancy time | - | - | - | $O_{an}$ | 24 | hr/d |
| Transfer coefficient for animal inhalation | - | - | - | $TF_{prodinh}$ | 1.3E-05 [d] | d/kg |
| From animal feed (Bq/kg) | $Cd_{,f,1}$ | 9.68E-06 | Bq/kg | $C_{prod,fodd}$ | 1.15E-05 | Bq/kg |
| From animal water (Bq/kg) | $Cd_{,w,1}$ | 7.80E-07 | Bq/kg | $C_{prod,wa}$ | 7.80E-07 | Bq/kg |
| From soil (Bq/kg) | $Cd_{,s,1}$ | 1.51E-05 | Bq/kg | $C_{prod,soil}$ | 1.31E-05 | Bq/kg |
| From dust inhalation (Bq/kg) | | | | $C_{prod,inh}$ | 3.4E-10 | Bq/kg |
| Meat concentration (Bq/kg) | $Cd_1$ | 2.56E-05 | Bq/kg | $C_{prod}$ | 2.54E-05 | Bq/kg |

NOTES:

[a] Results from Table 6.10-1. Some input values shown for comparison.

[b] BIOMASS ERB2A calculations are based on the equations in this table and input parameter values from the ERMYN model (Table 6.6-3) if possible, or default values suggested in BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522], Section 7.4).

[c] Value from soil-to-plant transfer factor (dry) × dry-to-wet ratio (forage) = 1E-3 × 0.22 = 2.2E-4; Table 6.6-3.

[d] Value selected to be the same as the transfer coefficient (ingestion), as suggested by BIOMASS (2000 [DIRS 154522], Table 14 to 17). Therefore, the animal product transfer coefficient for meat, 1.3E-5 d/kg, is selected for Pu-239 (Table 6.6-3).

### 7.4.6 Fish Submodel

There are no ACMs for the fish submodel (Section 6.3.3), and no complex numerical comparisons are required to validate the submodel.

### 7.4.7 Carbon-14 Special Submodel

The $^{14}C$ special submodel in the ERMYN model is different from the GENII-S submodel. The major difference is the released of $^{14}C$ from the soil into the air as radioactive carbon dioxide gas ($^{14}CO_2$). Furthermore, the ERMYN plant uptake submodel includes photosynthesis using $^{14}CO_2$ gas from the air. These differences are an ACM. The ERMYN and GENII-S methods for calculating concentrations of $^{14}C$ in plants are compared to validate the $^{14}C$ special submodel (Section 7.3.6).

The ERMYN and GENII-S $^{14}C$ special submodels are described in Sections 6.4.6 and 7.3.6, respectively. The $^{14}C$ concentrations in crops are calculated in Table 6.10-2. For example, the $^{14}C$ concentration in leafy vegetables is 0.032 Bq/kg. Using the same input parameter values as the ERMYN model (Table 6.10-2) if possible, the corresponding value, 0.0058 Bq/kg, is calculated using the GENII-S method (Table 7.3-21). The comparisons, including the input parameters, are shown in Table 7.4-13. Because the effective removal rate for $^{14}C$ is hard coded in GENII-S, a value of 0.8/yr is used. For leafy vegetables, a daily irrigation rate of

5.40 mm/d and a growing time of 75 d are used in the ERMYN model. Thus, the corresponding annual irrigation rate of 15.9 in/yr and irrigation duration of 2.5 month/yr are used for GENII-S. The calculations (Table 7.4-13) are performed in an Excel spreadsheet, *ERMYN validation.xls*, which is listed in Attachment I.

The ERMYN submodel gives a $^{14}C$ concentration for leafy vegetables that is about six times higher that the GENII-S value (Table 7.4-13). However, the removal rate ($\lambda s_c$ = 0.8 /yr) in the GENII-S model, which is written into the computer code, is a software defect (Wasiolek 2002 [DIRS 162977]). A more appropriate removal rate, 0.132/yr, was developed in the previous biosphere model (CRWMS M&O 2001 [DIRS 152539], Table 3). If this value is used in the GENII-S model, the crop $^{14}C$ concentration would be six times higher than the value shown in Table 7.4-13, and the ERMYN and GENII-S results would be almost the same. In addition, the ERMYN submodel is conceptually correct in that plants take carbon dioxide from air, instead of directly from the soil. Therefore, the $^{14}C$ submodel in the ERMYN model is valid because it includes photosynthesis. The RESRAD and BIOMASS ERB2A models also include photosynthesis. An evaluation of these methods, and a justification for selecting the method used in the ERMYN $^{14}C$ special submodel, is presented in Section 7.3.6. This evaluation shows that ACM 6 (Section 6.3.3) does not need further consideration.

Table 7.4-13. Evaluation of Plant Uptake in $^{14}C$ Special Submodel

| **Model** | **ERMYN [a]** | | | **GENII-S [b]** | | |
|---|---|---|---|---|---|---|
| Equation | Equation shown in Section 6.4.6, calculations shown in Table 10-2 | | | $Cc_p = \frac{25.4 \times I \times Cw_c}{\rho_s \, \lambda s_c} \times \frac{12}{ID} \times \frac{0.1}{0.01} \times Fc_p$ | | |
| **Parameter** | **Notation** | **Value** | **Units** | **Notation** | **Value** | **Units** |
| Removal rate | | | | $\lambda s_c$ | 0.8 | /yr |
| Surface density | $\rho_s$ | 375 | kg/m$^2$ | $\rho_s$ | 375 | kg/m$^2$ |
| Concentration in water | *Cw* | 1 | Bq/m$^3$ | *Cw* | 0.027 | pCi/L |
| Fraction of carbon | $fc_{plant}$ | 0.09 | - | $Fc_p$ | 0.09 | - |
| Irrigation rate | *IRD* | 5.40 | mm/d | *I* | 15.9 | in./yr |
| Irrigation duration | *Tg* | 75 | d | *ID* | 2.5 | month/yr |
| C-14 concentration | | | | $Cc_p$ | 1.57E-1 | pCi/kg |
| C-14 concentration | *Cp* | 3.2E-02 | Bq/kg | $Cc_p$ | 5.8E-03 | Bq/kg |

NOTES:

[a] Results from Table 6.10-2; some input values shown for comparison.

[b] Calculation described in Table 7.3-21; input values from Table 6.6-3.

### 7.4.8 External Exposure Submodel

For the ERMYN model, the external exposure submodel only includes surface soil contamination, although external exposure to air and water contamination is possible (Sections 6.4.7 and 6.5.5). In this section, calculations are presented to evaluate the importance of air submersion and water immersion relative to exposure to contaminated soil.

#### 7.4.8.1 Air Submersion

Air submersion is applicable to both exposure scenarios. To evaluate the importance of air submersion, dose coefficients for air submersion (including short-lived decay products) are developed (Table 7.4-14) and compared with dose coefficients for soil contamination (Table 6.4-2).

The dose coefficients for air submersion (Table 7.4-14) are in the same units as those for exposure to soil contaminated to an infinite depth (Table 6.4-2). However, the source of the radionuclides for the two dose coefficients differs: air versus soil. The ratio of the dose coefficients for air submersion to those for soil exposure (air/soil; Table 7.4-15) range from 1,471 to 6,051 (on the order of $10^3$).

To compare the relative importance of air submersion and soil exposure, activity concentrations in the air and soil are estimated. A soil contamination level of 1 Bq/m$^3$ corresponds to an activity concentration (in mass units) of $1 \times 10^{-3}$ Bq/kg, based on a soil density of $1 \times 10^3$ kg/m$^3$. If air contamination is only from contaminated resuspended soil, activity concentrations in the air can be calculated using the air submodel (Section 6.4.2, Equation 6.4.2-1). Using typical values of air mass loading (ranging from $10^{-6}$ to $10^{-7}$ kg/m$^3$; BSC 2003 [DIRS 160965], Section 6.1), the air concentration is about $10^{-9}$ to $10^{-10}$ Bq/m$^3$. Therefore, the activity concentration ratio between air submersion and soil exposure is on the order of $10^{-9}$ ($10^{-9}$ Bq/m$^3$ / 1 Bq/m$^3$). Considering the ratio of dose coefficients at the level of $10^3$, the air submersion dose is about 1 million times lower than soil exposure if the exposure times are the same, which is true because both exposures occur simultaneously. Because air submersion is much less important than soil exposure, there is no impact when this pathway is excluded from the ERMYN model.

Table 7.4-14. Effective Dose Coefficients for Air Submersion

| Primary Radionuclide | Short-lived Decay Product [c] | DC Value [d] (Sv/sec)/(Bq/m$^3$) | Effective DC (Sv/sec)/(Bq/m$^3$) |
|---|---|---|---|
| C-14 | - | 2.24E-19 | 2.24E-19 |
| Cl-36 | - | 2.23E-17 | 2.23E-17 |
| Se-79 | - | 3.03E-19 | 3.03E-19 |
| Sr-90D[a] | | 7.53E-18 | 1.98E-16 |
| | Y-90 (64.0 hr) | 1.90E-16 | |
| Tc-99 | - | 1.62E-18 | 1.62E-18 |
| Sn-126 | | 2.11E-15 | 9.63E-14 |
| | Sb-126m (19.0 min) | 7.50E-14 | |
| | Sb-126 (14%, 12.4 day) | 1.37E-13 | |
| I-129 | - | 3.80E-16 | 3.80E-16 |
| Cs-135 | - | 5.65E-19 | 5.65E-19 |
| Cs-137D | | 7.74E-18 | 2.73E-14 |
| | Ba-137m (94.6%, 2.552 min) | 2.88E-14 | |
| Pu-242 | - | 4.01E-18 | 4.01E-18 |
| U-238D | | 3.41E-18 | 1.37E-15 |
| | Th-234 (24.10 d) | 3.38E-16 | |
| | Pa-234m (99.80%, 1.17 min) | 7.19E-16 | |
| | Pa-234 (0.33%, 6.7 hr) | 9.34E-14 | |
| Pu-238 | - | 4.88E-18 | 4.88E-18 |
| U-234 | - | 7.63E-18 | 7.63E-18 |
| Th-230 | - | 1.74E-17 | 1.74E-17 |
| Ra-226D | | 3.15E-16 | 8.86E-14 |
| | Rn-222 (3.8235 d) | 1.91E-17 | |
| | Po-218 (3.05 min) | 4.48E-19 | |
| | Pb-214 (99.98%, 26.8 min) | 1.18E-14 | |
| | At-218 (0.02%, 2 sec) | 1.19E-16 | |
| | Bi-214 (19.9 min) | 7.65E-14 | |
| | Po-214 (99.98%, 1.64 × 10 -4 sec) | 4.08E-18 | |
| | Tl-210 (0.02%, 1.3 min) | 0.00E+00 | |
| Pb-210D | | 5.64E-17 | 8.97E-17 |
| | Bi-210 (5.012 d) | 3.29E-17 | |
| | Po-210 (138.38 d) | 4.16E-19 | |
| Pu-240 | - | 4.75E-18 | 4.75E-18 |
| U-236 | - | 5.01E-18 | 5.01E-18 |
| Th-232 | - | 8.72E-18 | 8.72E-18 |
| Ra-228D[b] | | 0.00E+00 | 4.78E-14 |
| | Ac-228 (6.13 hr) | 4.78E-14 | |
| U-232 | - | 1.42E-17 | 1.42E-17 |
| Th-228D | | 9.20E-17 | 8.03E-14 |
| | Ra-224 (3.66 d) | 4.71E-16 | |
| | Rn-220 (55.6 sec) | 1.85E-17 | |
| | Po-216 (0.15 sec) | 8.29E-19 | |
| | Pb-212 (10.64 hr) | 6.87E-15 | |
| | Bi-212 (60.55 min) | 9.24E-15 | |
| | Po-212 (64.07%, 0.305 µ-sec) | 0.00E+00 | |
| | Tl-208 (35.93%, 3.07 min) | 1.77E-13 | |
| Am-243D | | 2.18E-15 | 9.87E-15 |
| | Np-239 (2.355 d) | 7.69E-15 | |
| Pu-239 | - | 4.24E-18 | 4.24E-18 |
| U-235D | | 7.20E-15 | 7.72E-15 |
| | Th-231 (25.52 hr) | 5.22E-16 | |
| Pa-231 | - | 1.72E-15 | 1.72E-15 |

Table 7.4-14. Effective Dose Coefficients for Air Submersion (continued)

| Primary Radionuclide | Short-lived Decay Product [c] | DC Value [d] (Sv/sec)/(Bq/m$^3$) | Effective DC (Sv/sec)/(Bq/m$^3$) |
|---|---|---|---|
| Ac-227D | | 5.82E-18 | 1.85E-14 |
| | Th-227 (98.62%, 18.718 d) | 4.88E-15 | |
| | Fr-223 (1.38%, 21.8 min) | 2.29E-15 | |
| | Ra-223 (11.434 d) | 6.09E-15 | |
| | Rn-219 (3.96 sec) | 2.68E-15 | |
| | Po-215 (1.78 millisec) | 8.43E-18 | |
| | Pb-211 (36.1 min) | 2.49E-15 | |
| | Bi-211 (2.15 min) | 2.22E-15 | |
| | Tl-207 (99.72%, 4.77 min) | 1.62E-16 | |
| | Po-211 (0.28%, 0.516 sec) | 3.81E-16 | |
| Am-241 | - | 8.18E-16 | 8.18E-16 |
| Np-237D | | 1.03E-15 | 1.04E-14 |
| | Pa-233 (27.0 d) | 9.35E-15 | |
| U-233 | - | 1.63E-17 | 1.63E-17 |
| Th-229D | | 3.83E-15 | 1.49E-14 |
| | Ra-225 (14.8 d) | 2.79E-16 | |
| | Ac-225 (10.0 d) | 7.21E-16 | |
| | Fr-221 (4.8 min) | 1.46E-15 | |
| | At-217 (32.3 millisec) | 1.48E-17 | |
| | Bi-213 (45.65 min) | 6.39E-15 | |
| | Po-213 (97.84%, 4.2 µ-sec) | 0.00E+00 | |
| | Tl-209 (2.16%, 2.2 min) | 1.02E-13 | |
| | Pb-209 (3.253 hr) | 8.12E-18 | |

NOTES: DC = dose coefficient

[a] "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short half-life (< 180 d) decay product.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fraction and half-life from FGR-12 (Eckerman and Ryman 1993 [DIRS 107684], Table A.1).

[d] Values from FGR-12 (Eckerman and Ryman 1993 [DIRS 107684], Table III.1).

Table 7.4-15. Comparison of Dose Coefficients for Infinite Depth Soil and Air Submersion

| Primary Radionuclide | Infinite Depth Soil Effective DC [c] (Sv/sec)/(Bq/m$^3$) | Air Submersion Effective DC [d] (Sv/sec)/(Bq/m$^3$) | Ratio [e] (Air/Soil) |
|---|---|---|---|
| C-14 | 7.20E-23 | 2.24E-19 | 3111 |
| Cl-36 | 1.28E-20 | 2.23E-17 | 1742 |
| Se-79 | 9.96E-23 | 3.03E-19 | 3042 |
| Sr-90D [a] | 1.32E-19 | 1.98E-16 | 1500 |
| Tc-99 | 6.72E-22 | 1.62E-18 | 2411 |
| Sn-126 | 6.34E-17 | 9.63E-14 | 1519 |
| I-129 | 6.93E-20 | 3.80E-16 | 5483 |
| Cs-135 | 2.05E-22 | 5.65E-19 | 2756 |
| Cs-137D | 1.83E-17 | 2.73E-14 | 1492 |
| Pu-242 | 6.85E-22 | 4.01E-18 | 5854 |
| U-238D | 8.13E-19 | 1.37E-15 | 1685 |
| Pu-238 | 8.10E-22 | 4.88E-18 | 6025 |
| U-234 | 2.15E-21 | 7.63E-18 | 3549 |
| Th-230 | 6.47E-21 | 1.74E-17 | 2689 |
| Ra-226D | 5.99E-17 | 8.86E-14 | 1479 |
| Pb-210D | 3.27E-20 | 8.97E-17 | 2743 |
| Pu-240 | 7.85E-22 | 4.75E-18 | 6051 |
| U-236 | 1.15E-21 | 5.01E-18 | 4357 |
| Th-232 | 2.79E-21 | 8.72E-18 | 3125 |
| Ra-228D [b] | 3.20E-17 | 4.78E-14 | 1494 |
| U-232 | 4.83E-21 | 1.42E-17 | 2940 |
| Th-228D | 5.46E-17 | 8.03E-14 | 1471 |
| Am-243D | 4.79E-18 | 9.87E-15 | 2061 |
| Pu-239 | 1.58E-21 | 4.24E-18 | 2684 |
| U-235D | 4.06E-18 | 7.72E-15 | 1901 |
| Pa-231 | 1.02E-18 | 1.72E-15 | 1686 |
| Ac-227D | 1.08E-17 | 1.85E-14 | 1713 |
| Am-241 | 2.34E-19 | 8.18E-16 | 3496 |
| Np-237D | 5.88E-18 | 1.04E-14 | 1769 |
| U-233 | 7.48E-21 | 1.63E-17 | 2179 |
| Th-229D | 8.55E-18 | 1.49E-14 | 1743 |

NOTES: DC = dose coefficient

[a] "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short half-life (< 180 d) decay product.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Data from Table 6.4-2.

[d] Data from Table 7.4-14.

[e] Calculated from Column 3 divided by Column 2.

### 7.4.8.2 Water Immersion

Immersion in contaminated water only applies to the groundwater scenario, where water immersion involves activities such as swimming or bathing in contaminated water. To evaluate the importance of the water immersion exposure pathway, dose coefficients (including short-lived decay products) are developed for water immersion (Table 7.4-16), similar to the dose coefficients for soil contamination (Table 6.4-2).

The dose coefficients for water immersion (Table 7.4-16) are in the same units (Sv/sec)/(Bq/$m^3$) as those for exposure to soil contaminated to an infinite depth. However, the source of radionuclides differ: water versus soil. The ratio of dose coefficient for water immersion (Table 7.4-16) to soil exposure (Table 6.4-2) range from 2.9 to 14.1 (Table 7.4-17), with iodine and plutonium having the largest ratios (> 10).

To compare the relative importance of water immersion and soil exposure, exposure times and media concentrations are evaluated. Typically, daily baths last about 20 min, while showers last about 10 min (EPA 1997 [DIRS 116135], pp. 15 and 16). Typical rates for swimming are one swim per month that lasts for about 60 min (EPA 1997 [DIRS 116135], pp. 15 to 17), which gives an average swimming time of about 2 min/d. Therefore, the average daily water immersion time is about 17 min/d, based on equal frequency of bathing and showering. The effective soil exposure time is radionuclide dependent because of the external shielding factor. Based on the calculated environment-specific outdoor time of 1.90 hr/d, an indoor time of 17.75 hr/d (Table 6.10-1), and the shielding factors, the average effective exposure times and the ratios of soil exposure time to water immersion time are calculated (Table 7.4-18).

In addition, radionuclide concentrations in the water and soil are estimated. If the water contamination is 1 Bq/$m^3$, steady-state soil concentrations after long-term irrigation are estimated using Equations 6.4.1-4 and 6.4.1-5. Using an annual irrigation rate of 0.5 m/yr for the expected future climate, a surface soil depth of 0.25 m (Table 6.6-3), and an effective removal constant (Table 7.4-4), the average radionuclide concentration in the soil is calculated (Table 7.4-18). Using a unit concentration in the water, the ratio of radionuclide concentrations in the water and soil is numerically equal to the values of radionuclide concentration in soil.

The soil exposure and water immersion doses depend on exposure time, media concentrations, and dose coefficients, and a comparison of soil exposure to water immersion can be calculated as the soil/water exposure time ratio times the soil/water radionuclide concentration ratio, and then divided by the water/soil dose coefficient ratio. Soil exposure doses range from 13 (for $^{99}$Tc) to more than 20,000 ($^{231}$Pa) times higher than that for water immersion (Table 7.4-18). Because the external exposure pathway is not important compared with all pathways (e.g., about 7.6 percent of the total dose for $^{226}$Ra and less than 0.01 percent for $^{239}$Pu and $^{14}$C; Tables 6.10-1 to 6.10-3), eliminating the water immersion pathway is reasonable and does not underestimate the dose. Because water immersion is much less important than soil exposure, there is no impact when this pathway is excluded from the ERMYN model.

Table 7.4-16. Effective Dose Coefficients for Water Immersion

| Primary Radionuclide | Short-lived Decay Product [c] | DC Value [d] (Sv/sec)/(Bq/m$^3$) | Effective DC (Sv/sec)/(Bq/m$^3$) |
|---|---|---|---|
| C-14 | - | 4.39E-22 | 4.39E-22 |
| Cl-36 | - | 4.48E-20 | 4.48E-20 |
| Se-79 | - | 5.93E-22 | 5.93E-22 |
| Sr-90D [a] | | 1.46E-20 | 3.78E-19 |
| | Y-90 (64.0 hr) | 3.63E-19 | |
| Tc-99 | - | 3.14E-21 | 3.14E-21 |
| Sn-126 | | 4.76E-18 | 2.10E-16 |
| | Sb-126m (19.0 min) | 1.63E-16 | |
| | Sb-126 (14%, 12.4 day) | 2.99E-16 | |
| I-129 | - | 8.91E-19 | 8.91E-19 |
| Cs-135 | - | 1.10E-21 | 1.10E-21 |
| Cs-137D | | 1.49E-20 | 5.92E-17 |
| | Ba-137m (94.6%, 2.552 min) | 6.26E-17 | |
| Pu-242 | - | 9.35E-21 | 9.35E-21 |
| U-238D | | 7.95E-21 | 2.96E-18 |
| | Th-234 (24.10 d) | 7.64E-19 | |
| | Pa-234m (99.80%, 1.17 min) | 1.52E-18 | |
| | Pa-234 (0.33%, 6.7 hr) | 2.03E-16 | |
| Pu-238 | - | 1.14E-20 | 1.14E-20 |
| U-234 | - | 1.75E-20 | 1.75E-20 |
| Th-230 | - | 3.94E-20 | 3.94E-20 |
| Ra-226D | | 6.95E-19 | 1.93E-16 |
| | Rn-222 (3.8235 d) | 4.16E-20 | |
| | Po-218 (3.05 min) | 9.71E-22 | |
| | Pb-214 (99.98%, 26.8 min) | 2.59E-17 | |
| | At-218 (0.02%, 2 sec) | 2.75E-19 | |
| | Bi-214 (19.9 min) | 1.66E-16 | |
| | Po-214 (99.98%, 1.64 × 10 -4 sec) | 8.85E-21 | |
| | Tl-210 (0.02%, 1.3 min) | 0.00E+00 | |
| Pb-210D | | 1.31E-19 | 1.95E-19 |
| | Bi-210 (5.012 d) | 6.33E-20 | |
| | Po-210 (138.38 d) | 9.03E-22 | |
| Pu-240 | - | 1.11E-20 | 1.11E-20 |
| U-236 | - | 1.16E-20 | 1.16E-20 |
| Th-232 | - | 1.99E-20 | 1.99E-20 |
| Ra-228D [b] | | 0.00E+00 | 1.04E-16 |
| | Ac-228 (6.13 hr) | 1.04E-16 | |
| U-232 | - | 3.22E-20 | 3.22E-20 |
| Th-228D | | 2.05E-19 | 1.74E-16 |
| | Ra-224 (3.66 d) | 1.03E-18 | |
| | Rn-220 (55.6 sec) | 4.03E-20 | |
| | Po-216 (0.15 sec) | 1.80E-21 | |
| | Pb-212 (10.64 hr) | 1.52E-17 | |
| | Bi-212 (60.55 min) | 2.00E-17 | |
| | Po-212 (64.07%, 0.305 µ-sec) | 0.00E+00 | |
| | Tl-208 (35.93%, 3.07 min) | 3.84E-16 | |
| Am-243D | | 4.94E-18 | 2.19E-17 |
| | Np-239 (2.355 d) | 1.70E-17 | |
| Pu-239 | - | 9.60E-21 | 9.60E-21 |
| U-235D | | 1.59E-17 | 1.71E-17 |
| | Th-231 (25.52 hr) | 1.18E-18 | |
| Pa-231 | - | 3.78E-18 | 3.78E-18 |

Table 7.4-16. Effective Dose Coefficients for Water Immersion (continued)

| Primary Radionuclide | Short-lived Decay Product [c] | DC Value [d] (Sv/sec)/(Bq/m$^3$) | Effective DC (Sv/sec)/(Bq/m$^3$) |
|---|---|---|---|
| Ac-227D | | 1.30E-20 | 4.06E-17 |
| | Th-227 (98.62%, 18.718 d) | 1.07E-17 | |
| | Fr-223 (1.38%, 21.8 min) | 5.11E-18 | |
| | Ra-223 (11.434 d) | 1.35E-17 | |
| | Rn-219 (3.96 sec) | 5.85E-18 | |
| | Po-215 (1.78 millisec) | 1.84E-20 | |
| | Pb-211 (36.1 min) | 5.41E-18 | |
| | Bi-211 (2.15 min) | 4.85E-18 | |
| | Tl-207 (99.72%, 4.77 min) | 3.38E-19 | |
| | Po-211 (0.28%, 0.516 sec) | 8.27E-19 | |
| Am-241 | - | 1.88E-18 | 1.88E-18 |
| Np-237D | | 2.32E-18 | 2.28E-17 |
| | Pa-233 (27.0 d) | 2.05E-17 | |
| U-233 | - | 3.64E-20 | 3.64E-20 |
| Th-229D | | 8.56E-18 | 3.2E-17 |
| | Ra-225 (14.8 d) | 6.49E-19 | |
| | Ac-225 (10.0 d) | 1.61E-18 | |
| | Fr-221 (4.8 min) | 3.22E-18 | |
| | At-217 (32.3 millisec) | 3.22E-20 | |
| | Bi-213 (45.65 min) | 1.39E-17 | |
| | Po-213 (97.84%, 4.2 µ-sec) | 0.00E+00 | |
| | Tl-209 (2.16%, 2.2 min) | 2.22E-16 | |
| | Pb-209 (3.253 hr) | 1.57E-20 | |

NOTES: DC = dose coefficient.

[a] "D" after a radionuclide denotes that it is treated together with its short half-life (< 180 d) decay product.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching ratio and half-life from FGR-12 (Eckerman and Ryman 1993 [DIRS 107684], Table A.1).

[d] Dose coefficient values from FGR-12 (Eckerman and Ryman 1993 [DIRS 107684], Table III.2).

Table 7.4-17. Effective Dose Coefficients for Infinite Depth Soil and Water Immersion

| Primary Radionuclide | Infinite Depth Soil Effective DC [c] (Sv/sec)/(Bq/m$^3$) | Water Immersion Effective DC [d] (Sv/sec)/(Bq/m$^3$) | Ratio [e] (Water/Soil) |
|---|---|---|---|
| C-14 | 7.20E-23 | 4.39E-22 | 6.1 |
| Cl-36 | 1.28E-20 | 4.48E-20 | 3.5 |
| Se-79 | 9.96E-23 | 5.93E-22 | 5.6 |
| Sr-90D [a] | 1.32E-19 | 3.78E-19 | 2.9 |
| Tc-99 | 6.72E-22 | 3.14E-21 | 4.7 |
| Sn-126 | 6.34E-17 | 2.10E-16 | 3.3 |
| I-129 | 6.93E-20 | 8.91E-19 | 12.9 |
| Cs-135 | 2.05E-22 | 1.10E-21 | 5.4 |
| Cs-137D | 1.83E-17 | 5.92E-17 | 3.2 |
| Pu-242 | 6.85E-22 | 9.35E-21 | 13.6 |
| U-238D | 8.13E-19 | 2.96E-18 | 3.6 |
| Pu-238 | 8.10E-22 | 1.14E-20 | 14.1 |
| U-234 | 2.15E-21 | 1.75E-20 | 8.1 |
| Th-230 | 6.47E-21 | 3.94E-20 | 6.1 |
| Ra-226D | 5.99E-17 | 1.93E-16 | 3.2 |
| Pb-210D | 3.27E-20 | 1.95E-19 | 6.0 |
| Pu-240 | 7.85E-22 | 1.11E-20 | 14.1 |
| U-236 | 1.15E-21 | 1.16E-20 | 10.1 |
| Th-232 | 2.79E-21 | 1.99E-20 | 7.1 |
| Ra-228D [b] | 3.20E-17 | 1.04E-16 | 3.3 |
| U-232 | 4.83E-21 | 3.22E-20 | 6.7 |
| Th-228D | 5.46E-17 | 1.74E-16 | 3.2 |
| Am-243D | 4.79E-18 | 2.19E-17 | 4.6 |
| Pu-239 | 1.58E-21 | 9.60E-21 | 6.1 |
| U-235D | 4.06E-18 | 1.71E-17 | 4.2 |
| Pa-231 | 1.02E-18 | 3.78E-18 | 3.7 |
| Ac-227D | 1.08E-17 | 4.06E-17 | 3.8 |
| Am-241 | 2.34E-19 | 1.88E-18 | 8.0 |
| Np-237D | 5.88E-18 | 2.28E-17 | 3.9 |
| U-233 | 7.48E-21 | 3.64E-20 | 4.9 |
| Th-229D | 8.55E-18 | 3.20E-17 | 3.8 |

NOTES: DC = dose coefficient.

[a] "D" denotes that the radionuclide is treated together with its short half-life (< 180 d) decay product.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Data from Table 6.4-2.

[d] Data from Table 7.4-16.

[e] Calculated from Column 3 divided by Column 2.

Table 7.4-18. Evaluation of Water Immersion Pathway

| Primary Radionuclide | Effective Removal Constant (/yr) | Radionuclide Concentration Ratio (Soil/Water) | Effective Exposure Time for Soil (hr/d) | Effective Exposure Time Ratio (Soil/Water) | Dose Coefficient Ratio (Water/Soil) | Dose Contribution Ratio (Soil/Water) |
|---|---|---|---|---|---|---|
| C-14 | 1.13E-02 | 1.77E+02 | 5.5 | 19 | 6.1 | 560 |
| Cl-36 | 6.10E-01 | 3.28E+00 | 9.0 | 32 | 3.5 | 30 |
| Se-79 | 2.51E-03 | 7.98E+02 | 3.7 | 13 | 5.6 | 1849 |
| Sr-90D | 3.40E-02 | 5.89E+01 | 9.0 | 32 | 2.9 | 645 |
| Tc-99 | 6.10E-01 | 3.28E+00 | 5.5 | 19 | 4.7 | 13 |
| Sn-126 | 1.71E-03 | 1.17E+03 | 9.0 | 32 | 3.3 | 11256 |
| I-129 | 3.97E-02 | 5.04E+01 | 3.7 | 13 | 12.9 | 51 |
| Cs-135 | 1.35E-03 | 1.48E+03 | 3.7 | 13 | 5.4 | 3567 |
| Cs-137D | 2.45E-02 | 8.18E+01 | 9.0 | 32 | 3.2 | 812 |
| Pu-242 | 1.46E-03 | 1.37E+03 | 3.7 | 13 | 13.6 | 1310 |
| U-238D | 6.70E-03 | 2.99E+02 | 9.0 | 32 | 3.6 | 2636 |
| Pu-238 | 9.36E-03 | 2.14E+02 | 3.7 | 13 | 14.1 | 197 |
| U-234 | 6.70E-03 | 2.99E+02 | 5.5 | 19 | 8.1 | 709 |
| Th-230 | 1.38E-03 | 1.45E+03 | 7.2 | 26 | 6.1 | 6080 |
| Ra-226D | 1.74E-03 | 1.15E+03 | 9.0 | 32 | 3.2 | 11379 |
| Pb-210D | 3.24E-02 | 6.17E+01 | 9.0 | 32 | 6 | 327 |
| Pu-240 | 1.56E-03 | 1.28E+03 | 3.7 | 13 | 14.1 | 1179 |
| U-236 | 6.70E-03 | 2.99E+02 | 3.7 | 13 | 10.1 | 384 |
| Th-232 | 1.37E-03 | 1.46E+03 | 5.5 | 19 | 7.1 | 3967 |
| Ra-228D | 1.22E-01 | 1.64E+01 | 9.0 | 32 | 3.3 | 158 |
| U-232 | 1.63E-02 | 1.23E+02 | 7.2 | 26 | 6.7 | 466 |
| Th-228D | 3.64E-01 | 5.50E+00 | 9.0 | 32 | 3.2 | 55 |
| Am-243D | 1.49E-03 | 1.34E+03 | 9.0 | 32 | 4.6 | 9270 |
| Pu-239 | 1.48E-03 | 1.35E+03 | 7.2 | 26 | 6.1 | 5633 |
| U-235D | 6.70E-03 | 2.99E+02 | 9.0 | 32 | 4.2 | 2259 |
| Pa-231 | 1.43E-03 | 1.40E+03 | 9.0 | 32 | 3.7 | 12033 |
| Ac-227D | 3.33E-02 | 6.01E+01 | 9.0 | 32 | 3.8 | 503 |
| Am-241 | 3.00E-03 | 6.67E+02 | 5.5 | 19 | 8 | 1604 |
| Np-237D | 8.41E-03 | 2.38E+02 | 9.0 | 32 | 3.9 | 1937 |
| U-233 | 6.70E-03 | 2.99E+02 | 9.0 | 32 | 4.9 | 1935 |
| Th-229D | 1.46E-03 | 1.37E+03 | 9.0 | 32 | 3.8 | 11447 |

NOTES: Column 2 from Table 7.4-4. Column 3 calculated using Equation 6.4.1-4, 6.4.1-5, and input values from Table 6.6-3. Column 4 calculated using part of Equation 6.4.7-1 (outdoor time + indoor time × external shielding factor). Column 5 calculated as the ratio of Column 4 to an average water immersion time of 17 minutes. Column 6 taken from Table 7.4-17. Column 7 calculated as Column 3 × Column 5 ÷ Column 6. These calculations are performed using Excel spreadsheet, *ERMYN validation.xls*, which is listed in Attachment I.

### 7.4.9 Inhalation Submodel

The ERMYN inhalation submodel uses human activity and environment-specific exposure times, breathing rates, and mass loading. The magnitude of other factors, such as particle size enhancement factors, also are a function of human activities. Information on human activity and environments is used to obtain accurate results and to include uncertainty about the input parameters. The validation models use simpler methods than are used in the ERMYN model, using, for example, average exposure times rather than population and activity related exposure times (Section 7.3.8). Therefore, a comparison of activity inhaled per day (Table 7.4-19), using average values, is done to evaluate differences between the two approaches.

Using input values from Table 6.6-3, the inhaled activity is $1.5 \times 10^{-5}$ Bq/d. Using the approach from the validation models and a method similar to that used for the biosphere model for the TSPA-SR, the dose is $1.2 \times 10^{-5}$ Bq/d. This result is based on a weighted average exposure time where indoor time is weighted at 50 percent of outdoor time, and other parameter values are shown in Table 7.4-19. The results of the two methods are comparable, and ACM 7 (Section 6.3.3) does not need further consideration.

Table 7.4-19. Evaluation of Population and Environmental Related Inhalation Submodel

| Parameter | Units | Notation | Environment | | | | | Selected Average Value for Simple Inhalation Submodel |
|---|---|---|---|---|---|---|---|---|
| | | | Active Outdoors | Inactive Outdoors | Active Indoors | Asleep | Away from Area | |
| Exposure time, commuter | hr/day | *t(n,m)* | 0.3 | 1.4 | 6.0 | 8.3 | 8.0 | 8.9 |
| Exposure time, outdoor worker | hr/day | *t(n,m)* | 3.1 | 4.0 | 6.6 | 8.3 | 2 | 14.6 |
| Exposure time, indoor worker | hr/day | *t(n,m)* | 0.3 | 1.3 | 12.1 | 8.3 | 2 | 11.8 |
| Exposure time, non-worker | hr/day | *t(n,m)* | 0.3 | 1.2 | 12.2 | 8.3 | 2 | 11.8 |
| Exposure time, weighted average | hr/day | *t(n,m)* | 0.45 | 1.45 | 9.45 | 8.30 | 4.35 | 10.8 |
| Breathing rate | $m^3$/hr | *BR(n)* | 1.57 | 1.08 | 1.08 | 0.39 | 1.08 | 1.08 |
| Mass loading | kg/$m^3$ | *S(n)* | 5.0E-6 | 6.0E-8 | 1.0E-7 | 3.0E-8 | 0 | 1.0E-06 |
| Particle size enhance factor | none | $f_{enhance,n}$ | 4.0 | 0.7 | 0.7 | 0.7 | 0 | 1.0 |
| Calculated inhaled activity per day | Bq/d | | 1.4E-05 | 6.6E-08 | 7.1E-07 | 6.8E-08 | 0.0E+00 | |
| Sum | Bq/d | | 1.5E-05 | | | | | 1.2E-05 |

NOTE: Calculations based on population group fractions: commuters = 0.392; outdoor workers = 0.055; indoor workers = 0.161; non-workers = 0.392. Calculation performed using an Excel spreadsheet, *ERMYN validation.xls*, which is listed in Attachment I.

### 7.4.10 Ingestion Submodel

The ERMYN ingestion submodel is similar to the validation models (Section 7.3.9). There are no ACMs for the ingestion submodel (Section 6.3.3), and no complex numerical comparisons are required to validate the submodel.

## 7.5 VALIDATION OF THE GOLDSIM OUTPUT

To validate the GoldSim implementation, BDCFs generated with the ERMYN model are compared to those from the previous biosphere model (implemented in GENII-S) to determine if they are similar. For the groundwater scenario, a direct comparison of BDCFs is possible; however, the conceptual models for the volcanic ash scenarios differ, so a conversion is required before the BDCFs can be compared. The comparisons are based on the results of stochastic runs using $^{239}$Pu as an example radionuclide.

### 7.5.1 Validation of the GoldSim Output for the Groundwater Scenario

For the groundwater scenario, the $^{239}$Pu BDCF generated using the ERMYN model is $(9.16 \pm 3.59) \times 10^{-2}$ (rem/yr)/(pCi/L) (Section 6.10.1.2), while that generated using the GENII-S model is $(5.78 \pm 2.14) \times 10^{-3}$ (rem/yr)/(pCi/L) (CRWMS M&O 2001 [DIRS 152539], Table 9, sixth irrigation period). In general, the ERMYN BDCFs are higher than the GENII-S BDCFs because several new pathways are added to the ERMYN model (e.g., inhalation of aerosols from evaporative coolers). The use of radionuclide saturation concentrations in the soil also increases the BDCFs. The uncertainty associated with BDCFs for the two models is comparable, with one standard deviation equaling about 40 percent of the mean value.

### 7.5.2 Validation of the GoldSim Output for the Volcanic Ash Scenario

For the volcanic ash scenario, the $^{239}$Pu BDCF generated using the ERMYN model (Section 6.10.2.2) is $(1.24 \pm 1.58) \times 10^{-9}$ (rem/yr)/(pCi/m$^2$) for external exposure and ingestion, $(9.12 \pm 5.52) \times 10^{-7}$ (rem/yr)/(pCi/m$^2$) for inhalation under post-volcanic conditions, and $(1.84 \pm 1.13) \times 10^{-6}$ (rem/yr)/(pCi/m$^2$) for inhalation under normal conditions. The $^{239}$Pu BDCF from the GENII-S model (CRWMS M&O (2001 [DIRS 152536], Table 11), is $(1.51 \pm 1.31) \times 10^{-7}$ (rem/yr)/(pCi/m$^2$) for the transition phase, 1-cm ash layer and annual average mass loading. To make the comparison, the BDCFs from the ERMYN model are combined using Equation 6.5.8-2, converted to a 1-cm ash layer using Equation 6.5.1.5, and calculated for 1-year of decay using the mass loading function $f(t)$ defined for 1-cm initial ash depth in Table 6.6-3. The time function is 0.82 (= $e^{-0.2/\text{yr} \times 1\text{ yr}}$), and the ash thickness function is 0.2 (= 2 mm / 1 cm). Therefore, the combined BDCF from the ERMYN model is about $5.19 \times 10^{-7}$ (rem/yr)/(pCi/m$^2$), which is comparable to the BDCF from the GENII-S model, $1.51 \times 10^{-7}$ (rem/yr)/(pCi/m$^2$). The BDCFs from the ERMYN model are higher than the BDCFs from the GENII-S model because of increased overall mass loading concentrations from the environment-specific parameters, which makes inhalation an important pathway.

In conclusion, BDCFs generated with the ERMYN model are similar to those from the GENII-S model, which validates the GoldSim implementation of the ERMYN model.

## 7.6 MODEL VALIDATION RANGE

The ERMYN model is valid for all reasonable input parameter values, where reasonable values are those expected to occur in the arid to semi-arid region surrounding Yucca Mountain. Therefore, users of this model must consider whether input parameter values are reasonable for these site-specific conditions.

Detailed mathematical evaluations across the range of all parameters are not required to validate the ERMYN model for reasonable inputs. This is primarily because the model is based on linear equations expressing the proportional transfer of radionuclides from one medium to another. Thus, the equations will produce proportional results over the entire range of input parameters. Equations that include non-liner calculations have results that asymptote to reasonable limits (e.g., the weathering function in the calculation of the dust interception fraction, Equation 6.4.3-6, asymptotes to 1.0 at relatively low values of growing time) or are limited in the GoldSim implementation to prevent calculating invalid results (e.g., the irrigation interception fraction, Equation 6.4.3-5, is limited to a maximum of 1.0; Section 6.8.4). In addition, none of the validation models that use equations similar to those in this model identify limits to input parameters.

Numerical comparisons for model validation and ACM evaluations (Section 7.4) use the mean, mode, or other single values representative of the input parameters distributions listed in Table 6.6-3. The same values are used for both methods being compared (unless the ERMYN model does not use a parameter value). Using values representative of distributions other than those in Table 6.6-3 would cause the results of both methods to change proportionally. Therefore, conclusions of the validation analyses generally are independent of input parameter values.

The outputs of the ERMYN model, BDCFs, represent the annual dose to the average receptor, and the use of input data for other time frames or for specific items might produce invalid results. In particular, seven parameters might cause problems if unreasonable values are used (Table 7.6-1). Thus, input parameters representative of periods other than a year or representative of individual people, dwellings, cultivated fields, or other items may cause invalid results. For example, using a minimum daily wind speed rather than the average annual wind speed (Equation 6.4.6-3) would result in invalid output.

Table 7.6-1. Unreasonable Parameters Input Values

| Parameter name | Used in Equation | Discussion |
|---|---|---|
| Surface soil depth | 6.4.1-5<br>6.4.1-6<br>6.4.1-11<br>6.5.1-2 | Very low values of surface soil depth (i.e., mm to few cm) would result in invalid, high concentrations of radionuclides in the soil. Such low values are unreasonable because crops cannot grow in soil irrigated or tilled to a very shallow depth. The distribution of surface soil depths (Table 6.6-3 ; BSC 2003 [DIRS 160976], Section 6.10) is based on typical tilling depths. |
| Evaporative cooler air flow rates | 6.4.2-3 | Unreasonably low air flow rates would result in invalid, high concentrations of radionuclides in indoor air. Typical air flow rates for evaporative coolers range from about 2,000 to 10,000 $m^3$/h (BSC 2003 [DIRS 160964] Section 6.5.2). Much lower rates are unreasonable because building cooling would be ineffective. In addition, low rates would not transfer radionuclides from water to the entire volume of indoor air. |
| House ventilation rate | 6.4.2-7<br>6.4.2-8 | Unreasonably low house ventilation rates would result in an accumulation of indoor radon and high estimates of indoor radon concentrations. Typical ventilation rates are about 0.5 exchanges per hour or greater (BSC 2003 [DIRS 160964], Section 6.6.2), and according to the *Manufactured Home Construction and Safety Standards*, the whole house ventilation rate for manufactured homes should be at least 0.35 air exchanges per hour (24 CFR 3280.103(b) [160555]). |
| Crop wet yield | 6.4.3-3<br>6.4.3-6<br>6.5.3-3 | Very low values of crop yield would result in invalid, high estimates of radionuclide concentrations in crops. Typical values of average annual yield for all production in a region range from about 1 to 8 kg/$m^2$ for leafy vegetables to 0.3 to 1.2 kg/$m^2$ for grain (BSC 2003 [DIRS 160976], Section 6.11). Much lower values are unreasonable because few or no contaminated foodstuffs would be available for consumption. |
| Annual average wind speed | 6.4.6-3 | Very low wind speeds, such as daily minimum wind speeds or wind speeds on very calm days, would result in an invalid, high estimate of the annual average $^{14}C$ concentration in air. Parameter values must represent annual average speeds to ensure that a reasonable annual average concentration is calculated. |
| Fraction of stable carbon in soil | 6.4.6-4 | If the fraction of stable carbon in the soil is zero, calculations of root uptake of $^{14}C$ in crops would be invalid. This value is unreasonable because there is always some stable carbon in the soil. |
| Concentration of stable carbon in air | 6.4.6-5 | If the fraction of stable carbon in the air is zero, calculations of leaf uptake of $^{14}C$ in crops would be invalid. This value is unreasonable because there is always some stable carbon in the air. |

## 7.7 EXTERNAL REVIEW OF THE ERMYN MODEL

An external review (Daniels 2003 [DIRS 163016]), conducted in accordance with AP-SIII.10Q ([DIRS 164074], Section 5.4.1d; see also Section 7.1.1), adds to confidence in the model. The external review concluded:

> The ERMYN model is a more complete biosphere modeling tool than its predecessor. It is well constructed, it conforms to design requirements prescribed by site-specific features, events, and processes, and it is appropriate for the specified human receptor (the reasonably maximally exposed individual). The model contains a thorough assembly of applicable multimedia, multipathway exposure-related processes, and it uses a credible dose-assessment strategy using reliably calculated, acceptable, and applicable biosphere dose conversion factors for the radionuclides of interest. The authors provide a more transparent framework and a better explanation of the applicability and validity of the submodels, and they better document the assumptions.
>
> The ERMYN model contains several new exposure pathways, including inhalation of aerosols generated by residential evaporative cooling, animal soil ingestion, and radon-gas inhalation, particularly from surface deposited Ra-226. The outputs (biosphere dose conversion factors) are understandable and appropriate, and I agree that differences in biosphere dose conversion factors between those generated by the ERMYN model and those produced by the earlier model are reasonable and can be explained by changes in the input parameters necessary to accommodate the ERMYN model framework. Thus, the ERMYN model displays progress and commitment to applying a scientifically defensible approach to a comprehensive assessment of the biosphere as a consequence of a potential release of radionuclides from the proposed repository.
>
> Accordingly, the ERMYN model is an improvement over the previous model. Furthermore, the modeling deficiencies noted in the *Model Validation Status Review* technical report have been addressed adequately through the construction and description of the ERMYN model.

INTENTIONALLY LEFT BLANK

# 8. CONCLUSIONS

This report documents the development of the ERMYN biosphere model, which supports the TSPA-LA. The reference biosphere, the human receptor, two exposure scenarios, and the primary radionuclides used in the model are described. The conceptual model incorporates site-specific FEPs, the site-specific reference biosphere, a theoretical human receptor, and assumptions. The mathematical model incorporates the conceptual model, using site-specific information and other information from five published models. The mathematical model input parameters are described. Improvements made to the ERMYN model over the predecessor model, GENII-S for the TSPA-SR, are identified. The GoldSim stochastic simulation software package is used for building the ERMYN implementation tool. The ERMYN implementation tool (i.e., the constructed ERMYN model) is verified by comparing outputs with hand calculations to ensure that the GoldSim implementation works in the manner described by the mathematical model. The ERMYN model is validated by corroboration of conceptual models, mathematical models, and the necessary numerical results. All of the NRC acceptance criteria (NRC 2003 [DIRS 162418], Section 2.2.1.3.14) listed in Section 4.2 are adequately addressed in Section 6. Model and model inputs are discussed in Sections 6.3 to 6.5. Uncertainty in the model and input parameters are discussed in Section 6.6, and they are considered in the model implementation in Sections 6.8 and 6.9.

## 8.1 MODEL OUTPUT

As discussed in the structure of biosphere documentation (Section 1), the model outputs from this report are not numerical results; rather they are the model implementation tools built with the GoldSim software. Two biosphere model implementation tools, one for the groundwater scenario (*ERMYN_GW.gsm*) and one for the volcanic ash scenario (*ERMYN_VA.gsm*), are the model outputs to be used for generating BDCFs (listed in Attachment I). These two model implementation tools will be used to calculate BDCFs for individual radionuclides, as well as for pathway, uncertainty, and sensitivity analyses. The output DTN for the model implementation tools is MO0306MWDBGSMF.001 [DIRS 163816].

## 8.2 BIOSPHERE MODEL LIMITATIONS

The ERMYN model applies to the specific environments identified in 10 CFR 63.305 [DIRS 156605]. It uses certain assumptions and simplifications. Therefore the ERMYN model only applies within a certain context. If used for other situations, the BDCFs may not apply. The radionuclide sources for the biosphere model are specific to the two exposure scenarios considered (contaminated groundwater and contaminated volcanic ash deposited on the ground). Although the mathematical models described in Sections 6.4 and 6.5 apply to all radionuclides, the ERMYN model focuses on the radionuclides that were screened for the TSPA-LA (BSC 2002 [DIRS 160059]). The model output, the ERMYN GoldSim model, is built for 28 primary radionuclides (Section 6.1.3). This model applies to assessing chronic radiation doses (Section 6.1). This model is valid for all values of input parameters reasonably expected to occur in the arid to semi-arid region surrounding Yucca Mountain. Users should be aware that some unreasonable input parameters values will produce invalid results (Section 7.6).

For the contaminated groundwater scenario, the ERMYN model applies to an agricultural situation with long-term irrigation and soil contamination at long-term saturation conditions. If soils are not saturated, the ERMYN model might overestimate the radiation dose. The biosphere model applies to an arid or semi-arid climate (Section 6.1.1.1), and it is valid only for limited groundwater discharge to the surface and limited surface water transport, as long as the radionuclide concentration in the surface water is the same as in the groundwater, and the reference biosphere is not greatly altered. For example, if permanent surface waters such as rivers or lakes are present, the environmental would be sufficiently different to change the reference biosphere, and other pathways would have to be added for the ERMYN model to remain valid.

For the contaminated volcanic ash exposure scenario, the model applies to a layer of small ash particles that could be resuspended into the air. The ash could be deposited directly on the land surface or it could be moved in by wind or water and redistributed. The model does not apply to other volcanic media, such as contaminated gas, lava, or coarse ash. Some assumptions (Sections 5.12 and 5.15) used in the model development are based on thin ash deposits; if thick ash deposits occur, the model might overestimate the radiation dose. In addition, the ERMYN model does not apply during a volcanic eruption when volcanic ash is still in the air (i.e., before initial settling on the ground). If radionuclide concentrations in the air and the exposure time are known, a dose assessment for the eruption period could be considered as a simple inhalation scenario.

# 9. INPUTS AND REFERENCES

## 9.1 DOCUMENTS CITED


100117 CRWMS M&O 1997. *Engineering Design Climatology and Regional Meteorological Conditions Report.* B00000000-01717-5707-00066 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980304.0028.

100131 D'Agnese, F.A.; Faunt, C.C.; Turner, A.K.; and Hill, M.C. 1997. *Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Ground-Water Flow System, Nevada and California.* Water-Resources Investigations Report 96-4300. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19980306.0253.

100332 DOE (U.S. Department of Energy) 1997. *The 1997 "Biosphere" Food Consumption Survey Summary Findings and Technical Documentation.* Las Vegas, Nevada: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19981021.0301.

100458 IAEA (International Atomic Energy Agency) 1994. *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments.* Technical Reports Series No. 364. Vienna, Austria: International Atomic Energy Agency. TIC: 232035.

100464 Leigh, C.D.; Thompson, B.M.; Campbell, J.E.; Longsine, D.E.; Kennedy, R.A.; and Napier, B.A. 1993. *User's Guide for GENII-S: A Code for Statistical and Deterministic Simulations of Radiation Doses to Humans from Radionuclides in the Environment.* SAND91-0561. Albuquerque, New Mexico: Sandia National Laboratories. ACC: MOL.20010721.0031.

100909 Kotra, J.P.; Lee, M.P.; Eisenberg, N.A.; and DeWispelare, A.R. 1996. *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program.* NUREG-1563. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 226832.

101069 Eckerman, K.F.; Wolbarst, A.B.; and Richardson, A.C.B. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.* EPA 520/1-88-020. Federal Guidance Report No. 11. Washington, D.C.: U.S. Environmental Protection Agency. ACC: MOL.20010726.0072.

101074 ICRP (International Commission on Radiological Protection) 1975. *Report of the Task Group on Reference Man: A Report Prepared by a Task Group of Committee 2 of the International Commission on Radiological Protection.* ICRP Number 23. Tarrytown, New York: Elsevier. ACC: MOL.20000516.0124.

101076 ICRP (International Commission on Radiological Protection) 1978. "Limits for Intakes of Radionuclides by Workers." *Annals of the ICRP*. ICRP Publication 30 Supplement to Part 1. New York, New York: Pergamon Press. TIC: 221575.

101079 LaPlante, P.A. and Poor, K. 1997. *Information and Analyses to Support Selection of Critical Groups and Reference Biospheres for Yucca Mountain Exposure Scenarios.* CNWRA 97-009. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. ACC: MOL.20010721.0035.

101085 Smith, G.M.; Watkins, B.M.; Little, R.H.; Jones, H.M.; and Mortimer, A.M. 1996. *Biosphere Modeling and Dose Assessment for Yucca Mountain.* EPRI TR-107190. Palo Alto, California: Electric Power Research Institute. TIC: 231592.

101090 CRWMS M&O 1997. *Yucca Mountain Site Characterization Project Summary of Socioeconomic Data Analyses Conducted in Support of the Radiological Monitoring Program First Quarter 1996 to First Quarter 1997.* Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971117.0460.

101895 Till, J.E. and Meyer, H.R. 1983. *Radiological Assessment, A Textbook on Environmental Dose Analysis.* NUREG/CR-3332. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 223809.

102235 CRWMS M&O 1996. *The Vegetation of Yucca Mountain: Description and Ecology.* B00000000-01717-5705-00030 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19970116.0055.

103178 Lide, D.R. and Frederikse, H.P.R., eds. 1997. *CRC Handbook of Chemistry and Physics.* 78th Edition. Boca Raton, Florida: CRC Press. TIC: 243741.

103776 Kennedy, W.E., Jr. and Strenge, D.L. 1992. *Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent.* Volume 1 of *Residual Radioactive Contamination from Decommissioning.* NUREG/CR-5512. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20010721.0030.

103784 NCRP (National Council on Radiation Protection and Measurements) 1984. *Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment.* Report No. 76. Bethesda, Maryland: National Council on Radiation Protection and Measurement. TIC: 223622.

103831 Zach, R.; Amiro, B.D.; Bird, G.A.; Macdonald, C.R.; Sheppard, M.I.; Sheppard, S.C.; and Szekely, J.G. 1996. *Biosphere Model.* Volume 4 of *The Disposal of Canada's Nuclear Fuel Waste: A Study of Postclosure Safety of In-Room Emplacement of Used CANDU Fuel in Copper Containers in Permeable Plutonic Rock.* AECL-11494-4. Pinawa, Manitoba, Canada: Atomic Energy of Canada Limited. TIC: 226735.

107684 Eckerman, K.F. and Ryman, J.C. 1993. *External Exposure to Radionuclides in Air, Water, and Soil, Exposure-to-Dose Coefficients for General Application, Based on the 1987 Federal Radiation Protection Guidance.* EPA 402-R-93-081. Federal Guidance Report No. 12. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air. TIC: 225472.

107736 CRWMS M&O 1999. *Evaluation of Soils in the Northern Amargosa Valley.* B00000000-01717-5705-00084 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990224.0268.

107744 Rittmann, P.D. 1993. *Verification Tests for the July 1993 Revision to the GENII Radionuclide and Dose Increment Libraries.* WHC-SD-WM-TI-596. Richland, Washington: Westinghouse Hanford Company. TIC: 233965.

109606 Baes, C.F., III and Sharp, R.D. 1983. "A Proposal for Estimation of Soil Leaching and Leaching Constants for Use in Assessment Models." *Journal of Environmental Quality, 12,* (1), 17-28. Madison, Wisconsin: American Society of Agronomy. TIC: 245676.

110012 Troeh, F.R.; Hobbs, J.A.; and Donahue, R.L. 1980. *Soil and Water Conservation for Productivity and Environmental Protection.* Englewood Cliffs, New Jersey: Prentice-Hall. TIC: 246612.

110351 ICRP (International Commission on Radiological Protection) 1980. *Limits for Intakes of Radionuclides by Workers.* Volume 4, No. 3/4 of *Annals of the ICRP*. Sowby, F.D., ed. ICRP Publication 30 Part 2. Reprinted 1990. Elmsford, New York: Pergamon Press. TIC: 4941.

110352 ICRP (International Commission on Radiological Protection) 1981. *Limits for Intakes of Radionuclides by Workers.* Volume 6, No. 2/3 of *Annals of the ICRP*. Sowby, F.D., ed. ICRP Publication 30 Part 3, Including Addendum to Parts 1 and 2. New York, New York: Pergamon Press. TIC: 4943.

110386 ICRP (International Commission on Radiological Protection) 1979. *Limits for Intakes of Radionuclides by Workers.* Volume 2, No. 3/4 of *Annals of the ICRP*. Sowby, F.D., ed. ICRP Publication 30 Part 1. New York, New York: Pergamon Press. TIC: 4939.

110951 State of Nevada 1997. *Ground Water Pumpage Inventory Amargosa Valley, No. 230 1997.* Carson City, Nevada: State of Nevada, Department of Conservation and Natural Resources. ACC: MOL.19990329.0141.

116135 EPA (U.S. Environmental Protection Agency) 1997. *Activity Factors.* Volume III of *Exposure Factors Handbook.* EPA/600/P-95/002Fc. Washington, D.C.: U.S. Environmental Protection Agency. TIC: 241062.

117076 SNL (Sandia National Laboratories) 1998. *Software Code: GENII-S V1.4.8.5.* V1.4.8.5. PC, Windows NT. 30034 V1.4.8.5.

123696 Anspaugh, L.R. 1987. *Retention by Vegetation of Radionuclides Deposited in Rainfall: A Literature Summary.* UCRL-53810. Livermore, California: Lawrence Livermore National Laboratory. TIC: 237907.

124110 Hoffman, F.O.; Frank, M.L.; Blaylock, B.G.; von Bernuth, R.D.; Deming, E.J.; Graham, R.V.; Mohrbacher, D.A.; and Waters, A.E. 1989. *Pasture Grass Interception and Retention of (131)I, (7)BE, and Insoluble Microspheres Deposited in Rain.* ORNL-6542. Oak Ridge, Tennessee: Oak Ridge National Laboratory. TIC: 237241.

124114 Hoffman, F.O.; Thiessen, K.M.; Frank, M.L.; and Blaylock, B.G. 1992. "Quantification of the Interception and Initial Retention of Radioactive Contaminants Deposited on Pasture Grass by Simulated Rain." *Atmospheric Environment, 26A,* (18), 3313-3321. New York, New York: Pergamon Press. TIC: 243594.

124120 Hoffman, F.O.; Thiessen, K.M.; and Rael, R.M. 1995. "Comparison of Interception and Initial Retention of Wet-Deposited Contaminants on Leaves of Different Vegetation Types." *Atmospheric Environment, 29,* (15), 1771-1775. New York, New York: Pergamon Press. TIC: 243593.

124149 Horak, C. and Carns, D. 1997. *Amargosa Focus Group Report.* Biosphere Study. Las Vegas, Nevada: University of Nevada, Las Vegas. TIC: 241712.

145212 Chow, J.C.; Watson, J.G.; Green, M.C.; Lowenthal, D.H.; DuBois, D.W.; Kohl, S.D.; Egami, R.T.; Gillies, J.; Rogers, C.F.; Frazier, C.A.; and Cates, W. 1999. "Middle- and Neighborhood-Scale Variations of PM10 Source Contributions in Las Vegas, Nevada." *Journal of the Air & Waste Management Association, 49,* 641-654. Pittsburgh, Pennsylvania: Air & Waste Management Association. TIC: 247013.

149069 Lamarsh, J.R. 1983. *Introduction to Nuclear Engineering.* 2nd Edition. Menlo Park, California: Addison-Wesley. TIC: 244841.

151615 CRWMS M&O 2000. *Biosphere Process Model Report.* TDR-MGR-MD-000002 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000620.0341.

151945 CRWMS M&O 2000. *Yucca Mountain Site Description.* TDR-CRW-GS-000001 REV 01 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001003.0111.

152446 ICRP (International Commission on Radiological Protection) 1996. *Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients.* Volume 26, No. 1 of *Annals of the ICRP*. Smith, H., ed. ICRP Publication 72. New York, New York: Pergamon Press. TIC: 235870.

152517 CRWMS M&O 2001. *Evaluate Soil/Radionuclide Removal by Erosion and Leaching.* ANL-NBS-MD-000009 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010214.0032.

152536 CRWMS M&O 2001. *Disruptive Event Biosphere Dose Conversion Factor Analysis.* ANL-MGR-MD-000003 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010125.0233.

152539 CRWMS M&O 2001. *Nominal Performance Biosphere Dose Conversion Factor Analysis.* ANL-MGR-MD-000009 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010123.0123.

152549 EPA (U.S. Environmental Protection Agency) 1997. *Food Ingestion Factors.* Volume II of *Exposure Factors Handbook.* EPA/600/P-95/002Fb. Washington, D.C.: U.S. Environmental Protection Agency. TIC: 241061.

153056 ICRP (International Commission on Radiological Protection) 1981. *Limits for Intakes of Radionuclides by Workers.* Volume 5, No. 1-6 of *Annals of the ICRP*. ICRP Publication 30, Supplement to Part 2. New York, New York: Pergamon Press. TIC: 4942.

153057 ICRP (International Commission on Radiological Protection) 1982. *Limits for Intakes of Radionuclides by Workers.* Volume 8, No. 1-3 of *Annals of the ICRP*. ICRP Publication 30, Supplement B to Part 3 Including Addendum to the Supplements of Parts 1 and 2. New York, New York: Pergamon Press. TIC: 4945.

153207 CRWMS M&O 2001. *Distribution Fitting to the Stochastic BDCF Data.* ANL-NBS-MD-000008 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010221.0148.

153246 CRWMS M&O 2000. *Total System Performance Assessment for the Site Recommendation.* TDR-WIS-PA-000001 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001220.0045.

154522 BIOMASS (Biosphere Modelling and Assessment) 2000. *Example Reference Biosphere 2A: Agricultural Well, Constant Biosphere.* Draft TECDOC. BIOMASS/T1/WD08. Vienna, Austria: International Atomic Energy Agency, Division of Radiation and Waste Safety. TIC: 249456.

155188 IAEA (International Atomic Energy Agency) 2001. *An International Peer Review of the Biosphere Modelling Programme of the US Department of Energy's Yucca Mountain Site Characterization Project, Report of the IAEA International Review Team.* Vienna, Austria: International Atomic Energy Agency. TIC: 250092.

155894 NCRP (National Council on Radiation Protection and Measurements) 1999. *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies.* NCRP Report No. 129. Bethesda,

Maryland: National Council on Radiation Protection and Measurements. TIC: 250396.

156257 BSC (Bechtel SAIC Company) 2001. *Model Validation Status Review.* TDR-WIS-MD-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011211.0095.

156858 Bureau of the Census. 2001. *Census 2000 Summary File 1 (ASCII) 2000, Census of Population and Housing, California, Montana, Nebraska, Nevada, New Hampshire, New Jersey, and New Mexico.* Washington, D.C.: Bureau of the Census. TIC: 251242.

157090 Reamer, C.W. 2001. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (June 21 - 22, 2001)." Letter from C.W. Reamer (NRC) to S. Brocoum (DOE/YMSCO), June 29, 2001, with enclosure. ACC: MOL.20010918.0001.

157927 Napier, B.A.; Peloquin, R.A.; Strenge, D.L.; and Ramsdell, J.V. 1988. *Conceptual Representation.* Volume 1 of *GENII - The Hanford Environmental Radiation Dosimetry Software System.* PNL-6584. Richland, Washington: Pacific Northwest Laboratory. TIC: 252237.

158069 EPRI (Electric Power Research Institute) 2002. *Evaluation of the Proposed High-Level Radioactive Waste Repository at Yucca Mountain Using Total System Performance Assessment, Phase 6.* Technical Report 1003031. Palo Alto, California: Electric Power Research Institute. TIC: 252239.

158212 YMP (Yucca Mountain Site Characterization Project) 1999. *Yucca Mountain Site Characterization Project: Summary of Socioeconomic Data Analyses Conducted in Support of the Radiological Monitoring Program, April 1998 to April 1999.* North Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.19991021.0188.

158378 USGS (U.S. Geological Survey) 2001. *Future Climate Analysis.* ANL-NBS-GS-000008 REV 00 ICN 01. Denver, Colorado: U.S. Geological Survey. ACC: MOL.20011107.0004.

158380 Reamer, C.W. 2001. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6 through 10, 2001)." Letter from C.W. Reamer (NRC) to S. Brocoum (DOE/YMSCO), August 23, 2001, with enclosure. ACC: MOL.20011029.0281.

158519 IAEA (International Atomic Energy Agency) 2001. *Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment.* Safety Reports Series No. 19. Vienna, Austria: International Atomic Energy Agency. TIC: 251295.

158592 BSC (Bechtel SAIC Company) 2002. *Guidelines for Developing and Documenting Alternative Conceptual Models, Model Abstractions, and Parameter Uncertainty in the Total System Performance Assessment for the License Application.* TDR-WIS-PA-000008 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020312.0155.

158643 USDA (U.S. Department of Agriculture) 1999. *1997 Census of Agriculture, Nevada State and County Data.* Volume 1, Geographic Area Series Part 28. AC97-A-28. Washington, D.C.: U.S. Department of Agriculture, National Agricultural Statistics Service. TIC: 246010.

158644 UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2000. *Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes.* Two volumes. New York, New York: United Nations. TIC: 249863.

159465 Yu, C.; Zielen, A.J.; Cheng, J.-J.; LePoire, D.J.; Gnanapragasam, E.; Kamboj, S.; Arnish, J.; Wallo, A., III.; Williams, W.A.; and Peterson, H. 2001. *User's Manual for RESRAD Version 6.* ANL/EAD-4. Argonne, Illinois: Argonne National Laboratory. TIC: 252702.

159468 BIOMASS (The IAEA Programme on Biosphere Modelling and Assessment Methods) 2001. "Themes for a New Co-ordinated Research Programme on Environmental Model Testing and Improvement: Theme 1: Radioactive Waste Disposal, Theme 2: Environmental Releases, Theme 3: Biospheric Processes." *Working Material, Limited Distribution, Biosphere Modelling and Assessment, Biomass Programme.* Version {beta}2. Vienna, Austria: International Atomic Energy Agency. TIC: 252966.

159470 Karlsson, S.; Bergström, U.; and Meili, M. 2001. *Models for Dose Assessments, Models Adapted to the SFR-Area, Sweden.* SKB TR-01-04. Stockholm, Sweden: Svensk Kärnbränsleförsörjning A.B. TIC: 252806.

159497 Watt, J.R. and Brown, W.K. 1997. *Evaporative Air Conditioning Handbook.* 3rd Edition. Lilburn, Georgia: Fairmont Press. TIC: 252688.

159545 Sheppard, M.I.; Sheppard, S.C.; and Amiro, B.D. 1991. "Mobility and Plant Uptake of Inorganic {superscript 14}C and {superscript 14}C-Labelled PCB in Soils of High and Low Retention." *Health Physics, 61,* (4), 481-492. New York, New York: Pergamon Press. TIC: 252687.

159577 Pinnick, R.G.; Fernandez, G.; Hinds, B.D.; Bruce, C.W.; Schaefer, R.W.; and Pendleton, J.D. 1985. "Dust Generated by Vehicular Traffic on Unpaved Roadways: Sizes and Infrared Extinction Characteristics." *Aerosol Science and Technology, 4,* (1), 99-121. New York, New York: Elsevier. TIC: 252364.

159728 Bureau of the Census. 2002. "2000 Summary File 3 (SF 3) Sample Data, Amargosa Valley CCD, Nye County, Nevada." Washington, D.C.: U.S. Department of Commerce, Bureau of the Census. Accessed August 28, 2002. TIC: 253098. http://factfinder.census.gov/servlet/DTTable?_ts=48597952130

159894 Reamer, C.W. 2001. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter from C.W. Reamer (NRC) to S. Brocoum (DOE/YMSCO), September 12, 2001, with enclosure. ACC: MOL.20011114.0008.

160001 Jensen, M.E.; Burman, R.D.; and Allen, R.G., eds. 1990. *Evapotranspiration and Irrigation Water Requirements.* ASCE Manuals and Reports on Engineering Practice No. 70. New York, New York: American Society of Civil Engineers. TIC: 246697.

160057 BSC (Bechtel SAIC Company) 2003. *Evaluation of Features, Events, and Processes (FEP) for the Biosphere Model.* ANL-MGR-MD-000011 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030214.0006.

160059 BSC (Bechtel SAIC Company) 2002. *Radionuclide Screening.* ANL-WIS-MD-000006 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020923.0177.

160094 Klepeis, N.E. 1999. "An Introduction to the Indirect Exposure Assessment Approach: Modeling Human Exposure Using Microenvironmental Measurements and the Recent National Human Activity Pattern Survey." *Environmental Health Perspectives, 107,* (Supplement 2), 365-374. [Research Park Triangle, North Carolina: National Institute of Environmental Health Sciences, National Institutes of Health]. TIC: 250567.

160146 BSC (Bechtel SAIC Company) 2002. *Total System Performance Assessment-License Application Methods and Approach.* TDR-WIS-PA-000006 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020923.0175.

160313 BSC (Bechtel SAIC Company) 2002. *Scientific Processes Guidelines Manual.* MIS-WIS-MD-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020923.0176.

160402 IAEA (International Atomic Energy Agency) 1996. *Modelling of Radionuclide Interception and Loss Processes in Vegetation and of Transfer in Semi-Natural Ecosystems, Second Report of the VAMP Terrestrial Working Group.* IAEA-TECDOC-857. Vienna, Austria: International Atomic Energy Agency. TIC: 253017.

160440 McKone, T.E. and Bogen, K.T. 1992. "Uncertainties in Health-Risk Assessment: An Integrated Case Study Based on Tetrachloroethylene in California Groundwater." *Regulatory Toxicology and Pharmacology, 15,* 86-103. [New York, New York]: Academic Press. TIC: 253420.

160441 McKone, T.E. and Daniels, J.I. 1991. "Estimating Human Exposure Through Multiple Pathways from Air, Water, and Soil." *Regulatory Toxicology and Pharmacology, 13,* 36-61. [New York, New York]: Academic Press. TIC: 253419.

160643 GoldSim Technology Group. 2002. *GoldSim, Graphical Simulation Environment, User's Guide.* Version 7.40. Redmond, Washington: Golder Associates. TIC: 253564.

160674 Roe, L.K. 2002. "Summary of RDA Investigation ID: 4/10/02 Fish Farming in Amargosa Valley." Interoffice memorandum from L.K. Roe (BSC) to File, November 5, 2002, 1105024986, with an attachment. ACC: MOL.20021107.0091 ; MOL.20020821.0002.

160964 BSC (Bechtel SAIC Company) 2003. *Environmental Transport Input Parameters for the Biosphere Model.* ANL-MGR-MD-000007 REV 01. Las Vegas, Nevada: Bechtel SAIC Company.

160965 BSC (Bechtel SAIC Company) 2003. *Inhalation Exposure Input Parameters for the Biosphere Model.* ANL-MGR-MD-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company.

160976 BSC (Bechtel SAIC Company) 2003. *Agricultural and Environmental Parameters for the Biosphere Model.* ANL-MGR-MD-000006 REV 01. Las Vegas, Nevada: Bechtel SAIC Company.

161239 BSC (Bechtel SAIC Company) 2003. *Soil-Related Input Parameters for the Biosphere Model.* ANL-NBS-MD-000009 REV 01. Las Vegas, Nevada: Bechtel SAIC Company.

161241 BSC (Bechtel SAIC Company) 2003. *Characteristics of the Receptor for the Biosphere Model.* ANL-MGR-MD-000005 REV 02. Las Vegas, Nevada: Bechtel SAIC Company.

161572 BSC (Bechtel SAIC Company) 2003. *Software Code: GoldSim.* 7.50.100. PC. 10344-7.50.100-00.

161770 Canori, G.F. and Leitner, M.M. 2003. *Project Requirements Document.* TER-MGR-MD-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030404.0003.

162418 NRC (U.S. Nuclear Regulatory Commission) 2003. *Yucca Mountain Review Plan, Information Only.* NUREG-1804, Draft Final Revision 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. TIC: 254002.

162452 MO0303SEPFEPS2.000. LA FEP List. Submittal date: 03/26/2003.

162465 Mage, D.T. 1985. "Concepts of Human Exposure Assessment for Airborne Particulate Matter." *Environment International, 11,* 407-412. [New York, New York]: Pergamon Press. TIC: 250582.

162466 Duan, N. 1982. "Models for Human Exposure to Air Pollution." Environment In*ternational, 8,* 305-309. [New York, New York]: Pergamon Press. TIC: 250558.

162977 Wasiolek, M. 2002. "Re: GENII-S Defect Notification Meeting." E-mail from M. Wasiolek to J. Mason, January 4, 2002, with attachments. ACC: MOL.20020130.0040.

162999 Chow, J.C.; Watson, J.G.; Lowenthal, D.H.; Solomon, P.A.; Magliano, K.L.; Ziman, S.D.; and Richards, L.W. 1993. "PM{subscript 10} and PM{subscript 2.5} Compositions in California's San Joaquin Valley." *Aerosol Science and Technology, 18,* (2), 105-128. New York, New York: Elsevier. TIC: 251303.

163016 Daniels, J.I. 2003. "Summary of Review Actions for Development Drafts of Biosphere Model Report [MDL-MGR-MD-000001 Development Drafts of Rev 00A Dated between September–December 2002] Which Includes a Description of An Environmental Radiation Model for the Yucca Mountain, Nevada (ERMYN)." Letter from J.I. Daniels (LLNL) to A.J. Smith (BSC), March 20, 2003. ACC: MOL.20030428.0001.

163602 BSC (Bechtel SAIC Company) 2003. *Technical Work Plan for: Biosphere Modeling and Expert Support.* TWP-NBS-MD-000004 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030604.0001.

## 9.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

156605 10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available.

160555 24 CFR 3280. Housing and Urban Development: Manufactured Home Construction and Safety Standards. Readily available

155892 AP-2.12Q, Rev. 0, ICN 3. *Peer Review*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20010904.0452.

159604 AP-2.27Q, Rev. 0, ICN 0. *Planning for Science Activities.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020701.0184.

163021 AP-2.22Q, Rev. 0, ICN 1. *Classification Criteria and Maintenance of the Monitored Geologic Repository Q-List.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030422.0009.

163085 AP-SI.1Q, Rev. 5, ICN 0. *Software Management*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030422.0012.

164073 AP-3.15Q, Rev. 4, ICN 2. *Managing Technical Product Inputs*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030627.0002.

164074 AP-SIII.10Q, Rev. 1, ICN 2. *Models*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030627.0003.

## 9.3 DEVELOPED DATA

163816 MO0306MWDBGSMF.001. Biosphere GoldSim Model Files. Submittal date: 06/13/2003.

INTENTIONALLY LEFT BLANK

# ATTACHMENT I

# ELECTRONIC FILES USED FOR THE MODEL REPORT

INTENTIONALLY LEFT BLANK

## ELECTRONIC FILES USED FOR THE MODEL REPORT

This attachment lists all of the electronic files generated for this model report. All of the files are stored on a data compact disk, titled *BioModFiles*. All of the GoldSim files can be reproduced using the model output files for the groundwater (*ERMYN_GW.gsm*) and volcanic ash (*ERMYN_VA.gsm*) scenarios (Table I-1). Two Excel files containing various calculations using standard Excel functions also are on the compact disk (Table I-3). The Excel calculation methods are explained on the individual spreadsheets and need no further explanation in this Attachment. The file names, purpose, date, time last modified, and volume size (file size in kB) are given in the tables below for each electronic file.

Table I-1. GoldSim Model Files

| File Name | Purpose | Date and Time | Size (kB) |
|---|---|---|---|
| ERMYN_GW.gsm | GoldSim model for the groundwater scenario | 6/10/2003 10:58a | 3,930 |
| ERMYN_VA.gsm | GoldSim model for the volcanic ash scenario | 6/10/2003 10:59a | 2,705 |

Table I-2. GoldSim Model Verification Files

| File Name | Purpose | Date and Time | Size (kB) |
|---|---|---|---|
| ERMYN_GW _Pu239verf.gsm | Deterministic run for $^{239}$Pu groundwater scenario; used in Table 6.10-1 | 06/23/2003 03:29p | 3,931 |
| ERMYN_GW _C14verf.gsm | Deterministic run for $^{14}$C groundwater scenario; used in Table 6.10-2 | 06/23/2003 03:29p | 3,931 |
| ERMYN_GW _Ra226verf.gsm | Deterministic run for $^{226}$Ra groundwater scenario; used in Table 6.10-3 | 06/23/2003 03:29p | 3,931 |
| ERMYN_GW _Pu239stoc.gsm | Stochastic run for $^{239}$Pu groundwater scenario; used in Table 6.10-4 | 06/23/2003 03:32p | 11,865 |
| ERMYN_VA _Pu239verf.gsm | Deterministic run for $^{239}$Pu volcanic ash scenario; used in Table 6.10-5 | 06/23/2003 03:33p | 2,705 |
| ERMYN_VA _Ra226verf.gsm | Deterministic run for $^{226}$Ra volcanic ash scenario; used in Table 6.10-6 | 06/23/2003 03:33p | 2,705 |
| ERMYN_VA _Pu239stoc.gsm | Stochastic run for $^{239}$Pu volcanic ash scenario; used in Table 6.10-7 | 06/23/2003 03:34p | 8,496 |

Table I-3. Microsoft Excel Files

| File Name | Purpose | Date and Time | Size (kB) |
|---|---|---|---|
| ERMYN verification.xls | File contains five worksheets for model hand calculations; used in Tables 6.10-1, 6.10-2, 6.10-3, 6.10-5, and 6.10-6 | 07/14/2003 09:44a | 194 |
| ERMYN validation.xls | File contains five worksheets for model validation calculations; used in Tables 7.4-4, 7.4-7, 7.4-12, 7.4-13, 7.4-18, and 7.4-19 | 07/14/2003 05:37p | 69 |

Table I-4. GENII-S Files

| File Name | Purpose | Date and Time | Size (kB) |
|---|---|---|---|
| RMDLIB.dat | GENII-S radionuclide library file for model validation that was used in Table 7.4-5 | 11/29/1990 05:24p | 14 |
| C14subroutine.txt | GENII-S $^{14}C$ Fortran subroutine taken from GENII-S source code, referenced in Table 7.3-21 | 12/24/2002 03:44p | 13 |

# ATTACHMENT II

# ANALYTICAL SOLUTION FOR RADON CONCENTRATIONS IN THE AIR DUE TO RADIUM CONTAMINATED SOIL

INTENTIONALLY LEFT BLANK

## ANALYTICAL SOLUTION FOR RADON CONCENTRATIONS IN THE AIR DUE TO RADIUM CONTAMINATED SOIL

An analytical solution for the radon diffusion equation used in the RESRAD model (Yu et al. 2001 [DIRS 159465], Appendix C) and typical numerical results from this method are presented in this Attachment. The purpose of this analytical solution is to evaluate radon concentrations in the air using the RESRAD method, which is considered an ACM for the ERMYN radon submodel (Section 6.3.3). The numerical results presented here are compared to the selected radon model, which is suggested by NCRP-129 (NCRP 1999 [DIRS 155894] Section 4.3.6). By using the analytical solution, use of the RESRAD software can be avoided, and therefore software qualification is unnecessary.

As discussed in the RESRAD manual (Yu et al. 2001 [DIRS 159465], p. C-9), the annual average radon concentration in outdoor air is calculated as

$$C_0 = \frac{J_0 F_{ao}}{\lambda H_0}\left[1 - e^{-\left(\frac{\lambda X}{2U}\right)}\right] \qquad \text{(Eq. II-1)}$$

where

| | | |
|---|---|---|
| $C_0$ | = | annual average concentration of radon outdoors (Bq/m$^3$) |
| $J_0$ | = | radon flux at the soil surface outdoors (Bq/(m$^2$ s)) |
| $F_{ao}$ | = | outdoor area factor (dimensionless), it is equal to 1 if $A$ > 100 m$^2$ |
| $H_0$ | = | height into which plume is uniformly mixed (m) |
| $\lambda$ | = | radon decay constant (/s) |
| $U$ | = | annual average wind speed (m/s). |
| $X$ | = | effective length of the contaminated zone (m), and can be calculated as |

$$X = \sqrt{A} \qquad \text{(Eq. II-2)}$$

where

| | | |
|---|---|---|
| $A$ | = | area of the contaminated zone, which can be estimated by dividing the total of water usage by the average annual irrigation rate that are defined in Equation 6.4.6-3 (m$^2$) |

In equation II-1, everything on the right-hand side is known except $J_0$ (the radon flux at the soil surface outdoors), but solving for $J_0$ requires the solution to the applicable radon diffusion equation for radium contaminated soil (not given in text). Normally this radon diffusion equation can only be solved by numerical methods, which are used in the RESRAD code, due to the complicated geometry of the contaminated soil and uncontaminated cover. However, considering only a special, but applicable, case (large area of radium contaminated soil, uniform contamination over depth, and steady-state conditions), the radon diffusion equation can be solved analytically.

The radon concentration in a slab of contaminated soil is governed by the differential equation and boundary conditions that are discussed in the RESRAD manual (Yu et. al. 2001 [DIRS 159465], pp. C-5 to C-7). For steady state conditions, these equations are

$$\begin{cases} -\dfrac{d}{dz}\left(D\dfrac{dC}{dz}\right)+\lambda C=Q \\ C(z_a)=0 \\ J(0)=\left.\dfrac{dC}{dz}\right|_{z=0}=0 \end{cases} \qquad \text{(Eqs. II-3 to II-5)}$$

where

| | | |
|---|---|---|
| $C$ | = | radon concentration in the pore space of soil (Bq/m$^3$) |
| $D$ | = | diffusion coefficient of radon in soil (m$^2$/s) |
| $z$ | = | vertical axial distance in the direction of diffusion (m). $z = 0$ is the bottom of the contaminated soil, while $z = z_a$ is the interface between the ground and the air. |
| $C(z_a)$ | = | radon concentration at the upper boundary of the contaminated soil |
| $J(0)$ | = | radon flux at the bottom boundary of the contaminated soil. |
| $Q$ | = | radon source term into the pore space (Bq/(m$^3$ s)). |

The radon source term into the pore space (Bq/(m$^3$ s)) is evaluated as

$$Q=\frac{\varepsilon\rho_b S_{Ra}\lambda}{p_t} \qquad \text{(Eq. II-6)}$$

| | | |
|---|---|---|
| $\varepsilon$ | = | radon emanation coefficient, which represents the fraction of radon generated by radium decay that escapes from the soil particles (dimensionless) |
| $\rho_b$ | = | soil bulk density (kg/m$^3$) |
| $S_{Ra}$ | = | radium concentration in the soil (Bq/kg) |
| $p_t$ | = | total porosity (dimensionless) |
| $\lambda$ | = | radon decay constant (/s). |

Because the radon concentration and flux are continuous across the interface of the two media (i.e., air and ground), radon flux at the soil surface outdoors $J_0$ is numerically equal to radon flux at the upper boundary of the contaminated soil, but an opposite direction. It can be calculated as

$$J_0=-J(z_a)=-p_t D\left.\frac{dC}{dz}\right|_{z=z_a} \qquad \text{(Eq. II-7)}$$

As the diffusion coefficient, $D$, does not change with distance $z$, the differential equation (Equation II-3) can be solved with a general solution of

$$C=C_1e^{-z/k}+C_2e^{z/k}+C_3 \qquad \text{(Eq. II-8)}$$

where

| | | |
|---|---|---|
| $C_1$, $C_2$, and $C_3$ | = | constants to be determined by the differential equation and its boundary conditions (Equations 3 to 5) (Bq/m$^3$) |

$k$ = diffusion length (m).

which, by substituting Equation II-8 in to Equation II-3, can be shown to be

$$k = \sqrt{\frac{D}{\lambda}} \qquad \text{(Eq. II-9)}$$

Taking the first and second derivatives of Equation II-8 gives

$$\frac{dC}{dz} = -\frac{C_1}{k} e^{-z/k} + \frac{C_2}{k} e^{z/k} \qquad \text{(Eq. II-10)}$$

$$\frac{d^2C}{dz^2} = \frac{C_1}{k^2} e^{-z/k} + \frac{C_2}{k^2} e^{z/k} \qquad \text{(Eq. II-11)}$$

By inserting Equations II-11 and II-8 into the differential equation (Equation II-3), the constant $C_3$ can be determined as

$$C_3 = \frac{Q}{\lambda} \qquad \text{(Eq. II-12)}$$

Using the second boundary condition (Equation II-5) within Equation II-10, the relationship between $C_1$ and $C_2$ can be determined as

$$C_1 = C_2 \qquad \text{(Eq. II-13)}$$

Using the first boundary condition (Equation II-4) and Equation II-13 into Equation II-8, the constants $C_1$ and $C_2$ can be determined as

$$C(z_a) = C_1 e^{-z_a/k} + C_2 e^{z_a/k} + C_3 = 0$$

(Eqs. II-14 and 15)

$$C_1 = C_2 = \frac{-C_3}{e^{-z_a/k} + e^{z_a/k}}$$

Then the radon flux at the soil surface outdoors $J_0$ can be calculated using Equations II-7, II-10, II-12, II-13, and II-15 as

$$\begin{aligned} J_0 = -J(z_a) &= -p_t D \left.\frac{dC}{dz}\right|_{z=z_a} \\ &= p_t k Q \left( \frac{e^{z_a/k} - e^{-z_a/k}}{e^{z_a/k} + e^{-z_a/k}} \right) \end{aligned} \qquad \text{(Eq. II-16)}$$

By inserting Equation II-13 into Equation II-1, the annual average radon concentration in the air ($C_0$) can be calculated as a function of the contaminated soil depth ($z_a$). When contaminated soil is very deep, $z_a = \infty$, radon flux at soil surface becomes independent of $z_a$ and reaches the maximum value

$$J_0 = p_t kQ \qquad \text{(Eq. II-17)}$$

The annual average radon concentration in the air can be calculated by combing Equations II-17, II-1, and II-6 as

$$\begin{aligned} C_0 &= \frac{p_t kQF_{ao}}{\lambda H_0}\left[1 - e^{-\left(\frac{\lambda X}{2U}\right)}\right] \\ &= \frac{kF_{ao}\varepsilon\rho_b S_{Ra}}{H_0}\left[1 - e^{-\left(\frac{\lambda X}{2U}\right)}\right] \end{aligned} \qquad \text{(Eq. II-18)}$$

The radon concentration ratio between outdoor air and soil, which is the radon release factor used in the ERMYN, can be evaluated using Equation II-18.

$$\frac{C_0}{S_{Ra}} = \frac{kF_{ao}\varepsilon\rho_b}{H_0}\left[1 - e^{-\left(\frac{\lambda X}{2U}\right)}\right] \qquad \text{(Eq. II-19)}$$

Using typical values from the ERMYN model, or using default values from the RESRAD code if the parameters are unique to that radon model, the radon release factor can be calculated using Equation II-19. The inputs and calculated results are shown in Table II-1.

Table II-1. Calculation of the Radon Release Factor

| Parameter name | Notation | Value | Units | Data Source |
|---|---|---|---|---|
| Outdoor area factor | $F_{ao}$ | 1 | - | RESRAD default |
| Radon emanation coefficient | $\varepsilon$ | 0.25 | - | RESRAD default |
| Soil bulk density | $\rho_b$ | 1500 | $kg/m^3$ | ERMYN input |
| Diffusion coefficient of radon in soil | $D$ | 2E-6 | $m^2/s$ | RESRAD default |
| Radon decay constant | $\lambda$ | 2.1E-6 | /s | ERMYN input |
| Diffusion length | $k$ | 0.976 | m | Calculated |
| Radon plume height | $H_0$ | 2 | m | RESRAD default |
| Area of the contaminated zone | A | 3.952E6 | $m^2$ | ERMYN input |
| Effective length of contaminated zone | X | 1.988E3 | m | Calculated |
| Annual average wind speed | $U$ | 2 | m/s | RESRAD default |
| Radon release factor | $C_0 / S_{Ra}$ | 0.19 | $kg/m^3$ | Calculated |

The calculated radon release factor used by the RESRAD radon diffusion model, 0.19 kg/m$^3$, is close to the selected value, 0.25 kg/m$^3$, in the ERMYN. To calculate the radon release factor as a function of contaminated soil depth, $z_a$, the exponential term in Equation II-16 is applied to Equation II-19.

$$\frac{C_0}{S_{Ra}} = \frac{kF_{ao}\varepsilon\rho_b}{H_0}\left[1 - e^{-\left(\frac{\lambda X}{2U}\right)}\right]\left(\frac{e^{z_a/k} - e^{-z_a/k}}{e^{z_a/k} + e^{-z_a/k}}\right) \qquad \text{(Eq. II-20)}$$

Using the data in Table II-1, the concentration of radon in the air can be calculated as shown in Table II-2.

Table II-2. Radon Release Factors Due to Radium Contaminated Soil

| Depth of Contaminant (m) | Source Exponential Term | Rn-222 Release Factor in Mass (Bq/m$^3$)/(Bq/kg) | Surface Soil Density (kg/m$^2$) | Rn-222 Release Factor in Surface (Bq/m$^3$)/(Bq/m$^2$) |
|---|---|---|---|---|
| 0.003 | 0.0031 | 5.86E-04 | 4.5 | 0.00013 |
| 0.01 | 0.0102 | 1.95E-03 | 15 | 0.00013 |
| 0.02 | 0.0205 | 3.91E-03 | 30 | 0.00013 |
| 0.05 | 0.0512 | 9.76E-03 | 75 | 0.00013 |
| 0.1 | 0.1021 | 1.95E-02 | 150 | 0.00013 |
| 0.2 | 0.2020 | 3.85E-02 | 300 | 0.00013 |
| 0.5 | 0.4716 | 9.00E-02 | 750 | 0.00012 |
| 1 | 0.7716 | 1.47E-01 | 1500 | 0.00010 |
| 2 | 0.9673 | 1.85E-01 | 3000 | 0.00006 |
| 5 | 0.9999 | 1.91E-01 | 7500 | 0.00003 |
| 10 | 1.0000 | 1.91E-01 | 15000 | 0.00001 |

NOTE: Column 1 is input for the calculations. Column 2 is the source exponential term in Equation 20. Column 3 is the result of using Equation II-20 and input values from Table II-1. Column 4 is converted from Column 1 with soil density of 1,500 kg/m$^3$. Column 5 is calculated as Column 3 / Column 4.

INTENTIONALLY LEFT BLANK

# ATTACHMENT III

# CALCULATION OF ABSOLUTE HUMIDITY FROM RELATIVE HUMIDITY

INTENTIONALLY LEFT BLANK

## CALCULATION OF ABSOLUTE HUMIDITY FROM RELATIVE HUMIDITY

In dry weather, a swamp cooler may deliver air at 60 percent relative humidity. However, the relative humidity of air discharged from the house is only about 40 percent because of the temperature increase upon mixing with the indoor air (Watt and Brown 1997 [159497], p. 24). If the indoor temperature is 75°F (24°C), the absolute humidity corresponding to this temperature can be estimated from the ideal gas law as

$$\frac{p \times V}{T} = n \times R \qquad \text{(Eq. III-1)}$$

where

| | | |
|---|---|---|
| $p$ | = | water vapor pressure (partial pressure of water vapor) |
| $V$ | = | volume ($m^3$) |
| $T$ | = | temperature (K) |
| $n$ | = | number of moles |
| $R$ | = | universal gas constant. |

After rearranging and multiplying Equation III-1 by the molecular weight of water, *mw*, the density of water vapor in the air, $\rho_w$ , can be calculated as

$$\frac{n \times mw}{V} = \frac{mw \times p}{R \times T} = \rho_w \qquad \text{(Eq. III-2)}$$

The molecular weight of water is 18.016 g/mole. The partial pressure of water vapor at saturation depends on temperature. For 24°C (297 K), the partial water pressure is 2.9850 kPa (Lide and Frederikse 1997 [DIRS 103178], p. 6-8). The numerical value of the universal gas constant, *R*, depends on the units of *p*, *V*, *n*, and *T*. For the units used in this calculation, $R = 0.00831451$ ($m^3$ kPa)/(mole K) (Lide and Frederikse 1997 [DIRS 103178], p. 1-40). The absolute humidity at saturation (the density of water vapor in the air), $\rho_w$, can be calculated as

$$\rho_w = \frac{mw \times p}{R \times T} = \frac{18.016 \frac{g}{mole} \quad 2.985\, kPa}{0.008315 \frac{m^3\ kPa}{mole\ K} \quad 297\, K} = 21.8 \frac{g}{m^3} \qquad \text{(Eq. III-3)}$$

At 40 percent relative humidity, the concentration of water vapor in the air is about 8.7 g/$m^3$.

Average absolute humidity at Yucca Mountain Weather Station #9 is calculated based on measured data in CRWMS M&O (1997 [DIRS 100117], Table A-9). From this table, monthly averaged relative humidity and temperature are given. Because evaporative coolers are used during the summer, average relative humidity and temperature from May to September are used to calculate the average absolute humidity.

Table III-1. Average Relative Humidity and Temperature at the Weather Station 9

| | May | June | July | August | September | Average |
|---|---|---|---|---|---|---|
| Temperature (C) | 21.3 | 27.6 | 31.4 | 30.5 | 25.4 | 27.2 |
| Relative Humidity (%) 0400 | 42.5 | 26.4 | 23.7 | 24.2 | 26.6 | 18.5 |
| 1000 | 23.5 | 14.1 | 12.6 | 14.0 | 15.6 | |
| 1600 | 16.0 | 7.8 | 7.2 | 8.2 | 9.1 | |
| 2200 | 30.1 | 17.0 | 15.4 | 16.6 | 19.0 | |

Using the same calculation method described above, and the partial water pressure for 27.2$^{o}$C (300.2 K) is 3.6100 kPa (Lide and Frederikse 1997 [DIRS 103178], p. 6-8). The absolute humidity at saturation (the density of water vapor in the air), $\rho_w$, can be calculated as 26.1 g/m$^3$. At 18.2 percent relative humidity, the concentration of water vapor in the air is about 4.8 g/m$^3$.