Low Level Waste Disposition FY 2011 Progress Report

Fuel Cycle Research & Development

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ACRONYMS

ACRS	Advisory Committee on Reactor Safeguards
BTP	Branch Technical Position
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
CNWRA	Center for Nuclear Waste Regulatory Analyses
CRP	Co-ordinated Research Project
DGR	Deep Geologic Repository
DOE	Department of Energy
DOE-NE	Department of Energy - Nuclear Energy
DU	depleted uranium
EDZ	excavation damaged zone
EFEPs	external features, events and processes
EIS	Environmental Impact Statement
EMWMF	Environmental Management Waste Management Facility
ERDF	Environmental Restoration Disposal Facility
ESC	Environmental Safety Case
FCT	Fuel Cycle Technologies
FEPs	features, events and processes
FY	Fiscal Year
GCD	Greater Confinement Disposal
GGM	Gas Generation Module
GNLLWM	Generic Near-Surface Low Level Waste Disposal Facility Model
GTCC	greater than Class C
HLW	high level waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
L&ILW	low and intermediate level waste
LLW	low level waste
LLWR	low level waste repository
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
OPG	Ontario Power Generation
PA	performance assessment
RCRA	Resource Conservation and Recovery Act
RESRAD	Residual Radioactive
THCMBR	thermal-hydrologic-chemical-mechanical-biological-radiological
TRU	transuranic
UFD	Used Fuel Disposition
UFDC	Used Fuel Disposition Campaign
UNF	used nuclear fuel

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1.0 INTRODUCTION

This report has been prepared by the Used Fuel Disposition (UFD) campaign of the Fuel Cycle Technology (FCT) program. The UFD campaign is responsible for identifying alternatives for the disposition of used nuclear fuel (UNF). These alternatives, which include advanced fuel cycles, will inherently generate low level waste (LLW) in the process. Waste streams from these advanced fuel cycles have the potential to be very different than the LLW currently disposed of in the United States and generated by the once through fuel cycle currently employed. The waste streams could differ in regards to volume, waste form, radionuclide content and concentration, and chemical content and concentration. For example, waste streams, generated from reactor operations, separations, and fuel fabrication, could include mixed hazardous/radioactive waste and greater than class C (GTCC) LLW, potentially with significant volume generation.

The performance of disposal facilities may be significantly impacted by the different characteristics of wastes from advanced fuel cycles. The LLW Disposition activity of the UFD campaign is tasked with evaluating disposal options for LLW and identifying issues associated with disposal of LLW from advanced fuel cycles. In fiscal year (FY) 2010, the LLW Disposition activity identified several alternatives for disposal of LLW from advanced fuel cycles [Jones 2010]. In support of this task, generic performance assessment (PA) models will be developed for use in evaluating various disposal options for LLW to ensure that LLW generated by advanced fuel cycles has a viable disposition path. The generic PA models will evaluate the relative impacts for various disposal environments and alternatives such as near surface disposal as currently practiced in the United States, above ground vault disposal and intermediate depth borehole disposal.

In addition, the U.S. Nuclear Regulatory Commission is considering revising 10 CFR Part 61 to be more risk-based, potentially involving long-term performance assessment. The generic risk-based models developed by the UFD campaign can be used to evaluate different disposal alternatives using techniques and approaches consistent with a potential future regulatory framework that would include performance assessment.

In FY 2011, the LLW Disposition activity began the development of the generic PA models for disposal of LLW from advanced fuel cycles. The work conducted in FY 2011 can be broken down into the following tasks:

1. Prior Model Assessment - Work initially focused on the identification and evaluation of existing PA models that might be useful as a basis for the generic LLW disposal models. The intent of the evaluation was to avoid duplication of effort if possible and to identify features of the existing models useful to the generic LLW disposal models.
2. Features, Events and Processes - Features, events and processes (FEPs) from a variety of sources were compiled and screened for applicability to the generic LLW disposal models.
3. Generic Model Development - Development of the generic LLW disposal models was begun. Model concepts were developed and initial modeling in GoldSim was begun.
4. Disposal History Update - The history of LLW disposal in the United States was documented by the LLW Disposition activity in FY 2010 [Jones 2010]. A summary of significant events occurring in FY 2011 was prepared to supplement the history prepared in FY 2010.

The sections that follow provide a more detailed summary of the work accomplished in FY 2011 for the tasks described above.

2.0 PRIOR MODEL ASSESSMENT

The generic LLW disposal models are envisioned to be flexible to allow evaluation of a wide range of disposal techniques (e.g. above ground vault disposal versus shallow land burial), configurations (e.g. caps, liners, high integrity waste packages, other engineered barriers, disposal depth, etc.) and environments (saturated, unsaturated, clay, dry, humid, etc.). Parameters governing key features of the disposal site such as soil type, waste packaging, engineered barriers, disposal depth, etc. should be readily varied by the user. Although the model is expected to be flexible, two distinct models are nevertheless anticipated to encompass a range of configurations (i.e. shallow land burial and intermediate depth borehole). Further division of the borehole model may be required to accommodate two distinct environments, a low permeability environment and an unsaturated environment.

2.1 Purpose of Assessment

PA models for LLW disposal have been developed in the past. The purpose of this study is to identify and evaluate prior PA models with the potential to provide a basis for the generic LLW disposal models. The prior models are evaluated for:

- their direct suitability to function as generic LLW disposal models without modification,
- their suitability as a foundation for the generic LLW disposal models with some modification (if not directly suitable), and
- their relevant features that should be incorporated into the generic LLW disposal models (if not directly useable or usable with modification)

The goal of the evaluation is to avoid unnecessary and duplicate effort in developing the generic LLW disposal models. Selection of an appropriate modeling tool (i.e. software) for the generic models is also an objective of this evaluation (if an existing model is not directly useable or usable with modification).

The following performance assessment models were identified as potentially applicable to the generic LLW disposal models.

- BDOSE^{TM} 2.0 (Nuclear Regulatory Commission)
- Drigg Low Level Waste Repository (Nuclear Decommissioning Authority, United Kingdom)
- Generic Radiological Performance Assessment Model for a Radioactive Waste Disposal Site (Neptune and Company, Inc.)
- Depleted Uranium (DU) Screening Model (Nuclear Regulatory Commission)
- Bruce Low and Intermediate Level Waste (L&ILW) Deep Geologic Disposal Facility (Ontario Power Generation)
- A 40 CFR 191 Based Special Analysis Model for TRU Waste at the Area 5 Radioactive Waste Management Site , Nevada Test Site (National Security Technologies)
- Performance Assessment Model for the Greater Confinement Boreholes 1-4 at the Area 5 Radioactive Waste Management Site (Neptune and Company, Inc.)

The evaluation of these models is documented in a separate report [Jones 2011b]. A summary of the evaluation is provided in the sections that follow.

2.2 Summary of Prior Models Evaluated

2.2.1 BDOSE^{TM}

BDOSE^{TM} 2.0 was prepared by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC). It was developed using GoldSim Version 9.6. Groundwater and waste concentrations must be determined externally and must be entered by the user. As such BDOSE is simply a dose model and as such it cannot model radionuclide fate and transport from the source to the receptor location; however it could be combined with a radionuclide fate and transport model. The following dose-to-public scenarios are considered: (i) resident farmer, (ii) resident gardener, and (iii) recreationist. The following intruder scenarios are considered (i) chronic intruder, and (ii) acute intruder.

Although BDOSE^{TM} is available for use, it is not suitable as a generic LLW disposal model or as a basis for the models since it is not a full scope performance assessment model.

2.2.2 Drigg

The Drigg model is a site specific model developed to support the revised Environmental Safety Case (ESC) for the Low-Level Waste Repository (LLWR) near Drigg in Cumbria (United Kingdom). Separate models have been developed to represent the transport of contaminated groundwater from the facility for each of the following three main components and implemented as numerical models using GoldSim.

- Near field: the wastes and engineered system, from which radionuclides may be released;
- Geosphere: the geological formations and sub-surface environment, through which radionuclides may migrate; and
- Biosphere: the accessible surface environment that may become contaminated, giving rise to potential for radiological exposures to humans.

The model considers global warming resulting in a rise in sea level, coastal erosion and ultimate destruction of the LLW disposal facility. As a result of the coastal erosion, waste will be distributed on the beach and exposed in a cliff anticipated to be present at the rear of the beach. Erosion of the facility will supply contaminated material to the beach, which will be dispersed and removed by the action of the sea. Occupants of the beach, for example, recreational users engaged in various activities and occupational users engaged in fishing may be exposed to radiation from contaminated sediments by a range of pathways including external irradiation, inhalation and ingestion.

The model considers three human intrusion exposure pathways: agricultural, outdoor exposure to contaminated ground, and inhalation of thoron and radon by occupants of a house constructed on contaminated soils. A simple empirical approach is adopted for the inhalation of thoron and radon by occupants of a house constructed on contaminated soils.

The Drigg model is primarily unusable simply because it is not readily available. The model also represents a specific site and as such does not provide adequate flexibility to model a range of disposal scenarios. The model includes features that would not likely be incorporated into the generic LLW disposal models; however, those features could easily be disabled or disregarded.

2.2.3 Neptune Generic Model

Neptune and Company, Inc. developed this generic model using GoldSim software to demonstrate their ongoing modeling capability. The case chosen for the generic model is a radiological PA of an entirely fictitious LLW disposal facility. The model considers the following modes of transport:

- Air transport
    - Diffusion in the porous medium
    - Diffusion to the atmosphere
    - Aeolian transport offsite
    - Volatile and non-volatile (particulate) radionuclides
- Water transport
    - Infiltration to the water table
    - Horizontal flow to a drinking water well
- Plant transport
    - Uptake and redistribution of contaminants to the surface
- Animal transport
    - Burrowing animals
    - Transport to the surface through excavation and to other layers through collapse

The model is not suitable as is for the generic LLW disposal models; however, it could be used as a basis for the models. The Neptune generic model is available free of charge from the Neptune website.

2.2.4 NRC Depleted Uranium Screening Model

This Depleted Uranium (DU) Screening model was developed by the Nuclear Regulatory Commission (NRC) as a screening model to evaluate the risk and uncertainties associated with the disposal of DU as LLW. The model is constructed using GoldSim and is structured as a near surface disposal facility at a generic site. The model was developed to evaluate the radiological risk to potential future residents and intruders (acute or chronic exposures) near or on the land overlying a hypothetical disposal facility for the large quantities of DU anticipated from fuel enrichment facility operations. The model is designed to provide the user flexibility in evaluating different waste types and forms, disposal configurations, performance periods, institutional control periods, pathways, and scenarios.

The model considers the following modes of transport:

- Gaseous transport of radon into the interior of a residence placed over the disposal area or to the external environment
- Water transport
    - Infiltration to the water table
    - Transport through the saturated zone
    - Transport through the unsaturated zone

Dose assessments are modeled using BDOSE. The BDOSE submodel considers unit inputs of groundwater concentrations and estimates dose for a resident farmer or a resident gardener. Acute and chronic intruder scenarios are also considered, using inputs of actual waste concentrations with units of activity per unit volume. Exposure pathways include external exposure from surface, air, and water; internal exposure from inhalation of air; and internal exposure from ingestion of drinking water, vegetables/fruits, milk, beef, game, fish, and soil.

The NRC DU Screening Model is not available for use by the LLW Disposition task. The model is probably not suitable as is for the generic LLW disposal models; however, it could probably be used as a basis for the models.

2.2.5 Bruce

This site specific model was developed to support the proposed Deep Geologic Repository (DGR) that Ontario Power Generation (OPG) is proposing to build for disposal of low and intermediate level waste (L&ILW) near the existing Western Waste Management Facility at the Bruce site in the Municipality of Kincardine, Ontario. A normal evolution scenario and four disruptive scenarios are considered. The four disruptive scenarios considered are:

- Human intrusion
- Severe shaft seal failure
- Open borehole
- Extreme earthquake

Assessment-level (system) models are implemented in AMBER 5.2, which is a compartment-model code that can be used to represent package degradation, contaminant transport through the repository, the geosphere and the surface environment, and the associated impacts such as dose. Detailed groundwater flow and transport calculations are implemented in the 3-D finite element/ finite-difference code FRAC3DVS. Detailed gas generation and transport calculations are implemented in T2GGM, a code that couples the Gas Generation Model (GGM) and TOUGH2.

The Bruce model is primarily unusable simply because it is not readily available. The model also represents a specific site and as such does not provide adequate flexibility to model a range of disposal scenarios.

2.2.6 Area 5 Radioactive Waste Management Site

This model was identified late in the fiscal year and was not evaluated prior to the development of this report. This model will be considered as work on the generic LLW disposal models continues in FY 2012.

2.2.7 Greater Confinement Boreholes

This model was identified late in the fiscal year and was not evaluated prior to the development of this report. This model will be considered as work on the generic LLW disposal models continues in FY 2012.

2.3 Conclusions

None of the existing models evaluated are usable “as is” for the generic LLW disposal models. Of the five models investigated, the Neptune generic model could be considered with modification as the UFD Generic LLW Disposal Model for near surface disposal. The Neptune generic model appears to provide the most features anticipated for this UFD Generic LLW Disposal Model. The use of the Neptune generic model could provide an economical and efficient path to the development of the UFD Generic LLW Disposal Model for near surface disposal. The Neptune model could be easily modified to provide the features and parameters that are not included such as additional engineered barriers to provide the flexibility to evaluate a variety of configurations. The model is readily available for use from Neptune and Co.; in fact its use as a starting point for specific performance assessment models is encouraged by Neptune. The model uses the GoldSim platform which is well known within the performance assessment community of the United States and the UFD LLW Disposition team; therefore, no learning curve is required to begin modification of the model. In addition, the availability of the free GoldSim Player allows the model to be viewed by those that do not have licensed versions of GoldSim.

The RESRAD-OFFSITE code and the GoldSim platform both can be used in a complementary manner for LLW performance assessment. For the near surface disposal option it is recommended that source term be developed independently using the GoldSim platform and this source term be linked to the RESRAD-OFFSITE code. This approach will utilize the capabilities and strength of each software tool to develop one single, integrated simulation approach. RESRAD-OFFSITE is an integrated, stand-along regulatory code that has been widely used in simulating radionuclide transport through the geosphere environments similar to those of LLW disposal facilities. It is therefore appropriate to continue serving in this unique role for performance assessment. In this context, the GoldSim platform will be utilized to model the disposal facility, its degradation, and the subsequent transport of radionuclides through and out of the facility. GoldSim will be used to develop the time-dependent evolution of the disposal facility (engineered barrier system and near field) and model radionuclide transport through and out of the engineered barriers. The information generated in GoldSim will feed into RESRAD-OFFSITE which will be used to simulate the subsequent transport of radionuclides through the geosphere via atmospheric, surface water, and groundwater pathways to complete the assessment. With this approach, further development in RESRAD-OFFSITE can also include the assessment of various intruder scenarios to complement the long-term performance assessment.

None of the models are suitable for the UFD Generic LLW Disposal Model for intermediate depth boreholes; however, the Greater Confinement Disposal model looks promising. The Greater Confinement Disposal model should be investigated more thoroughly to determine its suitability for modification as the UFD Generic LLW Disposal Model for intermediate depth boreholes. If determined to not be suitable, then a new model should be developed. It is recommended that the GoldSim platform be used to develop the UFD Generic LLW Disposal Models for borehole disposal.

3.0 FEATURES, EVENTS AND PROCESSES

The objective of the UFD Campaign FEPs activity is to identify and categorize FEPs that are important to disposal system performance for a variety of disposal alternatives (i.e., combinations of waste forms, disposal concepts, and geologic environments). The FEPs provide guidance to the identification of (1) important considerations in disposal system design, and (2) gaps in the technical bases. The FEPs also support the development of PA models to evaluate the long-term performance of waste forms in the engineered and geologic environments of a radioactive waste disposal system. This requires consideration of the coupled thermal-hydrologic-chemical-mechanical-biological-radiological (THCMBR) processes that govern radionuclide movement through the disposal system for the range of candidate disposal system alternatives. At least two generic PA models are planned within the UFD Campaign LLW Disposition activity to evaluate alternatives for LLW disposal. The near surface disposal model is typical of current LLW disposal practices in the United States. A second model, the intermediate depth borehole model, is representative of a practical disposal alternative, especially for GTCC waste.

3.1 Identification of FEPs

The Nuclear Energy Agency (NEA) maintains the NEA International FEP Database [NEA 1999; NEA 2006] that includes approximately 1,650 FEPs from 10 different national radioactive waste disposal programs worldwide. The NEA FEP Database is generally considered to be the most comprehensive compilation of radioactive waste disposal FEPs available. The identification and categorization of 208 preliminary UFD FEPs for UNF and HLW disposal [Freeze 2011, Appendix A] derived from, and encompasses the scope of, the NEA FEPs. While the NEA FEPs and the UFD FEPs were developed for deep disposal of UNF and HLW, they still provide a relevant starting point for the identification of LLW FEPs.

Additional sources of FEPs were used to supplement the UNF/HLW FEPs in order to develop a comprehensive initial set of FEPs to consider for LLW disposal. The supplemental FEPs were obtained from the following sources:

- International Atomic Energy Agency (IAEA) Co-ordinated Research Project (CRP) [IAEA 2004]
- Greater Confinement Disposal Facility [Guzowski 1993]
- Ontario Power Generation Deep Geologic Repository for Low and Intermediate Level Waste [Garisto 2009]
- Deep Borehole Disposal [Brady 2009]
- Drigg Low Level Waste Repository [Phifer 2011]

A total of 1,194 FEPs were collected as shown in Table 3.1-1.

Table 3.1-1, Sources for the Initial Set of Features, Events and Processes for the Disposal of Low Level Waste

Source	**FEP Quantity**
UFD Campaign UNF and HLW FEPs	208
IAEA Coordinated Research Project	137
Greater Confinement Disposal Facility	205
Ontario Power Generation Deep Geologic Repository	242
Deep Borehole Disposal	374
Drigg Low Level Waste Repository	28
TOTAL	**1,194**

Because the initial 1,194 LLW FEPs are a compilation of FEPs from 6 different sources they contain: (1) considerable redundancy (e.g., the same FEP is often identified up to 6 different times – especially in cases where it derives from the same NEA source); (2) varying levels of detail (e.g., the scope captured by a single broad FEP in one program may be captured in several finer FEPs in another program); (3) overlapping scope (due to the coupled nature of the many LLW disposal processes, many of the FEPs are related and therefore not mutually exclusive); (4) some site-specific phenomena; and (5) some FEPs that are not applicable to LLW disposal. To make the initial LLW FEPs more broadly applicable to the generic shallow disposal concepts to be developed, the initial 1,194 LLW FEPs were grouped and categorized so that FEPs of similar or related scope could be consolidated, generalized, and given a more consistent level of detail. The initial LLW FEPs were categorized using the groups shown in Table 3.1-2. These groups and group numbers are consistent with, and traceable to, the FEP categorization and numbering schemes used for the UFD UNF/HLW FEPs and the NEA FEP Database.

Table 3.1-2, Grouping and Categorization of Features, Events and Processes

FEP Group Number	FEP Group Description
0.00	**Assessment Basis** - Factors that the analyst will consider in determining the scope of the analysis. These may include factors related to regulatory requirements, definition of desired calculation end-points, requirements in a particular phase of assessment, description of the domain of concern and a description of the target groups in the assessment. Decisions at this point will affect the phenomenological scope of a particular phase of assessment, i.e. what “physical FEPs” will be included.
1.00	**External Factors** - Features, events and processes with causes or origin outside the repository system, i.e. natural or human-induced factors of a more global nature and their immediate effects on the performance of the disposal system. Included in this group are decisions related to repository design, operation and closure since these are outside the temporal boundary of the repository domain for the purpose of the post closure safety assessment. The external FEPs (EFEPs) are generally not influenced (or are only weakly influenced) by processes within the repository domain. In developing conceptual and mathematical models of the repository, external factors are often represented as boundary conditions or initiating events and processes.
1.10	**Repository Factors** - Factors related to decisions taken, and events occurring during the life cycle of the repository (e.g. design, construction, operation, closure and decommissioning) that could have an influence on the post closure performance of the facility and therefore have to be considered in the safety assessment process. The “Repository Factors” category of FEPs is outside the temporal boundary of the disposal system domain and predominantly associated with the pre-operational and operational period of the repository. These factors are an example of the interdependencies that exist between these periods and the post closure period and give rise to issues of how to treat these interdependencies in the safety assessment process.
1.20	**Geological Processes and Effects** - Factors related to the long-term processes arising from the wider geological setting and their effects on the performance of the repository. The "Geological Processes and Effects" category of FEPs refers to regional geological processes and effects, which generally are outside the temporal and spatial boundaries of the disposal system domain.
1.20.01	Long Term Processes
1.20.02	Seismic Processes
1.20.03	Igneous Processes
1.30	**Climatic Processes and Effects** - Processes related to global climate change and consequent regional effects.
1.40	**Future Human Actions** - Human actions and regional practices, in the post-closure period, that can potentially affect the performance of the engineered and/or geological barriers, e.g. intrusive actions, but not the passive behavior and habits of the local population.
1.50	**Other External Factors** - Any other external scenario-defining factors or events not accommodated in other FEP categories.

Table 3.1-2, Grouping and Categorization of Features, Events and Processes (continued)

FEP Group Number	FEP Group Description
2.00	**Disposal System Domain: Environmental Factors** - Features and processes occurring within that spatial and temporal (post-closure) domain whose principal effect is to determine the evolution of the physical, chemical, biological and human conditions of the domain that are relevant to estimating the release and migration of radionuclides and consequent exposure to man.
2.10	**Wastes and Engineered Features** - Features and processes within the waste and engineered components of the disposal system (output – source term characteristics).
2.10.01	Inventory
2.10.02	Waste Form
2.10.03	Waste Container
2.10.04	Buffer and Backfill
2.10.05	Engineered Barriers
2.10.06	Other EBS Materials
2.10.07	Mechanical Processes
2.10.08	Hydrologic Processes
2.10.09	Chemical Properties and Processes - Chemistry
2.10.10	Chemical Properties and Processes - Radionuclide and Hazardous Chemical Transport
2.10.11	Biological Processes
2.10.12	Thermal Processes
2.10.13	Gas Sources and Effects
2.10.14	Radiation Effects
2.10.15	Nuclear Criticality Effects

Table 3.1-2, Grouping and Categorization of Features, Events and Processes (continued)

FEP Group Number	FEP Group Description
2.20	**Geological Environment** - The features and processes of the geological environment surrounding the repository including, for example, the hydrogeological, geomechanical and geochemical features and processes, both in pre-emplacement state and as modified by the presence of the repository and other long changes.
2.20.01	Excavation Disturbed/Damage Zone
2.20.02	Host Geologic Media
2.20.03	Flow and Transport Pathways
2.20.04	Mechanical Processes
2.20.05	Hydrologic Processes
2.20.06	Chemical Properties and Processes - Chemistry
2.20.07	Chemical Properties and Processes - Radionuclide Transport
2.20.08	Biological Processes
2.20.09	Thermal Processes
2.20.10	Gas Sources and Effects
2.20.11	Nuclear Criticality
2.30	**Surface Environment** - The features and processes within the surface environment, including near surface aquifers and unconsolidated sediments but excluding human activities and behavior.
2.30.01	Surface Characteristics
2.30.02	Mechanical Processes
2.30.03	Hydrologic Processes
2.30.04	Chemical Processes - Chemistry
2.30.05	Chemical Processes - Transport
2.30.06	Biological Processes
2.30.07	Thermal Processes

Table 3.1-2, Grouping and Categorization of Features, Events and Processes (continued)

FEP Group Number	FEP Group Description
2.40	**Human Behavior** - The habits and characteristics of the individuals or populations, e.g. critical groups, to whom exposures are calculated, not including intrusive or other activities which will have an impact on the performance of the engineered or geological barriers.
2.40.01	Human Characteristics
2.40.02	Human Lifestyle
2.40.03	Land and Water Use
3.00	**Radionuclide/Contaminant Features** - FEPs that take place in the disposal system domain that directly affect the release and migration of radionuclides and other contaminants, or directly affect the dose to members of a critical group from given concentrations of radiotoxic and chemo-toxic species in environmental media.
3.10	**Contaminant Characteristics** - The characteristics of the radiotoxic and chemo-toxic species that might be considered in a post closure safety assessment.
3.20	**Contaminant Release/Migration Factors** - The processes that directly affect the release and/or migration of radionuclides in the disposal system domain.
3.30	**Exposure Factors** - Processes and conditions that directly affect the dose to members of the critical group, from given concentrations of radionuclides in environmental media.
3.30.01	Radionuclide/Contaminant Concentrations
3.30.02	Exposure Modes
3.30.03	Toxicity Effects

A workshop was help in May 2011 for UFD LLW Disposition team members to review the groupings of the initial 1,194 FEPs and to collectively identify (1) where FEPs of similar or related scope could be consolidated, generalized, and/or given a more consistent level of detail, and (2) where FEPs were not applicable to LLW disposal. As a result of the workshop, the initial 1,194 were reduced and consolidated into a preliminary list of 381 potentially relevant LLW FEPs. Each LLW FEP is defined by a “FEP Number”, “Title”, and “Description” at a broad level of detail such that it is potentially applicable to the full range of LLW disposal alternatives. The FEP Number is based on the FEP Group Number in Table 2-4. Because the consolidation process subsumed redundant/overlapping phenomena into single common FEPs and did not eliminate any unique phenomena, the scope of the preliminary list of 381 potentially relevant FEPs is considered to capture the range of phenomena encompassed by the initial set of 1,194 FEPs and the full range of potentially relevant phenomena (and associated time- and length-scales) applicable to LLW disposal.

3.2 Screening Process

The objective of FEP screening is to evaluate the potentially relevant FEPs using specified criteria to identify those FEPs that should be included (screened in) in a PA model analysis and those that can be excluded (screened out) from the analysis. The included FEPs represent a subset of the complete set of potentially relevant FEPs.

In FY 2011, the 381 potentially relevant LLW FEPs were screened for possible inclusion in the two generic LLW PA models identified in Section 3: the near surface disposal model and the intermediate borehole disposal model. Because the two generic LLW PA models have only been broadly conceptualized [Jones 2011, Section 4], the FY 2011 screening was, by necessity, a preliminary effort to identify those FEPs which were likely to be important. As the PA models become more refined, the screening and implementation of the FEPs will be correspondingly revised.

The preliminary LLW FEP screening was performed by UFD LLW Disposition team members at the same May 2011 workshop where the FEP consolidation was made (Section 2.2). The 381 potentially relevant LLW FEPs were screened for applicability and importance to each of the two generic LLW PA models. The LLW FEPs were screened for applicability based on the following exclusion criteria:

- Not Applicable - Not applicable to near surface or intermediate borehole disposal of LLW. Specific to other methods of disposal (e.g., deep geologic disposal).
- Regulatory Guidance – Not applicable due to inconsistency with regulatory requirements.
- Non-Generic Applicability – Not applicable to a generic model. Site and design specific information and data are needed.
- Low Probability - Low probability of affecting long-term performance. For preliminary screening this is a qualitative criterion.
- Low Consequence - While the FEP may occur, its effects are expected to be of low consequence to long-term performance.

A total of 189 FEPs were screened out leaving 192 FEPs for consideration by the generic PA model(s).

The resulting set of 381 preliminary UFD LLW FEPs is listed in Appendix A of the FY 2011 FEPs report [Jones 2011a]. Each UFD LLW FEP is defined by a "Description" at a broad level of detail such that it is potentially applicable to the full range of disposal system alternatives. The technical scope of the 381 preliminary UFD LLW FEPs captures the full range of potentially relevant phenomena (and associated time- and length-scales) applicable to LLW disposal.

In future years, the UFD Campaign LLW Disposition activity will evaluate and/or compare specific disposal system alternatives. At that time, it may be necessary to enhance the level of detail of certain FEPs to support the FEP screening and/or PA model implementation steps of FEP analysis. Most commonly, this enhanced level of detail would be captured within an existing FEP; however, a new FEP could be created if a new or unique phenomenon were identified as part of a disposal alternative.

FEP identification is an iterative process that evolves as new information (e.g., experimental data, model results, regulatory guidance) becomes available. While the preliminary UFD LLW FEPs list of 381 FEPs is considered comprehensive, examinations and audits of the list will always be ongoing, for example, further comparisons with newly created FEP lists from other programs and further reviews by subject matter experts.

3.3 Final List of FEPs

At least two generic PA models are planned within the UFD Campaign LLW Disposition activity to evaluate options for LLW disposal. The near surface disposal model is typical of current LLW disposal practices in the United States. The near surface model is envisioned to be flexible enough to accommodate above ground vault disposal as well. A second model, the borehole model, is representative of a practical disposal alternative, especially for greater than Class C (GTCC) waste. The borehole model may require separate models for two unique disposal environments, an unsaturated environment and a low permeability environment.

Not all of the 192 FEPs designated for inclusion in the generic models are applicable to all model cases (i.e. near surface or borehole). Also, some of the FEPs, although deemed important to the generic models, will not be implemented in the first iteration of the models. These FEPs, such as those requiring substantial, supporting process modeling, will be implemented at a future date. Accordingly, each of the 192 FEPs considered for implementation in a generic LLW disposal PA model was evaluated during the FEPs screening workshop held in May 2011 for their:

- Applicability to specific physical configurations (i.e. either near surface disposal or intermediate depth borehole disposal)
- Priority for implementation in the generic models (i.e. implement in the initial iteration of the model or defer to future iterations)

Of the 192 FEPs designated for inclusion in the generic models, only 3 FEPs pertain specifically to near surface disposal and 7 pertain only to intermediate depth borehole disposal. The remaining FEPs are applicable to both means of disposal. Thirty-six FEPs have been deferred to future iterations of the models. Eight FEPs were identified for phased implementation in the models (e.g. more simplistic implementation initially). Further definition of the FEPs is provided in a separate report [Jones 2011a].

4.0 GENERIC MODEL DEVELOPMENT

At least two generic PA models are planned within the UFD Campaign (UFDC) LLW Disposition activity to evaluate alternatives for LLW disposal. The near surface disposal model is typical of current LLW disposal practices in the United States. A second model, the intermediate depth borehole model, is representative of a practical disposal alternative, especially for GTCC waste.

The generic LLW disposal models are envisioned to be flexible to allow evaluation of a wide range of disposal techniques (e.g. above ground vault disposal versus shallow land burial), configurations (e.g. caps, liners, high integrity waste packages, other engineered barriers, disposal depth, etc.) and environments (saturated, unsaturated, clay, dry, humid, etc.). Parameters governing key features of the disposal site such as soil type, waste packaging, engineered barriers, disposal depth, etc. should be readily varied by the user.

The work completed in FY 2011 to develop the FEPs relevant to LLW disposal will guide the development of the generic models in FY 2012. Development of the models was begun in FY 2011. Model concepts and structure for both the near surface and borehole generic models were developed. The sections that follow provide more detail of the work completed for model development in FY 2011.

4.1 Near-Surface Disposal

This section summarizes the approach that will be applied in developing a generic model of near-surface low level radioactive waste disposal facilities. The model will be termed the UFDC Generic Near-Surface Low Level Waste Disposal Facility Model (GNLLWM).

The development of the UFDC GNLLWM will center on a requirement of being flexible to accommodate a variety of different scenarios. These scenarios range from different material properties, different waste forms with varying radionuclide inventories, different facility designs (i.e., sub-surface or above-ground), and different site conditions. As such, tool development will not begin with defining a specific scenario around which models would be developed, but rather will focus on developing a modeling tool that could then be used to evaluate a wide range of alternative scenarios.

The UFD LLW FEP list described in Section 3.3 will guide the development of the model. Ultimately, all FEPs relevant to near-surface disposal facilities identified as needing to be included will ultimately be implemented in the UFDC GNLLWM. However, a step-wise, phased approach will be applied to development of the model. Those FEPs identified as needing to be included in the model initially will be implemented first, followed by those identified as being implemented in future model development. In addition, the initial implementation of the FEPs will be at a very high level, applying simplified representations, with additional detail being added, as warranted, in future model development.

Model development will first focus on what is termed a “normal evolution” scenario capability. This capability will implement the FEPs relevant to the long-term evolution of a near-surface facility in the absence of discrete disruptive FEPs that could affect the isolation capability of the facility. Next, capabilities to analyze such disruptive FEPs and scenarios will be implemented. Again, the intent of model development is not to define a disruptive scenario that would be implemented, but rather to develop a tool with the capabilities to evaluate a wide range of disruptive scenarios that could be postulated in the future.

It is likely that the disposal of low-level radioactive waste from advanced nuclear fuel cycle facilities will be a commercial endeavor. As such, model development will be informed by the U.S. regulatory framework at 10 CFR Part 61. It is recognized that the U.S. Nuclear Regulatory Commission is considering revising 10 CFR Part 61 and has proposed the inclusion of site-specific performance assessment in the licensing of near-surface low-level radioactive waste disposal facilities (76 Federal Register, page 24831). The proposed language in the revised rule will also be used to guide model development.

Model development will also be informed by U.S. Nuclear Regulatory Commission and International Atomic Energy Agency (IAEA) guidance regarding the safety assessment and performance assessment for low-level waste disposal facilities. These include:

- U.S. Nuclear Regulatory Commission, A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities, Recommendations of NRC's Performance Assessment Working Group, NUREG-1573, 2000.
- International Atomic Energy Agency, Safety Assessment Methodologies for Near Surface Disposal Facilities, Results of a Co-Ordinated Research Project, Volume 1 – Review and Enhancement of Safety Assessment Approaches and Tools, 2004.
- International Atomic Energy Agency, Safety Assessment Methodologies for Near Surface Disposal Facilities, Results of a Co-Ordinated Research Project, Volume 2 – Test Cases, 2004.

As pointed out in Section 2, a number of near-surface LLW disposal facility models have been developed. These models, plus others, will also inform the development of the UFDC GNLLWM.

The process of conceptual model development, mathematical abstraction, and implementation using computer tools is shown in Figure 4.1-1 [IAEA 2004, Figure 8]. In this context, the assessment context refers to the purpose for which a model is being developed and the system description refers to the facility design, the wastes that would be disposed, and the properties of the site.

For the UFDC GNLLWM the assessment context is the development of a flexible tool to evaluate LLW disposal options to ensure the disposition of LLW that would be generated from potential future advanced fuel cycles safely and in a cost-effective manner to ensure that all radioactive wastes that would be generated can be disposed. Future systems for the disposal of LLW from advanced fuel cycles cannot be described, necessitating the development of flexible generic models that can be used to evaluate a wide range of disposal alternatives.

The remainder of this section will discuss conceptual models, mathematical models, data, and implementation.

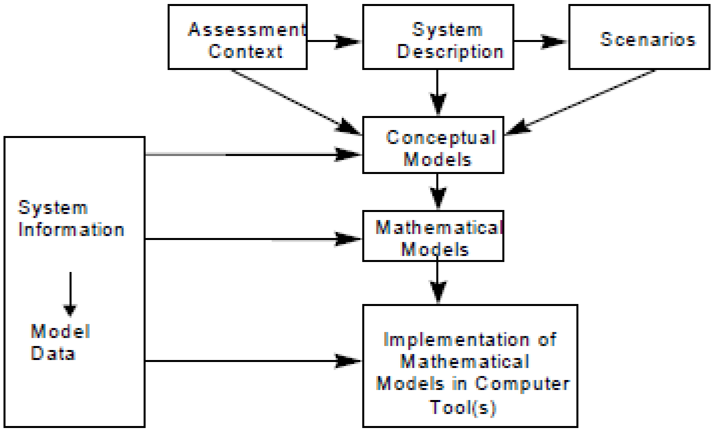

Figure 4.1-1, Model Formulation and Implementation Process

4.1.1 General Conceptual Model

The development of conceptual models is a crucial phase of overall model development process. Conceptual models describe the features, events, and processes (FEPs) included in the representation of a disposal system and qualitatively describe how radionuclides [IAEA 2004, Section 5.2]:

- are released from the disposal facility (near field or source term);
- are transported in the geosphere and biosphere; and
- through what exposure pathways they lead to environmental contamination and/or exposure to people.

The development of the conceptual models for the UFDC GNLLWM will focus primarily on radionuclide release from a disposal facility and transport through generic geospheres and biospheres. While the development of conceptual models would ultimately depend on site- and design-specific information, generic models can be developed to evaluate a wide range of disposal systems. Describing exposure pathways in the biosphere are also very site specific and also depend on the habits of people in the vicinity of the disposal facility. Given the undue speculation that would be needed to develop biosphere exposure pathways, a very simple approach will be utilized.

Radiation exposure, or dose, is used as an initial metric of GNLLWM performance. The dose conversion factors based on ICRP-60 [ICRP 1991] methodology (external from FGR-12 [Eckerman and Ryman 1993] and internal from ICRP-72 [ICRP 1996] will be used. Future efforts will involve developing the capability to assess the risk associated with any hazardous constituents that may be included in mixed hazardous/radioactive wastes that would be generated in future advanced nuclear fuel cycles. Again, simplified approaches using existing information will be used to develop exposure pathway models. In lieu of a specific site, such simplified approaches to modeling exposure pathways in the biosphere allows for the assessment of generic disposal systems environments using a common, representative biosphere.

Conceptual model development for near-surface disposal facilities was initiated in FY 2011 and will continue into FY 2012. Mathematical implementation will begin after the conceptual models have been developed. As discussed above, conceptual models will be developed and mathematical models are being implemented first for the nominal evolution FEPs, followed by the development of capabilities to analyze such disruptive FEPs. The overall conceptual framework developed by the U.S. Nuclear Regulatory Commission, shown in Figure 4.1-2 [NRC 2000, Figure 2], was used as the starting point for the nominal evolution conceptual model. Note that the numbers next to the process blocks correspond to the conceptual approaches described in Sections of NUREG-1573.

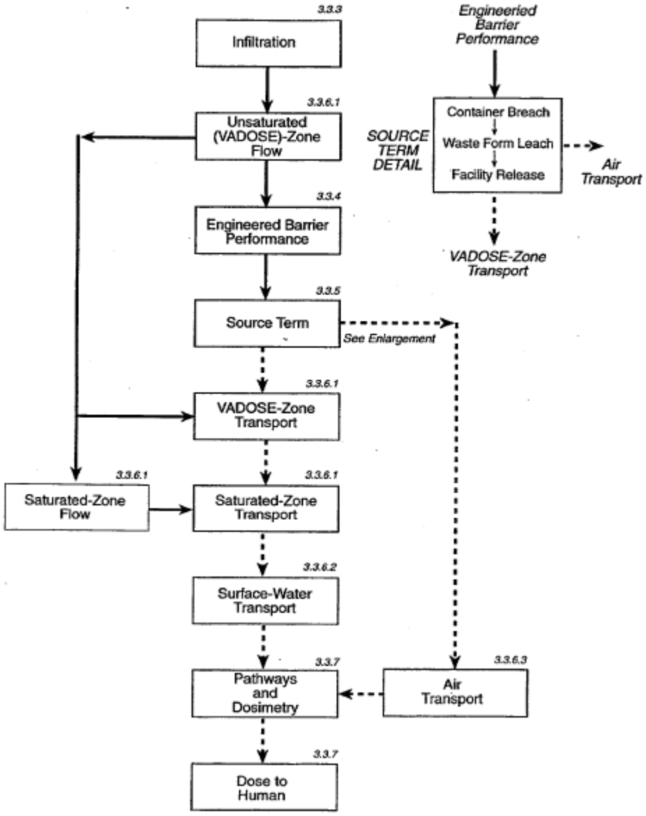

Figure 4.1-2, Conceptual Model Showing Processes to be Considered in a LLW Performance Assessment

A near surface disposal facility is considered to consist of the following three components:

- The near field - the waste, the disposal area, the engineered barriers of the disposal facility including the disturbed zone of the natural barriers that surround the disposal facility.
- The geosphere - the rock and unconsolidated material that lies between the near field and the biosphere. It consists of both the unsaturated zone and the saturated zone.
- The biosphere - the physical media (atmosphere, soil, sediments, well water and surface waters) and the receptor interaction with them.

The source term refers to both the radionuclide inventory at the closure of the disposal facility, and the time-series of releases from the facility to the immediate environment. Such releases can occur through numerous pathways during the natural evolution of the facility, depending on the physical configuration of the LLW facility (e.g., shallow burial, above ground vault, below ground vault), and the characteristics of the waste forms, waste containers, and the engineered barriers. The primary radionuclide transport media are:

> **Liquid**: Once the waste containers and engineered barriers no longer act as a barrier to water contacting the waste, radionuclides can be released into the water and transported from the disposal facility by advection, dispersion and diffusion. If the disposal units are located above the water table then releases will occur into the unsaturated (vadose) zone and contaminated water migrates down into the saturated zone. If the disposal units are below the water table, releases occur directly into groundwater. In arid climates, upward liquid advection can also be an important mechanism in moving radionuclides through the unsaturated zone above the facility.
>
> **Gaseous**: Volatile radionuclides can be released by diffusion into atmosphere and groundwater. Gaseous advection can also release volatile radionuclides into atmosphere.
>
> **Solid**: Burrowing animal activity may bring radionuclides attached to the soil particles into the surface soils. When the structural integrity of the facility has been lost, and the closure cover has eroded, thus exposing the waste, two further solid release mechanisms can be considered: wind erosion will suspend particulates into air from the contaminated surface soils and exposed waste; and precipitation induced runoff and erosion will carry radionuclides into surface waters. Plant uptake also can move significant quantities of radionuclides to the surface soils, especially after the institutional control period (no maintenance) and native plants inhabit the site.

Figures 4.1-3 and 4.1-4 show the initial generic conceptual models for the engineered barrier portion of the UFDC GNLLWM. These figures are an expansion of Figure 4.1-2 and include high-level descriptions of potential modeling approaches. As discussed above, the intent of the UFDC GNLLWM is to be flexible to model different facility concepts (below- and above-grade) and different design configurations and materials (i.e., cover and drain layers). How this flexibility could be accommodated is also described in Figures 4.1-3 and 4.1-4.

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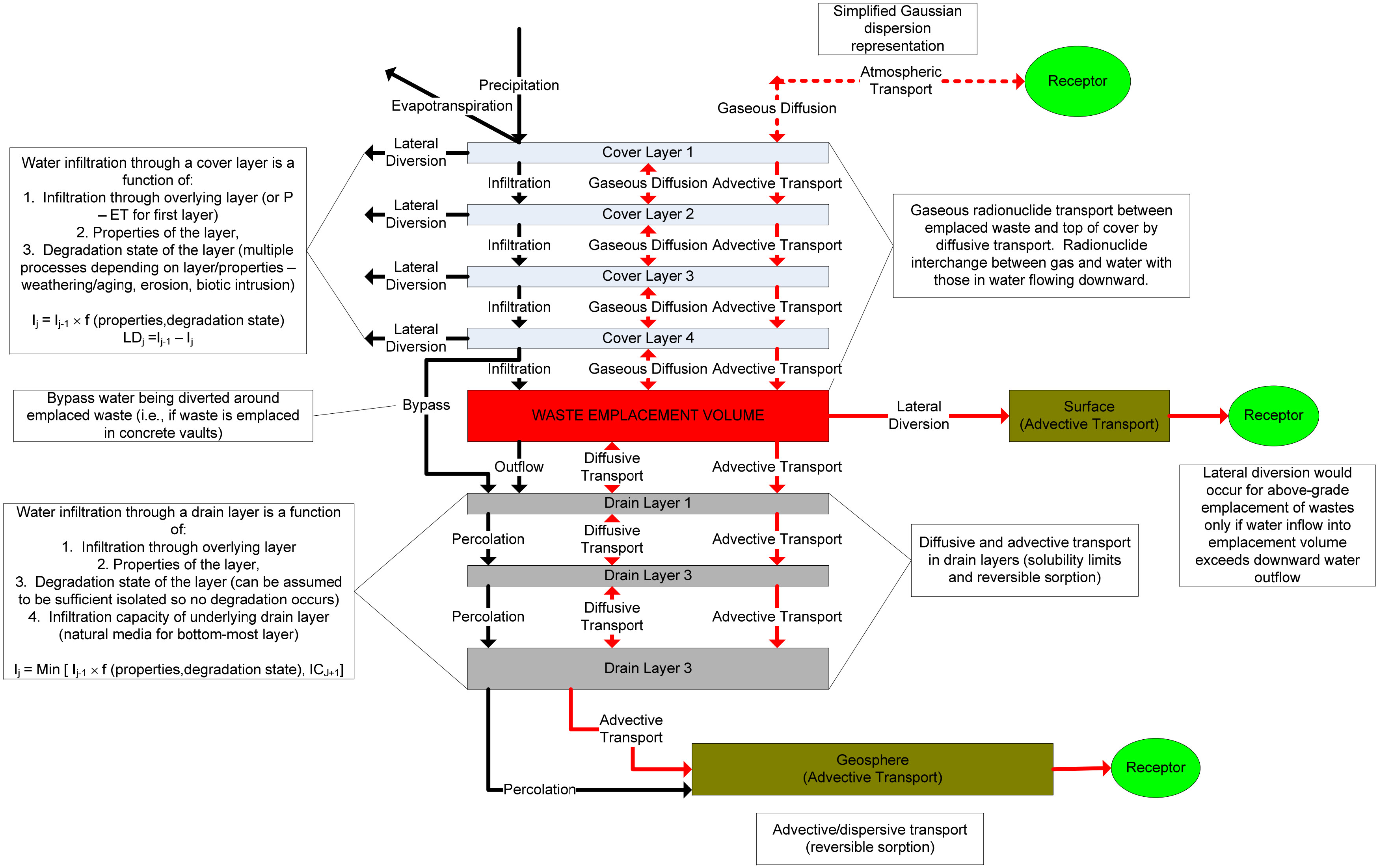


Water infiltration through a cover layer is a function of:
1. Infiltration through overlying layer (or P – ET for first layer)
2. Properties of the layer,
3. Degradation state of the layer (multiple processes depending on layer/properties – weathering/aging, erosion, biotic intrusion)

$I_j = I_{j-1} \times f$ (properties,degradation state)
$LD_j = I_{j-1} - I_j$

Gaseous radionuclide transport between emplaced waste and top of cover by diffusive transport. Radionuclide interchange between gas and water with those in water flowing downward.

Bypass water being diverted around emplaced waste (i.e., if waste is emplaced in concrete vaults)

Lateral diversion would occur for above-grade emplacement of wastes only if water inflow into emplacement volume exceeds downward water outflow

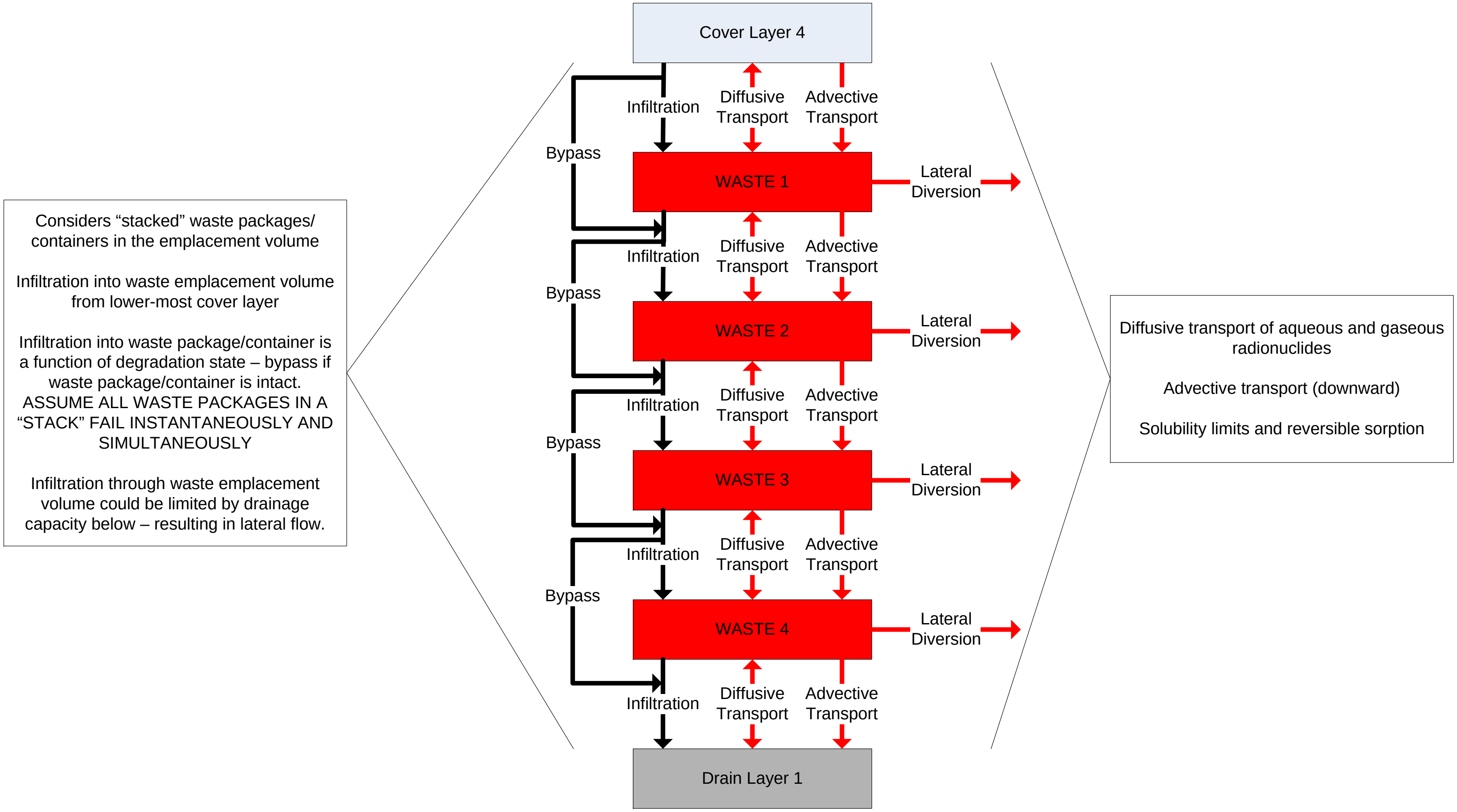
Water infiltration through a drain layer is a function of:
1. Infiltration through overlying layer
2. Properties of the layer,
3. Degradation state of the layer (can be assumed to be sufficient isolated so no degradation occurs)
4. Infiltration capacity of underlying drain layer (natural media for bottom-most layer)

$I_j = \mathrm{Min}\,[\,I_{j-1} \times f$ (properties,degradation state), $IC_{J+1}]$

Diffusive and advective transport in drain layers (solubility limits and reversible sorption)

Advective/dispersive transport (reversible sorption)

Figure 4.1-3, UFDC Generic Near-Surface LLW Facility Model Overall Conceptualization



Considers “stacked” waste packages/ containers in the emplacement volume

Infiltration into waste emplacement volume from lower-most cover layer

Infiltration into waste package/container is a function of degradation state – bypass if waste package/container is intact. ASSUME ALL WASTE PACKAGES IN A “STACK” FAIL INSTANTANEOUSLY AND SIMULTANEOUSLY

Infiltration through waste emplacement volume could be limited by drainage capacity below – resulting in lateral flow.

Diffusive transport of aqueous and gaseous radionuclides

Advective transport (downward)

Solubility limits and reversible sorption

Figure 4.1-4, UFDC Generic Near-Surface LLW Facility Model Waste Emplacement Volume Conceptualization

The engineered barriers of a disposal facility would be designed to provide long term isolation of the LLW. A principal function of the engineered barrier system is to reduce the amount of water contacting the waste. Other functions include reducing the potential for erosion and deterring human intrusion. It is expected that each component of the engineered barrier will perform its functions for several hundred years, resulting in complete isolation of the contained waste. The function of each barrier is as follows:

- Engineered Cover - Reduce the amount of infiltrating water from precipitation. Divert any infiltrating water from the top of the facility to the sides. Reduce downward infiltration. Reduce the potential for erosion of the cover. Deter human intrusion.

- Disposal Vault - Deter human intrusion. Provide structural support of the engineered cover. Reduce the amount of water infiltrating into the interior.

- Waste Package - Contain the waste. Reduce the infiltration of water to the wasteform through the use of impermeable materials. Deter human intrusion.

- Engineered Foundation - Provide a pathway for the drainage of water into the underlying natural material and provide structural support to the disposal unit and engineered cover.

The most likely long term exposure pathway for humans is via water which eventually infiltrates through the disposal modules, contacts the waste, leaches radionuclides, enters the geosphere, and then reaches the accessible environment as either groundwater and/or surface water flow. To minimize the potential for the development of this pathway, a facility would be designed to reduce infiltration into the disposal modules and to drain any infiltration which does occur away from the waste.

The design, construction, and maintenance of the disposal facility would ensure that during the operation, closure, and institutional control periods the infiltration into the disposal facility would be extremely small. Following institutional control a number of natural processes will ultimately cause the various components of the engineered barrier system to degrade and lead to an increase in the rate of infiltration through the facility. Examples of such processes include:

- A soil layer could begin to slowly erode, trees may become established on the cover, be uprooted and enhance erosion. Infrequent, high intensity rainfall events may lead to the formation of gullies in the soil layer.
- After some period of time, it is possible that the low permeability layers in the cover (such as high-density polyethelyne or geosynthetic clay liners) could degrade, leading to an increase in the infiltration rate.
- Erosion of a soil layer may expose underlying layers to the environment which could cause them to degrade due to freeze/thaw and wet/dry cycles, leading to a further increase in the infiltration rate.
- Ultimately, erosion may remove all layers of the engineered cover, exposing a disposal vault to the environment.

- After a period of time, a concrete disposal module roof could become cracked due to the stresses induced from the weight of the engineered cover and not provide a substantial barrier to infiltration.
- Chemicals in the water contacting a disposal vault roof could cause it to slowly degrade and lose strength until it eventually collapses. If this occurs before any of the layers in the engineered cover are degraded, the resulting subsidence in the engineered cover could lead to their rapid degradation and increased infiltration.
- Removal of the engineered cover by erosion would expose the disposal vault roof to freezing conditions, which will result in rapid degradation of the concrete making the disposal modules susceptible to the forces of erosion.
- Water infiltrating into a disposal vault would contact the waste packages, causing them to slowly degrade.

4.1.2 Mathematical Implementation

Figure 4.1-5 shows the mathematical construct being considered for implementing the UFDC GNLLWM. It consists of two components, the GNLLWM "engine" and linked external input. It is envisioned that the needed flexibility can be implemented by developing an overall facility framework representation that includes material degradation and radionuclide transport logic. This logic would be "driven" by input that would be external to, but linked to the GNLLWM "engine." This approach would allow the user the flexibility to evaluate multiple scenarios and conduct sensitivity analyses without having to make changes to the GNLLWM itself, rather only the input needs to be changed. An example set of data types that would be externally linked to the GNLLWM is shown in Table 4.1-1.

Two software platforms are envisioned for the GNLLWM engine. GoldSim will be utilized to model the disposal facility, its degradation, and the subsequent transport of radionuclides through and out of the facility. GoldSim will be used to develop the time-dependent evolution of the disposal facility (engineered barrier system and near field) and model radionuclide transport through and out of the engineered barriers. RESRAD-OFFSITE will be used to simulate the subsequent transport of radionuclides through the geosphere via atmospheric, surface water, and groundwater pathways. This approach will utilize the capabilities of each software tool and develop a single, linked simulation framework.

4.1.3 Fiscal Year 2012 Model Development

The following activities will be undertaken in Fiscal Year 2012 that will lead to a demonstration of model capability.

- Finalize conceptual model development, including linkage to FEPs identified as to be included in the initial model.
- Pursue linkage between GoldSim and RESRAD-OFFSITE; both the ability to link radionuclide mass flux exiting the facility (GoldSim) and the geosphere (RESRAD-OFFSITE) and simulation input data.
- Disposal facility model development (GoldSim)
- Geosphere model development (RESRAD-OFFSITE)

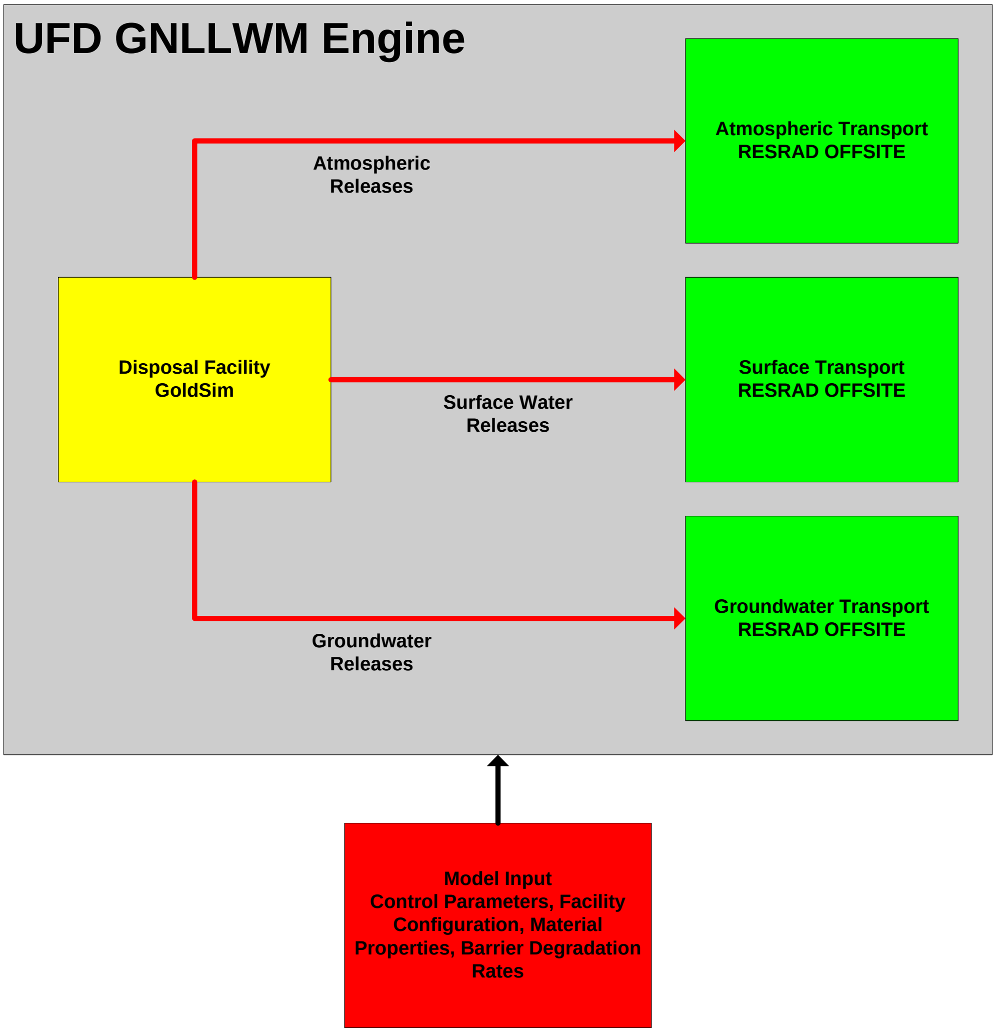


Figure 4.1-5, Schematic of Envisioned Computational Framework for the UFDC GNLLWM

Table 4.1-1, Example Data Needed for Source Term Representation

Category	Data Types
Climate	Precipitation Temperature Radiation Wind Relative humidity Evapotranspiration
Soils and Vegetation	Soil depth Soil stratigraphy Soil structure Soil texture Particle size distribution Porosity Fractures Soil-water characteristics Pressure, soil moisture measurements Hydraulic conductivity Infiltration measurements Plant types Plant rooting depths and density
Engineered Barriers	Closure cover design elements Geotechnical properties of cover materials Hydraulic properties of cover materials Design elements of liners, vaults, units Geotechnical properties of these elements Hydraulic properties of these elements Properties of backfill materials Geochemistry Corrosion rates for metal; components Rates of degradation of concrete
Containers	Types of containers Geometry of containers Burial depths of containers Material properties of containers Void space Corrosion and degradation rates
Waste Forms	Types of waste forms Stabilization Geochemistry of waste forms Degradation rates

4.2 Borehole Disposal

Reprocessing activities in potential future fuel cycles will not only produce a primary fission product waste stream, but will also produce secondary waste streams in the form of process waste, contaminated equipment, activated metals, cladding hulls, etc. Significant portions of the secondary waste streams are likely to be classed as Greater-Than-Class-C (GTCC) radioactive waste. GTCC waste is generally not considered suitable for shallow land burial because of its higher activity levels, which makes robust isolation from the environment necessary. In this study undertaken for the DOE-NE Office of Fuel Cycle Technologies Used Fuel Disposition (UFD) Campaign project, modeling tools are being developed for use in generic system-level analyses of disposal options for GTCC waste. These modeling tools will support the analyses of potential future fuel cycles by providing the capability to evaluate disposal options for GTCC waste streams.

Two intermediate-depth borehole disposal concepts are considered here: a large-diameter borehole placed in the unsaturated zone and a smaller diameter borehole drilled into a low-permeability zone beneath the water table. The former concept is similar to the greater confinement disposal (GCD) borehole concept that has been used to store transuranic (TRU) waste on the Nevada Test Site. The latter concept has been studied [Little 2004] as a disposal option for disused medical sources. The results of generic model concept development are described here. In addition, process level modeling supporting the generic model development is also described. Process-level modeling is needed to evaluate thermal effects because GTCC waste is potentially heat generating (depending on the specific activity).

4.2.1 Model Concepts

The GCD borehole concept involves large (~3 m) augered holes in unsaturated unconsolidated material. Waste form material is placed in the bottom of the holes. The holes are then backfilled. The concept is intended for arid environments where little water would contact the waste material. In such environments, water movement can be either upward or downward. Upward movement may occur in very arid conditions when the average precipitation is insufficient to overcome evapotranspiration near the surface. However, large and infrequent precipitation events or increased average precipitation in future climate states could reverse the flow. In addition to radionuclide transport by advection/diffusion in the water phase, radionuclides that partition into the gas phase may diffuse in the gas phase to the atmosphere. The model concept with transport pathways is illustrated in Figure 4.2-1. The two upward pathways are diffusion in the gas phase and advection/diffusion/dispersion in pore water. Because of the potential for radionuclide transport in the near-surface soil by plant uptake, burrowing animals or erosion, radionuclides arriving at the near-surface soil will be summed into dose assuming instantaneous transport into the biosphere from the near-surface soil. The downward pathway, which will be triggered by random and infrequent precipitation events or future climate, is through the unsaturated zone to an underlying aquifer and then through the aquifer to a pumping well. The unsaturated leg of the downward pathway will be modeled similarly to the upward pathway. The aquifer leg of that pathway will be characterized by an advective travel time, a dispersivity, and retardation factors for each element. In addition, dilution at the pumping well will be represented using an analytical model for dilution.

The model concept with transport pathways for borehole disposal in a low-permeability layer is shown in Figure 4.2-2. In this case, two parallel transport pathways exist. One of these pathways is through an excavation damage zone (EDZ) adjacent to the borehole. Flow in this case is driven by thermal buoyancy from heat-generating waste or from a natural upward gradient. Thermal buoyancy induced flow in the EDZ is highly dependent on the amount of heat generated by the waste and on time. Detailed process level modeling has been undertaken and will be described in the following section. These results will be abstracted for use in the system level model. The properties of an excavation damage zone (EDZ) – if it exists at all – are uncertain and a wide parameter range will be used. The modeling concept also allows for a parallel pathway through interconnected fractures. Such a pathway is only expected to contribute significantly if the EDZ does not exist or has very low permeability. Matrix diffusion coupled with sorption will be modeled in the fracture pathway. Both pathways will connect to an aquifer pathway.

4.2.2 Model Structure

The GoldSim software will be used for both models.

The structure of the GoldSim model for the GCD-like concept is shown in Figure 4.2-3. Processes in the unsaturated zone above and below the waste will be modeled as a GoldSim cell network. In the initial versions, only the cells in the borehole will be modeled. This pessimistically neglects lateral diffusion into the surrounding material. Liquid saturation for each cell and advective flux for each connection between cells will be specified from a simple numerical one-dimensional model or an analytic model. The direction of flow will be initially upward, consistent with an arid environment. Random events representing large rainfall events or changes to future climate states will allow the flow direction to change, thus flushing any accumulated radionuclides to the water table and activating the pathway to the pumping well. Use of a GoldSim cell between the aquifer pathway and the dose accumulator cell allows dilution to be modeled.

The structure of the GoldSim model for the borehole in low-permeability material is shown in Figure 4.2-4. This model is a simple pipe network to a GoldSim cell that represents dilution at the pumping well. The main complication in this model is the abstraction for the upward buoyancy driven flow in the EDZ (see Section 4.2.3). In addition, such a borehole concept relies more on an engineered barrier system as compared to the GCD. Thus, a more complicated near-field model is required.

4.2.3 Process Modeling of Thermal Conditions

The decay heat of GTCC waste in a borehole may, depending on the specific activity, alter thermal and hydrological conditions within and adjacent to the borehole. Understanding the effects of these alterations to the thermal-hydrological conditions is essential in determining the ability of the borehole and surrounding geologic media to attenuate the transport of waste that potentially breaches the containment vessel (canister). Here, an intermediate-depth borehole located in a low-permeability confining unit (background rock) overlain by a high-permeability unit (aquifer) is considered. The effects of several parameters on performance of the borehole system are investigated using numerical modeling. Of particular interest is the possibility of buoyancy driven flow in an excavation damage zone immediately adjacent to the borehole. The objective of these simulations is to provide the basis for an abstraction that will be used in the generic modeling of the low-permeability borehole system.

The generic numerical model is two-dimensional (r-z) with axisymmetry in a cylindrical geometry. Six zones are included: (1) background rock, (2) low-permeability seal, (3) backfill, (4) damaged background rock surrounding the borehole (excavation damage zone, EDZ), (5) waste filled borehole (waste canisters encased in seal material), and (6) an overlying aquifer. A schematic of the general parameter zonation implemented in the modeling approach is shown in Figure 4.2-5. An unstructured grid with closely spaced nodes in and near the borehole and EDZ was developed using LaGriT [LaGriT 2003]. The control-volume finite-element code FEHM was used to solve the coupled flow and heat transport problem [Zyvoloski 2007].

The grid includes 14,046 nodes with the greatest level of refinement (radial and vertical grid spacing ~3 cm) within the EDZ. Outside of the EDZ, the grid spacing increases to a constant horizontal grid spacing of 62.5 m and vertical grid spacing of 30 m. The model domain is 2000 m in radius and 600 m vertically. A detail view of the grid near the EDZ is shown in Figure 4.2-6. Canisters containing radioactive waste are assumed to be placed within a borehole drilled to a depth of 30 m into the background rock. A 30 m thick aquifer is assumed to exist above the background rock. The borehole is 0.8 m in diameter and is surrounded by a 0.15 m ring (~0.45 m^2 area) of damaged rock (EDZ). The length of the waste-filled borehole is 15 m. A bentonite seal exists above the waste-filled borehole. The seal is assumed to be 15 m thick, filling the borehole up to the depth of the aquifer/confining unit interface. The remainder of the borehole above the bentonite seal is considered to be backfilled with non-seal material (perhaps with drillings available at the surface).

Initial conditions corresponding to pre-drilling conditions were established by running the model to steady state without a waste heat source. The pressure at the top of the aquifer was fixed at 1 MPa, while the temperature at the top of the aquifer was fixed at 20 °C. A geothermal heat flux of 0.06 W/m^2 was applied to the bottom of the model. The seal, backfill and EDZ were assumed to be water saturated; re-saturation of bentonite following waste emplacement was not addressed.

Parameter scans were performed around a base case. The following parameters were scanned: background permeability $k_{h,b}$, background thermal conductivity $k_{t,b}$, order of magnitude increase in EDZ permeability due to drilling $R_d=\log_{10}(k_{h,EDZ}/k_{h,b})$, initial power produced by radioactive waste per vertical meter of borehole E_0, and the half-life of the radioactive waste $t_{1/2}$. Note that for simplicity the decay heat is assumed to decrease exponentially with a single decay constant; more complicated decay heat histories accounting for multiple radionuclides are not addressed here. The base case parameter values are $k_{h,b} = 1 \times 10^{-14}$ m^2, $k_{t,b} = 2$ W/m°K, $R_d = 1$, $E_0 = 40$ W/m, and $t_{1/2} = 500$ years. Table 4.2-1 lists the parameter values for all zones, listing base case values for the scanned parameters. Table 4.2-2 lists the parameter sets evaluated in the scan.

Figure 4.2-7 shows a temperature profile near the canister for the base case 100 years after emplacement, which is approximately the time of the highest temperatures for the simulation. It is apparent that temperatures at the canister approaches 32 °C for the base case. Figure 4.2-8 shows the flow field at 100 years after emplacement near the borehole at the aquifer/background rock interface, while Figure 9 shows the corresponding flow field near the bottom of the borehole. Figures 4.2-8 and 4.2-9 demonstrate the “chimney effect” that is generated by the radioactive waste heat source, inducing flow up the borehole and into the aquifer.

Advective travel times for a contaminant released at the vertical midpoint of the waste canister to the aquifer are shown as a function of the time that the contaminant is released in Figure 10. The vertical distance of travel is 22.5 m. The travel time τ was calculated by numerically solving the ordinary differential equation initial value problem $\frac{d\tau}{ds} = \frac{1}{v(s,t)}$ along the flow trajectory aligned with the velocity field within the EDZ and parameterized by the distance s. Considering a constant flow trajectory within the EDZ is appropriate because the direction of flow there is independent of time, as indicated by the results of the simulation (i.e. the modeling scenario creates streamline trajectories within the EDZ that are fixed due to a chimney effect). The magnitude v of velocity varies in time and along the trajectory. The explicit embedded Runge-Kutta-Fehlberg method implemented through the GNU Scientific Library and bilinear interpolation of internodal fluxes in the EDZ collected from the simulations were used to obtain the τ solution [Galassi 2009]. For the parameter scans, travel times increase with increasing time of release. More complicated decay heat histories (for instance, considering a decay chain of radioactive elements with variable activities and modes of decay) may produce more complex travel time trends. It is important to note that the parameter scans are performed around the base case for each parameter, except for R_d, as $R_d = 0$ (i.e. no damage to the background rock) produces travel times longer than the time frame of interest. As a result, the identical base case is presented in each plot. The travel times for the half-life parameter scan produce similar travel times at early release times as the half-life only impacts the trend of heat source decay. It is apparent from the cases considered that extremely short travel times occur for high background permeability (1×10^{-13} m^2). While the effects of the other parameters are less dramatic, they do provide indications of the effects of alterations to the scanned thermal and hydrological properties on travel times.

The fraction of the radionuclide mass leaving the canister that reaches the aquifer is key for evaluating the performance of the borehole and surrounding geologic material in attenuating radionuclide transport. This metric is a conditional one, quantifying only the performance of the geosphere barriers given that a release has occurred at a particular time. An attenuation index defined as the fraction of released waste that decays after release but before entering the aquifer is plotted as a function of the time of release into the EDZ in Figure 4.2-10. Clearly it is a strong function of background permeability, damage factor R_d, and half-life, but is relatively weakly dependent on initial heat load and thermal conductivity of the rock.

The information shown in these plots will be abstracted for use in the generic system modeling.

Table 4.2-1, Borehole Disposal Modeling Parameter Values for the Base Case

	Permeability m^2	**Thermal Conductivity** W/mºK	**Density** kg/m^3	**Specific Heat** MJ/kgºK	**Porosity** [-]
Background rock	1×10^{-14}	2	2750	790	0.025
Seal	1×10^{-16}	0.8	2750	760	0.35
Backfill	1×10^{-16}	1.5	1700	760	0.35
EDZ	1×10^{-13}	2	2750	790	0.025
Waste	1×10^{-19}	46	2750	450	0.0001
Aquifer	1×10^{-11}	1.5	1700	760	0.35

Table 4.2-2, Values of Parameters for Scans (Case 2 is the base case)

Case	$k_{h,b}$ **[m²]**	R_d **[m²/m²]**	$k_{t,b}$ **[W/mºK]**	E_0 **[W/m]**	$t_{1/2}$ **[y]**
1	-13	1	2	40	500
2	-14	1	2	40	500
3	-15	1	2	40	500
4	-14	2	2	40	500
5	-14	1	1	40	500
6	-14	1	3	40	500
7	-14	1	2	20	500
8	-14	1	2	60	500
9	-14	1	2	40	250
10	-14	1	2	40	1000

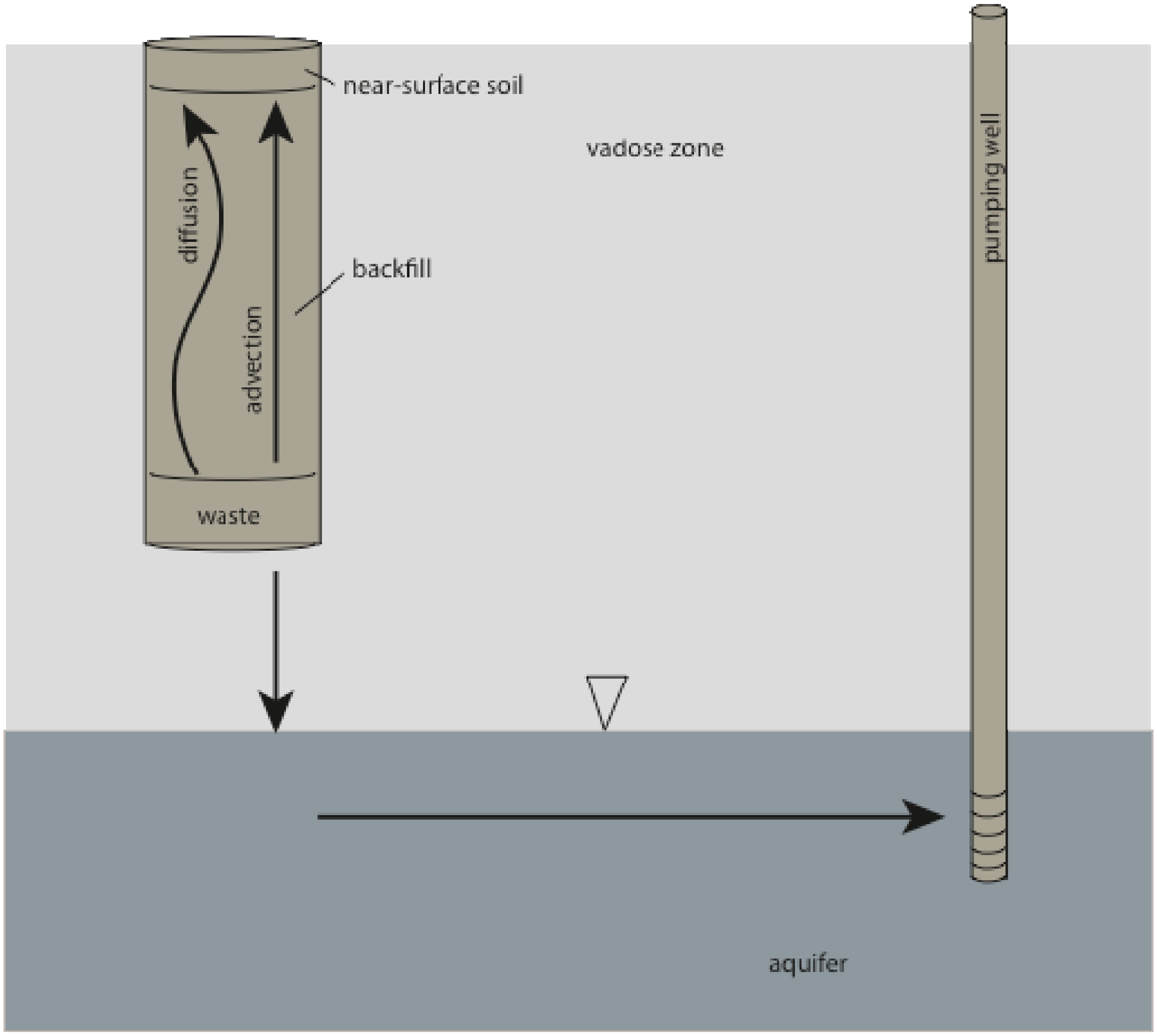


Figure 4.2-1, Schematic showing configuration and potential pathways for a GCD-type disposal facility for GTCC. Two potential transport pathways are shown. Upward advection, liquid-phase diffusion/dispersion and gas-phase diffusion may transport radionuclides to the near-surface surface soils. Alternatively, downward advection/dispersion following high-intensity infiltration events or in future climate may take radionuclides to the water table where they can be transported to a downstream pumping well.

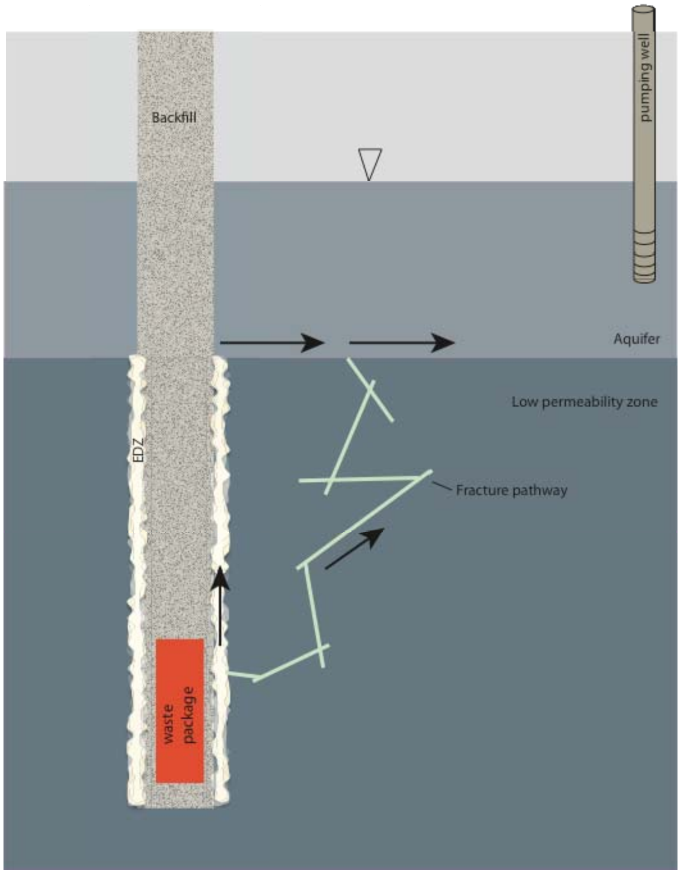


Figure 4.2-2, Schematic showing configuration and potential pathways for borehole disposal beneath the water table. Two potential pathways are shown: upward advective transport in an excavation damage zone (EDZ) adjacent to the borehole and advective transport along a fracture pathway. Matrix diffusion and retardation on matrix material will delay transport along both pathways. The final leg of the transport pathway is through the overlying aquifer to a pumping well.

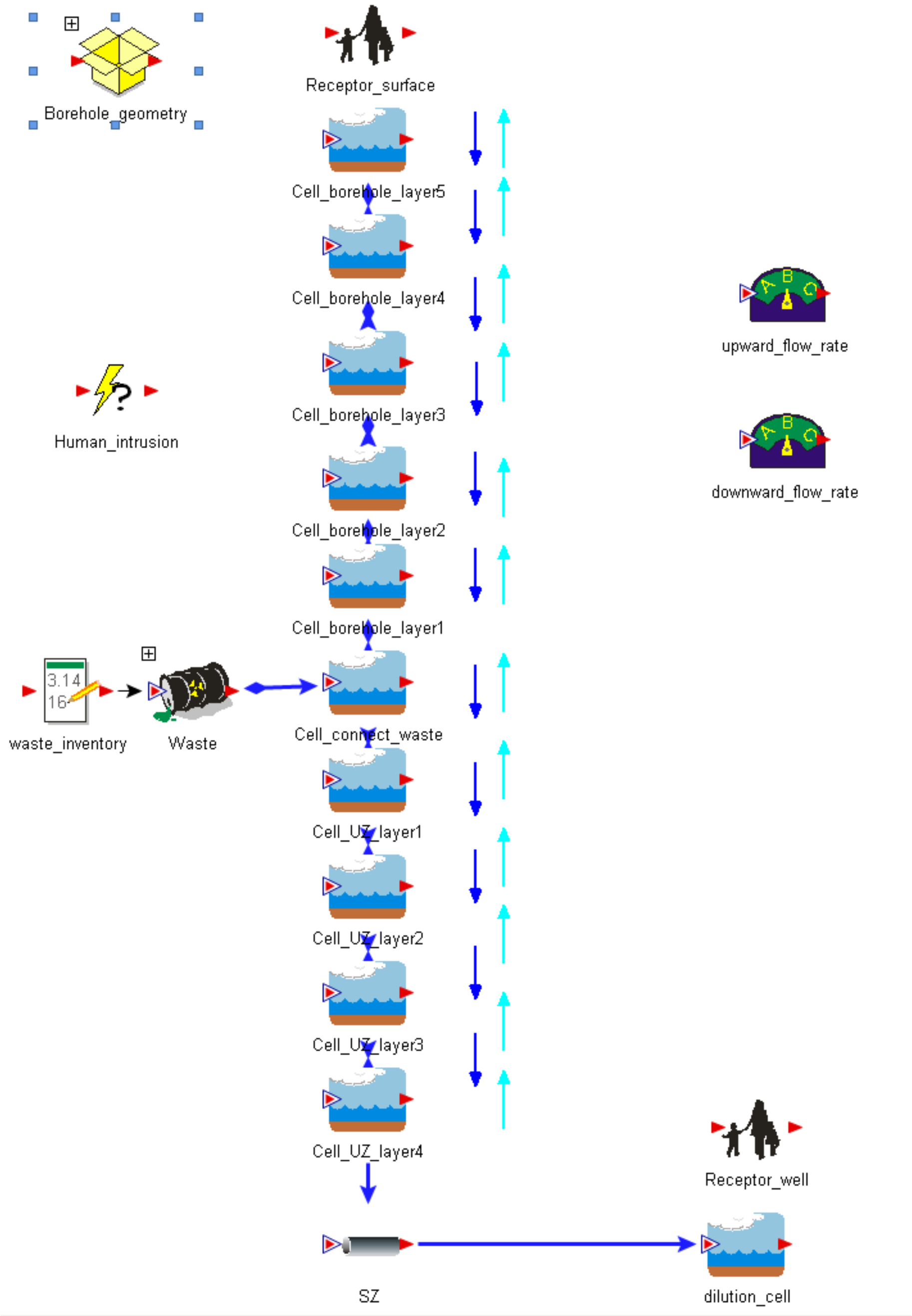


Figure 4.2-3, GoldSim implementation of the GCD-type borehole disposal system model.

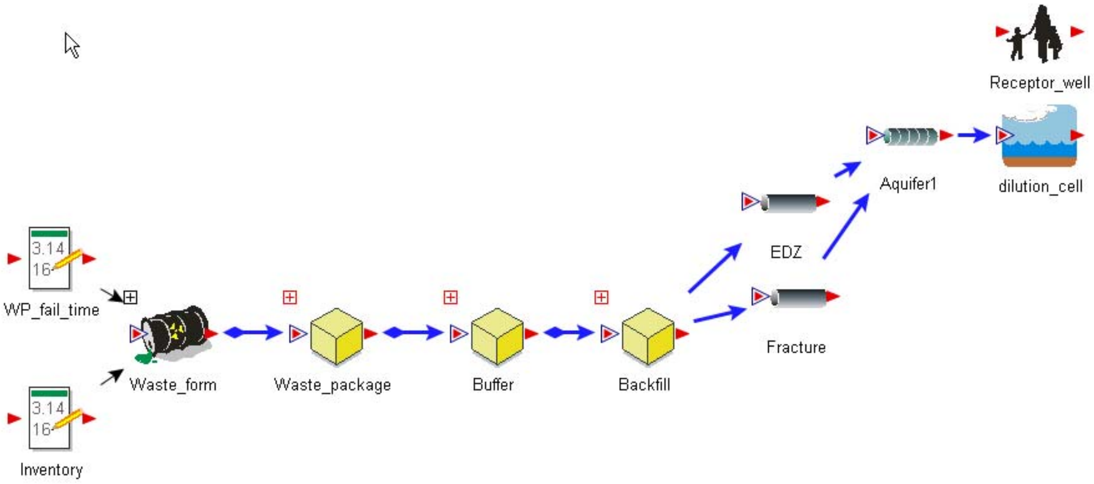


Figure 4.2-4, GoldSim implementation of a generic model of borehole disposal in low-permeability zone beneath the water table.

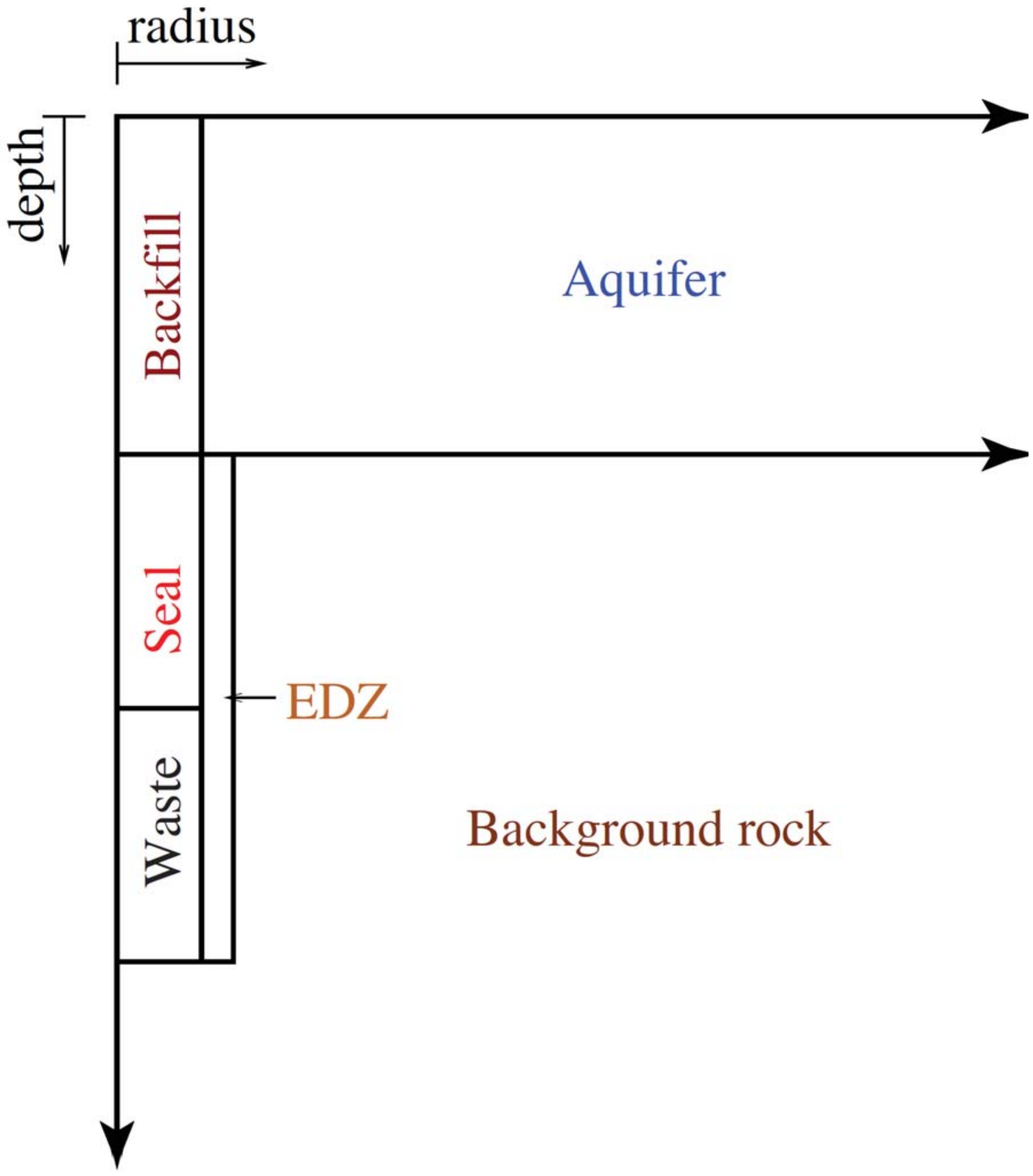


Figure 4.2-5, Cutout of the model zonation used in the process modeling of thermal conditions (not to scale). For reference, the aquifer is 30m deep and the borehole (not including the EDZ) is 0.4 m in the radial coordinate.

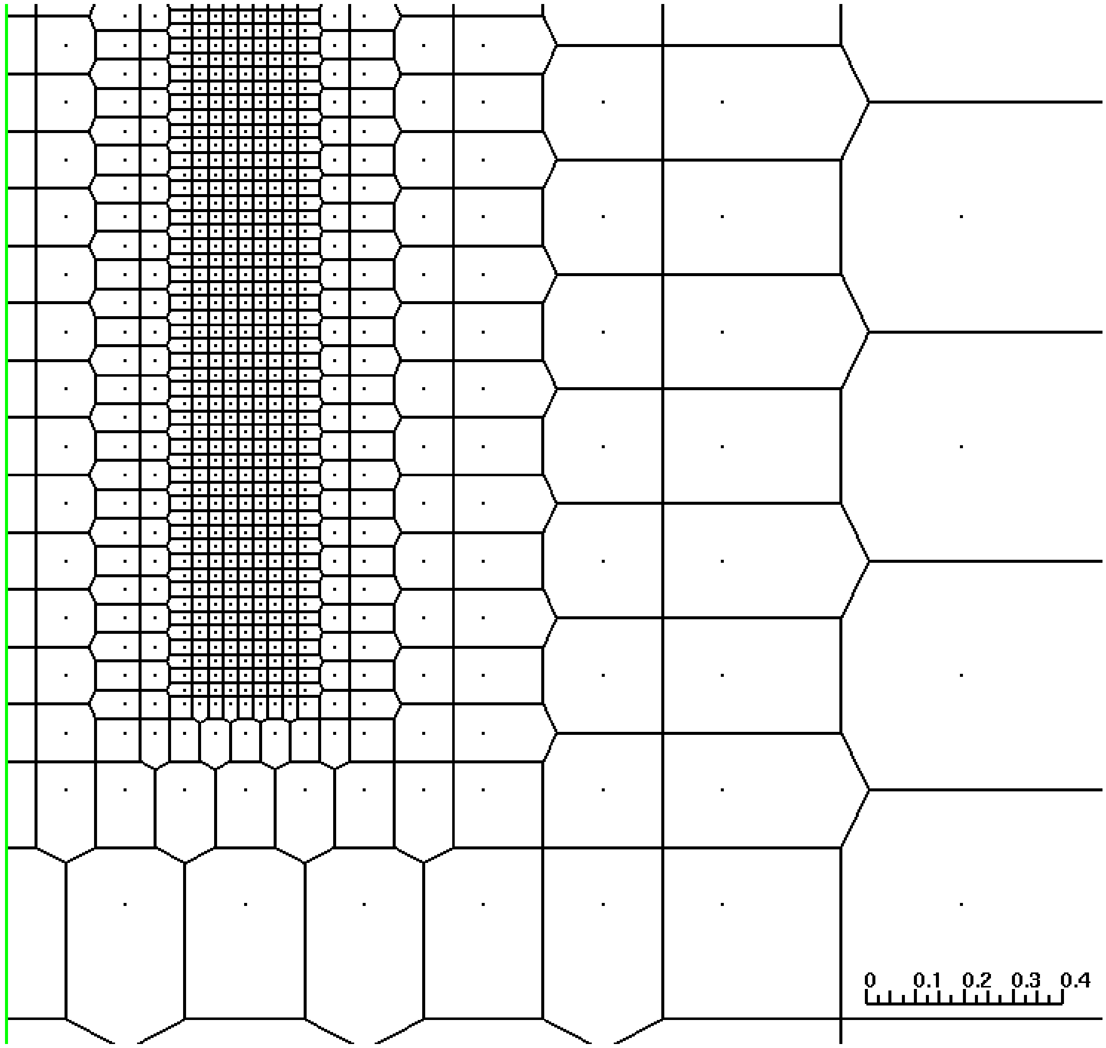


Figure 4.2-6, Detail from axisymmetric grid near the bottom of the borehole showing grid refinement in the borehole EDZ. The points are the nodes of the grid and the lines indicate the control volumes surrounding the nodes. The green vertical line is the center of the borehole (radius = 0 m). The distance scale in the lower right is in meters.

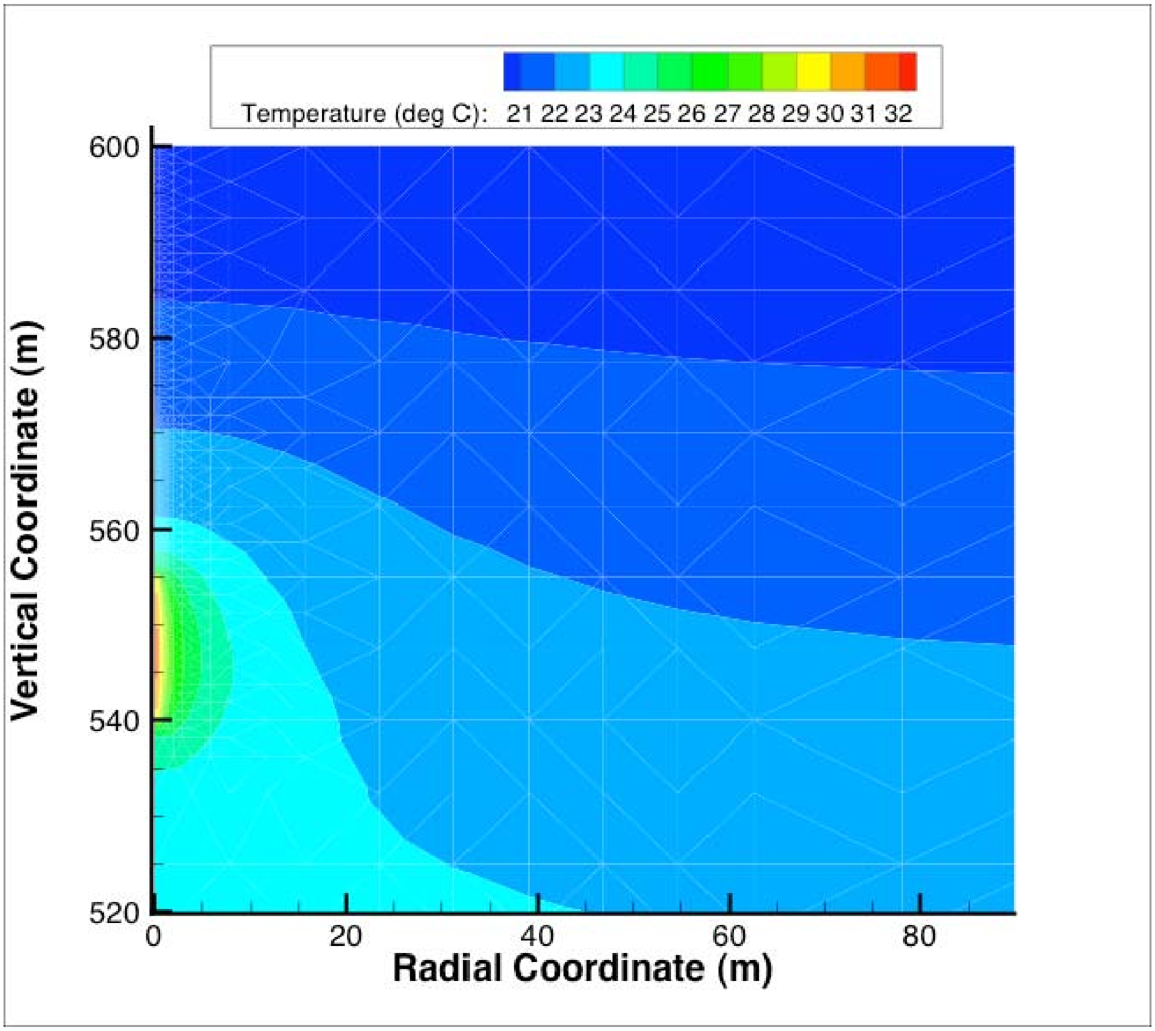


Figure 4.2-7, Temperature near the bottom of the borehole in the reference case 100 years after emplacement.

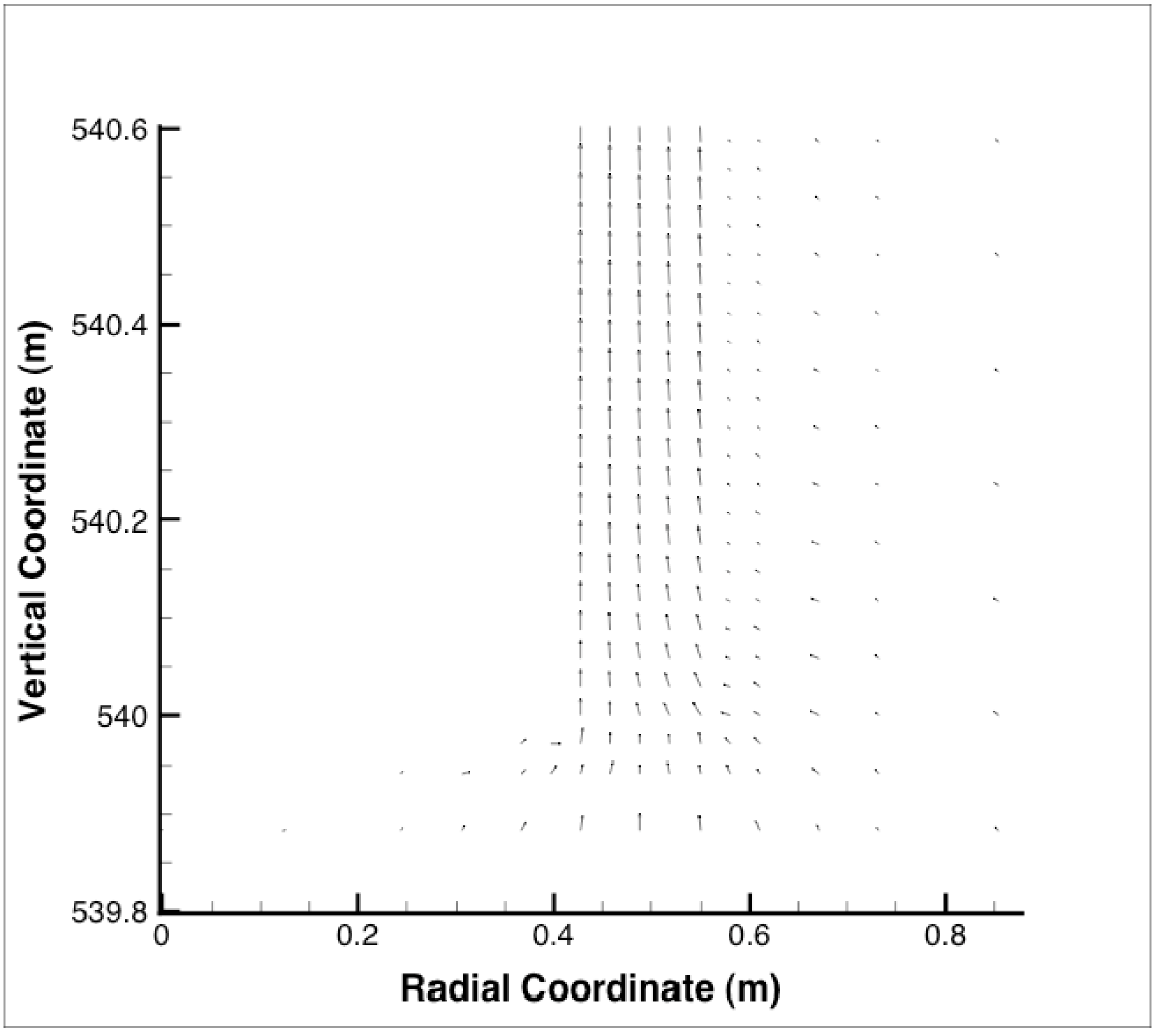


Figure 4.2-8, Flow field in the EDZ at the bottom of the heated zone for the base case 100 years after emplacement.

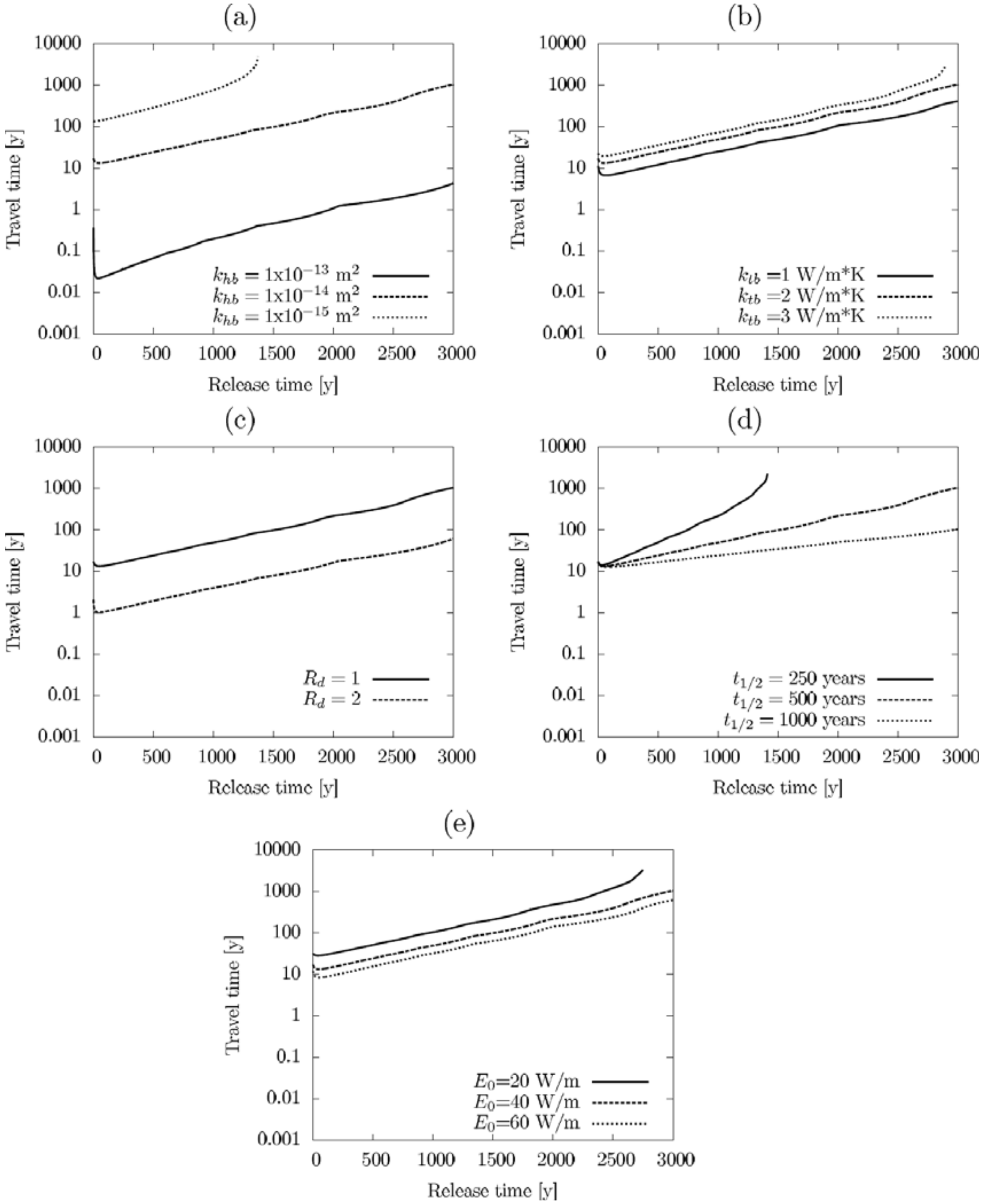


Figure 4.2-9, Travel times from the vertical midpoint of the canister to the aquifer (22.5 m) as a function of release time for different values of (a) hydraulic conductivity of the background material, (b) thermal conductivity of the background material, (c) orders of magnitude increase in hydraulic conductivity of the EDZ due to drilling, (d) half-life of the radioactive waste, and (e) initial enthalpy of the radioactive waste per vertical meter. Scans are around a base case of $k_{hb} = 1\times10^{-14}$ m^2, k_{tb} = 2 W/m°K, $R_d = 1$, $t_{1/2}$ = 500 y, and E_0 = 40 W/m.

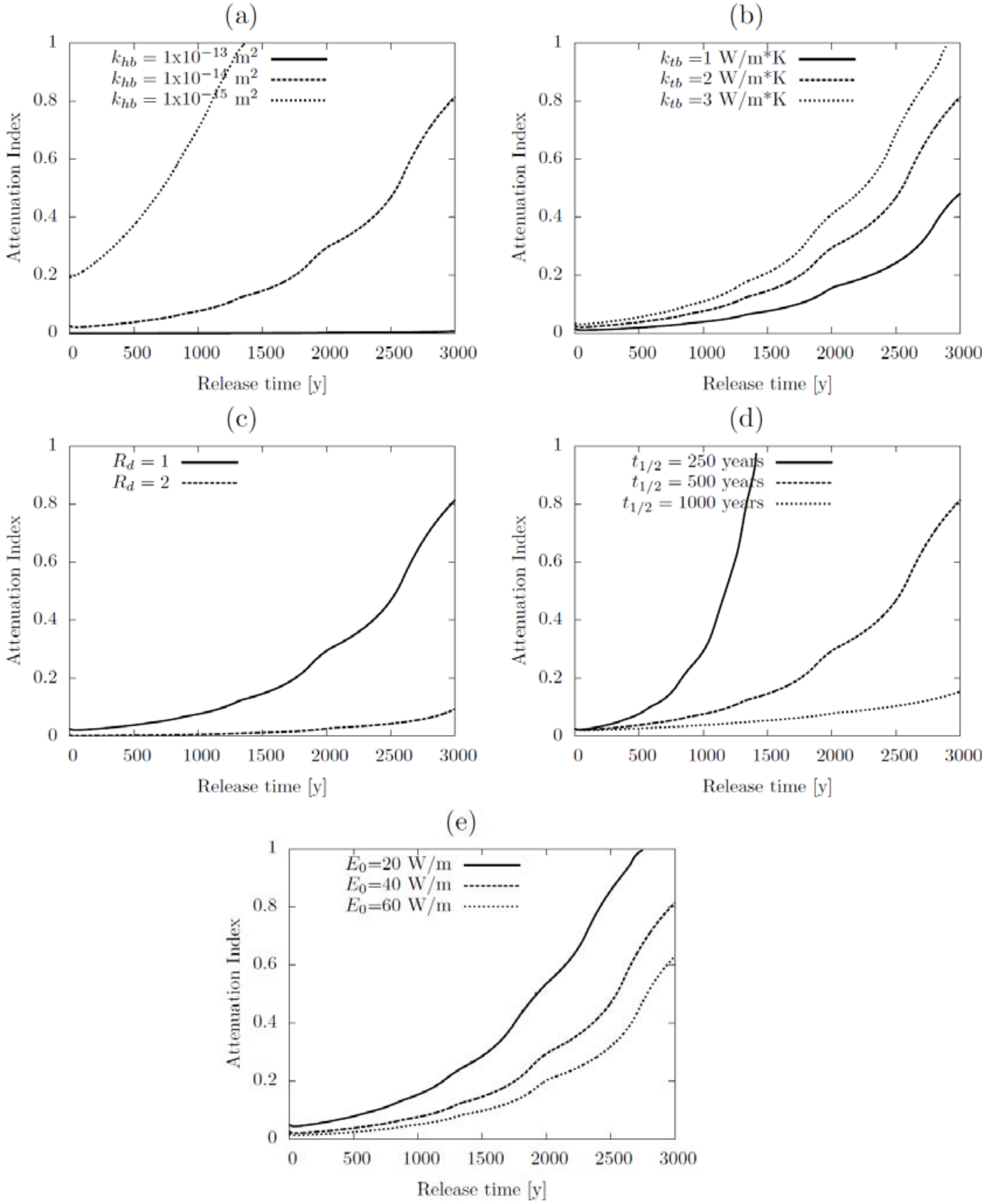


Figure 4.2-10, Fraction of released radionuclide mass that decays before reaching the aquifer (attenuation index) as function of release time for different values of (a) hydraulic conductivity of the background material, (b) thermal conductivity of the background material, (c) orders of magnitude increase in hydraulic conductivity of the EDZ due to drilling, (d) half-life of the radioactive waste, and (e) initial enthalpy of the radioactive waste per vertical meter. Scans are around a base case of $k_{hb} = 1 \times 10^{-14}$ m^2, k_{tb} = 2 W/m°K, $R_d = 1$, $t_{1/2}$ = 500 y, and E_0 = 40 W/m.

5.0 DISPOSAL HISTORY UPDATE

Fiscal Year 2011 has been eventful for activities related to LLW disposal. There have been a number of developments related to LLW disposal in the DOE Complex, the NRC, the commercial sector in the United States, and also internationally. This section includes a brief summary of some of the key developments. More information is provided in a separate report [Seitz 2011].

Greater Than Class C Environmental Impact Statement

The Department of Energy, Office of Environmental Management issued the Draft Environmental Impact Statement (EIS) for disposal of greater than class C (GTCC) waste for public comment in February 2011. A number of public meetings were held around the DOE Complex in April and May. The public comment period closed in June and comments are currently being addressed in a revision to the draft EIS.

The Draft EIS evaluates the potential environmental impacts associated with constructing and operating a new facility or facilities, or using an existing facility, for the disposal of GTCC low level radioactive waste and GTCC-like waste. DOE does not have, and therefore has not identified, a preferred alternative in the Draft EIS, but will do so in the Final EIS based on further consideration and public comment. The preferred alternative could be a combination of two or more alternatives, based on the characteristics of the waste, its availability for disposal, and other key factors.

United States Nuclear Regulatory Commission Regulatory Activities

Activities are moving forward at the US Nuclear Regulatory Commission (NRC) on efforts related to site-specific analysis rulemaking for unique waste streams as part of a potential update to 10 CFR Part 61 that was discussed in the previous LLW History report [Jones 2010]. Public meetings were held in FY 2011 to seek stakeholder input regarding the potential update. One of those meetings was held jointly with a discussion of efforts to update DOE Order 435.1, which is the equivalent DOE directive for LLW. The results of these meetings were considered during the development of preliminary proposed rule language and associated technical basis as well as a technical analysis supporting a definition of a period of performance included in the preliminary proposed rule. These documents were presented at a public meeting held on May 18, 2011. The public was invited to submit comments on the documents at that time.

Public comments have been received and proposed updates to the preliminary proposed rule and supporting documentation have been discussed in public meetings with the NRC Advisory Committee on Reactor Safeguards (ACRS), which also addresses radioactive waste. Three meetings with the ACRS were held. There has been public opposition to the NRC Staff proposal to consider a period of performance of 20,000 years for LLW disposal. Members of the ACRS have also suggested that the NRC Staff adopt time frames consistent with what DOE has used (i.e. 1,000 years). The NRC is planning to issue a formal proposed rule in FY 2012.

The issue of blending higher concentrated low-level radioactive waste (Class B and C waste) with lower concentration waste (Class A) waste has come to the forefront because of concerns about disposal options for Class B and C radioactive waste. Blending is seen as a means to combine lower classes of LLW (Class A) with higher-classes (Classes B and C) into mixture that could be classified as Class A and would have more options for disposal. In October 2010, the NRC directed its staff to revise the current position on blending to be risk-informed and performance-based. A draft revision of the Branch Technical Position (BTP) on concentration averaging was prepared to identify the circumstances under which large scale blending is acceptable. A public meeting was held in February 2011 to provide background on the concentration averaging BTP and to solicit public comments. Following the meeting a draft update to the BTP was prepared and submitted for public comment. A revised version of the document is scheduled to be completed by the end of FY 2011 with issuance of a final BTP scheduled in the June 2012 time frame.

DOE LLW Disposal Facilities

Efforts are continuing on the update to DOE Order 435.1, Radioactive Waste Management. A draft of the complete requirements and guide is planned to be completed by the end of FY 2011 and a supporting technical standard is also being prepared. The update is addressing a number of developments that have occurred over the last 11 years, since the original Order was published and also provides clarification as needed based on experiences and lessons learned over that time. Some of the specific topics being addressed include: waste incidental to reprocessing and tank closure, clarification of expectations for waste classification, probabilistic uncertainty analysis, in-situ closure and disposal, and CERCLA disposal cells.

A new state-of-the-art mixed waste disposal cell was completed at the Nevada Nuclear Security Site in December 2010. The RCRA compliant disposal cell received its first shipment of mixed LLW in January 2011 [DOE 2011]. Completion of this disposal facility was an important milestone for waste generators throughout the DOE Complex to support disposal of mixed LLW generated from environmental cleanup activities.

Construction was completed on two new super cells at the Environmental Restoration Disposal Facility (ERDF) at the Hanford Site in FY 2011. The two new super cells expand the disposal capacity of ERDF by 5.6 million tons for a total capacity of 16.4 million tons. Disposal operations are underway in Cell 5 of the Environmental Management Waste Management Facility (EMWMF) at the Oak Ridge Site that was completed in May 2010. An additional disposal cell (Cell6) was also completed at EMWMF this year. Each additional cell added 465,000 cubic yards of disposal capacity for an increase in total capacity to 2.2 million cubic yards. The expanded capacity at both of these disposal cells is expected to allow much of the waste generated during cleanup activities at Oak Ridge and Hanford to be disposed locally and results in significant cost savings relative to off-site disposal.

A draft Environmental Assessment has been completed addressing potential development of a new LLW disposal facility at the Idaho Site. The assessment was released for public comment in FY 2011. The proposed facility would provide long term disposal capacity for remote-handled LLW generated at the Idaho Site. Remote handled LLW is currently disposed at the Radioactive Waste Management Complex, but that facility is planned to close in the near future.

Commercial Disposal

Approval was received for construction of the commercial and Federal disposal cells at the Waste Control Specialists disposal facility in Texas and construction of both cells was started. The commercial cell was expected to be complete by September 30, 2011 and the Federal cell is expected to be completed in FY 2012. A certification report must be completed within 60 days after construction. The certification report must be approved prior to the start of operations. Operations for both facilities are expected to begin in FY 2012.

In the previous history report, the challenges associated with disposal of Class B and C waste were identified due to the restrictions applied to the Barnwell disposal facility in South Carolina. A critical milestone was achieved when Texas passed a State Law that was signed in June 2011. The State Law established the capability for out of Compact wastes to be accepted at the Waste Control Specialists disposal facility. This law establishes an alternative to Barnwell for disposal of Class B and C LLW from around the United States. Waste Control Specialists has started working on contractual arrangements with utilities to begin accepting waste. Any importation of waste from outside of the Compact must meet specific criteria and must be approved by a majority of the Compact Commissioners prior to disposal.

In accordance with a rule approved by the State of Utah Radiation Control Board in April 2010, Energy Solutions is conducting a performance assessment prior to continuing disposal of depleted uranium. This rule was related to on-going efforts at the NRC to address disposal of unique wastes as discussed above. As part of development of the performance assessment, public Technical Education discussion sessions were held in November 2010 and February 2011. The draft performance assessment was submitted to the State of Utah on June 1, 2011 and is in the review process. The review is expected to be completed in FY 2012.

IAEA Safety Standards

The International Atomic Energy Agency published the Disposal Requirements document in their safety standards series. The document includes higher-level requirements that are applicable for deep geologic and near-surface disposal of radioactive waste. The document combines and updates information previously published in separate near-surface and deep geologic safety standards. IAEA Safety Standards are not legally binding, but do provide a reference for acceptable practices.

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