AECL EACL

AECL-11494-1, COG-95-552-1

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
Volume 1: Summary

Le stockage permanent des déchets de combustible nucléaire du Canada : Étude de la sûreté post-fermeture de la mise en place en chambre du combustible CANDU irradié renfermé dans des conteneurs en cuivre enfouis dans la roche plutonique perméable
Volume 1 : Sommaire

A.G. Wikjord, P. Baumgartner, L.H. Johnson, F.W. Stanchell,
R. Zach, B.W. Goodwin

June 1996 juin

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

VOLUME 1: SUMMARY

by

A.G. Wikjord, P. Baumgartner, L.H. Johnson, F.W. Stanchell,
R. Zach and B.W. Goodwin

Atomic Energy of Canada Limited
Whiteshell Laboratories
Pinawa, Manitoba R0E 1L0
1996

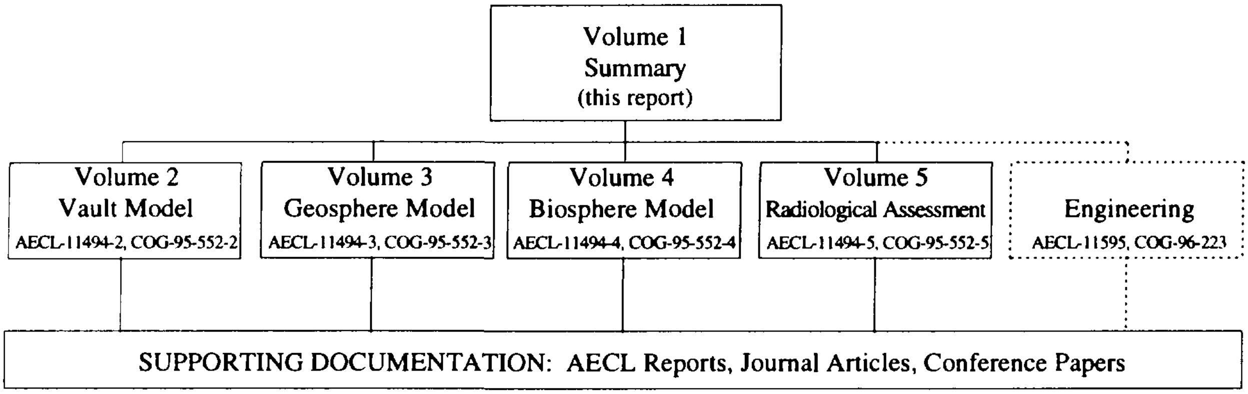
AECL-11494-1
COG-95-552-1

REPORTS IN THIS SERIES

General Title

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

Hierarchy



Scope

Volume 1, Summary (this report), provides an overview of this study and summarizes the design considerations and safety of in-room emplacement of used CANDU fuel in long-lasting copper containers in permeable plutonic rock.

Volume 2, Vault Model (Johnson et al. 1996), describes and justifies the assumptions, model and data used to analyze the long-term behaviour of the engineered system (the near-field), including the waste form (used CANDU fuel), container shell (deoxidized, low-phosphorous copper), buffer (precompacted bentonite clay and silica sand), backfill (glacial lake clay and crushed rock), and excavation disturbed zone.

Volume 3, Geosphere Model (Stanchell et al. 1996), describes and justifies the assumptions, model and data used to analyze the transport of contaminants through permeable plutonic rock of the Canadian Shield, including the effects of a pumping well. The geological characteristics assumed in this study are hypothetical; that is, they are not based on an integrated data set for any particular field research area.

Volume 4, Biosphere Model (Zach et al. 1996), describes and justifies the assumptions, model and data used to analyze the movement of contaminants through the near-surface and surface environments and to estimate radiological effects on humans and other biota.

Volume 5, Radiological Assessment (Goodwin et al. 1996), provides an estimate of long-term radiological effects of the hypothetical disposal system on human health and the natural environment, including an analysis of how uncertainties of the assumed site and design features affect system performance.

A separate engineering study (Baumgartner et al. 1996), shown by the dotted lines, is closely linked to this five-volume series. It describes the conceptual design, technical feasibility, thermal-mechanical analyses, and project life cycle for implementing an engineered system based on the in-room emplacement/copper container option. It is applicable to a broader range of geosphere conditions than those assumed in the present study.

AECL EACL

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
VOLUME 1: SUMMARY

by

A.G. Wikjord, P. Baumgartner, L.H. Johnson, F.W. Stanchell,
R. Zach and B.W. Goodwin

ABSTRACT

The concept for disposal of Canada's nuclear fuel waste involves isolating the waste in corrosion-resistant containers emplaced and sealed within a vault at a depth of 500 to 1000 m in plutonic rock of the Canadian Shield. The case for the acceptability of the concept as a means of safely disposing of Canada's nuclear fuel waste is presented in an Environmental Impact Statement (EIS) (AECL 1994a,b), supported by a set of nine primary references (Davis et al. 1993; Davison et al. 1994a,b; Goodwin et al. 1994; Greber et al. 1994; Grondin et al. 1994; Johnson et al. 1994a,b; Simmons and Baumgartner 1994).

The disposal concept permits a choice of methods, materials, site locations and designs. The EIS presents a case study of the long-term (i.e., postclosure) performance of a hypothetical implementation of the concept, referred to in this report as the reference disposal system. The reference disposal system is based on borehole emplacement of used CANDU® fuel in Grade-2 titanium alloy containers in low-permeability, sparsely fractured plutonic rock of the Canadian Shield. The geological characteristics of the reference geosphere in the EIS case study are derived from detailed investigations of the Whiteshell Research Area, located near Lac du Bonnet, Manitoba, including the investigations to locate and construct an underground laboratory.

In the present study, we evaluate the long-term performance of another hypothetical implementation of the concept based on in-room emplacement of used CANDU fuel in copper containers in permeable plutonic rock. The geological characteristics of the geosphere assumed for this study result in short groundwater travel times from the disposal vault to the surface. Such characteristics have not been encountered at depths below 500 m at any of AECL's field research areas on the Canadian Shield.

In the EIS case study, our analyses of the reference system indicated that the dominant safety feature was the domain of low-permeability, sparsely fractured rock immediately surrounding the disposal vault. The transport of contaminants in this lower rock domain was dominated by diffusion. In the present study, the principal barrier to the movement of contaminants is the long-lasting copper container. We show that the long-lasting container can effectively compensate for a permeable host rock which results in an unfavourable groundwater flow condition. These studies illustrate the flexibility of AECL's disposal concept to take advantage of the retention, delay, dispersion, dilution and radioactive decay of contaminants in a system of natural barriers provided by the geosphere and hydrosphere and of engineered barriers provided by the waste form, container, buffer, backfills, other vault seals and grouts. In an actual implementation, the engineered system would be designed for the geological conditions encountered at the host site.

Atomic Energy of Canada Limited
Whiteshell Laboratories
Pinawa, Manitoba R0E 1L0
1996

AECL-11494-1
COG-95-552-1

LE STOCKAGE PERMANENT DES DÉCHETS DE COMBUSTIBLE NUCLÉAIRE DU CANADA : ÉTUDE DE LA SÛRETÉ POST-FERMETURE DE LA MISE EN PLACE EN CHAMBRE DU COMBUSTIBLE CANDU IRRADIÉ RENFERMÉ DANS DES CONTENEURS EN CUIVRE ENFOUIS DANS LA ROCHE PLUTONIQUE PERMÉABLE

VOLUME 1 : SOMMAIRE

par

A.G. Wikjord, P. Baumgartner, L.H. Johnson, F.W. Stanchell,
R. Zach et B.W. Goodwin

RÉSUMÉ

Le concept du stockage permanent des déchets de combustible nucléaire du Canada prévoit l'isolement des déchets dans des conteneurs anticorrosion placés et scellés dans une installation de stockage creusée à une profondeur de 500 à 1 000 m dans la roche plutonique du Bouclier canadien. Les arguments apportés à l'appui de ce concept pour le stockage permanent sûr des déchets de combustible nucléaire du Canada sont présentés dans une Étude d'impact sur l'environnement (EIE) (EACL 1994a,b) accompagnée de neuf rapports principaux de référence (Davis et coll. 1993; Davison et coll. 1994a,b; Goodwin et coll. 1994; Greber et coll. 1994; Grondin et coll. 1994; Johnson et coll. 1994a,b; Simmons et Baumgartner 1994).

Le concept de stockage permanent permet d'effectuer un choix de méthodes, de matériaux, d'emplacements et de modèles. L'EIE présente une étude de cas sur les performances à long terme (post-fermeture) d'une installation hypothétique désignée dans le présent rapport sous le nom de système de stockage permanent de référence. Le système de stockage permanent de référence repose essentiellement sur la mise en place dans des trous de stockage du combustible CANDU® irradié renfermé dans des conteneurs en alliage de titane de nuance 2, enfouis dans la roche faiblement fracturée et de faible perméabilité du Bouclier canadien. Les caractéristiques géologiques de la géosphère de référence dans l'étude de cas de l'EIE ont été établies d'après des études détaillées réalisées dans l'Aire de recherches de Whiteshell, près de Lac du Bonnet, au Manitoba, tout comme les études nécessaires pour situer et construire le laboratoire souterrain.

Dans la présente étude, on évalue les performances à long terme d'une autre installation hypothétique qui repose sur la mise en place en chambre du combustible CANDU irradié renfermé dans des conteneurs en cuivre enfouis dans la roche plutonique perméable. Les caractéristiques géologiques de la géosphère qui ont été supposées pour cette étude indiquent un temps de déplacement court des eaux souterraines de l'installation de stockage permanent jusqu'à la surface. Aucune caractéristique du genre n'a été constatée à des profondeurs supérieures à 500 m dans les aires de recherche d'EACL dans le Bouclier canadien.

Dans l'étude de cas de l'EIE, nos analyses du système de référence indiquent que la caractéristique de sûreté dominante était la zone de roche peu fracturée et de faible perméabilité qui entourait l'installation de stockage. Le transport des contaminants dans cette zone était principalement par diffusion. Dans la présente étude, la principale barrière empêchant la migration des contaminants est le conteneur de longue durée de vie en titane. Nous démontrons que ce conteneur de longue durée peut effectivement compenser l'effet d'une roche d'accueil perméable qui crée des conditions d'écoulement des eaux souterraines peu favorables. Ces études témoignent de la souplesse du concept de stockage permanent d'EACL qui met à profit la rétention, le retardement, la dispersion, la dilution et la décroissance radioactive des contaminants dans un système de barrières naturelles – assurées par la géosphère et l'hydrosphère – et de barrières ouvragées – la forme de déchets, le conteneur, le matériau-tampon, le remblai, d'autres matériaux de scellement du stockage et les coulis. Dans une situation de mise en oeuvre réelle, le système ouvragé serait conçu en fonction des conditions géologiques qui prévalent sur le site d'accueil.

Énergie atomique du Canada limitée
Laboratoires de Whiteshell
Pinawa (Manitoba) R0E 1L0
1996

AECL-11494-1
COG-95-552-1

CONTENTS

1. BACKGROUND

1.1 THE DISPOSAL CONCEPT

The concept for disposal of Canada's nuclear fuel waste involves isolating the waste in corrosion-resistant containers emplaced in a sealed vault at a depth of 500 to 1000 m in plutonic rock of the Canadian Shield. The case for the acceptability of the concept as a means of safely disposing of Canada's nuclear fuel waste is presented in an Environmental Impact Statement (EIS) (AECL 1994a,b), supported by a set of nine primary references (Davis et al. 1993; Davison et al. 1994a,b; Goodwin et al. 1994a; Greber et al. 1994; Grondin et al. 1994; Johnson et al. 1994a,b; Simmons and Baumgartner 1994).

The proposed disposal concept (AECL 1994a,b), shown schematically in Figure 1, is a method for geological disposal of nuclear fuel waste in which

- the waste form is either used CANDU fuel or the solidified high-level waste from reprocessing the used fuel;
- the waste form is sealed in a container designed to last at least 500 years and possibly much longer;
- the containers of waste are emplaced in rooms in a disposal vault or in boreholes drilled from the rooms;
- the disposal rooms are nominally 500 to 1000 m below the surface;
- the geological medium is plutonic rock of the Canadian Shield;
- each container of waste is surrounded by a buffer;
- each room is sealed with backfills and other vault seals; and
- all tunnels, shafts, and exploration boreholes are ultimately sealed in such a way that the disposal facility would be passively safe; that is, long-term safety would not depend on institutional controls.

The disposal vault would be a network of horizontal tunnels and disposal rooms excavated deep in the rock, with vertical shafts extending from the surface to the tunnels. Rooms and tunnels might be excavated on more than one level. The vault would be designed to accommodate the rock structure, groundwater flow system, and other subsurface conditions at the disposal site. The disposal container and vault seals would also be designed to accommodate the subsurface conditions at the disposal site.

After the disposal facility is closed, a system of multiple barriers would protect humans and the natural environment from both radioactive and chemically toxic contaminants in the waste. These barriers would be the container; the waste form; the buffer, backfills, and other vault seals; and the geosphere. To perform effectively as barriers

- the container should isolate the waste form from groundwater by maintaining structural stability and resisting corrosion;

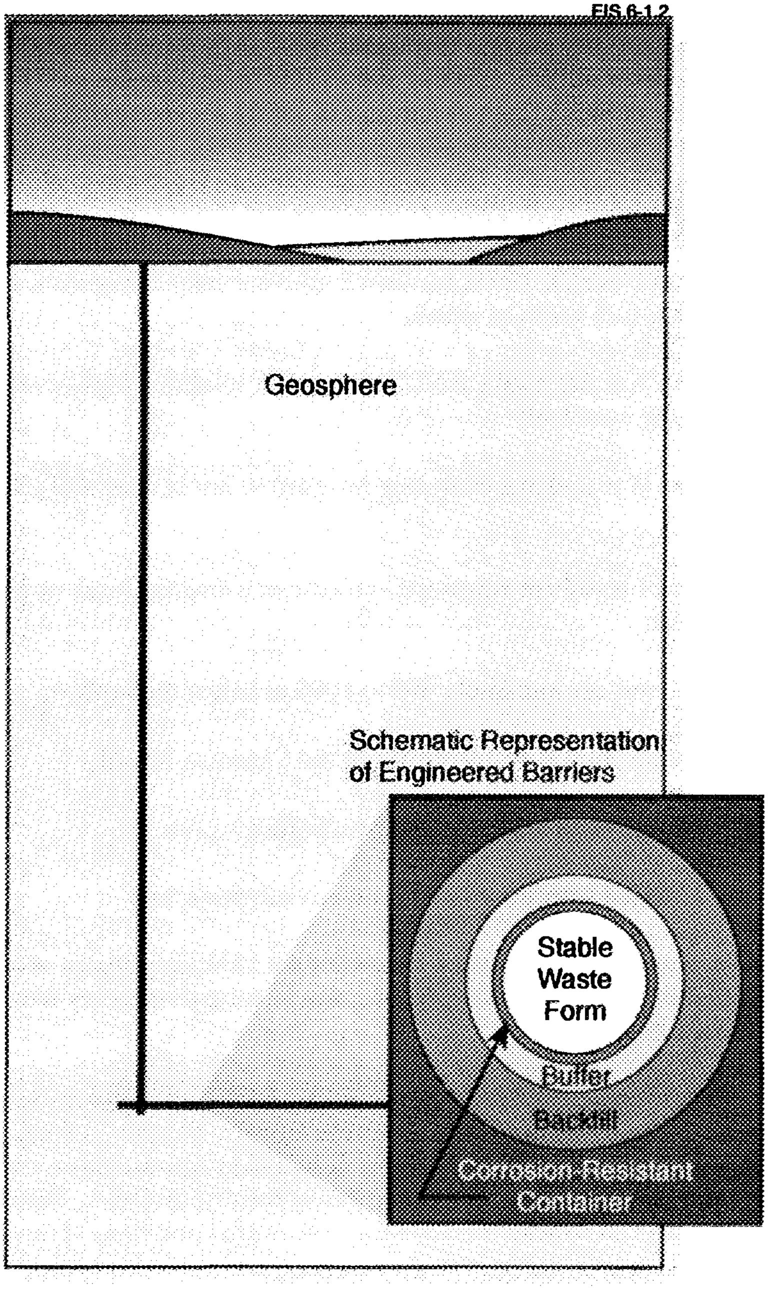


FIGURE 1: The Concept for Geological Disposal of Canada's Nuclear Fuel Waste

- the waste form should be a durable solid that retains contaminants under expected vault conditions;
- the vault seals, which include the buffer and backfills, should limit container corrosion, waste-form dissolution, and contaminant movement by inhibiting the flow of groundwater in the vault and controlling the chemical environment in the vault; and
- the geosphere should protect the waste form, container, and vault seals from disruptions from natural events and human intrusion; maintain conditions in the vault favourable for long-term waste isolation; and limit the rate at which contaminants from the waste could move from the vault to the biosphere.

The system of engineered and natural barriers should protect human health and the environment in the long term without relying on institutional controls.

The specific location and design of a disposal facility could only be decided during a future implementation of the disposal concept. At that time, an engineered system would be designed to accommodate the geological conditions encountered at the host site. However, information about specific site and design characteristics are required for a quantitative assessment of the long-term safety of a disposal system. Therefore, we perform case studies of hypothetical systems based on characteristics derived from conceptual engineering studies, laboratory experiments and field investigations.

1.2 RADIOLOGICAL CRITERIA FOR LONG-TERM SAFETY

The Atomic Energy Control Board (AECB) requires that quantitative estimates be made of the radiological risk associated with a disposal vault for times up to 10 000 years following closure (AECB 1987). As used by the AECB (1987), radiological risk is the probability that an individual or his or her descendants will incur a fatal cancer or serious genetic effect because of exposure to radiation. The individual of concern is a member of the critical group that is assumed to be located at a time and a place where risks are likely to be the greatest. The individual risk limit is specified to be one in a million per year, calculated without taking advantage of long-term institutional controls as a safety feature.

The period for demonstrating compliance with the individual risk requirements using predictive mathematical models need not exceed 10 000 years. Where predicted risks do not peak before 10 000 years, there must be reasoned arguments that beyond 10 000 years the rate of radionuclide release to the environment will not suddenly and dramatically increase and that acute radiological risks will not be encountered by individuals (AECB 1987).

1.3 THE POSTCLOSURE ASSESSMENT CASE STUDY PRESENTED IN THE EIS

The EIS (AECL 1994a,b) and four of the primary references (Davis et al. 1993, Davison et al. 1994b, Goodwin et al. 1994a and Johnson et al. 1994b) describe a case study of the long-term (i.e., postclosure) performance of a hypothetical implementation of the concept, referred to in this report as the *reference disposal system.*

The reference system for the EIS postclosure assessment case study, illustrated in Figure 2, is based on emplacement of used CANDU® fuel in Grade-2 titanium alloy containers in boreholes in the floor of rooms excavated in low-permeability, sparsely fractured plutonic rock of the Canadian Shield. The

EIS 6-2.4.1/3(cik-aa211)

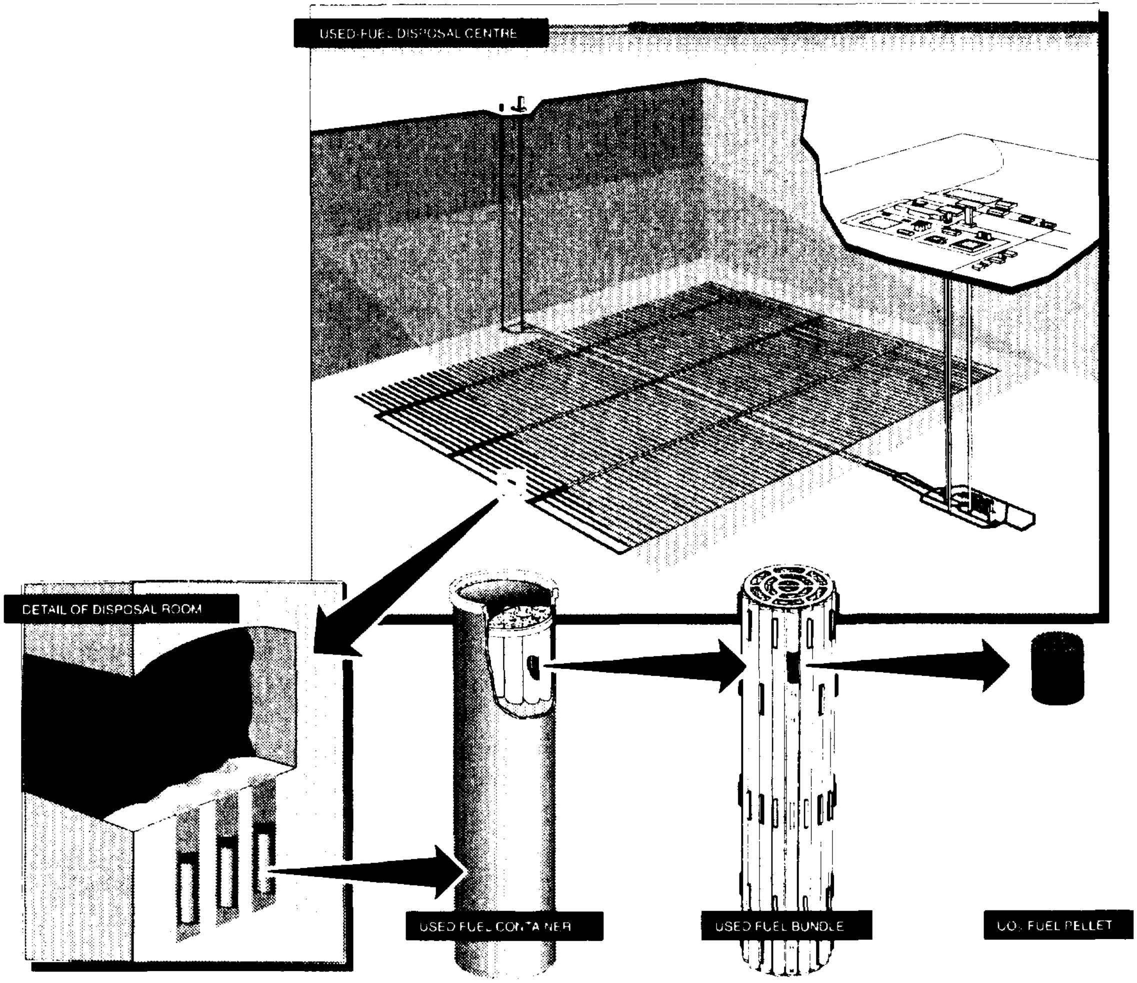


FIGURE 2: The Hypothetical Disposal System Specified for the Postclosure Assessment Case Study Presented in the EIS Based on Borehole Emplacement of Fuel Waste in Titanium Containers

technology specified is either available or judged to be readily available. The geological characteristics are based on one of AECL's field research areas.

The reference system illustrates what a disposal system, including the vault, geosphere and biosphere, might be like. Although it is hypothetical, it is based on information derived from extensive laboratory, field and engineering investigations. Many of the assumptions made about the long-term performance of the reference system are conservative; that is, they would tend to overestimate adverse effects. The reference disposal system includes one possible choice among the options for such things as the waste form, the disposal container, the buffer and backfills, the shaft seals and bulkheads, the location and depth of the vault, and the orientation and layout of the vault with respect to the geological features of the site.

The components and designs chosen for the engineered barriers and the site conditions represented in the reference system are not being recommended as preferred options; rather, they illustrate a technically feasible way of implementing the disposal concept. In an actual implementation of the concept, the engineered system would be designed to accommodate the lithostructural, hydrogeological, geochemical, geothermal, geomechanical, and geomicrobiological conditions of the host rock formation, and the expected evolution of those conditions over thousands of years.

The *reference vault* (Johnson et al. 1994b) includes used-fuel bundles comprising UO_2 pellets in Zircaloy cladding, encapsulated in thin-walled Grade-2 titanium alloy containers packed with particulate for mechanical support, emplaced in boreholes in the floor of rooms, and surrounded by a buffer composed of a sand-bentonite mixture. The rooms are filled with a lower backfill of crushed granite and glacial lake clay and an upper backfill of sand and bentonite, and the entrances are sealed with concrete bulkheads. The plan area and the design capacity of the vault were initially set at 4.0 km^2 and 10.1 million fuel bundles (191 000 Mg U) respectively. The fuel inventory is roughly equivalent to the waste that would accrue in 100 years at the current production rates in Canada. The plan area was subsequently reduced to 3.2 km^2 and the inventory to 8.5 million bundles (162 000 Mg U), as a result of design constraints chosen to ensure a large margin of safety in the case study. The borehole-emplacement geometry is modelled as layered planar elements (slabs) representing the waste form, buffer, backfills and host rock.

The *reference geosphere* (Davison et al. 1994b) consists of the host rock formation, its groundwater flow system, the materials used to seal the shafts and exploration boreholes, and a water-supply well. The geological characteristics of the reference geosphere are derived from field investigations at AECL's Whiteshell Research Area (WRA), located near Lac du Bonnet, Manitoba. The WRA includes a substantive portion of the Lac du Bonnet Batholith, a large granitic rock body several kilometres deep with a significant exposed surface over an area measuring over 60 km long and 20 km across at its widest part. The granitic body was intruded over 2.5 billion years ago into the rocks existing at the time. The batholith, the surrounding rocks, and the interfaces between them have been the subject of field investigations for more than 15 years. Most of the information about the rock mass, such as the location and orientation of fractures and fracture zones, is based on field studies of the WRA, including detailed investigations that were conducted to locate and construct an Underground Research Laboratory (URL) to a depth of 440 m. For geological structures outside the areas where detailed borehole information was available, inferences have been made on the basis of nearby boreholes; geological mapping; and satellite, airborne and ground-based geophysical surveys. The hypothetical vault for the reference system was located at a depth of 500 m within the rock mass investigated at the URL to ensure that the maximum amount of available subsurface data was used to construct the geosphere model. (As discussed in Section 1.4, the vault could have been located in a more hydraulically favourable setting.)

In the postclosure assessment of the reference system, we assumed that a large, low-dipping, fracture zone — designated LD1 — passed through the vault horizon. Although field evidence from the URL revealed that this fracture zone did not extend beyond a depth of about 400 m, we conservatively assumed that it continued to much greater depths and connected with other vertical fracture zones. In this situation, LD1 became a pathway for relatively rapid groundwater flow from the depth of the hypothetical vault to the accessible environment. We constrained all waste disposal rooms to be located beneath LD1 (i.e., to the footwall side of the fracture) and imposed a waste exclusion distance of 50 m within the low-permeability, sparsely fractured rock domain between this fracture zone and the nearest waste disposal room of the vault. To accommodate these constraints, we chose to restrict the waste capacity of the vault relative to the capacity specified in a conceptual engineering study (Simmons and Baumgartner 1994). These design constraints, together with the hydrogeological properties of the rock beneath LD1, ensured that (i) contaminants passed through the backfills, a large reservoir that reacts strongly with most of the contaminants; and (ii) diffusion was the dominant transport process from the waste disposal rooms through the lower rock domain to the fracture zone.

The *reference biosphere* (Davis et al. 1993) consists of the surface and near-surface environment, including the water, soil, air, people, and other organisms, as encountered on the Canadian Shield as a whole. However, the parts of the biosphere that interface with the geosphere are specific to the WRA. In all other respects, the biosphere is assumed to be typical of the Canadian Shield, consisting of rocky outcrops; bottom lands with pockets of soil, bogs, and lakes; and uplands with meadows, bush, and forests. No major changes in the topography of the region are likely to occur during the 10 000 years following closure of a disposal facility. Changes in climate, surface water flow patterns, soils, and vegetation types are expected to be within the range of variation currently observed across the Shield; such variations are included in the distributions of values of model parameters specified for the EIS case study.

The long-term safety analyses of the undisturbed system of engineered and geological barriers (Goodwin et al. 1994a) indicated that the maximum estimated mean dose rate to an individual in the critical group during the first 10 000 years is about 8 orders of magnitude smaller than the dose rate (3×10^{-3} Sv per year) from natural background radiation. The corresponding risk is about 6 orders of magnitude smaller than the radiological risk criterion (10^{-6} per year) specified by the AECB in Regulatory Document R-104 (AECB 1987).

If the system were disturbed by people who inadvertently drill into the vault and extract contaminated drill cores, the estimated risks would be greatest at earlier times, when the waste would be most radioactive. The risks of such intrusions depend upon the assumed exposure pathway and are 3 to 6 orders of magnitude below the risk criterion.

1.4 A STUDY TO IDENTIFY A FAVOURABLE VAULT LOCATION

In an actual implementation of the disposal concept, it would be advantageous to locate the vault in a hydraulically favourable setting within the large-scale groundwater flow system of a siting area. Recently, we completed a study to illustrate how such a location could be found within the WRA. The conceptual hydrogeological model of the WRA was revised using information from a program of regional geologic mapping, geophysical surveys and borehole drilling and testing (Stevenson et al. 1995, 1996). Large-scale groundwater flow modelling was then performed using a three-dimensional, finite-element hydrogeological code; and groundwater travel times, flow pathways and discharge locations were determined with a particle tracking code (Ophori et al. 1995, 1996).

This study has indicated that diffusion is the rate-determining transport process and diffusive transport times greater than 100 000 years could likely be achieved by selecting a vault location at 750 m depth about 5 km northeast of the URL. Advective travel times are about 2 orders of magnitude longer than the diffusive transport times. Since the groundwater flow and particle-tracking analyses of the undisturbed system indicated that such a favourable location would likely ensure a margin of safety even greater than that calculated for the EIS case study, a full systems analysis was not performed. Instead, we directed our efforts to the present study in which we evaluate the long-term effects of a hypothetical geological setting with a permeable host-rock condition.

2. SCOPE AND OBJECTIVES OF THE PRESENT STUDY

A wide range of design options is possible within the general definition of the disposal concept (AECL 1994a,b; Johnson et al. 1994a; Simmons and Baumgartner 1994). The present study illustrates the potential for designing the engineered barriers and the vault to increase the robustness of the long-term safety case or to compensate for hydrogeological conditions that could result in a less effective geosphere barrier than the one we specified for the EIS case study. It also illustrates the flexibility of the modelling approach to integrate new features, processes and data representing different design options and site characteristics into a full systems assessment.

In this study, we analyze the feasibility and safety of emplacing long-lasting copper containers within vault rooms (as opposed to deposition in boreholes in the floor of rooms as in the EIS case study). We have assumed the vault is located in a hypothetical volume of permeable plutonic rock where advective travel times from the vault to the biosphere are much shorter than those in the EIS case study. Although we have not encountered such conditions at disposal-vault depths in our investigations at various research areas on the Shield, performance assessments done for the Swedish and Finnish nuclear waste disposal programs have considered these conditions in the crystalline rocks of the Fennoscandian Shield (Safety Assessment Management 1996). We are not suggesting that such rock conditions might constitute desirable conditions for an eventual disposal site on the Canadian Shield. Rather, the study is intended to illustrate the effectiveness of the in-room emplacement method and copper containers in inhibiting the release of contaminants from the vault.

We use the same methodology for this postclosure assessment as was used in the EIS case study (Goodwin et al. 1994a); however, as discussed in Section 3, the scope of the assessment is more limited.

The conceptual design description and the thermal-mechanical analyses for the engineered system specified for this study are described in detail in a separate study by Baumgartner et al. (1996) and summarized in Section 4.

The system model developed for this study has three main components: a vault, a geosphere and a biosphere, which are described in detail in Johnson et al. (1996), Stanchell et al. (1996) and Zach et al. (1996), respectively, and are summarized in Section 5.

We estimate the long-term radiological effects of the disposal system, using probabilistic analysis techniques to account for variability and uncertainty in system behaviour. The results of this analysis are presented in Section 6.

A comparison of the key features of the EIS case study and the present study is presented in the Appendix.

3. POSTCLOSURE ASSESSMENT METHODOLOGY

We use the same approach to evaluate the long-term safety of the disposal system in the present study as we used for the EIS case study (Goodwin et al. 1994a). The approach consists of six main steps.

1. *Specify System Features:* We describe the characteristics of the hypothetical disposal system, including its design features, its location, and the properties of the host rock and nearby biosphere. The design and layout of the disposal rooms are derived from a conceptual engineering study (Baumgartner et al. 1996).

2. *Identify Scenarios:* We identify features, events and processes that could have a significant effect on the future performance of the disposal system, and then decide how these factors should be dealt with in the postclosure assessment (Goodwin et al. 1994b, 1996).

3. *Develop Models and Data:* We construct a mathematical representation of the disposal system. Volumes 2 to 4 of this series (Johnson et al. 1996, Stanchell et al. 1996 and Zach et al. 1996) provide details of the models and data for the vault, geosphere and biosphere, respectively, including the underlying scientific and engineering analyses.

4. *Estimate Effects*: We use the models and data to simulate the expected long-term behaviour of the disposal system and to provide quantitative estimates of potential effects of radiotoxic contaminants on humans and the environment (Goodwin et al. 1996). We follow an approach known as systems variability analysis or probabilistic systems analysis, which provides a comprehensive and systematic way of dealing with parameter uncertainties.

5. *Analyze Sensitivity:* We evaluate the performance of the modelled system, and identify parameters, radionuclides and pathways that have a strong influence on the estimated effects.

6. *Compare with Criteria:* We compare our estimates of the effects of the disposal system with regulatory criteria, standards and guidelines. In this study, we are interested primarily in the estimated radiological dose rate to members of the critical group. The associated radiological risk can be compared with the risk limit established by the AECB (1987).

This study is more limited in scope than the EIS case study because

- We examine only the scenario in which contaminants are transported from the vault to the biosphere by groundwater. This exposure scenario represents the most likely way in which people and the environment would be affected by the undisturbed system. A full postclosure assessment would deal with less likely disruptive events such as inadvertent human intrusion.

- We consider only the radionuclides expected to be the most important contributors to dose and risk. They were selected on the basis of a radionuclide screening study. A full postclosure assessment would include a more comprehensive set of radionuclides and chemically toxic species.

- We estimate the radiation dose rate to humans and non-human biota for times up to 10^4 years for comparison with the AECB radiological risk criterion (AECB 1987). A full postclosure assessment would include qualitative arguments covering longer time frames. (To illustrate how the system might behave if it were left undisturbed, we extrapolate results for time periods up to 10^7 years.)

- We use a "prototype" computer code. Our software development procedures allow the creation of preliminary (or prototype) code to examine the accuracy and computational efficiency of new mathematical algorithms and to perform scoping studies. Although this prototype code was subject to many elements of software quality assurance, it has not been tested and documented as thoroughly as the SYVAC3-CC3 code used for the EIS case study.

4. SYSTEMS ENGINEERING

The design process, system description, technical feasibility, thermal and mechanical analyses, and project life cycle are presented in a separate engineering study (Baumgartner et al. 1995, 1996). Figure 3 shows the features of the disposal room and the layout of the rooms within the host rock formation. The key specifications are as follows:

- The used fuel is from the Bruce Nuclear Generating Station; it has a burnup of 720 GJ/kg and has been cooled for ten years following discharge from the reactor. The total quantity of used fuel is 82 000 Mg.

- The container holds 72 used-fuel bundles and is one of two designs: (1) a copper-shell, packed particulate design, or (2) a steel-shell-supported copper design. Both have a 25.4-mm-thick copper shell. Approximately 60 000 containers are emplaced within disposal rooms and surrounded by sealing materials.

- The sealing materials used within disposal rooms include

  (i) a floor constructed of low-heat high-performance concrete;

  (ii) precompacted blocks of dense backfill, comprising a 70:25:5 wt% mixture of crushed granite, glacial lake clay and sodium bentonite, overlying the concrete floor;

  (iii) precompacted blocks of buffer, at least 0.5 m thick and composed of a 50:50 wt% mixture of silica sand and sodium bentonite, surrounding the containers; and

  (iv) pneumatically-emplaced light backfill, comprising a 50:50 wt% mixture of finely crushed granite and sodium bentonite, overlying the buffer.

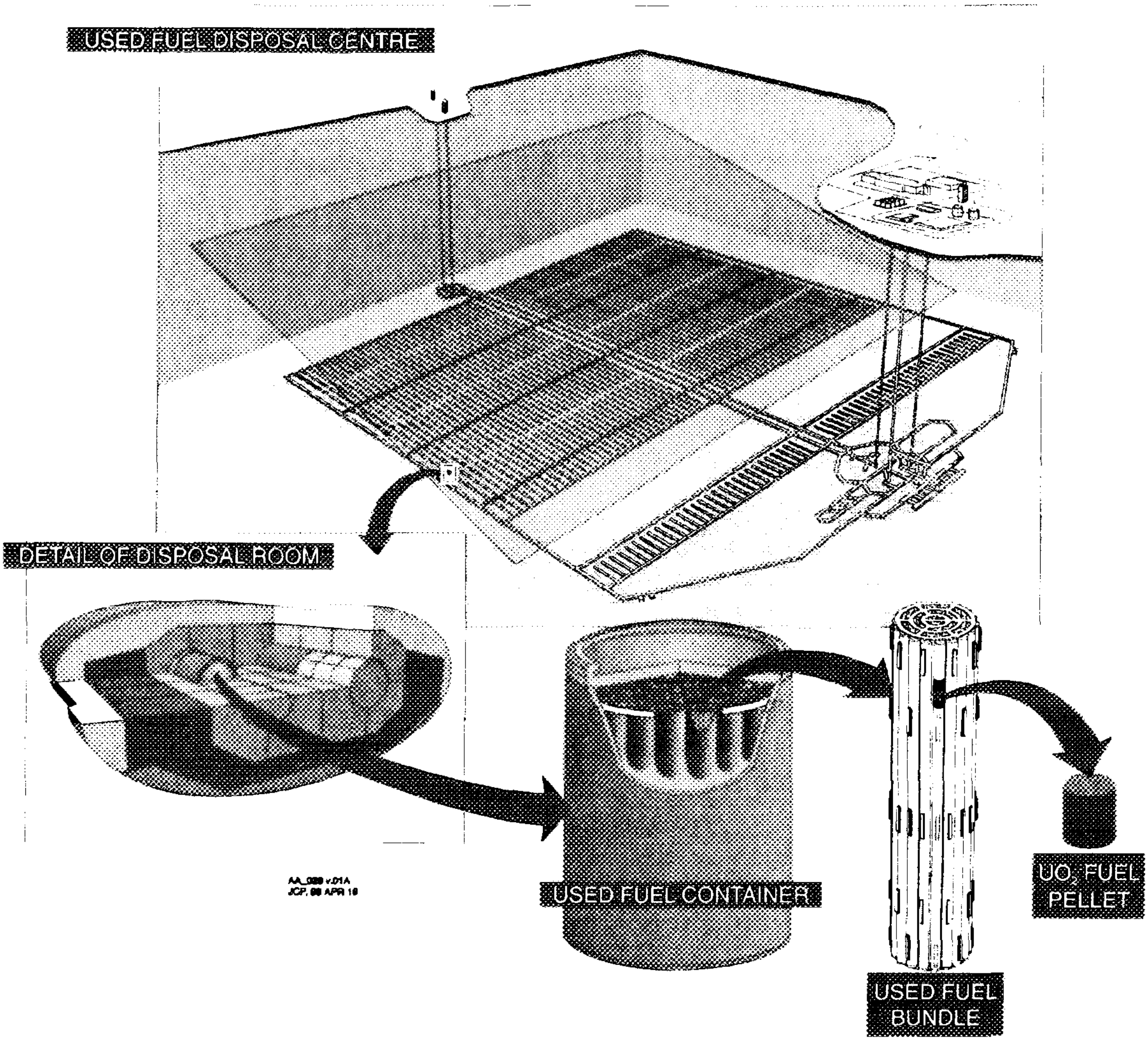


FIGURE 3: The Hypothetical Disposal System Specified for the Present Study Based on In-Room Emplacement of Fuel Waste in Copper Containers

- The maximum hydraulic conductivity of the buffer is 10^{-11} m/s. The maximum hydraulic conductivity of the other clay-based sealing materials is 10^{-10} m/s.

- The maximum temperature in the disposal vault would occur soon after closure and decrease to ambient conditions after more than 10^5 years. The maximum temperature on the surface of the containers is about 75°C, occurring about 15 years after closure (Wai and Tsai 1995; Tsai 1995).

- The mechanical properties of the rock are based on measurements in granites of the Canadian Shield, including measurements of the granitic batholith in which the URL is located.

- The Hoek-Brown (1980) empirical failure criterion model is used for the rock mass stability analyses. The peak strength design limit of the rock under excavation conditions is 100 MPa. If the 100 MPa strength under excavation conditions is not exceeded, the rock strength under the thermal load when the rooms are backfilled and sealed is 150 MPa. The disposal rooms are elliptical in cross section to accommodate the possibility of high in situ stresses and anisotropy in the stress field.

- The disposal vault depth is 500 m. The waste emplacement area of the disposal vault is 3.4 km^2, similar to the value used in the EIS case study (Goodwin et al. 1994a).

- A 20-m-thick, low-angle (18º) fault transects the waste emplacement area of the vault. By assuming a 50-m waste exclusion distance (i.e., perpendicular to the fault) between the fault and the nearest excavation, the total horizontal distance between the two vault sections is about 375 m.

- The temperature limits and radiation shielding required for this in-room emplacement design result in a reduction in the density of waste containers to about 50% of the density specified for the borehole emplacement design used in the EIS case study.

The design could be applied to a range of conditions found in plutonic rock of the Canadian Shield. In an actual implementation, the aspect ratio of the elliptical shape of the disposal room, the functional operations within the room, and the dimensions of the waste emplacement components would be adjusted to suit the in situ stress and rock strength conditions of the host rock formation.

5. SYSTEM MODEL

5.1 INTRODUCTION

The quantitative evaluation of long-term performance uses a mathematical model of the disposal system to infer long-term behaviour and to estimate potential effects. The disposal system model consists of three linked models that represent the vault, the geosphere and the biosphere. There are many similarities between the models used in the EIS case study and in the present study. However, there are also significant differences, notably in the vault model and in the parameter values describing properties of the rock domain surrounding the vault.

5.2 VAULT MODEL

The vault model for the present study (Johnson et al. 1996) differs substantially from the vault model developed for the EIS case study (Johnson et al. 1994b). It simulates dissolution of used CANDU fuel in a geochemical environment, which evolves from an initial oxidative condition, caused by residual air and radiolysis, to an eventual steady-state anoxic condition. The model simulating the performance of copper containers is based on diffusion of contaminants through pinhole manufacturing defects. No corrosion-induced failures are assumed to occur. The in-room emplacement geometry is modelled as a line source representing the waste form, random point sources representing pinholes in the defected containers, and nested concentric cylinders representing the buffer, backfills, excavation disturbed zone, and surrounding rock domain.

Johnson et al. (1996) describe and justify the assumptions, model and data used to analyze the long-term behaviour of the engineered system (the near-field), including the waste form (used CANDU fuel), container shell (deoxidized, low-phosphorous copper), buffer (precompacted bentonite clay and silica sand), backfills (glacial lake clay and coarsely crushed rock, or bentonite and finely crushed rock), and excavation disturbed zone. The model is based on the conceptual design and thermal-mechanical analyses presented in Baumgartner et al. (1996).

The plan area of the disposal vault in the present study is about 3.4 km^2. Over such an area, the rock surrounding the vault exhibits significant variations in its hydrogeological properties, notably groundwater velocities. To account for these variations, we divide the vault into sectors and estimate contaminant releases from each sector. Each sector then serves as a source to a contaminant transport pathway through the geosphere. In calculating releases from the vault to the geosphere, we assume that resaturation of the vault is complete at the time of closure and that steady-state groundwater flow conditions have been established.

For each vault sector, we simulate the following processes:

- failure of the copper containers;
- release of contaminants from the UO_2 fuel and Zircaloy fuel sheaths to the interior of the container;
- precipitation of contaminants inside the container if solubility limits are exceeded;
- transport by diffusion of dissolved contaminants through a small pinhole-sized defect in the container to enter the surrounding buffer; and
- transport by diffusion and advection of contaminants through the buffer, backfills and excavation disturbed zone into the surrounding host rock.

The transport processes are illustrated schematically in Figure 4a. The in-room emplacement geometry is modelled as a line source representing the waste form, random point sources representing pinholes in defected containers, and concentric cylinders representing the buffer, backfills and excavation disturbed zone, as shown in Figure 4b. The surrounding rock, not shown in Figure 4b, is treated as an outer cylinder of infinite radius.

We expect the lifetime of most of the copper containers would exceed a million years. There would be no corrosion-induced failures because of a limited supply of oxidants at 500-m depth. The only failure mechanism would be undetected fabrication defects. These defects are envisioned to be small, pinhole-sized openings in the outer copper shell that permit the ingress of groundwater and the subsequent escape of contaminants. We expect that such defects would be rare, occurring, on average, in only about 1 in

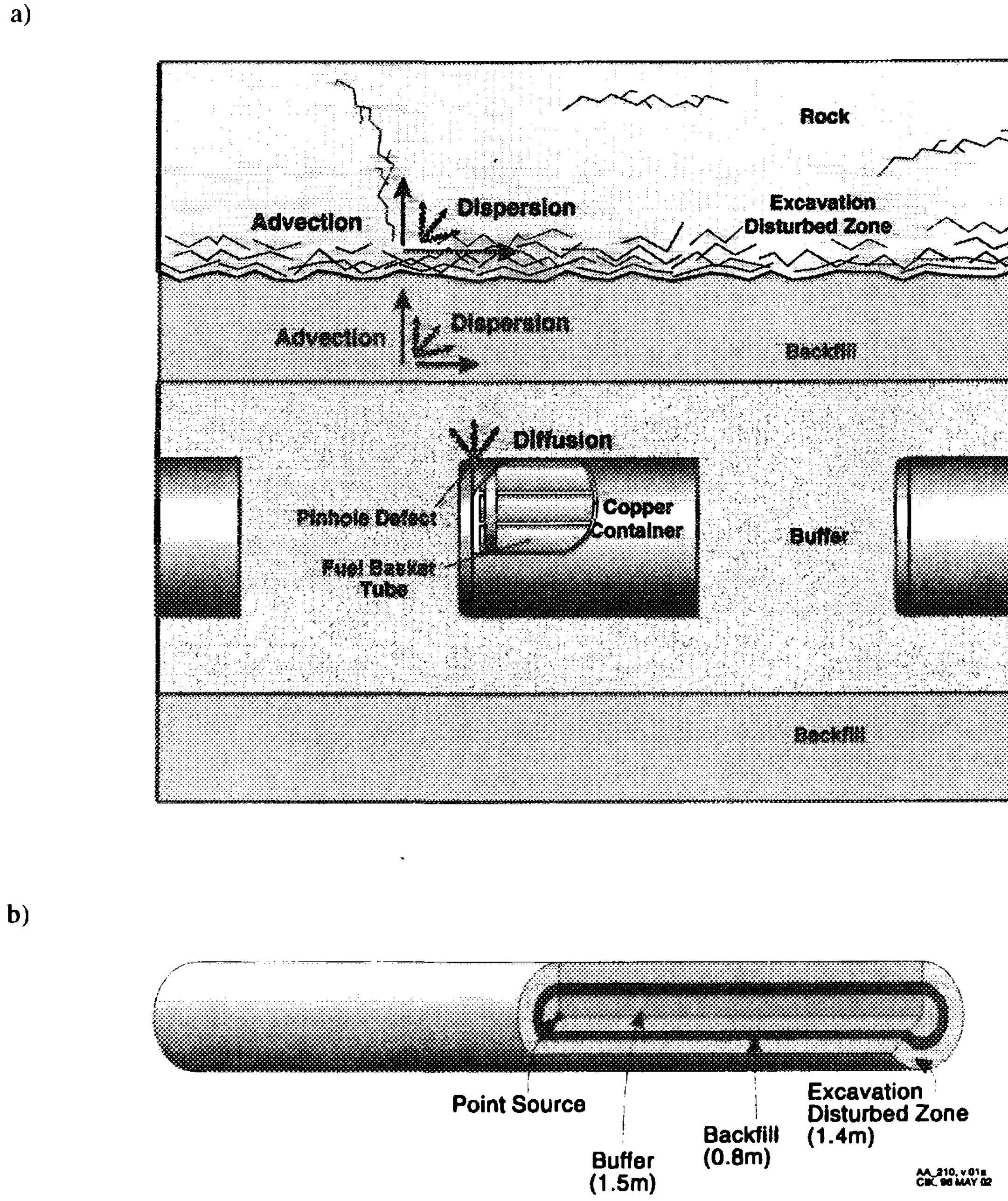


FIGURE 4: Schematic showing (a) the diffusion, advection and dispersion processes for contaminant transport from pin-hole defects in containers and (b) the geometry assumed for the mathematical representation of the vault model.

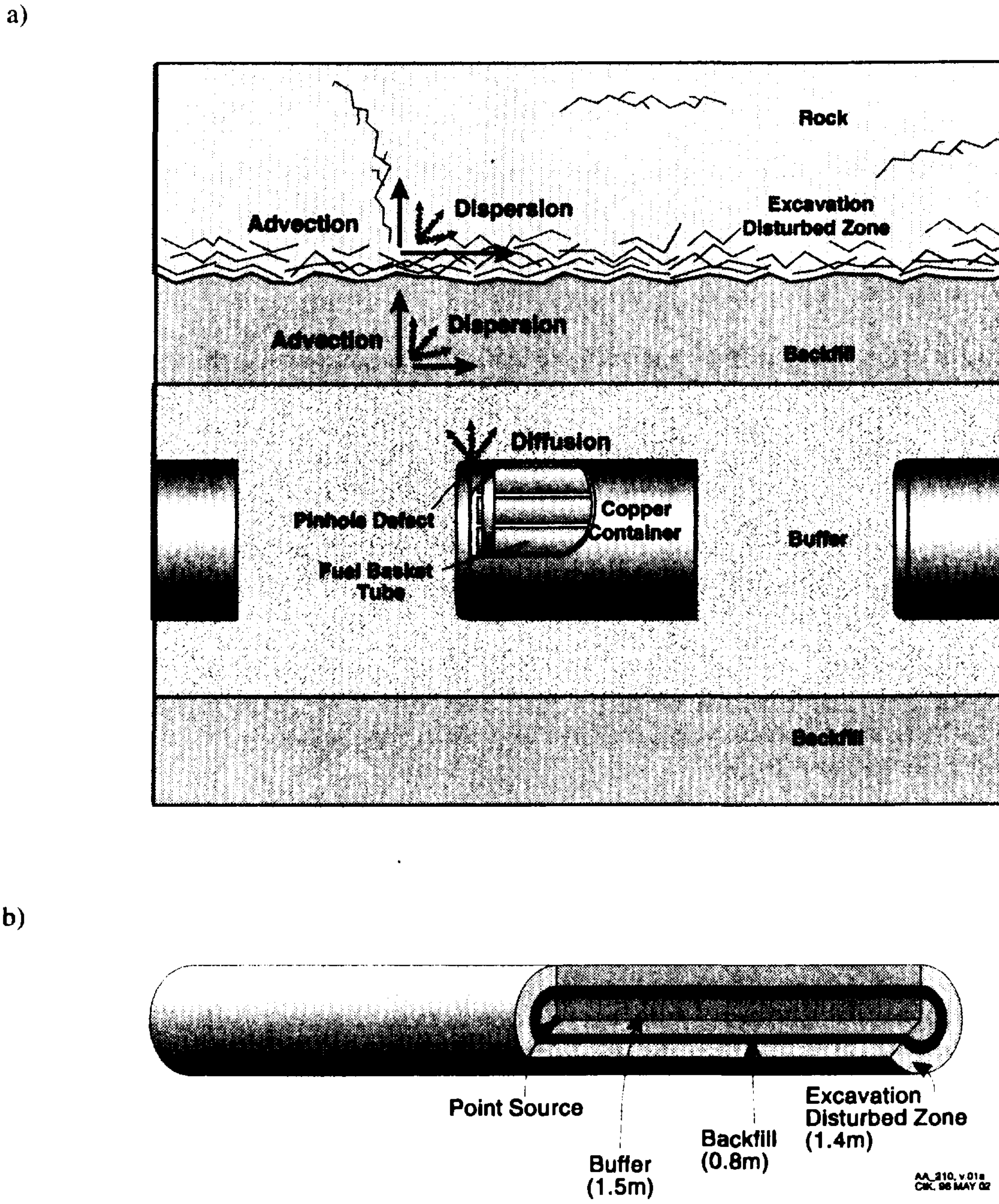


FIGURE 4: Schematic showing (a) the diffusion, advection and dispersion processes for contaminant transport from pin-hole defects in containers and (b) the geometry assumed for the mathematical representation of the vault model.

5000 containers. We assume the size of the openings does not change with time. The net release rate of a contaminant from a vault sector is equal to the product of the number of failed containers in that sector and the calculated release rate from one failed container for that sector. In many respects, the expected container performance is similar to that assumed in the Swedish assessment (SKB 1992).

We assume that a failed container fills with groundwater immediately upon closure of the disposal vault, and that the Zircaloy sheaths fail immediately by localized corrosion, exposing the used-fuel pellets to groundwater. Thus contaminants move out of the defected containers at the time of closure of the vault. We model two radionuclide release mechanisms: instant and congruent release for the used-fuel matrix and congruent release for the Zircaloy matrix.

Instant release pertains to the fraction of contaminants located in the gaps and at the grain boundaries of the fuel pellets. Such contaminants are assumed to be released instantly to the interior of the failed container. Instant release fractions are specified for ^{14}C, ^{36}Cl, ^{135}Cs, ^{137}Cs, ^{129}I, ^{126}Sn, ^{79}Se, ^{90}Sr and ^{99}Tc.

Congruent release pertains to the contaminants that are uniformly distributed and immobilized in the host matrices, the UO_2 used-fuel pellets and the Zircaloy sheaths. We assume that such contaminants are released at a rate that is proportional to their concentration within the matrix and to the rate of dissolution of the matrix. The concentration of a radioactive contaminant within a matrix changes with time because of processes of radiological decay and in-growth.

The rate of dissolution of the UO_2 fuel matrix is strongly dependent on the extent of radiolysis of water caused by alpha, beta and gamma radiation at the fuel surface. Beta and gamma radiation diminishes rapidly with time. After about a thousand years, a steady rate of dissolution persists indefinitely because of alpha radiation from long-lived actinides.

The rate of dissolution of the Zircaloy matrix is determined by two factors: the solubility of zirconium and the rate at which zirconium diffuses through the defect in the container into the surrounding buffer.

Some contaminants released from the used-fuel and Zircaloy matrices to the interior of the container are sparingly soluble and would precipitate within the container if their solubility limit is exceeded. Elements such as carbon, chlorine, cesium and iodine are very soluble and are not expected to precipitate under the geochemical conditions within the container. Elements such as neptunium, technetium, plutonium, thorium and uranium are relatively insoluble. We calculate their solubility limits using thermodynamic relationships and the groundwater composition at the depth of the disposal vault (Johnson et al. 1994b).

We assume that contaminants released to the interior of a failed container diffuse into the surrounding buffer through small, pinhole-sized defects that restrict and delay the movement of radionuclides out of the container. The vault model provides two different mathematical solutions to this diffusion process, depending on whether or not a contaminant precipitates within the container. Contaminants that have precipitated inside the container are modelled using a constant-concentration source term; those that have not precipitated are modelled using a time-dependent source term. The result of these calculations is the time-dependent rate of release of contaminants into the surrounding buffer.

Since the permeability of the buffer is very small, contaminants would move through it only by diffusion. In the backfills, excavation disturbed zone and surrounding rock, where advection could occur, we represent the movement of contaminants by uniform radial and axial flows as well as diffusion. Most of the parameters of the vault model are described using probability distribution functions to account for uncertainty. Parameters that vary from one sector to the next (such as groundwater velocities in the backfills, excavation disturbed zone and surrounding rock) are sampled for each vault sector in a single simulation.

5.3 VAULT-GEOSPHERE INTERFACE

The vault model simulates the performance of the engineered barriers. The geosphere model simulates the transport of contaminants through the rock domains and fracture zones in the geological formation extending from the vault to the surface. Linkages between the two models provide an integrated description of interactions between the two models, so that the combined models provide a consistent representation of the vault within the host rock.

The main output from the vault model is the time-dependent rate of flow of contaminants from each vault sector into the surrounding geosphere. These flow rates are dependent, in turn, on the hydrogeological properties of the rock domain adjoining each sector. The geosphere model provides information on the direction and magnitude of groundwater flow in the rock immediately surrounding each vault sector. It also provides information on groundwater velocities through the backfills and excavation disturbed zone for each vault sector. In this way, we ensure that the estimated flow of contaminants from a vault sector is consistent with the properties of the adjoining rock domain.

5.4 GEOSPHERE MODEL

The geosphere model for the present study (Stanchell et al. 1996) is hypothetical because it does not represent conditions we have encountered at depths below 500 m at any of our geologic research areas. We assume that the vault depth, the geometry of the geosphere model, and the arrangement of major fracture zones and rock mass domains surrounding the disposal vault are identical to those of the EIS case study (Davison et al. 1994b). However, we assume much higher permeability and lower porosity conditions in the rock domain adjacent to the vault than the conditions observed at the URL and used in the EIS case study. As a result, contaminant transport in the lower rock domain is not diffusion-dominated and the low-dipping fracture zone, LD1, is not the dominant advection pathway to the surface. The effects of geothermal gradient, vault heat and a water-supply well on the groundwater flow field have been simulated and the implications on the long-term redox conditions in the vault have been assessed. The groundwater travel times from the disposal vault to the surface are up to 10 000 times shorter in this geosphere model than in the model used for the EIS case study.

For this study, there is no advantage to constraining the location of the disposal rooms relative to LD1 as was done in the EIS case study. Thus the waste disposal rooms are located both below and above LD1 (i.e., on both the footwall and the hangingwall sides of the fracture). The 50-m distance between LD1 and the nearest waste disposal rooms is retained but is relatively insignificant because advection is the dominant transport process in the permeable lower rock domain.

The finite-element model of transport in fractured/porous media, MOTIF, is used for detailed analyses of radionuclide movement in the groundwater flow system (Stanchell et al. 1996). These analyses provide the three-dimensional groundwater flow patterns for the original, unperturbed geosphere and for a geosphere perturbed by the hypothetical disposal vault located at a depth of 500 m. The perturbations include the effects of geothermal gradients, radiogenic heat of the vault, and a water-supply well that draws water from fracture zone LD1.

We use the detailed information from MOTIF to construct a network of flow lines representing the three-dimensional groundwater flow patterns incorporated into GEONET, the geosphere component of the system model. GEONET simulates groundwater flows and contaminant movement in the region around the hypothetical vault through a network of segments and the nodes that connect them. These GEONET segments are selected to (i) represent individual parts of the modelled geosphere that have distinct chemical and physical properties, and (ii) duplicate the overall pattern of groundwater movement resulting from the analyses with MOTIF.

The geosphere model simulates the transport of contaminants released from the vault through different domains of rock, fracture zones and vertical joints, overburden and deep lake sediment, to discharge in the biosphere at topographic lows and at a water-supply well. A central feature of the geosphere model is the network of pathways representing the groundwater flow system. Figure 5 illustrates the sections of the vault and the network of segments used by GEONET to represent the flowpaths through the hypothetical geosphere assumed in this study. A flow path originates at one of the vault sectors and terminates as a discharge in the biosphere. All properties of the network are chosen to be consistent with the results from MOTIF.

For each geosphere segment in Figure 5, we simulate the movement of contaminants by advection, dispersion and diffusion. We simulate the increase and loss of contaminants caused by radioactive ingrowth and decay. We simulate sorption of contaminants on minerals through the use of a retardation factor, which is equivalent to the ratio of the groundwater velocity to the contaminant velocity. The magnitude of a retardation factor for a particular contaminant is dependent upon the composition of the groundwater and the types and amounts of minerals along the flow path (Vandergraaf et al. 1992, Ticknor and Vandergraaf 1996).

The geologic structure, and the associated geological and hydrological data, are similar in many respects to those used in the EIS case study (Davison et al. 1994b). Two changes, however, have a major effect on groundwater velocities in the geosphere for this study.

1. The first change concerns the permeability of the rock domain immediately surrounding the disposal vault. For the present study, we have assumed that the permeability of this rock domain is 10^{-17} m^2 (Stanchell et al. 1996); this value is 100 times greater than the permeability used in the EIS case study. This assumption is not based on field observations at the Whiteshell Research Area. Rather, it reflects a hypothetical situation that we introduced so that we could investigate the potential of long-lasting containers and in-room emplacement to compensate for a geosphere that is less effective as a barrier than the geosphere used in the EIS case study.

2. The second change involves the effective transport porosity of the rock domain immediately surrounding the disposal vault. For the present study, we assume that this rock domain contains a network of permeable fractures through which contaminants move. Thus the effective transport porosity is equal to the fracture porosity. We assume that the transport porosity varies from 10^{-5} to 10^{-3} to reflect different possible conceptualizations of the fractures (Stanchell et al. 1996). The range of porosities has a strong influence on the calculated variability of the rate at which contaminants move through the geosphere. In the EIS case study, we specified the effective transport porosity in the domain of low-permeability, sparsely fractured rock to be 0.003 (Davison et al. 1994b), based on measurements of rock specimens from the URL.

The smaller values assumed for effective transport porosity, plus the larger values assumed for permeability, result in much larger groundwater velocities in the present study compared with the EIS case study. In particular, calculated groundwater velocities in rock that surrounds the disposal vault are

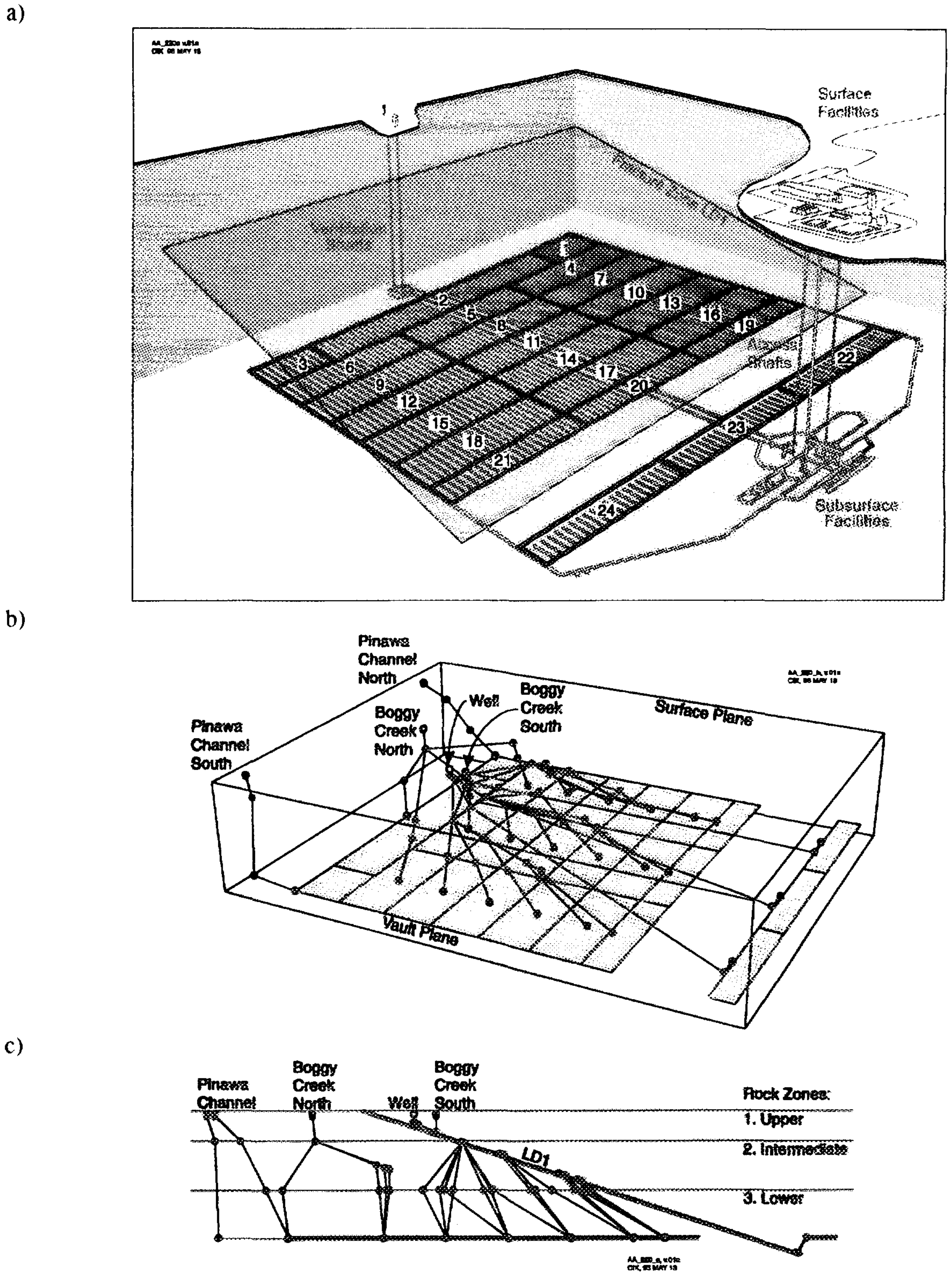


FIGURE 5: Vault Sectors and Geosphere Segments of the System Model. Part (a) illustrates the location of vault sectors relative to the intersecting fracture zone LD1; Parts (b) and (c) are a three-dimensional view and a vertical projection of the network of geosphere segments, respectively.

up to 5 orders of magnitude greater in this study than in the EIS case study. Groundwater transit times are thus much shorter in the present study. For instance, Stanchell et al. (1996) show that groundwater transit times from the disposal vault to the surface can be less than 100 years. The corresponding groundwater transit times in the EIS case study were of the order of 100 000 years or more (Davison et al. 1994b).

The net effect of these assumptions in the present study is a significant reduction of the effectiveness of the geosphere as a barrier to contaminant transport, relative to the effectiveness of the geosphere in the EIS case study. Goodwin et al. (1994a) have shown that the lower rock zone of the EIS case study is a very effective barrier because contaminant transport in the rock immediately surrounding the location of the disposal vault was dominated by slow diffusion in pore water. In this study, groundwater velocities are sufficiently large in the rock domain immediately surrounding the disposal vault such that the movement of water and the transport of contaminants is dominated by advection.

5.5 GEOSPHERE-BIOSPHERE INTERFACE

The geosphere model simulates the rate of release of contaminants to four aquatic and four terrestrial discharge zones and to a water-supply well (if it is present) in the biosphere. The biosphere model uses the output from the geosphere model as a source term to simulate contaminant movement through the biosphere and to estimate effects on humans and other biota. Linkages connecting the two models provide a consistent representation of interactions that occur between the modelled geosphere and the modelled biosphere.

The pathways leading to the aquatic discharge zones include segments representing a layer of overburden and a layer of lake sediment; and pathways leading to the associated terrestrial discharge zones include a segment representing a layer of overburden. The properties of these segments are consistent with the types and amounts of minerals found in the overburden and the sediment and with the magnitude and direction of groundwater flow determined by MOTIF for adjacent segments in the bedrock.

Figure 6 shows in plan view the locations of the discharges to the biosphere superimposed on the layout of the vault at 500-m depth. Four locations (designated Boggy Creek North, Boggy Creek South, Pinawa Channel North and Pinawa Channel South) include both an aquatic discharge at topographic lows and an adjacent terrestrial discharge. We assume these locations are equivalent to a lake in the biosphere model. The fifth location is a water-supply well used by the critical group as their source of domestic water. In simulations where a well is present, it may be one of the more important discharge points of contaminants from the vault.

The biosphere model specifies whether the critical group uses a lake or a water-supply well as their source of water. Based on current-day usage of water-supply wells on the Canadian Shield, there is about a 50% probability that the critical group would rely on a water-supply well (Davis et al. 1993).

When a water-supply well is present, we restrict its depth to 100 m. We exclude deeper wells because they could have large perturbations on groundwater flow patterns, which would invalidate the network of segments described above. (A full postclosure assessment would deal with deeper wells; however, historic usage indicates that wells deeper than 100 m are relatively unlikely (Goodwin et al. 1996).)

For simulations that include a water-supply well, we ensure that the well-water demands set in the biosphere model are consistent with the flow capacity that is determined in the geosphere model. The well-water demand depends on factors such as the size of the critical group and whether or not well water

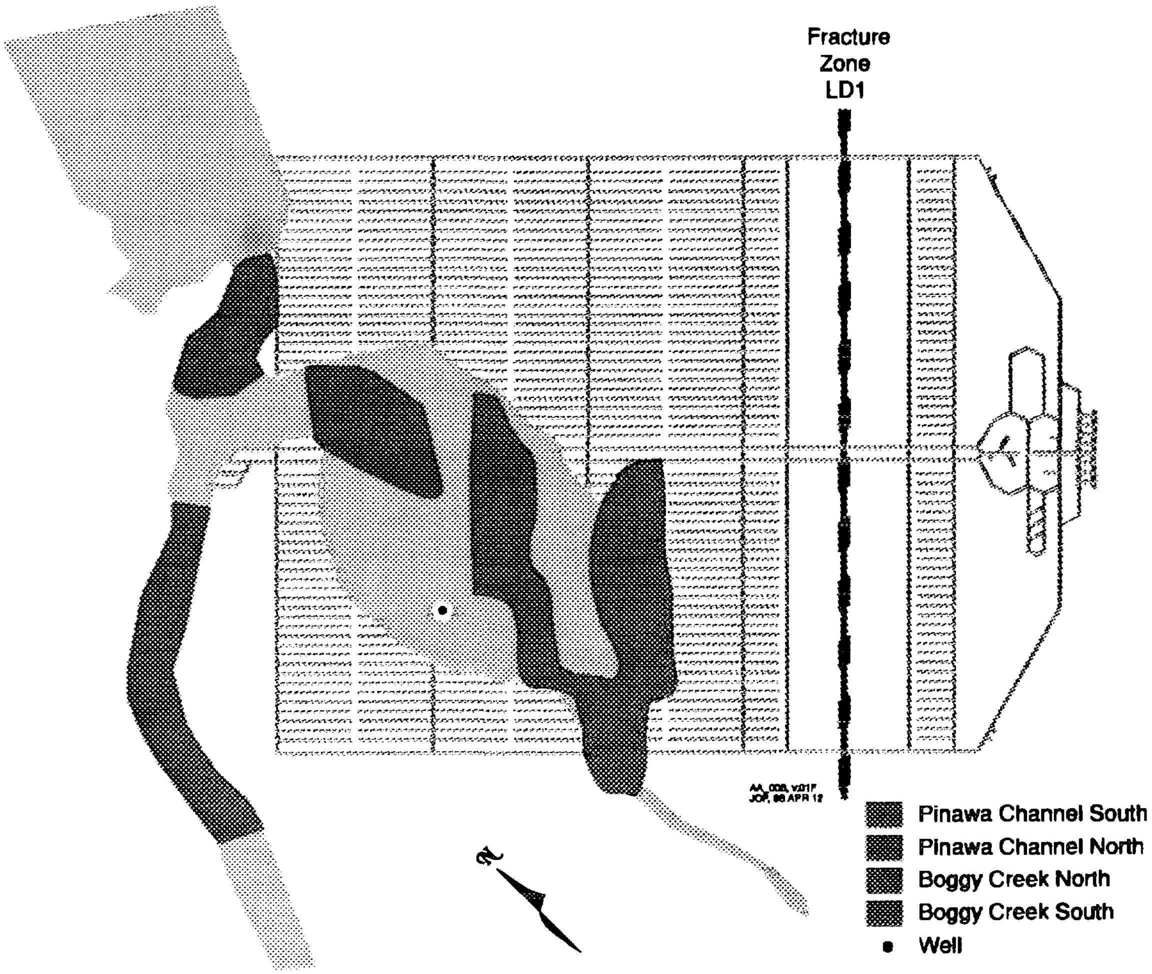


FIGURE 6: Plan View Illustrating the Location of the Discharge Zones Superimposed on the Layout of the Vault

is used for irrigation. The flow capacity of the well depends on the depth and location of the well and the physical properties of the rock zones from which the water is drawn.

If the demand exceeds the capacity of the well to supply water, then we reduce the demand by assuming that the critical group augments their requirements with water drawn from the lake. The adjusted well demand is then used in the geosphere model to calculate the effects of the rates of water withdrawal on the hydraulic heads of all affected GEONET segments.

The geosphere model also provides the areal extents and discharge rates associated with the groundwater discharge zones as inputs to the biosphere model.

5.6 BIOSPHERE MODEL

The biosphere model for the present study (Zach et al. 1996) includes a number of changes, notably inclusion of additional radionuclides with shorter half-lives, inhalation pathways for animals, the most recent internal dose conversion factors of the International Commission on Radiological Protection (ICRP 1991a,b), geosphere dose limits for non-human biota, updated values of model input parameters, and a modified biosphere/geosphere interface to account more fully for terrestrial discharge of radionuclides.

Zach et al. (1996) describe and justify the assumptions, model and data used to analyze the movement of contaminants through the near-surface and surface environments and to estimate radiological doses to humans and other biota. The biosphere model for the present study is fundamentally the same as the BIOTRAC model for the postclosure assessment case study presented in the EIS (Davis et al. 1993). However, this model has been updated and expanded based on new research data (Zach et al. 1996). This updated model is called BIOTRAC2 (BIOsphere TRansport And Consequence model - version 2).

The BIOTRAC2 model, like its predecessor, is representative of the Canadian Shield for up to 10 000 years into the future, the quantitative assessment period specified by the AECB (1987). This period is assumed to be free from continental glaciation.

The BIOTRAC2 model is driven by the nuclides released from the geosphere. The nuclides are traced through the surface environment to estimate various environmental concentrations, and radiological doses for humans (annual committed effective dose equivalent) and other biota (annual absorbed dose). Humans are represented in the BIOTRAC2 model by the critical group, located where nuclides discharge from the geosphere into the biosphere and where dilution is at a minimum. Moreover, the critical group is totally self-sufficient and dependent for all of its needs on the local, potentially contaminated environment. Although this lifestyle is very unlikely, it ensures that consequences are not underestimated. Non-human biota are represented by several generic target organisms - a terrestrial plant, a mammal, a bird and a fish (Amiro and Zach 1993). They share the environment with the critical group and so are also exposed in the same conservative way.

Figure 7 shows the conceptual landscape of the modelled biosphere, which includes a lake and lake sediment, a water-supply well, the atmosphere outside and inside buildings, and the soils in cultivated and natural fields that supply food, fuel and building materials and that serve as the habitat for native plants and wildlife.

Figure 8 shows schematically the underlying structure of the biosphere model. The model consists of 6 submodels: one representing the geosphere-biosphere interface and 5 representing the surface water, soil, atmosphere, and human and non-human food-chain compartments (Zach et al. 1996).

The interface submodel estimates the concentrations of contaminants in the groundwaters arriving at the discharge zones shown in Figure 6. Since it links directly to the geosphere model, it has attributes specific to the WRA. Each of these discharge zones has an aquatic and a terrestrial portion. The interface submodel includes bedrock and overburden wells that can be used as a source of relatively undiluted water by the critical group.

The surface water submodel estimates contaminant concentrations in nearby lake and lake sediments. Once in the water, nuclides may be deposited to the mixed sediment or lost through lake flushing, gaseous evasion and radioactive decay. They may also be transferred to the land through irrigation.

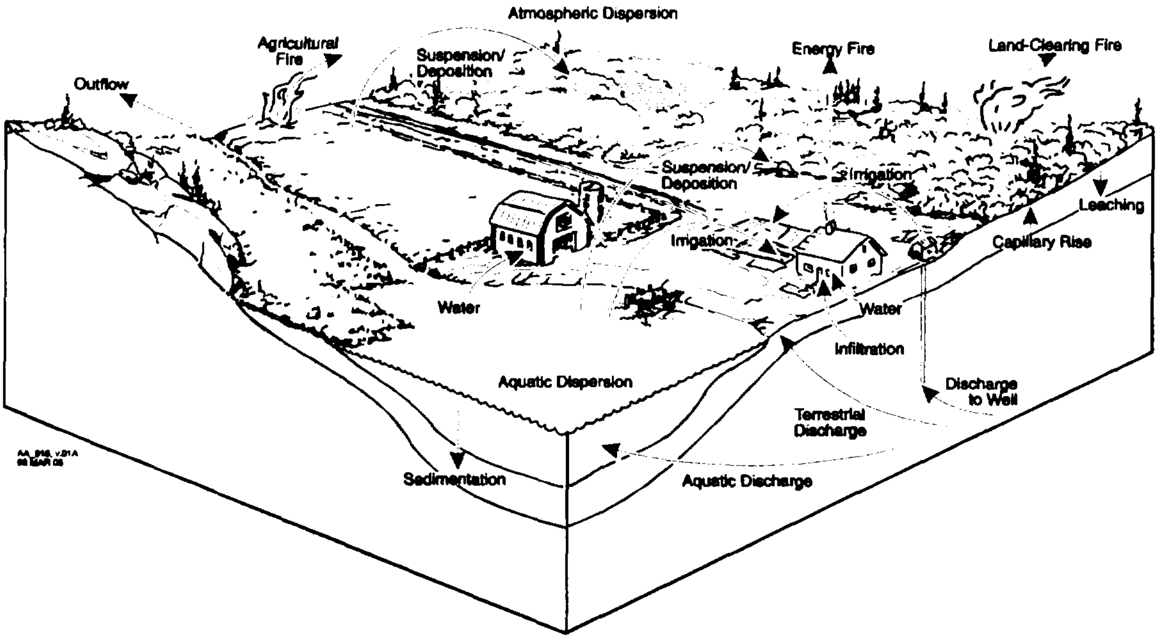


FIGURE 7: Conceptual Landscape of the Modelled Biosphere

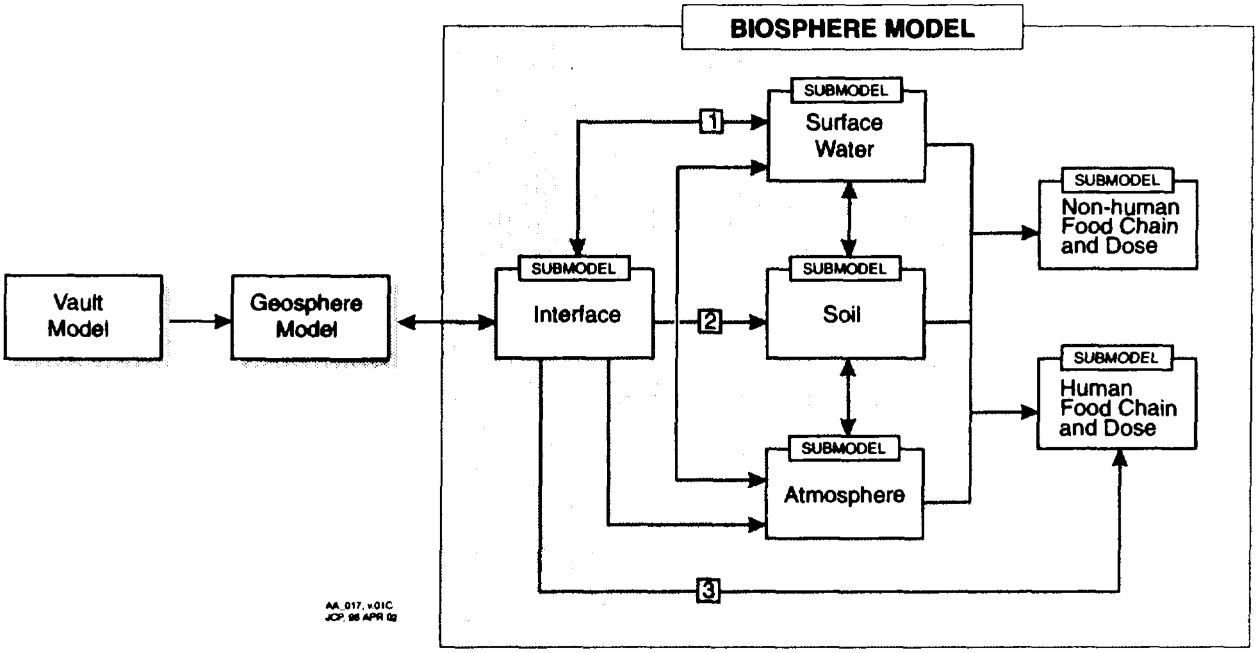


FIGURE 8: *Schematic* Showing the Compartments of the Biosphere Model BIOTRAC2

The soil submodel estimates contaminant concentrations in the soil of a garden, forage field, woodlot and peat bog used by the critical group. Several soil types are considered. The soil profile can become contaminated through terrestrial discharge to the bottom of the soil profile and through irrigation on top with contaminated water. Nuclides can move through the soil profile through capillary rise and leaching, and they may be lost through drainage, gaseous evasion and radioactive decay. Nuclide concentrations are estimated for several fields, including a garden and a forage field for animals.

The atmosphere submodel estimates contaminant concentrations in the air (indoor and outdoor) surrounding the critical group. It simulates nuclide suspension from the lake and soil as well as from burning of biomass. The model also allows for atmospheric dispersion and deposition that can result in the loss of nuclides.

The human food-chain and dose submodel estimates contaminant concentrations in plants and animals consumed by the critical group, and internal and external radiation exposures to members of the critical group. It includes all the important internal and external pathways that might lead to radiation exposure of the critical group, based on the estimated nuclide concentrations in the surface water (lake or well), soil and air. For most of the nuclides, transfer is handled through transport models. However, alternative specific-activity models are also used. They take into account the special attributes of radionuclides such as ^{3}H, ^{14}C, ^{36}Cl and ^{129}I. For the last three of these nuclides, specific-activity models based on isotopic dilution of nuclide concentrations in groundwater discharging to the biosphere are used to establish upper dose limits.

The non-human food-chain and dose submodel estimates internal and external radiation exposures to four generic non-human organisms. It closely reflects the submodel for humans. The non-human biota rely only on the lake water and the forage field for their survival.

5.7 RADIONUCLIDES CONSIDERED IN THIS STUDY

As mentioned in Section 4, we assume that all fuel bundles are from the Bruce Nuclear Generating Station, that each bundle has produced thermal energy amounting to 720 GJ/kg of initial uranium, and that they have been stored out of the reactor for at least ten years. The used-fuel bundles will contain UO_2 and constituents of Zircaloy, plus

- fission products generated during the fissioning of the UO_2 and neutron activation products of impurities in the UO_2 fuel,
- neutron activation products of the constituents and impurities in the Zircaloy sheaths, and
- members of the actinide decay chains produced by the neutron activation of uranium isotopes.

A comprehensive study (Johnson et al. 1996) provides the radionuclide inventories of these fission products, activation products, and decay chain members.

By a process of importance ranking and screening (Goodwin et al. 1996; Goodwin and Mehta 1994), we focus on the radionuclides that are expected to be the dominant contributors to the total radiation dose over times scales up to 100 000 years following closure of the disposal vault.

A total of 41 radionuclides are considered in this study, of which 16 are fission products or activation products (Table 1) and 25 are members of actinide decay series (Table 2). The actinide decay series are simplified as follows:

4n+1 chain: ^{241}Am → ^{237}Np (^{233}Pa) → ^{233}U → ^{229}Th (^{225}Ra) (^{225}Ac)

4n+2 chain: ^{238}U (^{234}Th) → ^{234}U → ^{230}Th → ^{226}Ra (^{222}Rn) (^{210}Pb) (^{210}Bi) (^{210}Po)

4n+3 chain: ^{243}Am (^{239}Np) → ^{239}Pu → ^{235}U (^{231}Th) → ^{231}Pa (^{227}Ac) (^{227}Th) (^{223}Ra)

Radionuclides in parentheses are treated as being in secular equilibrium with their precursor as discussed in Goodwin and Mehta (1994).

TABLE 1

FISSION PRODUCTS AND ACTIVATION PRODUCTS CONSIDERED IN THIS STUDY

Radionuclide	Source	Half-Life [a]	Inventory [mol/kg U][a]
^{14}C	F[e]	5.73×10^3	3.70×10^{-6}
^{14}C	Z[f]	5.73×10^3	1.46×10^{-6}
^{36}Cl	F	3.01×10^5	9.18×10^{-6}
^{36}Cl	Z	3.01×10^5	7.31×10^{-7}
^{135}Cs	F	2.30×10^6	1.78×10^{-4}
^{137}Cs	F	3.00×10^1	1.86×10^{-3}
^{129}I	F	1.57×10^7	3.80×10^{-4}
^{93m}Nb[b]	F	1.36×10^1	0.0
^{107}Pd	F	6.50×10^6	5.95×10^{-4}
^{126}Sb[c]	F	3.40×10^{-2}	0.0
^{79}Se	F	6.50×10^4	1.60×10^{-5}
^{126}Sn	F	1.00×10^5	4.55×10^{-5}
^{90}Sr	F	2.91×10^1	1.16×10^{-3}
^{99}Tc	F	2.13×10^5	2.21×10^{-3}
^{90}Y[d]	F	7.30×10^{-3}	0.0
^{93}Zr	F	1.53×10^6	1.26×10^{-3}

[a] Median values for 10-a cooled fuel, 720 GJ/kg burnup
[b] Progeny of ^{93}Zr
[c] Progeny of ^{126}Sn
[d] Progeny of ^{90}Sr
[e] F refers to used fuel
[f] Z refers to Zircaloy sheath

TABLE 2

MEMBERS OF THE ACTINIDE DECAY SERIES CONSIDERED IN THIS STUDY

Radionuclide	Decay Series	Half-Life [a]	Inventory [mol/kg U][a]
^{225}Ac	4n+1	2.74×10^{-2}	0.0
^{227}Ac	4n+3	2.18×10^{1}	0.0
^{241}Am	4n+1	4.32×10^{2}	4.00×10^{-4}
^{243}Am	4n+3	7.38×10^{3}	1.63×10^{-5}
^{210}Bi	4n+2	1.37×10^{-2}	0.0
^{237}Np	4n+1	2.14×10^{6}	1.34×10^{-4}
^{239}Np	4n+3	6.45×10^{-3}	0.0
^{231}Pa	4n+3	3.28×10^{4}	3.50×10^{-8}
^{233}Pa	4n+1	7.39×10^{-2}	0.0
^{210}Pb	4n+2	2.23×10^{1}	0.0
^{210}Po	4n+2	3.79×10^{-1}	0.0
^{239}Pu	4n+3	2.41×10^{4}	1.12×10^{-2}
^{223}Ra	4n+3	3.13×10^{-2}	0.0
^{225}Ra	4n+1	4.05×10^{-2}	0.0
^{226}Ra	4n+2	1.60×10^{3}	3.11×10^{-13}
^{222}Rn	4n+2	1.05×10^{-2}	0.0
^{227}Th	4n+3	5.12×10^{-2}	0.0
^{229}Th	4n+1	7.34×10^{3}	1.58×10^{-9}
^{230}Th	4n+2	7.70×10^{4}	6.06×10^{-9}
^{231}Th	4n+3	2.91×10^{-3}	0.0
^{234}Th	4n+2	6.60×10^{-2}	0.0
^{233}U	4n+1	1.59×10^{5}	3.55×10^{-5}
^{234}U	4n+2	2.44×10^{5}	1.92×10^{-4}
^{235}U	4n+3	7.04×10^{8}	8.15×10^{-3}
^{238}U	4n+2	4.47×10^{9}	4.14×10^{0}

[a] Median values for 10-year cooled fuel, 720 GJ/kg burnup

6. ESTIMATED LONG-TERM EFFECTS

The 10 000-year time frame for regulatory compliance, the large spatial domain of the groundwater flow system represented in the geosphere model, and the size, complexity and layout of the engineered system represented in the vault model all lead to a high variability and uncertainty in assessing the performance of the disposal system specified for this study. We deal with this variability and uncertainty using a probabilistic assessment method based on the Systems Variability Analysis Code, SYVAC. This method enables us to handle the spatial and temporal uncertainty over the entire parameter space of the system model in an efficient and systematic way.

In this study, our probabilistic analyses were based on 14 000 randomly sampled simulations. In each simulation, a value for every parameter is sampled randomly from its associated probability density function. We use the sampled values to simulate the release of contaminants from the vault and their movement through the geosphere and biosphere, and to estimate their effect on the critical group. The thousands of estimates yield a distribution of possible effects that directly reflects the underlying uncertainty in the long-term performance of the disposal system. We then compute the statistical expectation of an effect; it is simply its arithmetic average from the thousands of simulations. The arithmetic average is an unbiased representation of the entire set of estimates and is used to calculate the radiological risk, as prescribed in AECB (1987).

The time frame required for quantitative evaluation of effects is 10 000 years (AECB 1987), and the system model and data of the disposal system are considered to provide acceptable estimates for times up to the onset of the next continental glaciation, about 20 000 years from now. Some processes of the system model would be dramatically affected by glacial cycles while others would not. For example, a glaciation would disrupt the movement of contaminants in the biosphere; however, it would have relatively little affect on their movement away from the vault because the container can be designed to withstand glacial loads. Our analyses are therefore focused on quantitative estimates of effects for the first 10 000 years following closure of the disposal vault (Goodwin et al. 1996).

Nevertheless, we present some results that are extended to ten million years after closure. These results are clearly beyond the acceptable time frame of the system model; however, we show them because they provide evidence that the models and data exhibit the expected mathematical behaviour. For example, we expect that doses from all radionuclides must eventually decrease because of radioactive decay and that the time of arrival and duration of dose from a radionuclide will be strongly affected by its half-life and by its rate of movement through the engineered and natural barriers. The results extended to ten million years can be examined to confirm that these expectations are met and thereby give confidence in the behaviour of the system model at earlier times. Moreover, the extrapolated results describe trends in the behaviour of the undisturbed system over the very long term and these results can be compared with similar results produced by other national waste management programs (Safety Assessment Management 1996).

We present in this summary the average dose rate to members of the critical group from fission and activation products and from members of the actinide decay chains. Goodwin et al. (1996) provide a more comprehensive description of the analyses, including estimated effects on non-human biota.

Figure 9 shows the average dose rate as a function of time for the fission and activation products that contribute most to the total dose. This dose rate reaches a maximum of about 2×10^{-6} Sv per year at about 10 000 years following closure. The horizontal line, at 5×10^{-5} Sv per year, is the dose rate associated with the AECB radiological risk criterion (AECB 1987). The shaded area on the right-hand side of the plot indicates the models and data are less acceptable representations of the disposal system at very long time frames. Individual radionuclides reach their maxima at different times as shown: ^{129}I dominates the peak dose rate of 2×10^{-6} Sv per year at 10 000 years; ^{90}Sr and its progeny, ^{90}Y, dominates the leading edge of the rising dose rate curve for the first few hundred years; ^{36}Cl reaches a maximum estimated dose rate of 8×10^{-8} Sv per year at 10 000 years; ^{14}C peaks at 2×10^{-8} Sv per year at 20 000 years; and other radionuclides become important at longer times.

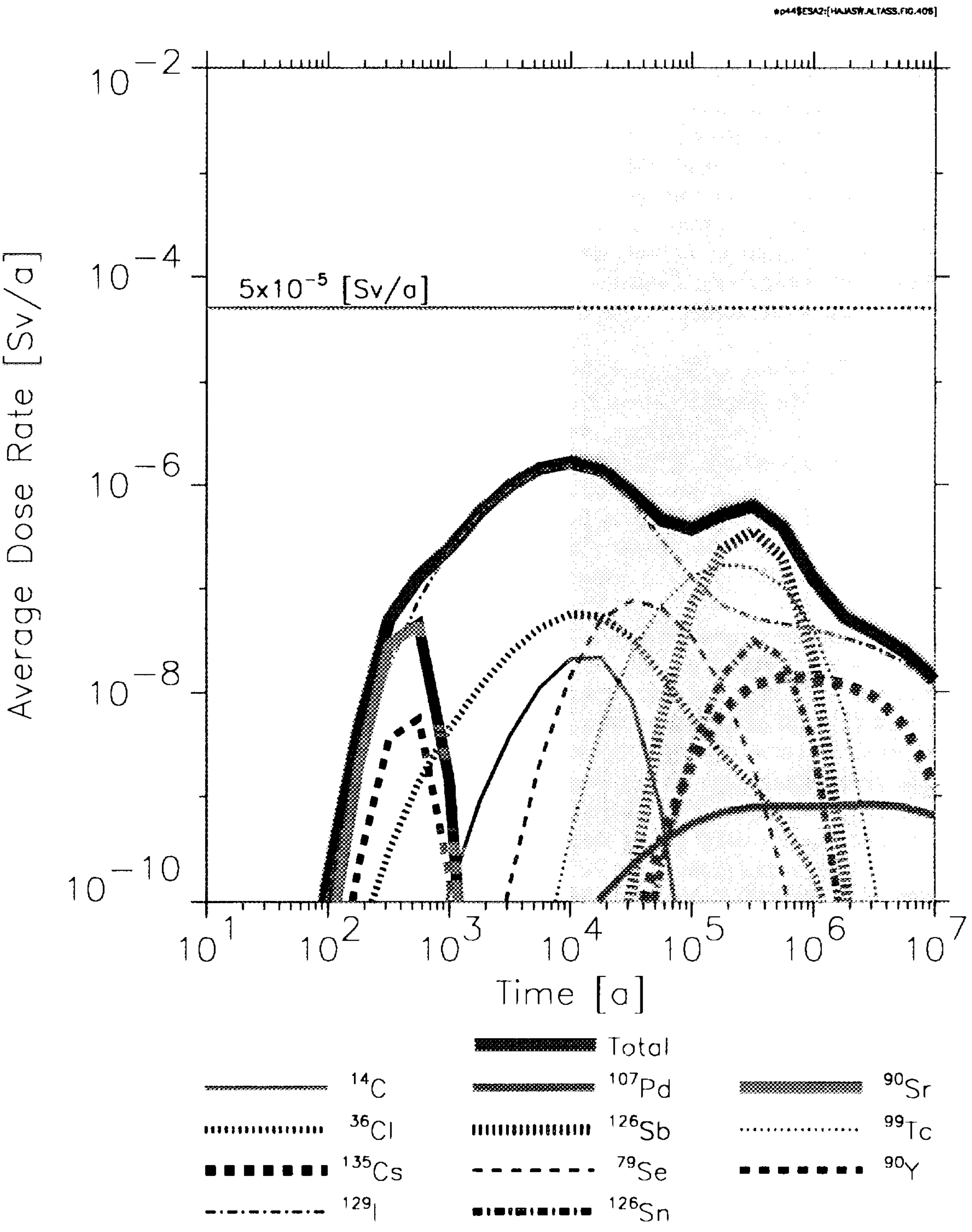


FIGURE 9: Contributions of Fission and Activation Products to the Average Dose Rate to the Critical Group

Figure 10 shows average dose rate as a function of time for members of the actinide decay chains. The dose rates are insignificant before 10 000 years and remain below 10^{-7} Sv per year for the entire time span of the simulation. These radionuclides are released slowly as the UO_2 matrix dissolves. The bulk of the inventory of each chain is found in isotopes of uranium (^{238}U, ^{235}U, ^{234}U and ^{233}U), neptunium (^{237}Np) and plutonium (^{239}Pu) (Table 2). These elements sorb on the buffer, the backfills and the rock surrounding the disposal vault and they would likely precipitate in the container, so that their releases to the biosphere are small. The largest contributions to the total estimated dose rate are associated with most members of the 4n+1 chain and with five radionuclides (^{210}Pa, ^{210}Pb, ^{222}Rn, ^{227}Ac and ^{231}Pa) near the ends of the 4n+2 and 4n+3 chains.

Effects occur relatively early for the system specified for this study compared with the reference system in the EIS case study. This is due primarily to the short travel times for groundwater to move from the depth of the vault to the surface environment, resulting in contributions from radionuclides with shorter half-lives and higher specific activities.

The more robust engineered barriers of the system specified for this study, notably the longer-lasting containers, limit the effects for times beyond 10 000 years. We assume that, on average, about 1 in 5000 containers have fabrication defects at the time of closure of the disposal vault and that contaminants are then slowly released from the containers by diffusion through small pinhole-sized defects into the surrounding buffer. Because there are no further container failures, the average dose rates eventually decline. The dose rate maxima obtained in this study indicate that suitable engineered barriers can compensate for a geosphere barrier that is assumed to be relatively ineffective.

The preceding discussion summarizes the average dose rate estimates from a large number of simulations. Figure 11 shows the distribution of total dose rate from 3000 randomly sampled simulations as a function of time. It illustrates the high variability from one simulation to another. Each of the percentile bands contains dose rates from 20% of the simulations; the bottom band corresponds to the 20% of the simulations that had the smallest total dose rate estimates, the next band corresponds to the next 20%, and so on. The upper envelope of the entire set of simulations is shown by the dashed line. The solid line crossing the bands is the total average dose rate estimate from Figure 9. This type of quantile analysis illustrates the large variability in the behaviour of the system specified for this study. Figure 11 also illustrates that the variability is highly skewed, since the average dose rate lies close to the 80th percentile, indicating that the simulations with the highest doses dominate the average value. The maximum dose rate from this set of probabilistic calculations is up to 1000 times greater than the average dose rate, and, throughout the entire simulation period, is below the dose rate of 3 x 10^{-3} Sv per year associated with natural background.

Goodwin et al. (1996) provide a detailed discussion of the results of the probabilistic analyses, showing the effects on both people in the critical group and nonhuman biota, the effects of selected simulations and sub-scenarios, the performance of the engineered and natural barriers, and the fate of individual radionuclides.

7. CONCLUSIONS

- The EIS case study and the present study demonstrate that our performance assessment methods and modelling approaches are flexible and can be readily adapted to different design features and site characteristics representing alternative hypothetical

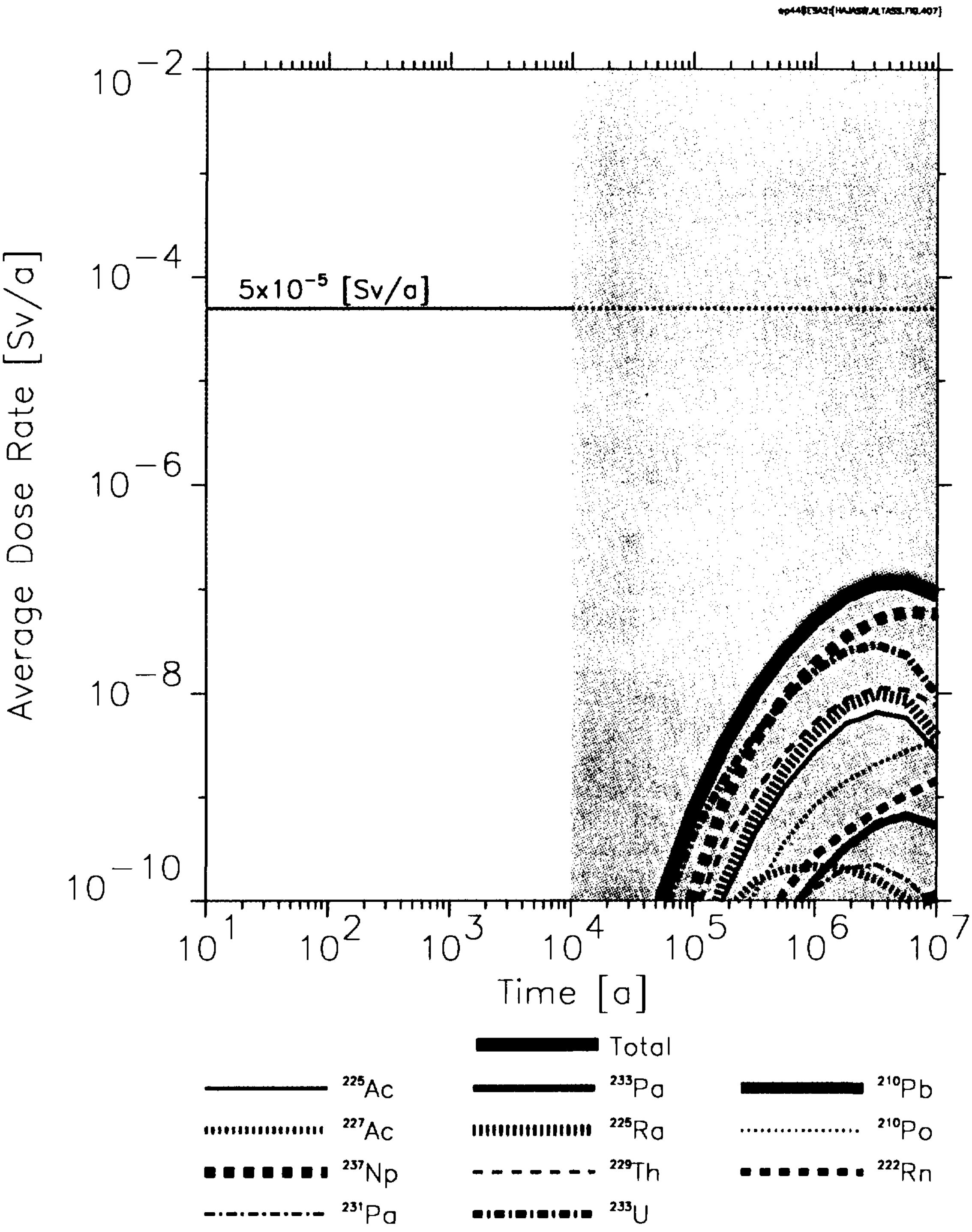


FIGURE 10: Contributions of Members of Actinide Decay Chains to the Average Dose Rate to the Critical Group

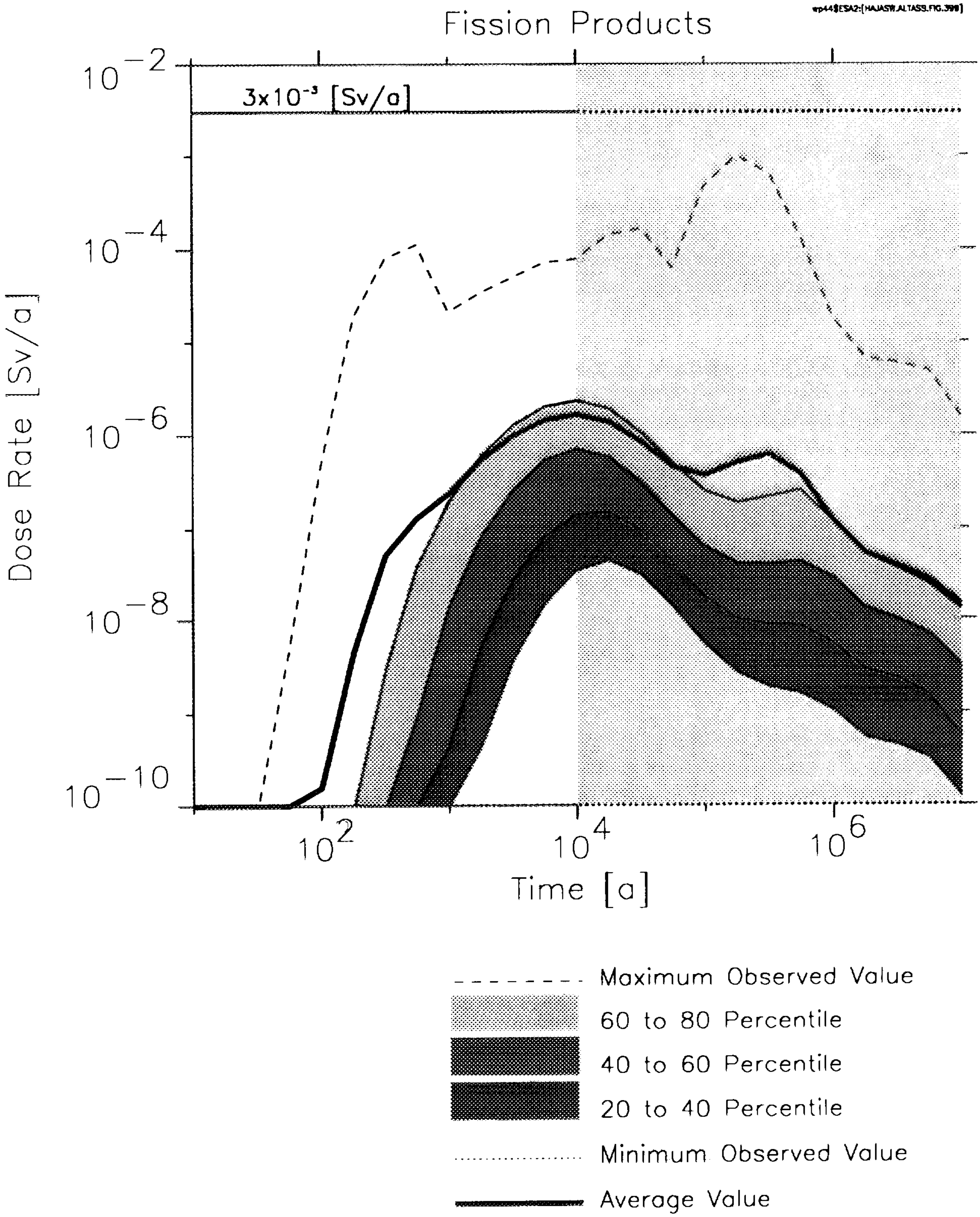


FIGURE 11: Percentile Bands of Dose Rate to the Critical Group for 3000 Random Simulations

implementations of the disposal concept. The probabilistic methodology is effective in handling the large uncertainties associated with the performance of the modelled systems.

- The EIS case study illustrates the potential effectiveness of a domain of low-permeability, sparsely fractured rock in inhibiting the movement of contaminants through the geosphere. Diffusion is the dominant contaminant process for such a host-rock condition.

- The present study illustrates the potential effectiveness of the in-room emplacement method and long-lasting containers in inhibiting the release of contaminants for a host-rock condition in which advection is the dominant contaminant transport process. (The geological conditions specified for this study have not been encountered at depths below 500 m at any of the field research areas investigated in the Canadian Shield.)

- The EIS case study, the study to identify a favourable vault location, and the present study illustrate the flexibility of AECL's disposal concept to take advantage of the retention, delay, dispersion, dilution and radioactive decay of contaminants in a system of natural barriers provided by the geosphere and the hydrosphere and of engineered barriers provided as design options (i.e., waste form, container, buffer and backfills).

- In an actual implementation of the disposal concept, the engineered system would be designed for the geological conditions encountered at the host site and the expected evolution of those conditions over the long term.

REFERENCES

AECB (Atomic Energy Control Board). 1987. Regulatory policy statement. Regulatory objectives, requirements and guidelines for the disposal of radioactive wastes — long-term aspects. Atomic Energy Control Board Regulatory Document R-104, 1987 June 5.

AECL (Atomic Energy of Canada Limited). 1994a. Environmental impact statement on the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10711, COG-93-1. Available in French and English.

AECL (Atomic Energy of Canada Limited). 1994b. Summary of the environmental impact statement on the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10721, COG-93-11. Available in French and English.

Amiro, B.D. and R. Zach. 1993. A method to assess environmental acceptability of releases of radionuclides from nuclear facilities. Environment International 19, 341-358.

Baumgartner, P., D.M. Bilinsky, C. Onofrei, Y. Ates, F. Bilsky, J.L. Crosthwaite and G.W. Kuzyk. 1995. The in-room emplacement method for a used-fuel disposal facility - preliminary design considerations. Atomic Energy of Canada Technical Record, TR-665, COG-94-533.

Baumgartner, P., D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, and D.A. Dixon. 1996. Engineering for a disposal facility using the in-room emplacement method. Atomic Energy of Canada Limited Report, AECL-11595, COG-96-223.

Davis, P.A., R. Zach, M.E. Stephens, B.D. Amiro, G.A. Bird, J.A.K. Reid, M.I. Sheppard, S.C. Sheppard and M. Stephenson. 1993. The disposal of Canada's nuclear fuel waste: The biosphere model, BIOTRAC, for postclosure assessment. Atomic Energy of Canada Limited Report, AECL-10720, COG-93-10.

Davison, C.C., A. Brown, R.A. Everitt, M. Gascoyne, E.T. Kozak, G.S. Lodha, C.D. Martin, N.M. Soonawala, D.R. Stevenson, G.A. Thorne and S.H. Whitaker. 1994a. The disposal of Canada's nuclear fuel waste: Site screening and site evaluation technology. Atomic Energy of Canada Limited Report AECL-10713, COG-93-3.

Davison, C.C., T. Chan, A. Brown, M. Gascoyne, D.C. Kamineni, G.S. Lodha, T.W. Melnyk, B.W. Nakka, P.A. O'Connor, D.U. Ophori, N.W. Scheier, N.M. Soonawala, F.W. Stanchell, D.R. Stevenson, G.A. Thorne, T.T. Vandergraaf, P. Vilks and S.H. Whitaker. 1994b. The disposal of Canada's nuclear fuel waste: The geosphere model for postclosure assessment. Atomic Energy of Canada Limited Report, AECL-10719, COG-93-9.

Goodwin, B.W. and K.K. Mehta. 1994. Identification of contaminants of concern for the postclosure assessment of the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10901, COG-93-265.

Goodwin, B.W., D.B. McConnell, T.H. Andres, W.C. Hajas, D.M. LeNeveu, T.W. Melnyk, G.R. Sherman, M.E. Stephens, J.G. Szekely, P.C. Bera, C.M. Cosgrove, K.D. Dougan, S.B. Keeling, C.I. Kitson, B.C. Kummen, S.E. Oliver, K. Witzke, L. Wojciechowski and A.G. Wikjord. 1994a. The disposal of Canada's nuclear fuel waste: Postclosure assessment of a reference system. Atomic Energy of Canada Limited Report, AECL-10717, COG-93-7.

Goodwin, B.W., M.E. Stephens, C.C. Davison, L.H. Johnson and R. Zach. 1994b. Scenario analysis for the postclosure assessment of the concept for the disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10969.

Goodwin, B.W., T.H. Andres, W.C. Hajas, D.M. LeNeveu, T.W. Melnyk, J.G. Szekely, A.G. Wikjord, D.C. Donahue, S.B. Keeling, C.I. Kitson, S.E. Oliver, K. Witzke and L. Wojciechowski. 1996. 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. Volume 5: Radiological assessment. Atomic Energy of Canada Limited Report, AECL-11494-5, COG-95-552-5.

Greber, M.A., E.R. Frech and J.A.R. Hillier. 1994. The disposal of Canada's nuclear fuel waste: Public involvement and social aspects. Atomic Energy of Canada Limited Report, AECL-10712, COG-93-2.

Grondin, L., K. Johansen, W.C. Cheng, M. Fearn-Duffy, C.R. Frost, T.F. Kempe, J. Lockhart-Grace, M. Paez Victor, H.E. Reid, S.B. Russell, C.H. Ulster, J.E. Villagran and M. Zeya. 1994. The disposal of Canada's nuclear fuel waste: Preclosure assessment of a conceptual system. Ontario Hydro Report N-03784-940010 (UFMED), COG-93-6.

Hoek, E. and E.T. Brown. 1980. Underground Excavations in Rock. The Institution of Mining and Metallurgy, London.

ICRP (International Commission on Radiological Protection). 1991a. 1990 recommendations of the International Commission on Radiological Protection. Annals of the ICRP 21(1-3) (ICRP Publication 60).

ICRP (International Commission on Radiological Protection). 1991b. Annual limits on intake of radionuclides by workers based on the 1990 recommendations. Annals of the ICRP 21(4) (ICRP Publication 61).

Johnson, L.H., J.C. Tait, D.W. Shoesmith, J.L. Crosthwaite and M.N. Gray. 1994a. The disposal of Canada's nuclear fuel waste: Engineered barriers alternatives. Atomic Energy of Canada Limited Report, AECL-10718, COG-93-8.

Johnson, L.H., D.M. LeNeveu, D.W. Shoesmith, D.W. Oscarson, M.N. Gray, R.J. Lemire and N. Garisto. 1994b. The disposal of Canada's nuclear fuel waste: The vault model for postclosure assessment. Atomic Energy of Canada Limited Report, AECL-10714, COG-93-4.

Johnson, L.H., D.M. LeNeveu, F. King, D.W. Shoesmith, M. Kolar, D.W. Oscarson, S. Sundar, C. Onofrei and J.L. Crosthwaite. 1996. 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. Volume 2: Vault Model. Atomic Energy of Canada Limited Report, AECL-11494-2, COG-95-552-2.

Ophori, D.U., D.R. Stevenson, M. Gascoyne, A. Brown, C.C. Davison, T. Chan and F.W. Stanchell. 1995. Revised model of regional groundwater flow of the Whiteshell Research Area: Summary. Atomic Energy of Canada Limited Report, AECL-11286, COG-95-115.

Ophori, D.U., A. Brown, T. Chan, C.C. Davison, M. Gascoyne, N.W. Scheier, F.W. Stanchell and D.R. Stevenson. 1996. Revised model of regional groundwater flow in the Whiteshell Research Area. Atomic Energy of Canada Limited Report, AECL-11435, COG-95-443.

Safety Assessment Management, UK. 1996. An international comparison of disposal concepts and postclosure assessments for nuclear fuel waste disposal. TR-M-43. Unpublished contractor's report prepared for Atomic Energy of Canada Limited, available from Library, Reports Services, AECL, Whiteshell Laboratories, Pinawa, Manitoba, Canada R0E 1L0.

Simmons, G.R. and P. Baumgartner. 1994. The disposal of Canada's nuclear fuel waste. Engineering for a disposal facility. Atomic Energy of Canada Limited Report, AECL-10715, COG-93-5.

SKB. 1992. SKB 91 Final disposal of spent nuclear fuel: Importance of the bedrock for safety. SKB Technical Report 92-20, Stockholm.

Stanchell, F.W., C.C. Davison, T.W. Melnyk, N.W. Scheier and T. Chan. 1996. 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. Volume 3: Geosphere model. Atomic Energy of Canada Limited Report, AECL-11494-3, COG-95-552-3.

Stevenson, D.R., A. Brown, C.C. Davison, M. Gascoyne, R.G. McGregor, D.U. Ophori, N.W. Scheier, F.W. Stanchell, G.A. Thorne and D.K. Tomsons. 1995. A revised conceptual hydrogeologic model of a crystalline rock environment, Whiteshell Research Area, Southeastern Manitoba, Canada. In Solutions '95, Proceedings of the International Association of Hydrogeologists, Congress XXVI, 1995, Edmonton, AB.

Stevenson, D.R., A. Brown, C.C. Davison, M. Gascoyne, R.G. McGregor, D.U. Ophori, N.W. Scheier, F.W. Stanchell, G.A. Thorne and D.K. Tomsons. 1996. A revised conceptual hydrogeologic model of a crystalline rock environment, Whiteshell Research Area, southeastern Manitoba, Canada. Atomic Energy of Canada Limited Report, AECL-11331, COG-95-271.

Ticknor K.V. and T.T. Vandergraaf. 1996. A revised compilation of sorption coefficients for use in geosphere models in performance assessments of used fuel disposal in granitic environments. Atomic Energy of Canada Limited Report, AECL-11343, COG-96-71.

Tsai, A. 1995. Supplementary thermal-mechanical near-field analyses for disposal vaults with the in-room emplacement method: 500 m and 750 m depths. Ontario Hydro Report N-REP-03788-0101 R00 (UFMED).

Vandergraaf, T.T., K.V. Ticknor and T.W. Melnyk. 1992. The selection and use of a sorption data base for the geosphere model in the Canadian nuclear fuel waste management program. In Radionuclide Sorption from the Safety Evaluation Perspective, Proceedings of an NEA Workshop, Interlaken, Switzerland, 1991 October, Nuclear Energy Agency, Organisation for Economic Cooperation and Development, Paris, 1992.

Wai, R.S.C. and A. Tsai. 1995. Three-dimensional thermal and thermal-mechanical analyses for a used-fuel disposal vault with the in-room emplacement option. Ontario Hydro Report No. N-REP-03780-0083 R00 (UFMED).

Zach, R., B.D. Amiro, G.A. Bird, C.R. Macdonald, M.I. Sheppard, S.C. Sheppard and J.G. Szekely. 1996. 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. Volume 4: Biosphere model. Atomic Energy of Canada Limited Report, AECL-11494-4, COG-95-552-4.

ACKNOWLDGEMENTS

The authors thank C.J. Allan, K. Nuttall, G.R. Simmons, P.A. Gillespie and S.H. Whitaker for their critical review of a draft of this report; C.I. Kitson, W.C. Hajas and S.E. Oliver for their assistance in reproducing the figures; and E.N. Henschell and M.A. Ryz for preparing the manuscript.

This study was conducted for the Canadian Nuclear Fuel Waste Management Program, which is jointly funded by AECL and Ontario Hydro under the auspices of the CANDU Owners Group.

APPENDIX

COMPARISON OF EIS CASE STUDY AND THE PRESENT STUDY

The key features of the EIS postclosure assessment case study and the present study are summarized as follows:

	EIS CASE STUDY	PRESENT STUDY
DESIGN CONSIDERATIONS		
Emplacement option	borehole	in-room
Vault area/depth	3.2 km^2/500 m	3.4 km^2/500 m
Fuel inventory: number of bundles	8.5 million	4.3 million
mass of uranium	162 000 Mg	82 000 Mg
Fuel Burnup	685 GJ/kg U	720 GJ/kg U
Fuel Cooling time	10 years	10 years
Number of bundles per container	72	72
Number of waste containers	118 700	60 100
Room locations	footwall of LD1	footwall and hangingwall of LD1
VAULT MODEL		
Vault model geometry	layered slabs	nested cylinders
Fuel dissolution model	thermodynamic	kinetic
Container shell material	Grade-2 Ti	high purity Cu
Container corrosion mechanisms	localized crevice and delayed hydride cracking	general corrosion and pitting
Fraction of containers failed instantly	10^{-3} to 10^{-4} (complete failure)	10^{-3} to 10^{-4} (pinhole failure)
Fraction of containers failed by 10^4 years	1.0	10^{-3} to 10^{-4}
Effective buffer thickness	0.25 m	1.48 m
Effective backfill thickness	1.4 m	0.76 m
Excavation disturbed zone	evaluated outside system model	evaluated explicitly within system model
GEOSPHERE MODEL		
Conceptual model of fracture zones and rock domains	URL area of WRA	URL area of WRA*
Permeability of rock domain surrounding vault	10^{-19} m^2	10^{-17} m^2
Effective transport porosity of rock domain surrounding vault	3 x 10^{-3}	10^{-3} to 10^{-5}
Minimum contaminant transport times from vault to biosphere	tens of thousands of years	tens of years
Rate-determining transport process	diffusion	advection
Maximum depth of water-supply well	200 m	100 m

	EIS CASE STUDY	PRESENT STUDY
BIOSPHERE MODEL	BIOTRAC1 - typical of the Canadian Shield	BIOTRAC2 - modifications to improve the model and update the parameters
SYSTEMS ANALYSIS		
Computer Code	third generation code (SYVAC3-CC3-ML3)	prototype (PR4) of fourth generation code (SYVAC3-CC4)
Maximum estimated dose rate to a member of critical group up to 10^4 years	about 10^{-11} Sv per year	about 10^{-6} Sv per year
Time at which estimated dose rate reaches peak	$>10^5$ years	about 10^4 years
Key radionuclides contributing to estimated dose rate up to 10^4 years	^{129}I ^{36}Cl ^{14}C	^{129}I, ^{36}Cl ^{14}C, ^{79}Se ^{90}Sr, ^{90}Y, ^{99}Tc
Principal safety feature	low permeability rock domain surrounding vault	long-lasting containers

* The conceptual model used for this study does not represent a combination of conditions that we have encountered at any of our geologic research areas on the Shield. It has the same geometric arrangement of fracture zones and rock domains as was used in the EIS case study; however, the permeability of the rock domain surrounding the vault has been assumed to be 10^{-17} m^2. This permeability is 100 times greater than the value specified for the EIS case study, which was based on actual measurements within the lower rock zone at the URL.

AECL-11494-1
COG-95-552-1

Cat. No. / N^{O} de cat.: CC2-11494/1E
ISBN 0-660-16500-7
ISSN 0067-0367

To identify individual documents in the series, we have assigned an AECL- number to each. Please refer to the AECL- number when requesting additional copies of this document from

Scientific Document Distribution Office (SDDO)
AECL
Chalk River, Ontario
Canada K0J 1J0

Fax: (613) 584-1745 Tel.: (613) 584-3311
ext. 4623

Price: B

Pour identifier les rapports individuels faisant partie de cette série, nous avons affecté un numéro AECL- à chacun d'eux. Veuillez indiquer le numéro AECL- lorsque vous demandez d'autres exemplaires de ce rapport au

Service de Distribution des documents officiels (SDDO)
EACL
Chalk River (Ontario)
Canada K0J 1J0

Fax: (613) 584-1745 Tél.: (613) 584-3311
poste 4623

Prix: B

Printed on recycled paper with vegetable-oil-based inks