PRELIMINARY SAFETY ASSESSMENT OF CONCEPTS FOR A PERMANENT WASTE REPOSITORY AT THE WESTERN WASTE MANAGEMENT FACILITY BRUCE SITE

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ABSTRACT

This report describes the preliminary postclosure safety assessment of permanent repository concepts for radioactive waste at OPG's Bruce Site. Four geotechnically feasible repository concepts considered are:

- Covered Above Grade Concrete Vault on sand (CAGCV-S);
- Covered Above Grade Concrete Vault on till (CAGCV-T);
- Deep Rock Cavern Vault in shale at a depth of 460 m (DRCV-S); and
- Deep Rock Cavern Vault in limestone at a depth of 660 m (DRCV-L).

An approach consistent with best international practice is used that is designed to provide a reasoned and sufficiently comprehensive analysis of postclosure impacts of the repository concepts. The report:

- specifies the assessment context (what is being assessed and why it is being assessed);
- describes the repository system (the repository (near field), geosphere and biosphere);
- develops and justifies the scenarios (illustrative descriptions of the system's future evolution) to be assessed;
- describes, for selected calculation cases, the formulation of conceptual and mathematical models and associated data, and their implementation in a computer tool; and
- presents and analyses the results.

The results demonstrated that, from a postclosure radiological safety assessment perspective, the deep repository concepts in shale (DRCV-S) and in limestone (DRCV-L), and the surface repository concept on sand (CAGCV-S) should meet the radiological protection criteria adopted for this study, even without grouting of the waste and repository voids. For the surface repository concept on till (CAGCV-T), increased engineering such as grouting of waste and voids needs to be considered in order to reduce the calculated dose rate to below the relevant dose constraint. Whilst grouting has benefits for the surface repository concepts such as reducing and/or delaying dose rates, its benefits for the deep repository concepts are minimal. Although extending the institutional control period from 100 to 300 years has no significant impact on the dose rates for the limiting calculation cases for the Reference Scenario, it does reduce calculated dose rates by about a factor of three for Human Intrusion Scenario calculation cases. Nevertheless, the calculated dose rates at 100 years for the most restrictive calculation case are still more than an order of magnitude below the level above which reasonable efforts should be made to reduce the likelihood of human intrusion or to limit its consequences.

It is important to remember that the present assessment is a preliminary postclosure radiological safety assessment, and the associated calculations have been undertaken at a scoping level. This preliminary safety assessment would need to be updated based on future site-specific geotechnical investigations and/or design updates, should it be decided to proceed with a permanent repository at the site.

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1. INTRODUCTION

1.1 BACKGROUND

In April 2002, a Memorandum of Understanding (MOU) was signed between Ontario Power Generation Inc. (OPG) and the Municipality of Kincardine, Ontario. This MOU sets out the terms under which OPG, in consultation with the Municipality of Kincardine, will develop a long-term plan to manage low level radioactive waste (LLW) and intermediate level radioactive waste (ILW) at the Western Waste Management Facility (WWMF) on the Bruce Site (Figure 1 and Figure 2). The plan also includes a review of permanent repository concepts at the Bruce Site.

As part of this review, OPG has commissioned a Geotechnical Feasibility Study of the Bruce Site between September 2002 and February 2003 (Golder Associates, 2003). The objectives of the study have been:

- to develop descriptive conceptual geologic and hydrogeologic models of the Bruce Site based on existing site-specific and transferable off-site information;
- to document precedent experience relevant to the excavation of permanent repositories within the sediment underlying the Bruce Site;
- to screen and assess the geotechnical feasibility of generic permanent repository concepts adapted to the Bruce Site setting; and
- to assess technical gaps in site specific knowledge that would improve confidence in the construction and long-term performance of geotechnically feasible permanent repository concepts.

In light of the findings of the Geotechnical Feasibility Study, four geotechnically feasible permanent repository concepts have been identified in Golder Associates (2003). In parallel, Quintessa has undertaken a preliminary postclosure radiological safety assessment of the concepts, taking account of the site-specific information gained from the study by Golder Associates and other site-specific information. The results of this preliminary safety assessment are described in this report.

1.2 APPROACH

A key objective of any postclosure safety assessment is to provide sufficient information and supporting arguments to develop the confidence of interested parties that the proposed actions to manage the radioactive wastes will provide an acceptable level of future protection for human health and the environment. Confidence building involves the practice of citing references and the use of transparent logical arguments, multiple lines of reasoning, factual data and quality assurance to support the safety assessment. Activities associated with use of good science and good engineering practice can add additional levels of confidence. Consideration of the sensitivity of assessment end points to assumptions and the degree of uncertainty in calculations is also helpful.

Fulfilling these objectives is made easier by the application of a systematic safety assessment methodology that is clear and transparent. This approach has been adopted internationally as best practice for safety assessments of radioactive waste repositories. In particular, the ISAM (Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities) Coordinated Research Project of the International Atomic Energy Agency (IAEA) is a key contributor (IAEA, 2002a). The main stages in the ISAM safety assessment methodology are illustrated in Figure 3. In order to be consistent with best international practice, the preliminary safety assessment of the Bruce Site uses an approach consistent with the ISAM methodology.

In particular, the assessment uses mathematical models implemented in a compartment modelling software tool to assess radionuclide transport through the waste form, the engineering barrier systems, the geosphere, and the biosphere and the resulting dose consequences. With respect to mass transport, the models simulate advection, dispersion, diffusion, dilution, sorption, radioactive decay and, within the engineered repository, solubility limitation and time dependent geochemical and hydraulic conditions. The models reflect the site specific repository setting and geometry as described in Golder Associates (2003).

The assessment is based on readily available site-specific and other data to give an indication of the safety of the LLW repository concepts at the Bruce Site. While preliminary, the safety assessment approach, through development of alternative release scenarios and supporting conceptual and mathematical models, is designed to provide a reasoned and sufficiently comprehensive analysis of release pathways to determine LLW repository performance relative to safety criteria. Further, more detailed modelling and data collection would be required in subsequent investigative phases, should they occur, to develop a robust Safety Assessment in support of a LLW Repository Safety Case.

1.3 STRUCTURE OF THE REPORT

The sections of this report reflect the steps in the ISAM methodology. Section 2 specifies the assessment context and answers two fundamental questions: what is to be assessed, and why? The OPG permanent repository concepts, together with the present-day geosphere and biosphere characteristics in the vicinity of the Bruce Site are described in Section 3. In light of the assessment context and the system description, the scenarios for consideration in this preliminary safety assessment are developed and justified in Section 4, whilst the formulation of the corresponding conceptual and mathematical models and their implementation, together with associated data, into a computer code are described in Section 5. The results produced from the safety assessment are presented and analysed in Section 6. In Section 7, conclusions from the assessment are presented, together with recommendations for work to be undertaken as part of future assessments, if required.

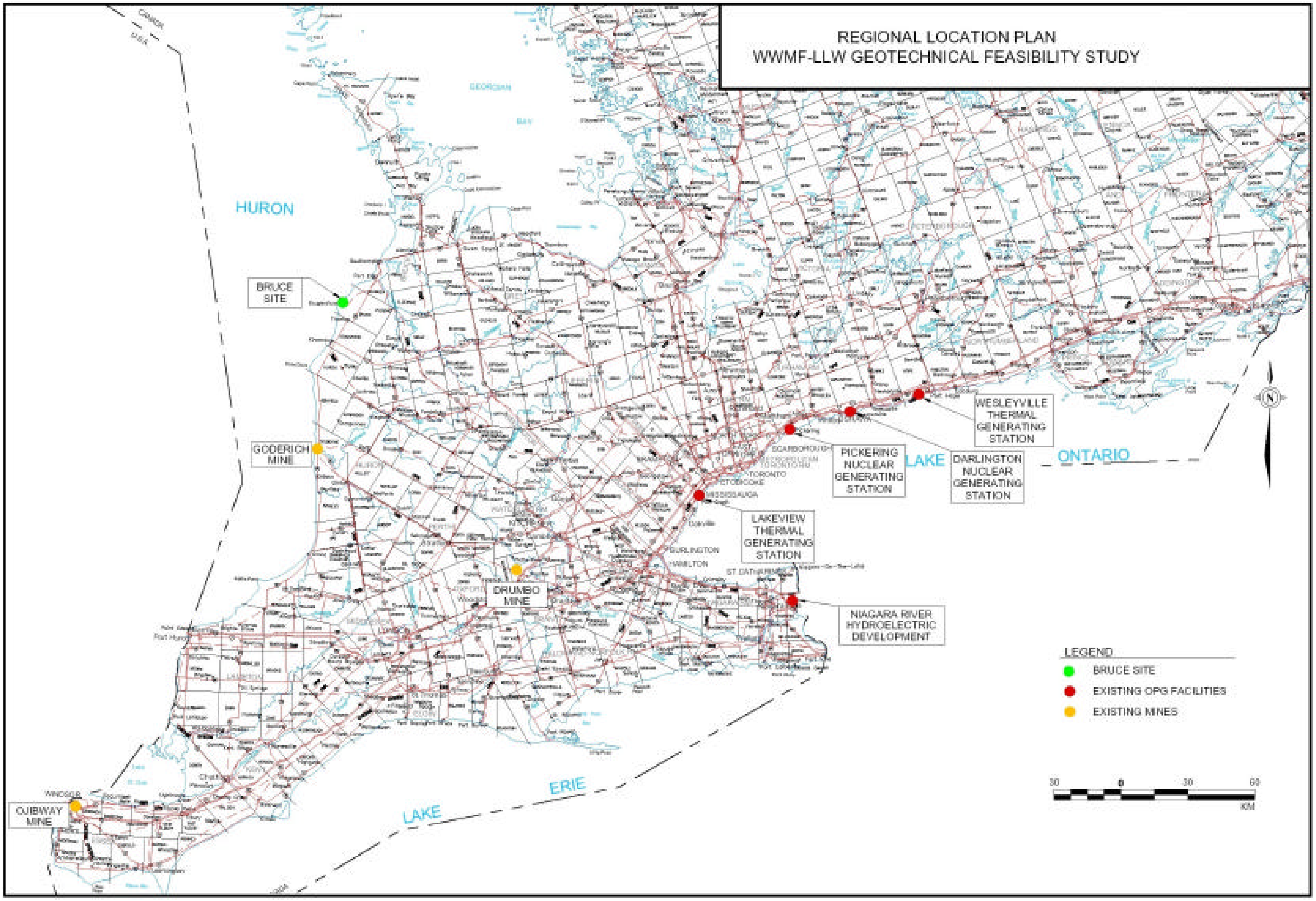

Figure 1: Regional Setting of the Bruce Site (Golder Associates, 2003)

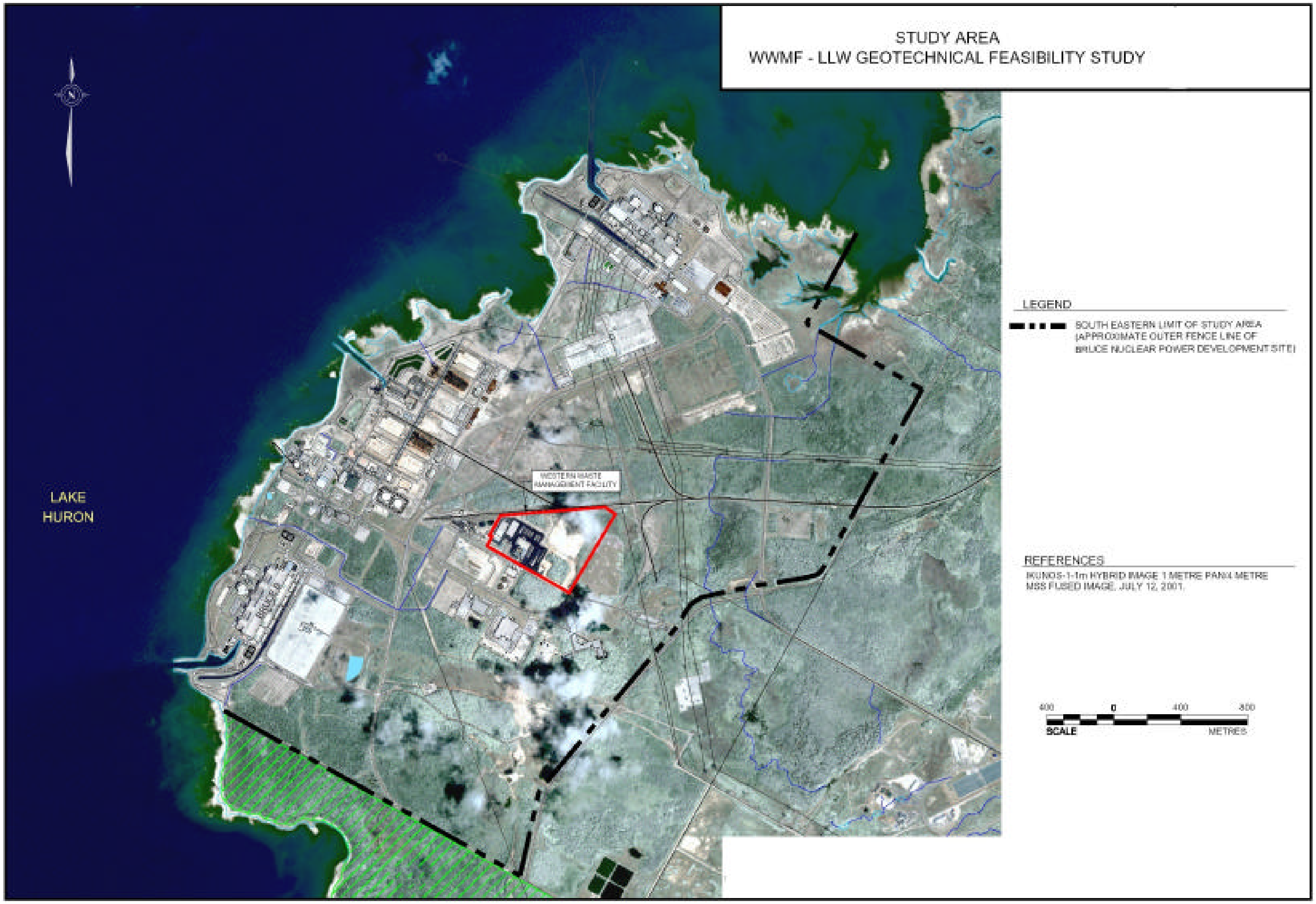

Figure 2: Location of the WWMF within the Bruce Site (Golder Associates, 2003)

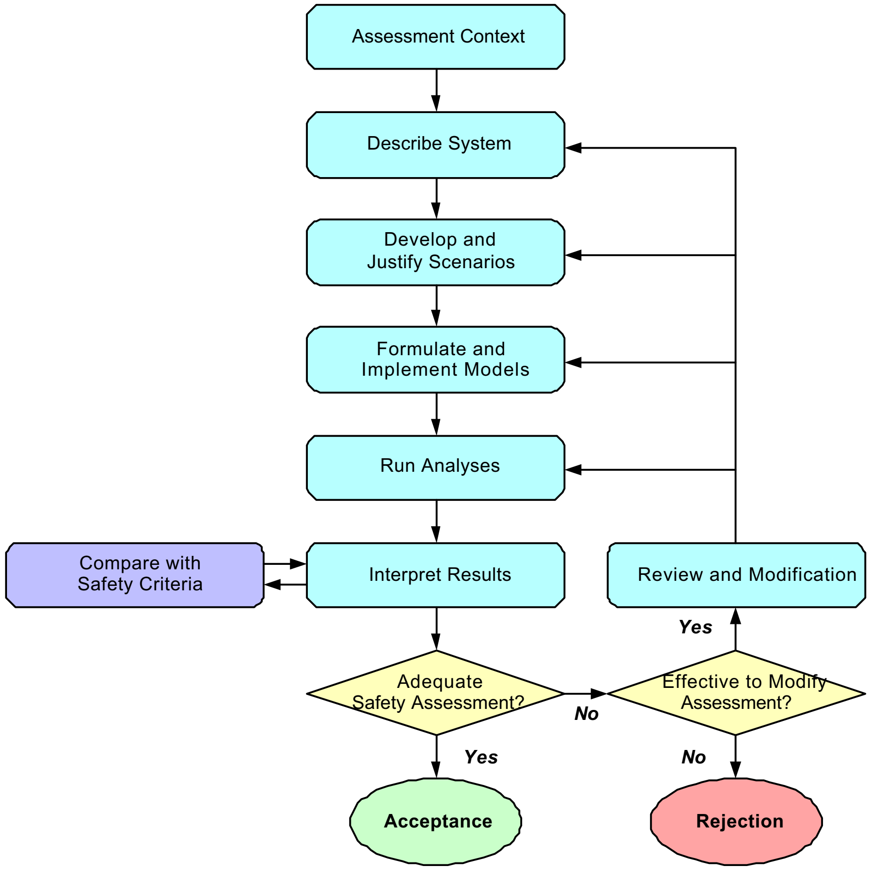

Figure 3: The ISAM Safety Assessment Methodology, the Basis of the Approach Applied in this Study

2. SPECIFICATION OF THE ASSESSMENT CONTEXT

2.1 INTRODUCTION

The assessment context considers the following topics:

- the purpose and scope of the assessment;
- the audience (stakeholders) to whom the results of the safety assessment will be presented;
- the regulatory framework that applies (including any criteria and limits);
- the assessment end points;
- the 'assessment philosophy' or the nature of the approach used to calculate the end points; and
- the timeframes that are relevant to consider.

These issues are documented for this preliminary safety assessment in the following sub-sections. The main characteristics of the repository system (including the waste) are described in Section 3.

2.2 PURPOSE AND SCOPE OF THE ASSESSMENT

OPG is at the early stage of investigating the suitability of permanent repository concepts at the Bruce Site (i.e., in the first box in the repository life cycle shown in Figure 4). Therefore, the specific purposes of the current safety assessment, in order of importance, are:

a) to assess the postclosure radiological safety from a permanent waste repository at the Bruce Site;

b) to help identify potentially acceptable permanent repository concept(s) at the Bruce Site;

c) to provide insight with respect to the level of engineering barrier systems required for the identified concept(s); and

d) to identify where further data or information would be most useful.

For this safety assessment study, a permanent repository concept is considered 'potentially acceptable', if the concept is geotechnically feasible and if the preliminary postclosure radiological safety assessment results for the concept, when compared against the safety assessment criteria set out in Section 2.4, are acceptable.

It should be noted that the current safety assessment is a preliminary assessment prepared to give an indication of the safety of the permanent repository concepts at the Bruce Site. The early stage in the lifecycle of the potential repository means that it should not be seen as a comprehensive safety assessment. Indeed, recommendations are made in Section 7 on further data or information that would be most useful for future assessments. This is consistent with a step-wise approach to long-term management of radioactive waste and with the recommendation of the ISAM project that sees safety assessment as an iterative processes with the completeness and level of detail of each assessment increasing with subsequent iterations (IAEA, 2002a).

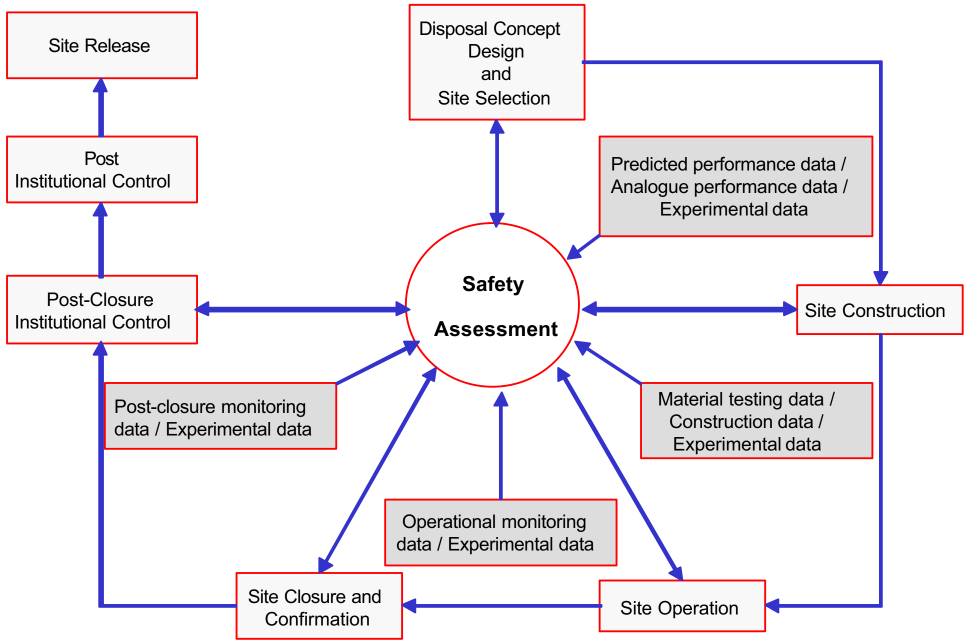

Figure 4: The Role of Safety Assessment in the Life Cycle of a Radioactive Waste Repository

Operational safety and non-radiological safety and impacts associated with the development of the permanent repository are not considered in this preliminary assessment, since such operational impacts can be readily maintained within acceptable levels through the use of appropriate engineering (see for example BNFL (2002) and IAEA (2002b)). Radiological impacts on non-human biota are also not considered in this study, since it is assumed that if individual humans are shown to be adequately protected, then non-human biota will also be protected, at least at the species level (ICRP, 1991). The basis of this assumption is currently being investigated by various international organisations such as the International Commission on Radiological Protection (ICRP) and the IAEA (see for example IAEA (1999)). However, in the absence of any, as yet, clear consensus and guidance on the assessment of radiological impacts on non-human biota, the recommendations of ICRP Publication 60 (ICRP, 1991) are adopted.

2.3 AUDIENCE

There are four main audiences that are considered within this assessment.

First, there are technical experts internal and external to OPG who may wish to critically review the detailed safety assessment modelling methods, assumptions and results presented within this report. It is envisaged that these may include technical experts from the Canadian Nuclear Safety Commission (CNSC).

In addition to the current detailed technical report, a summary report has been produced to synthesise key aspects from the detailed report. The summary report has been produced for three additional audiences, i.e.:

- members of the public in Kincardine and nearby communities, including aboriginal groups.
- representatives from the Municipality of Kincardine; and
- Ontario Power Generation management.

2.4 REGULATORY FRAMEWORK

2.4.1 Dose Constraints

The dose[1] constraint of no more than 0.3 mSv y^{-1} recommended in Publication 81 of the ICRP (ICRP, 2000) is used for the evaluation of the safety of the permanent repository from natural processes (i.e., all processes other than human intrusion into the waste). It is used in this study as a criterion for judging potential acceptability of repository concepts. If calculated dose rates for a repository concept from natural processes do not exceed the constraint, then the concept is judged to be potentially acceptable.

For inadvertent human intrusion, dose rates are assessed in accordance with the recommendations set out in ICRP 81 (ICRP, 2000). However, the criteria considered in this study are slightly more restrictive than those recommended in ICRP 81, since the current Canadian Nuclear Safety Commission (CNSC) regulations (CNSC, 2000) suggest the need for action if potential exposures could exceed the public dose rate limit of 1 mSv y^{-1} and therefore a more cautious approach is adopted in this study pending further guidance from the CNSC[2]. The suggested human intrusion criteria for this study are:

a) below 1 mSv y^{-1} (instead of ICRP 81 recommended level of 10 mSv y^{-1}), optimisation of the repository system is not required;

b) above a level of 1 mSv y^{-1} (instead of ICRP 81 recommended level of 10 mSv y^{-1}), reasonable efforts should be made to reduce the likelihood of human intrusion or to limit its consequences; and

c) above a level of 100 mSv y^{-1} (consistent with the ICRP 81 recommended level) efforts must be made to reduce the consequences of human intrusion (implying these dose rates are unacceptable).

Consistent with international practice (NEA, 1995), the consequences of deliberate human intrusion into the permanent repository are not considered within this preliminary safety assessment. It is assumed that current society should not be required to protect future societies from their own actions if the latter are aware of the radioactive materials in the permanent repository and the consequence of disturbing the repository.

Human intrusion scenarios are treated separately from other scenarios and are not summed over all significant scenarios to calculate the risk. Consistent with the recommendations of ICRP 81 (ICRP, 2000), both dose rate and likelihood, instead of risk (probability x consequence), are considered in evaluating the impacts of human intrusion.

[1] Unless otherwise stated, the term 'dose' refers to the annual individual effective radiation dose, calculated using the method described in ICRP (1991). Postclosure doses are calculated with mathematical models for hypothetical individuals.

[2] In 2002, the CNSC indicated that they are planning to issue revised documents on managing radioactive wastes in Canada. These documents will include policy, guidance and regulation documents. The policy document may be issued for public review in 2003.

2.4.2 Institutional Controls

Active institutional controls may be used for a reasonable period (up to 300 years[3]) after repository closure as a safety feature to prevent future human actions having untoward effects on the repository or the loss of containment. During the active institutional control period, reasonable maintenance of those repository features that can be easily maintained (e.g., the cap for a near-surface repository) is assumed. Some corrective actions and maintenance could also be undertaken. However, no invasive maintenance (e.g., to remediate inaccessible or sub-surface engineered structures) is assumed. Active control would also preclude the inadvertent disturbance of the waste, e.g., by digging into it.

It is probable that memory of the Bruce Site's presence would persist even after active control of the site has been relinquished. Such a period is usually referred to as the passive institutional control period. However, no credit is taken for the passive period because it is not the intention of the safety assessment to rely upon it.

The duration of the institutional control period is of interest for the safety assessment, as it provides a period during which radioactive decay can be effective in reducing the concentrations of radionuclides in the repository whilst it remains under control. Consequently, potential dose rates are reduced, particularly those associated with inadvertent disturbance situations. However, it requires the commitment of responsibilities to future generations, with associated financial provisions. The relationship of potential consequences to the period of institutional control is therefore of interest and the sensitivity of calculated dose rates to the duration of the active institutional period is considered by assuming a range from an institutional control period of ranging from 100 years to 300 years.

2.5 ASSESSMENT END POINTS

Consistent with the recommendations in ICRP Publication 81 (ICRP, 2000), the principal assessment end-point is annual individual effective dose rate to an average adult member of a hypothetical potential exposure group expected to receive the highest annual dose rate (i.e., the critical group) from each scenario that is assessed. For each permanent repository concept in the safety assessment, the dose rates are calculated and presented in Section 6 for the potential exposed group for each relevant scenario.

It is increasingly being recognised that it is important not to rely on evaluation of just a single end-point such as individual dose rate (IAEA, 1994 and 2002a). Multiple lines of reasoning may be useful since regulatory bodies and other stakeholders may use a wide range of arguments and end points to help determine the adequacy of a safety assessment. Furthermore, the reliability of dose as an indicator of safety over long time scales has been questioned (IAEA, 1994). Therefore, radionuclide concentrations in various environmental media are used in this study as additional safety indicators to complement dose. These can be compared against background concentrations in the vicinity of the site resulting from natural sources as well as weapons testing fallout but excluding contributions from existing nuclear facilities such as nuclear power plants. In addition, calculated concentrations can be compared against relevant environment quality standards such as the Canadian and Ontario Drinking Water Objectives.

[3] Institutional control over a LLW repository is planned for 300 years in France – see for example Potier (1997).

2.6 ASSESSMENT PHILOSOPHY

The assessment philosophy for this study is given below.

The nature of the overall approach used for the assessment - An approach consistent with the ISAM safety assessment methodology is used to evaluate the postclosure radiological safety of a permanent repository at the Bruce Site. The approach is logical and transparent (e.g., providing rationales for the assumptions, clear audit trails for the models and parameters). Where appropriate, simple arguments are used to support the safety assessment (e.g., discussion of a variety of safety indicators).

The derivation of scenarios for the assessment - Key scenarios can be identified taking account of related experiences from other safety assessment studies, consideration of the international Features, Events and Processes (FEP) list, and site-specific conditions. However, given that this study is a preliminary safety assessment, a detailed systematic analysis for scenario development and definitions was not undertaken.

The nature of the assumptions adopted – In undertaking an assessment, various assumptions have to be adopted. Any assumption can be categorised as 'realistic' (a realistic assumption is an assumption that is physically possible and quite likely to occur) or 'cautious' (a cautious assumption is an assumption that will not result in the end point(s) being underestimated) (see for example BIOMOVS II,1996). It can often be appealing to adopt the cautious approach, thereby ensuring that impacts are not under-estimated. However there is a danger that aggregation of large numbers of cautious assumptions, each of which may be appropriate in its own right, may result in an unrealistic estimate of potential impacts. An approach that balances simplicity, conservatism and realism is often considered to be the best starting point for assessments and is the approach that is used in this preliminary assessment. The key issue is to document and justify the nature of each assumption in the assessment (be it cautious or realistic).

The availability of data for use in the assessment – Data from studies that consider the Bruce Site specifically are used if available; otherwise, data from other sources, relating to other sites or situations, are used. All data sources are documented. Reasonable values for model parameters are used where site-specific data are available; otherwise, 'best estimates' derived from expert judgement are used where some understanding of the parameter and uncertainty is known, whilst cautious values are used only where the value is highly uncertain.

The approach adopted for the treatment of the various sources of uncertainty (e.g., scenario, model and data) – A range of scenarios (see Section 4) and calculation cases (see Section 5.2.3) are considered to address future uncertainty and conceptual model uncertainties, respectively. The preliminary nature of the safety assessment means that detailed sensitivity analysis has not been used to address model and data uncertainty and to explore the range of key parameters that are considered to be important to the postclosure safety. However, consideration is given to the effect of different repository concepts, engineering options and institutional control periods on calculated dose rates.

The potential exposure groups considered – Consistent with the recommendations of the ICRP (ICRP, 2000), dose to an average member of a maximally exposed group is calculated for each scenario. Due to the long timescales over which impacts might arise (see Section 2.7) and the associated high level of uncertainty in the evolution of human activities and behaviour, each group is hypothetical rather than based upon the precise characteristics of humans currently living in the vicinity of the Bruce Site, who might not have habits resulting in maximal exposure. The calculated dose rate for each potential exposure group is maximised through the self-sufficient use of contaminated resources and/or the consumption of contaminated foodstuffs produced in the immediate vicinity of the release to the biosphere. The precise characteristics of the potential exposure groups considered in the study are described in Section 5.2.4.

2.7 ASSESSMENT TIMEFRAMES

The postclosure safety assessment is carried out to a point in time that allows a clear demonstration that the peak calculated dose rate has been reached. However, it is recognised that uncertainties increase with time and beyond about 10,000 years, assessment results are only indicative (IAEA, 1994). (10, 000 years is generally taken to be the start of a time frame when the impacts of long-term natural changes in climate such as glacial/interglacial cycling are likely to become significant.)

Although the climate is expected to change over the assessed timeframe, present-day conditions in the vicinity of the Bruce Site (e.g., climate, hydrogeology and human activities) are used to define the repository system evolution and exposure scenarios regardless of the time frames. Therefore, although the evolution of engineered repository components is considered, the effects of major climate change (e.g., global warming, glaciation) on the repository system evolution are not considered in this study.

3. DESCRIPTION OF THE REPOSITORY SYSTEM

3.1 INTRODUCTION

For the purposes of this study, the 'repository system' is defined as:

> *The engineered repository system and that part of its environment relevant to the determination of assessment end points.*

The repository system will evolve with time. The evolution of the near field occurs naturally within the system. Other aspects of the system evolve, because of the effects of processes and events that are external to it – e.g., local climatic conditions, in response to global climate change. Both are relevant to safety assessment, and the former are considered in this study. Evolution of the natural environment has not been considered as indicated in the assessment context (Section 2.7). The system description therefore focuses on the information available to describe the present-day conditions. This information:

- provides the background context for the study;
- describes the recent studies and data that are available; and
- provides a basis for the development of scenarios (Section 4), and conceptual and mathematical models of the system (Section 5).

The repository system consists of the near field comprising the engineered features, the geosphere or sub-surface environment and the biosphere or surface environment, which is directly accessible to humans. The key information needed to describe them for the purposes of safety assessment is shown in Table 1. This information can also be expressed in terms of features, events and processes (FEPs). However, the use of FEPs is not needed until the model development stage, when both the description of the present-day system and scenarios describing the potential mechanisms by which people can be exposed are described.

The data indicated in Table 1 have been derived from a series of reports, as no one source provides all the information needed to describe the whole system. Although a range of documents have been considered, four provide the most important fundamental information for the system description:

- Leung and Krochmalnek (2000) provides a detailed description of the LLW inventory and its characteristics;
- Golder Associates (1998) describe the reference permanent repository concepts;
- Golder Associates (2003) presents key information on the geosphere and repository concepts; and
- OPG (2000) presents the key information needed to describe the biosphere.

Table 1: Key Information Requirements for the System Description

Near Field	Geosphere	Biosphere
Radionuclide and waste inventory	Geology	Climate
Waste packaging	Hydrogeology	Topography
Repository design	Geochemistry	Surface water
		Soil types
		Land use
		Flora and fauna
		Natural resources

3.2 THE NEAR FIELD

3.2.1 Inventory and Waste Characteristics

Leung and Krochmalnek (2000) present the most recent estimates of OPG's inventory of LLW, both wastes currently in storage and due to arise in the future. Data are available for operational and decommissioning wastes. However, the focus of the current study is the development of emplacement capacity for operational wastes alone. Should consideration be given to extending the capacity of the potential permanent repository to accept decommissioning waste, a revised safety assessment would be required.

Leung and Krochmalnek (2000) present a range of detailed assumptions that are used to assist in the derivation of estimates of LLW volume and radionuclide inventory. These are combined into two 'waste generation scenarios':

- all nuclear generating plants operate for a 40 year lifetime; or
- all nuclear generating plants operate for a 25 year lifetime with the exception of the Pickering A station.

In addition, various options are considered for volume reduction of the waste. The reference waste volume reduction scenario includes the incineration of wastes where possible, and the low force compaction of compactible wastes. This assumption, combined with the first waste generation scenario is the 'high (volume) scenario', and these data are conservatively assumed for this study.

3.2.1.1 Waste Categories and Packages

The operational LLW described by Leung and Krochmalnek (2000) is essentially categorised by container type, with additional consideration given to some specific types of waste that have characteristics of interest. The main categories are:

- ashes (bottom ash in metal ash bins and fly ash in metal drums);
- compacted wastes (in bales and 2.5 m^3 metal boxes); and
- non-processible wastes (in metal drums and boxes).

Leung and Krochmalnek (2000) present a detailed description of the waste containers used by OPG. The waste containers (drums and boxes) are constructed of either painted or galvanised mild steel. At present, some of the non-processible containers do not have lids.

3.2.1.2 Waste Conditioning

The compactible wastes are assumed to undergo low force compaction (with a 200 t press) into the metal boxes. Non-processible waste will not be subject to further processing in the reference plans that are assessed in this study. Super-compaction (2000 or 5000 t press) of all operational wastes (including ashes and non-processible wastes) might be considered in the future but is not assessed in this study. Super-compaction would principally reduce the volume of wastes, and increase radionuclide concentrations proportionately.

Currently, the operational wastes are not grouted into waste containers. The addition of a cement grout is a waste conditioning option and is considered in the current study. There is presently a small amount of bituminised waste, but there are no plans to use this waste conditioning method further, principally because of the potential flammability of the material.

These bituminised wastes are not considered in the current study due to their relatively small volume and activity.

3.2.1.3 Physical and Chemical Characteristics

The projected volumes and number of LLW containers for the 40-year operation (high volume) scenario are presented in Table 2. This table gives the volume of ‘raw waste’ (i.e., the volume of waste placed into containers), a packaged volume (the waste plus containers) and the total number of containers that are anticipated. The characteristics of the containers and the waste are shown in Table 3. An indication of the non-radioactive hazardous component of the wastes is presented in Leung and Krochmalnek (2000), but is not reproduced here, since the assessment of non-radiological impacts is beyond the scope of this preliminary safety assessment.

Table 2: Projected Volumes and Numbers of Containers of Operational LLW for the High (Volume) Scenario (Leung and Krochmalnek, 2000)

Waste Type	Unpackaged Waste Volume (m^3)	Packaged Waste Volume (m^3)	Number of Containers
Bottom Ash (bins)	$2.1x10^3$	$2.6x10^3$	$6.1x10^2$
Baghouse Ash (drums)	$1.2x10^2$	$3.5x10^2$	$1.0x10^2$
Compactor Bales	$3.0x10^3$	$5.1x10^3$	$1.5x10^3$
Compactor Boxes	$6.6x10^3$	$8.1x10^3$	$2.7x10^3$
Non-Processible Drums	$4.8x10^3$	$1.3x10^4$	$4.0x10^3$
Non- Processible Boxes	$2.8x10^4$	$3.9x10^4$	$1.0x10^4$
Non- Processible Other	$1.8x10^4$	$2.0x10^4$	$1.5x10^3$
Total	**$6.3x10^4$**	**$8.9x10^4$**	**$2.0x10^4$**

Table 3: Physical Characteristics of Operational LLW and Associated Containers (Leung and Krochmalnek, 2000)

Waste Type	Average Density (kg m^{-3})	Internal Volume (m^3)	Stored Volume (m^3)	Typical Content of Waste
Bottom Ash (bins)	680	3.4	4.2	Loose ash, heterogeneous, containing some heavy metals.
Baghouse Ash (drums)	340	0.2	0.25	Fine loose ash, homogeneous, containing some heavy metals.
Compactor Bales	770	0.5	0.85	Mainly plastic and paper
Compactor Boxes	1000	2.5	3	Mainly plastic, paper and metal
Non-Processible Drums	500	0.2	0.25	Miscellaneous materials, dominated by metals.
Non- Processible Boxes	230	0.9 – 3.1	1.6 – 4.2	Miscellaneous materials, dominated by metals.
Non- Processible Other	230*	0.9 – 40	1.6 – 42	Miscellaneous materials, dominated by metals.

Note:
* Assumed to be the same as non-processible waste in boxes

3.2.1.4 Radiological Characteristics

The radionuclide content of the LLW has been estimated using information obtained for existing operational wastes. Radionuclides for which direct measurement data have been used include Co-60, Nb-94, Ru-106, Sb-125, Cs-134, Cs-137, Eu-152, Eu-154 and Eu-155. The “difficult-to-measure” radionuclides such as C-14, I-129 and Pu-239 have been estimated by applying measured scaling factors or ratios based on radionuclide inventory in used fuel, to the “easy-to measure” radionuclides such as Cs-137 and Co-60. The resultant inventory is presented in Table 4 for 37 radionuclides.

3.2.2 Repository Designs

Four generic permanent repository concepts have been considered for the emplacement of LLW (Figure 5). These have been documented by Golder Associates (1998), and are identified by the following terminology:

- Covered Above Grade Concrete Vault (CAGCV);
- Shallow Concrete Vault (SCV);
- Deep Concrete Vault (DCV); and
- Rock Cavern Vault (RCV).

These permanent repository concepts were initially developed for generic sites. Site-specific adaptation of the generic concepts to the Bruce Site and geotechnical evaluation for implementation are discussed in a Geotechnical Feasibility Study by Golder Associates (2003). The conclusions of the Geotechnical Feasibility Study indicated that several of these concepts are geotechnically feasible at the Bruce Site (Table 5).

The geotechnically feasible repository concepts are:

- Covered Above Grade Concrete Vault on sand (CAGCV-S) (Figure 6);
- Covered Above Grade Concrete Vault on till (CAGCV-T) (Figure 6);
- Deep Rock Cavern Vault in shale (DRCV-S) (Figure 7); and
- Deep Rock Cavern Vault in limestone (DRCV-L) (Figure 7).

Note that for the purposes of the Bruce Site, the Rock Cavern Vault concept from Golder Associates (1988) has been differentiated into Shallow (at 60 m depth) and Deep (at 460 and 660 m depth) Rock Cavern Vault concepts (Golder Associates, 2003).

Two backfill options are considered in the current study: no backfill (the non-grouting option); or cement grout (the grouting option). Backfilling with cement grout would result in the void space between the waste packages in each vault being filled, as well as the central access aisle/tunnel and the primary drainage system.

The original dimensions for the permanent repository concepts in Golder Associates (1998) have been updated to reflect the most recent total waste volume estimate of 89,000 m^3 (Leung and Krochmalnek, 2000), which is lower than earlier value (130,000 m^3). Note that for reasons of flexibility, the dimensions given in Golder Associates (2003) are based on the earlier, higher waste volume. To accommodate the current projected volume of waste and to allow additional space for grouting (assumed 10% of waste volume), approximately 34 vaults would be required for the CAGCV concept, or approximately 14 vaults for the DRCV-S and DRCV-L concepts.

Table 4: Estimated Operational LLW Radionuclide Inventory for the High Scenario, in Bq at 2035 AD

Radio-nuclide	Bottom Ash (bins)	Baghouse Ash (drums)	Compact Bales	Compact Boxes	Non-pro Drums	Non-pro Boxes	Non-pro Other	Total	Decay Corrected Total*
H-3 [A]	5.2x10^{10}	0.0x10^{0}	7.2x10^{13}	9.8x10^{12}	1.4x10^{12}	8.3x10^{12}	5.5x10^{12}	9.7x10^{13}	9.6x10^{12}
C-14 [A]	1.8x10^{10}	6.5x10^{8}	3.8x10^{9}	1.0x10^{10}	2.0x10^{10}	1.2x10^{11}	7.8x10^{10}	2.5x10^{11}	2.5x10^{11}
Cl-36 [B]	4.0x10^{6}	6.1x10^{4}	2.4x10^{6}	6.6x10^{6}	2.5x10^{6}	1.5x10^{7}	9.9x10^{6}	4.0x10^{7}	4.0x10^{7}
Fe-55 [A]	2.1x10^{12}	3.2x10^{10}	4.3x10^{11}	1.2x10^{12}	6.5x10^{11}	3.8x10^{12}	2.5x10^{12}	1.1x10^{13}	1.3x10^{11}
Co-60	3.5x10^{8}	4.8x10^{6}	3.0x10^{7}	8.2x10^{7}	4.7x10^{7}	2.8x10^{8}	1.8x10^{8}	9.7x10^{8}	9.7x10^{8}
Ni-59 [B]	3.4x10^{11}	5.1x10^{9}	2.0x10^{11}	5.5x10^{11}	2.1x10^{11}	1.2x10^{12}	8.2x10^{11}	3.4x10^{12}	1.4x10^{11}
Ni-63 [A]	5.0x10^{10}	6.7x10^{8}	4.2x10^{9}	1.2x10^{10}	6.5x10^{9}	3.9x10^{10}	2.5x10^{10}	1.4x10^{11}	1.1x10^{11}
Se-79 [B]	4.4x10^{5}	2.0x10^{5}	3.3x10^{5}	8.9x10^{5}	7.4x10^{5}	4.4x10^{6}	2.9x10^{6}	9.8x10^{6}	9.8x10^{6}
Sr-90 [A]	1.1x10^{10}	5.2x10^{8}	4.2x10^{9}	1.1x10^{10}	5.5x10^{9}	3.2x10^{10}	2.1x10^{10}	8.6x10^{10}	3.9x10^{10}
Zr-93 [B]	4.7x10^{4}	3.7x10^{2}	2.3x10^{4}	6.3x10^{4}	7.9x10^{3}	4.7x10^{4}	3.1x10^{4}	2.2x10^{5}	2.2x10^{5}
Nb-94	2.8x10^{9}	0.0x10^{0}	2.5x10^{9}	6.9x10^{9}	5.3x10^{8}	3.1x10^{9}	2.1x10^{9}	1.8x10^{10}	1.6x10^{10}
Tc-99 [B]	1.6x10^{7}	7.5x10^{6}	1.2x10^{7}	3.3x10^{7}	2.7x10^{7}	1.6x10^{8}	1.1x10^{8}	3.7x10^{8}	3.7x10^{8}
Ru-106	7.5x10^{10}	2.0x10^{9}	1.5x10^{11}	4.0x10^{11}	3.3x10^{9}	2.0x10^{10}	1.3x10^{10}	6.6x10^{11}	1.0x10^{9}
Ag-108m [B]	1.3x10^{6}	6.0x10^{5}	9.8x10^{5}	2.7x10^{6}	2.2x10^{6}	1.3x10^{7}	8.6x10^{6}	3.0x10^{7}	2.5x10^{7}
Sb-125	3.3x10^{10}	5.1x10^{9}	3.5x10^{10}	9.5x10^{10}	6.3x10^{9}	3.7x10^{10}	2.5x10^{10}	2.4x10^{11}	2.5x10^{9}
Sn-126 [B]	6.8x10^{5}	3.1x10^{5}	5.0x10^{5}	1.4x10^{6}	1.1x10^{6}	6.7x10^{6}	4.4x10^{6}	1.5x10^{7}	1.5x10^{7}
I-129 [B]	3.7x10^{4}	1.7x10^{4}	2.7x10^{4}	7.4x10^{4}	6.2x10^{4}	3.7x10^{5}	2.4x10^{5}	8.2x10^{5}	8.2x10^{5}
Cs-134	1.6x10^{10}	6.3x10^{9}	1.7x10^{10}	4.5x10^{10}	1.3x10^{10}	7.9x10^{10}	5.2x10^{10}	2.3x10^{11}	1.5x10^{9}
Cs-135 [B]	1.3x10^{5}	5.9x10^{4}	9.6x10^{4}	2.6x10^{5}	2.2x10^{5}	1.3x10^{6}	8.5x10^{5}	2.9x10^{6}	2.9x10^{6}
Cs-137	1.3x10^{11}	5.7x10^{10}	9.3x10^{10}	2.5x10^{11}	2.1x10^{11}	1.2x10^{12}	8.2x10^{11}	2.8x10^{12}	1.3x10^{12}
Sm-151 [B]	4.4x10^{5}	2.0x10^{5}	3.3x10^{5}	8.9x10^{5}	7.4x10^{5}	4.4x10^{6}	2.9x10^{6}	9.8x10^{6}	7.5x10^{6}
Eu-152	0.0x10^{0}	0.0x10^{0}	0.0x10^{0}	0.0x10^{0}	2.1x10^{8}	1.2x10^{9}	8.2x10^{8}	2.3x10^{9}	5.0x10^{8}
Eu-154	5.8x10^{9}	3.1x10^{8}	5.6x10^{9}	1.5x10^{10}	2.3x10^{8}	1.4x10^{9}	8.9x10^{8}	2.9x10^{10}	2.6x10^{9}
Eu-155	1.3x10^{9}	0.0x10^{0}	1.2x10^{9}	3.2x10^{9}	0.0x10^{0}	0.0x10^{0}	0.0x10^{0}	5.7x10^{9}	1.7x10^{8}
U-234 [B]	2.9x10^{5}	1.1x10^{4}	3.2x10^{5}	8.7x10^{5}	8.2x10^{4}	4.9x10^{5}	3.2x10^{5}	2.4x10^{6}	2.4x10^{6}
U-235 [B]	4.8x10^{3}	1.7x10^{2}	5.2x10^{3}	1.4x10^{4}	1.3x10^{3}	7.9x10^{3}	5.2x10^{3}	3.9x10^{4}	3.9x10^{4}
U-236 [B]	5.4x10^{4}	2.0x10^{3}	5.9x10^{4}	1.6x10^{5}	1.5x10^{4}	9.0x10^{4}	6.0x10^{4}	4.4x10^{5}	4.4x10^{5}
U-238 [B]	3.6x10^{5}	1.3x10^{4}	4.0x10^{5}	1.1x10^{6}	1.0x10^{5}	6.0x10^{5}	4.0x10^{5}	3.0x10^{6}	3.0x10^{6}
Np-237 [B]	2.7x10^{4}	9.8x10^{2}	3.0x10^{4}	8.2x10^{4}	7.7x10^{3}	4.6x10^{4}	3.0x10^{4}	2.2x10^{5}	2.2x10^{5}
Pu-238 [A]	1.0x10^{8}	4.3x10^{6}	1.2x10^{8}	3.4x10^{8}	2.2x10^{7}	1.3x10^{8}	8.4x10^{7}	8.1x10^{8}	5.7x10^{8}
Pu-239 [A]	1.8x10^{8}	6.4x10^{6}	2.0x10^{8}	5.3x10^{8}	5.0x10^{7}	3.0x10^{8}	2.0x10^{8}	1.5x10^{9}	1.5x10^{9}
Pu-240 [A]	2.6x10^{8}	9.2x10^{6}	2.8x10^{8}	7.7x10^{8}	7.2x10^{7}	4.3x10^{8}	2.8x10^{8}	2.1x10^{9}	2.1x10^{9}
Pu-241 [A]	2.4x10^{10}	8.5x10^{8}	2.6x10^{10}	7.1x10^{10}	6.7x10^{9}	4.0x10^{10}	2.6x10^{10}	1.9x10^{11}	4.0x10^{10}
Pu-242 [B]	2.5x10^{8}	1.2x10^{7}	3.7x10^{8}	1.0x10^{9}	8.7x10^{7}	5.2x10^{8}	3.4x10^{8}	2.6x10^{9}	2.3x10^{9}
Am-241 [A]	2.6x10^{5}	9.4x10^{3}	2.9x10^{5}	7.8x10^{5}	7.3x10^{4}	4.3x10^{5}	2.9x10^{5}	2.1x10^{6}	2.1x10^{6}
Am-243 [B]	5.7x10^{5}	2.0x10^{4}	6.2x10^{5}	1.7x10^{6}	1.6x10^{5}	9.5x10^{5}	6.3x10^{5}	4.7x10^{6}	4.7x10^{6}
Cm-244 [A]	1.1x10^{8}	7.8x10^{6}	2.4x10^{8}	6.5x10^{8}	2.7x10^{7}	1.6x10^{8}	1.1x10^{8}	1.3x10^{9}	3.4x10^{8}
Total [C]	**3.9x10^{12}**	**1.2x10^{11}**	**7.3x10^{13}**	**1.5x10^{13}**	**1.2 x10^{14}**	**6.8x10^{14}**	**4.5x10^{14}**	**1.3 x10^{15}**	**1.2x10^{13}**

Note:

A Estimated activity, using measured scaling factors.

B Estimated activity, using radionuclide inventories for used fuel.

C Includes short-lived radionuclides (with half-life of less than 1 year) not explicitly shown in the table.

* Decay correction applied to inventory before closure.

Table 5: Conclusions of the Geotechnical Feasibility Study (Golder Associates, 2003)

Permanent Repository Concept	Geotechnically Feasible	Possibly Feasible	Not Feasible
Covered Above Grade Concrete Vault (CAGCV-S), on Sand	✓		
Covered Above Grade Concrete Vault (CAGCV-T), on Till	✓		
Shallow Concrete Vault (SCV), Till, at 10 m depth		?	
Deep Concrete Vault (DCV)			X
Shallow Rock Cavern Vault (SRCV), Dolostone, at 60 m depth		?	
Deep Rock Cavern Vault (DRCV), Salt			X
Deep Rock Cavern Vault (DRCV-S), Shale, at 460 m depth	✓		
Deep Rock Cavern Vault (DRCV-L), Limestone, at 660m depth	✓		

3.2.2.1 Detailed Characteristics of the CAGCV

Each vault in the CAGCV concepts has internal dimensions of 17 m wide, 27 m long and 7 m high, with a capacity of 3,200 m^3. The vaults are arranged in two parallel rows on each side of a 9 m wide central access aisle. The vault walls, floor, roof and access closure panels are constructed of 0.9 m thick reinforced concrete. Each vault has interior support columns for structural support of the roof and cap, and are structurally independent from adjacent vaults. There is a 0.1 m gap between vaults, filled with sand. The engineered composite cap for the CAGCV is around 4 m thick.

A primary drain collects any infiltration entering the vaults. Two small trenches within the sloped concrete floor of each vault provide gravity drainage to a central trench in the access aisle. A secondary drain collects any water that penetrates the vault floors. Water collected in drains is assumed to be collected, monitored, treated (if necessary) and discharged during the operational and, if necessary, the institutional control period.

Two potential geologic settings for the CAGCV have been identified to allow consideration of a range of subsurface conditions at the Bruce Site (Golder Associates, 2003). The settings are referred to as Reference Facility 1 and Reference Facility 2. In both cases, the CAGCV is orientated with the long axis of the repository aligned perpendicular to the inferred direction of shallow groundwater flow (Golder Associates, 2003).

Reference Facility 1 (CAGCV-S) – located in the north-western portion of the Bruce Site in an area underlain by relatively thin deposits of granular overburden (silts, sands and gravels) directly overlying fractured dolostone in which the groundwater table is located.

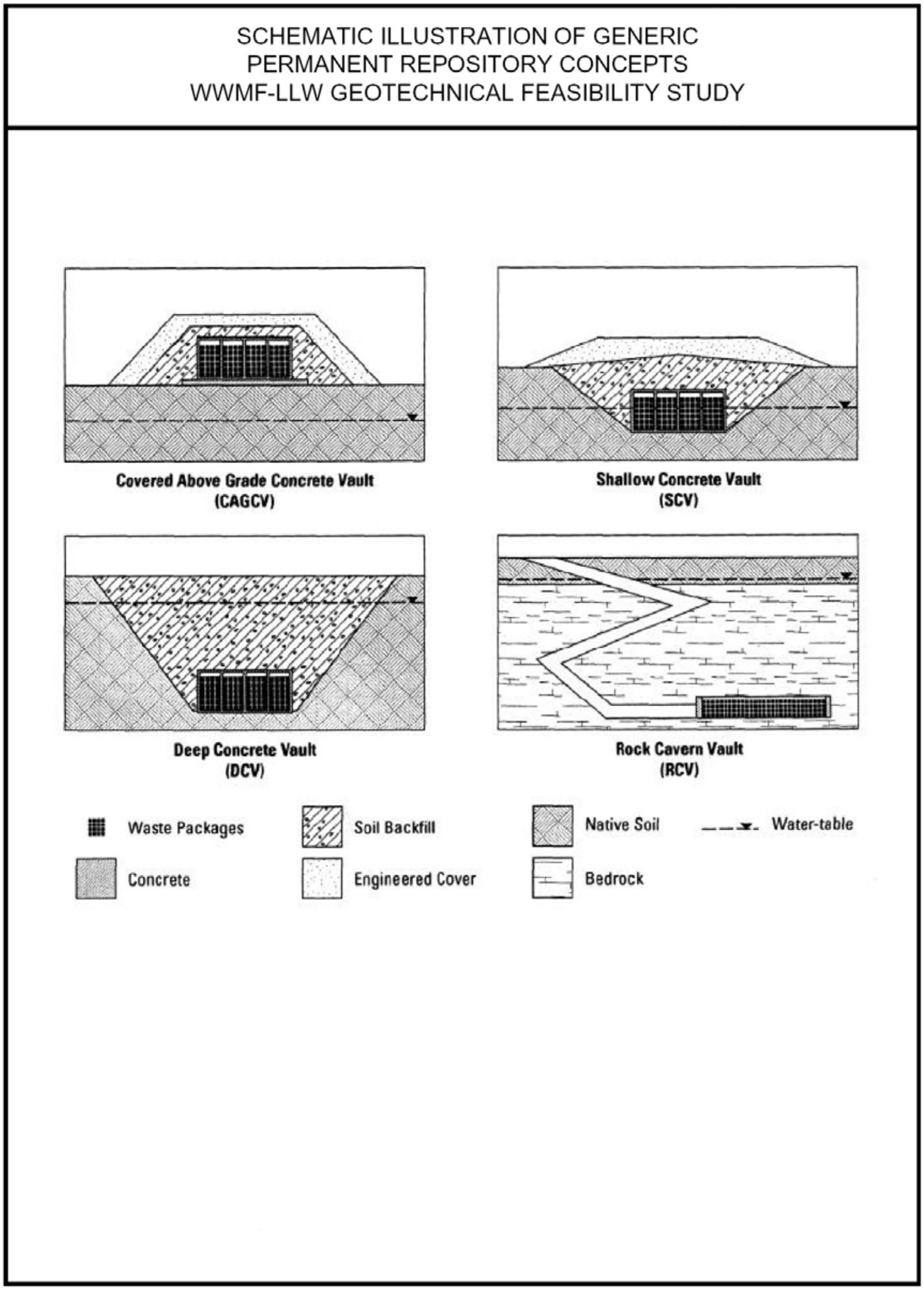

Figure 5: Generic Permanent Repository Concepts for LLW (Golder Associates, 2003)

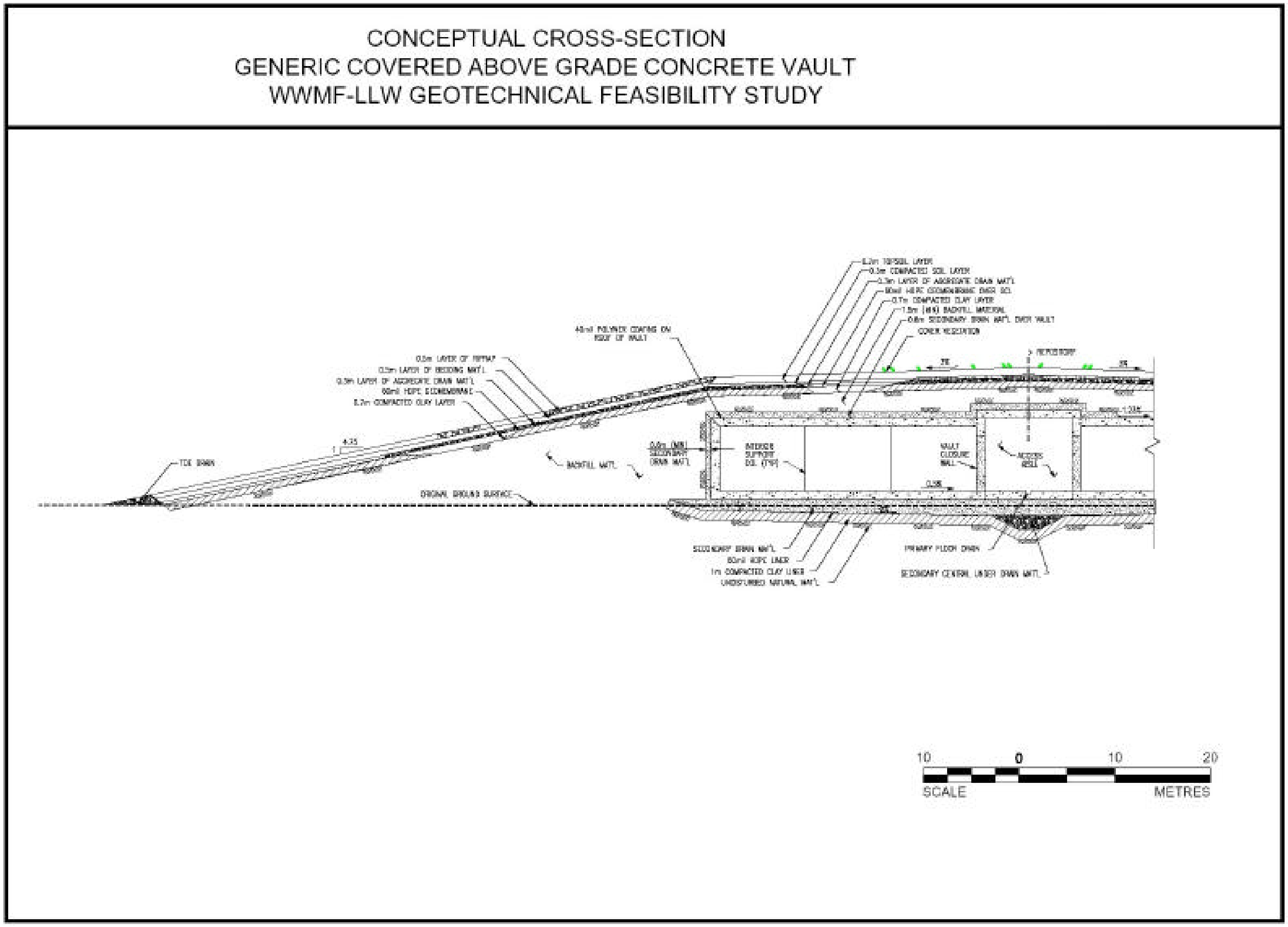

Figure 6: Conceptual Cross-section through the CAGCV (Golder Associates, 2003)

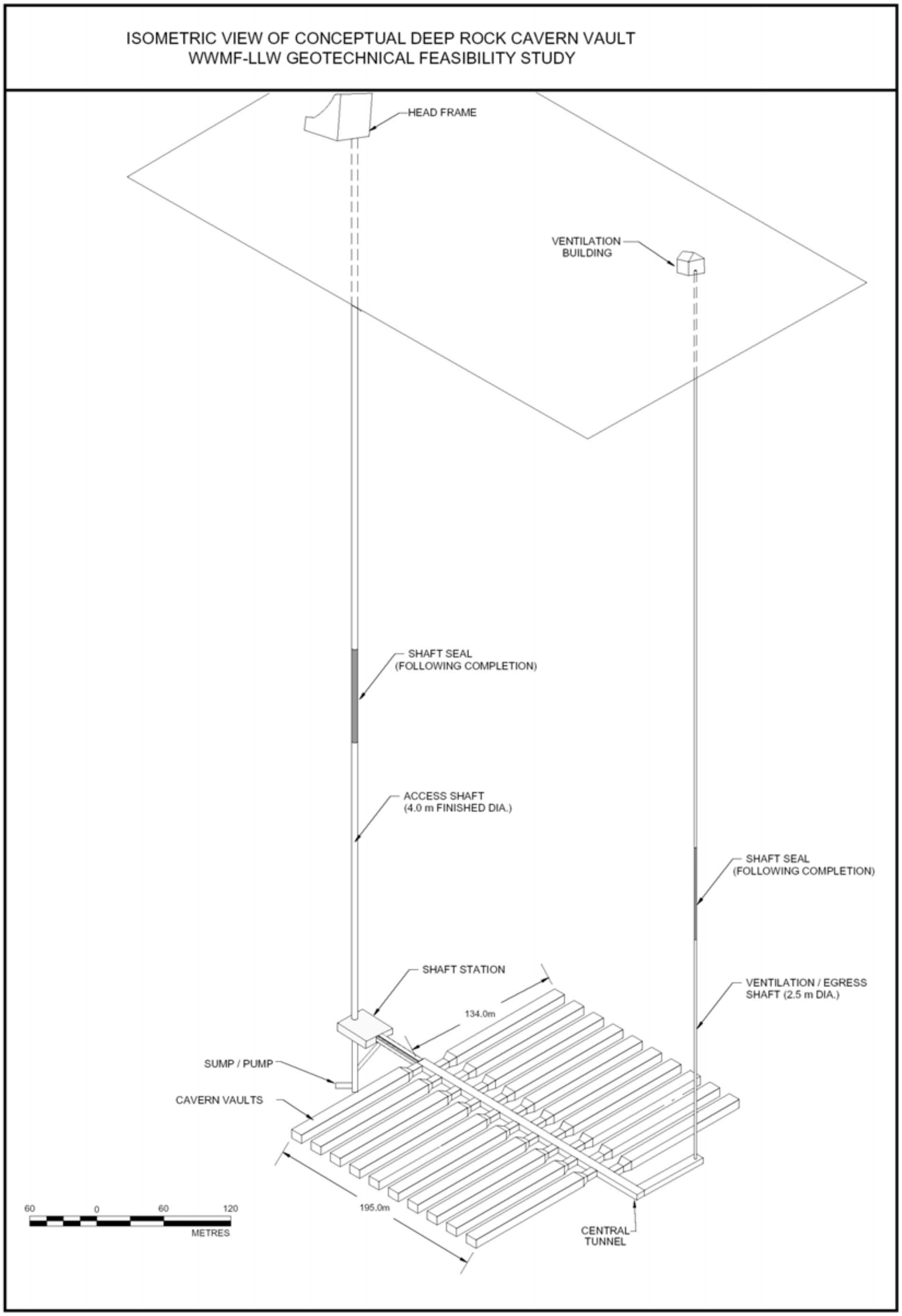

Figure 7: Conceptual Cross-section through the DRCV (Golder Associates, 2003)

Reference Facility 2 (CAGCV-T)– located in the central eastern part of the Bruce Site in an area underlain by relatively thick deposits of low permeability overburden (clayey to silty till) overlying fractured dolostone. Consistent with Golder Associates (2003), it is assumed that any sands are removed from beneath the footprint of Reference Facility 2 and the clayey to silty till deposit is homogeneous. The groundwater table in the till is assumed to be 1 m below the repository.

3.2.2.2 Detailed Characteristics of the DRCV

The DRCV concept has 14 vaults (waste emplacement tunnels), each vault having internal dimensions of approximately 10 m wide, 7 m high and 120 m long and a void space of approximately 8,400 m^3 (Figure 7). The vaults are arranged in two parallel rows either side of a central access tunnel, which is 8 m wide and 5 m high. Adjacent vaults are separated by a 15 m pillar of host rock. Each vault is accessed via an entrance that is 5 m wide by 5 m high by 10 m long. The walls, floor and roof of each vault are excavated from the host rock, and sprayed with shotcrete.

When the excavation of a vault is complete, a 0.1 m thick concrete floor is assumed to be poured to provide a stable base for stacking waste packages. The vault floors are constructed with a gradient toward the central access tunnel to allow drainage. The central access tunnel is, in turn, drained into a collection sump from where water is pumped during the operational period and, if necessary, the institutional control period to a Retention and Sedimentation Pond on surface through a pipe in the ventilation shaft. The water is monitored and treated, if necessary, before being discharged.

Once each vault has been filled with waste, it is assumed that a 10 m long concrete plug is constructed in the entrance to seal the waste vault from the central access tunnel.

Due to the depth of the DRCV concept, there is no engineered cap. Access to the DRCV is assumed to be via a vertical, concrete lined shaft with an internal diameter of 4 m (Golder Associates, 2003). Following completion of operations, the access and ventilation shafts are assumed to be filled with low permeability materials and the repository itself is allowed to fill with water due to inward groundwater seepage.

Two permanent repository concepts are identified for the DRCV concept in Golder Associates (2003); both of which are located beneath the Bruce Site.

The DRCV-S concept – located in the low permeability Ordovician shales which are projected to underlie the Bruce Site between depths of about 420 m and 630 m below ground surface. It is assumed that the permanent repository is located in the upper portion of the shale sequence within the Queenston Formation at a depth of 460 m below ground surface.

The DRCV-L concept – located in the low permeability Ordovician limestones which are projected to underlie the Bruce Site between depths of about 630 m and 820 m below ground surface. It is assumed that the permanent repository is located in the upper portion of the limestone sequence within the Lindsay Formation at a depth of 660 m below ground surface.

3.3 THE GEOSPHERE

The information describing the geological setting and the associated hydrogeology has been summarised from Golder Associates (2003) except where stated.

3.3.1 Geology

3.3.1.1 Regional Setting

The southwestern Ontario District is underlain by sedimentary rocks of Palaeozoic age (Figure 8). All rock units are essentially flat lying and relatively undeformed with a gentle regional dip to the southwest. Rocks on the southeast edge of the District were influenced by sedimentation in the foreland Appalachian Basin. Rocks in the northwest occupy the eastern edge of the Michigan basin (a large sedimentary basin developed over a bowl shaped depression, of uncertain origin, in the Precambrian crystalline basement). The edges of the basin are defined by a series of highs – the Wisconsin arch on the west, the Kankanee arch, Findlay and the Algonquin arch of Ontario on the south and southeast, and the Canadian Shield and Superior Province in the north and northwest. The Algonquin Arch dissects the District in a southwest-northeast orientation separating the two basins. The basins and arch controlled the distribution and accumulation of sediments.

The central Michigan basin has an accumulated sedimentary rock thickness (mostly marine sediments) of greater than 4 km. The sediments are mainly derived from the erosion of the Adirondacks, Wisconsin and Canadian shield during the episodic invasions of many inland seas throughout the Palaeozoic era. A cover of glacial deposits, and glacially created lakes, blanket most of the geology of the basin.

3.3.1.2 District and Site

Geologically, the Bruce Site lies on the eastern edge of the Michigan Basin. The Palaeozoic bedrock sequence overlying Precambrian granitic basement has been estimated by extrapolation from regional gas exploration drilling results to be about 800 m thick (Golder Associates, 2003). It comprises (from top to bottom) (Figure 9):

- approximately 375 m of Devonian and Silurian age dolostones (dolomitic limestones);
- approximately 230 m of Lower Silurian – Upper Ordovician shale; and
- 185 - 190 m of Middle Ordovician fine grained, argillaceous to shaly limestone.

Details of the geological history of these sediments and their lithological descriptions are given in Appendix A.

The overburden is comprised of a comparatively complex sequence of surface sands and gravels from former beach deposits overlying clayey-silt to sandy silt till with interbedded lenses and layers of sand of variable thickness and lateral extent. The overburden thickness varies from less than 1 m along the lakeshore to a maximum of about 20 m on the eastern margin (Figure 10). The glacial deposits have been characterised in detail in the vicinity of WWMF (Figure 11).

3.3.2 Hydrogeological and Geochemical Characterisation

Information concerning the hydrogeological and mass transport properties of the overburden sediments and bedrock at the Bruce Site are provided in Golder Associates (2003). A summary of this information is provided in Table 6.

Four groundwater systems are identified in Golder Associates (2003) (Figure 12).

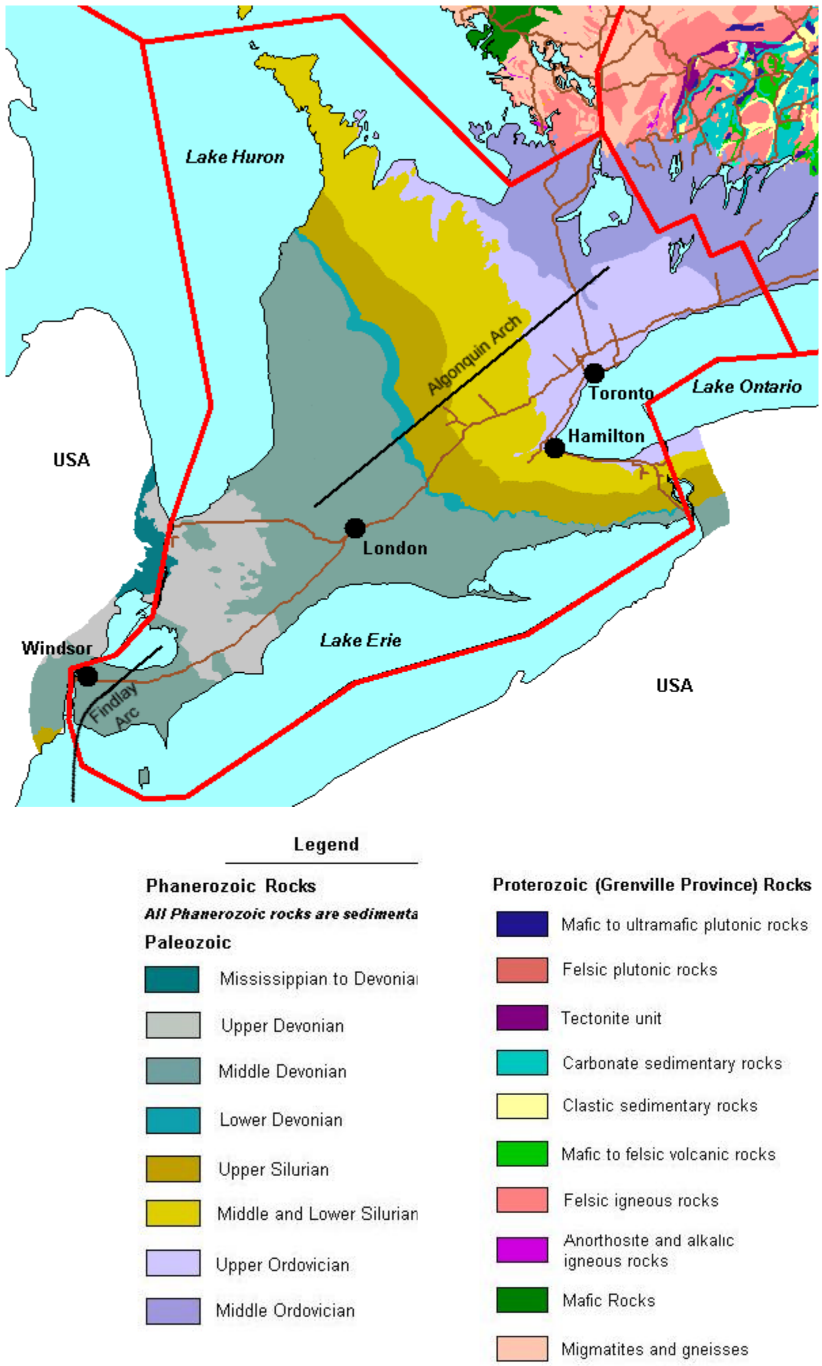

Figure 8: Regional Geological Setting (Ministry of Northern Development and Mines, 2003)

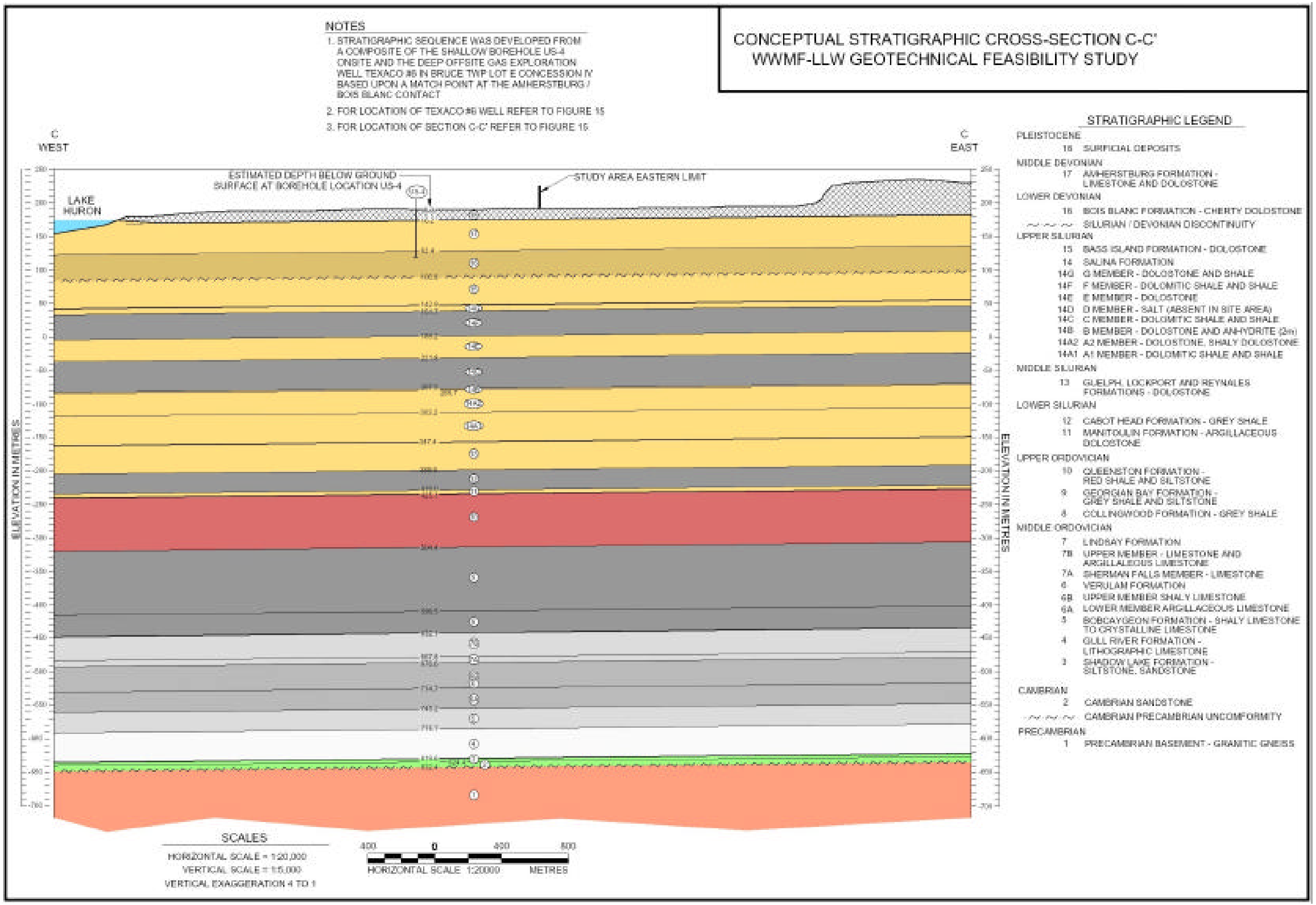

Figure 9: Cross-Section of the Stratigraphy below the Bruce Site (Golder Associates, 2003)

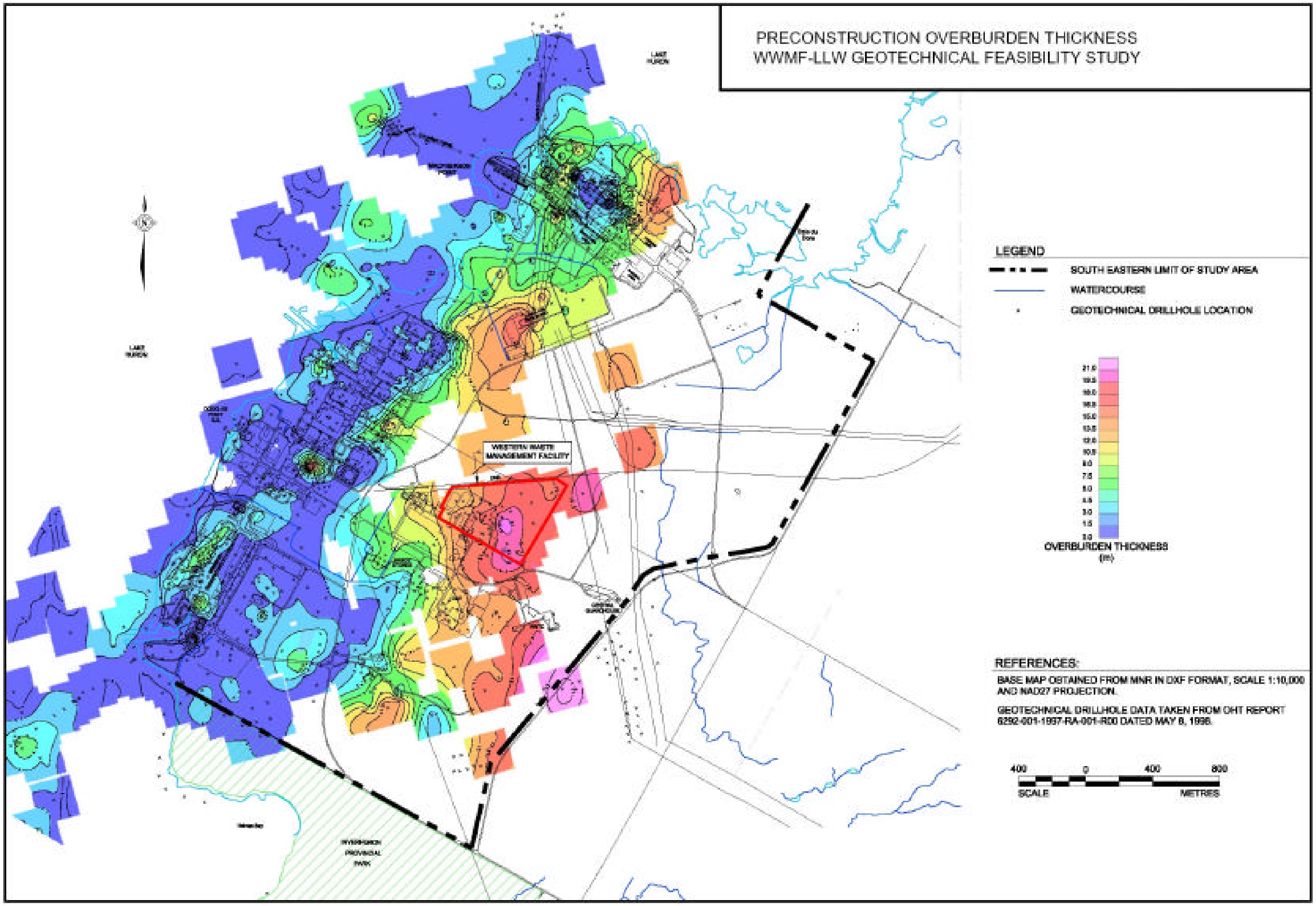

Figure 10: Overburden Thickness below the Bruce Site (Golder Associates, 2003)

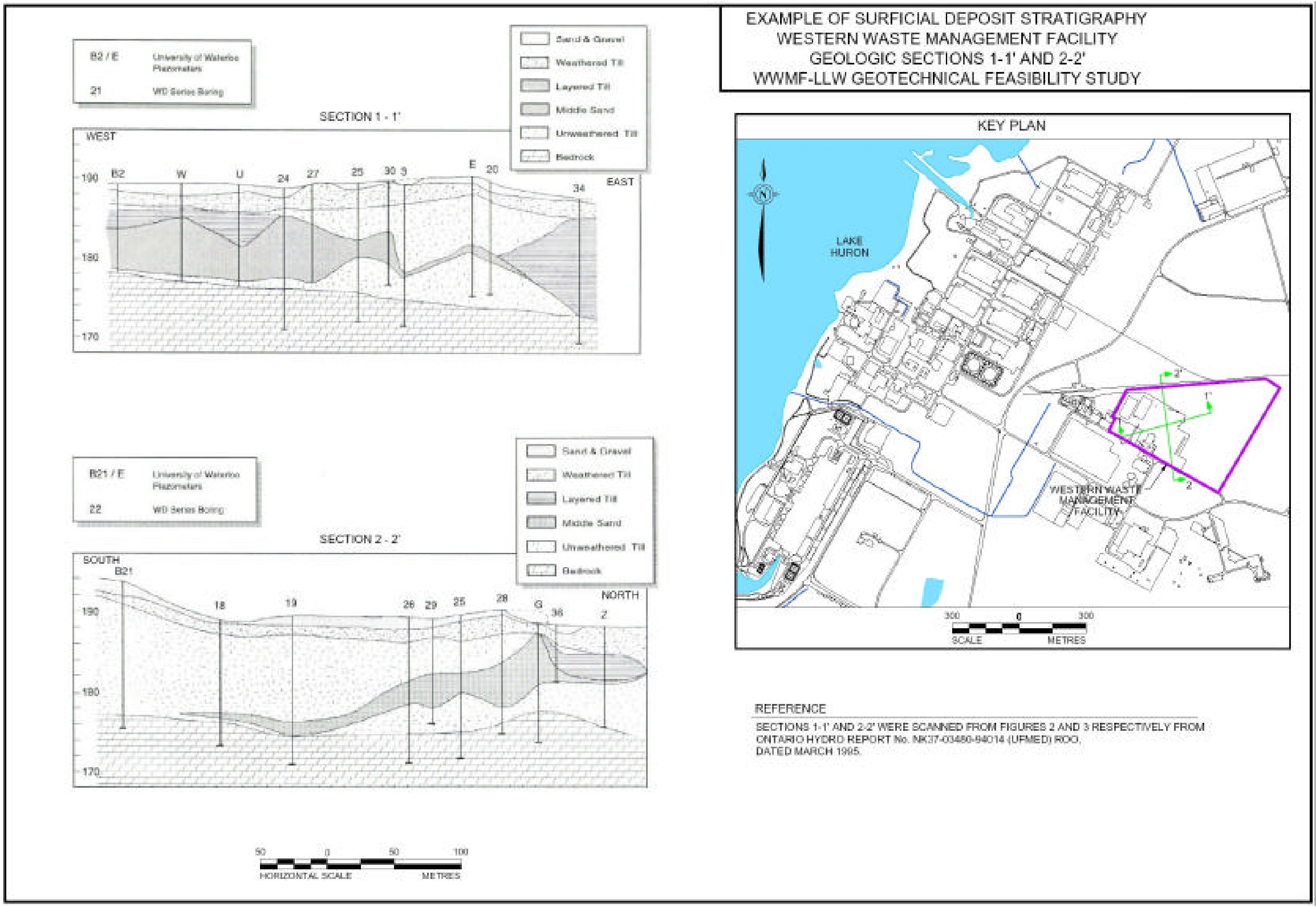

Figure 11: Cross-Section of the Glacial Deposit Stratigraphy below the WWMF (Golder Associates, 2003)

Table 6: Estimated Hydrogeological and Geosphere Transport Properties for the Bruce Site (Golder Associates, 2003)

Stratigraphic Sequence	Effective Hydraulic Conductivity (m/s)[1]			Groundwater Chemistry				Matrix Porosity	Effective Transport Porosity[3]	Dry Density	Chloride-Matrix Effective Diffusion Coefficient	Distribution Coefficient[4] (K_d)	Dispersivity (α)	Matrix Tortuosity Factor (τ)[5]
	min	max	Geometric Mean	TDS (mg/L)[2]	Chloride (mg / L)	pH	Redox Condition (mV)	%	%	(t/m3)	m^2/s @23°C	(mL/g)	(m)	Estimate
SURFICIAL SEDIMENTS GROUNDWATER SYSTEM						Neutral to slightly alkaline								
Sand and Gravel	4×10^{-8}	3×10^{-5}	(1×10^{-5})	Fresh	1-45	7.0 - 8.3	>100	30%	30%	1.8	7×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.7
TILL	1×10^{-10}	6×10^{-10}	2×10^{-10}								6×10^{-10}	C=20 Cl=0 I=0 Nb=160 Pu=1200 Tc=0.1		0.6
SHALLOW BEDROCK GROUNDWATER SYSTEM				Fresh to Brackish		Slightly Alkaline								
Bedrock Surface (Upper 15 m)	3×10^{-7}	6×10^{-5}	(1×10^{-5})	1,000 - 2,500	1-100		> 100	5 - 15	0.5 - 1.5	2.7	1.5×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.15
Devonian/Silurian/Limestone/ Dolostone Amherstburg, Bois Blanc and Bass Island Formations	7×10^{-10}	2×10^{-4}	(1×10^{-5})	Fresh to Brackish, sulphurous 1,000 - 2,500	10-100	7.2 - 7.7				2.6 - 2.7	1.5×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.15
INTERMEDIATE BEDROCK GROUNDWATER SYSTEM Silurian Dolostones Salina, Guelph and Lockport & Reynales Formations	n.a.	n.a.	(1×10^{-7})	Saline to Brine Sulphurous 100,000 - 300,000	50,000 - 200,000	Slightly Acidic 6.3 - 6.7	<0	4.8 - 11.0	0.5 - 1.1%	2.5 - 2.7	0.65×10^{-10} to 1.2×10^{-10}	C=5Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.04 - 0.08
Silurian Shales Salina C and F members,	n.a.	n.a.	(1×10^{-10})					1.9 - 3.1	0.2 - 0.3	2.6 - 2.7	0.5×10^{-10} to 1×10^{-10}	C=20 Cl=0 I=0 Nb=160 Pu=1200 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.03 - 0.07
DEEP BEDROCK GROUNDWATER SYSTEM Silurian Dolostones/Shales Cabot Head Formation	n.a	n.a.	(1×10^{-10})	Saline to Brine Sulphurous 100,000 - 300,000	50,000 - 200,000	Slightly Acidic n.a.	<0	1.9 - 3.1	0.2 - 0.3	2.6 - 2.7	0.5×10^{-10} to 1×10^{-10}	C=20 Cl=0 I=0 Nb=160 Pu=1200 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.03 - 0.07
Manitoulin Formation			(1×10^{-8})											
Ordovician Shales Queenston Formation	n.a.	n.a.	1×10^{-12}	Brine, Sulphurous 150,000 - 300,000	25,000 - 150,000	Slightly Acidic n.a.	<0	10.2- 11.4	1.0	2.6	1.4×10^{-10} to 1.6×10^{-10}	C=1 Cl=0 I=0 Nb=900 Pu=5100 Tc=1		0.095 to 0.108
Georgian Bay, Blue Mountain and Whitby Formations	9×10^{-14}	7×10^{-11}	1×10^{-12}											
Ordovician Limestones Lindsay Formation	3×10^{-14}	7×10^{-11}	7×10^{-13}	Brine, Sulphurous		Slightly Acidic		0.5 - 3	0.05 - 0.3	2.6	1×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.1
Verulam Formation	5×10^{-14}	7×10^{-9}	3×10^{-12}			6.2 - 6.3								
Bobcaygeon and Gull River Formations	2×10^{-15}	6×10^{-9}	4×10^{-12}	40,000-300,000	25,000-200,000		<0							
Shadow Lake Formation Cambrian Sandstone Precambrian Granitic Gneiss	4×10^{-4}	1×10^{-8}	8×10^{-12}			Slightly Acidic 5.1 - 6.2		<0.5	0.05	2.8	0.1×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.01

1 (1×10^{-5}) Bracketed values indicate "*Best Estimate*"
2 For TDS (total dissolved solids) classification:
Classification:
TDS mg/L
Fresh 100 - 1,000
Brackish 1,000 - 10,000
Saline 10,000 - 100,000
Brine >100,000

3 Effective Transport Porosity is assumed to be 10 percent of the Matrix Porosity
4 Distribution Coefficients for radionuclides (excluding iodine) are taken from Sheppard and Thibault 1990, Default Soil Solid/ Liquid Partition Coefficients, K_ds, for Four Major Soil Types: A Compendium, Health Phyries Vol. 59, No. 4 (October) pp 471-482,1990.
5 Matrix Tortuosity Factor x Free Water Diffusion Coefficient = Effective Diffusion Coefficient
n.a. indicates data not available.

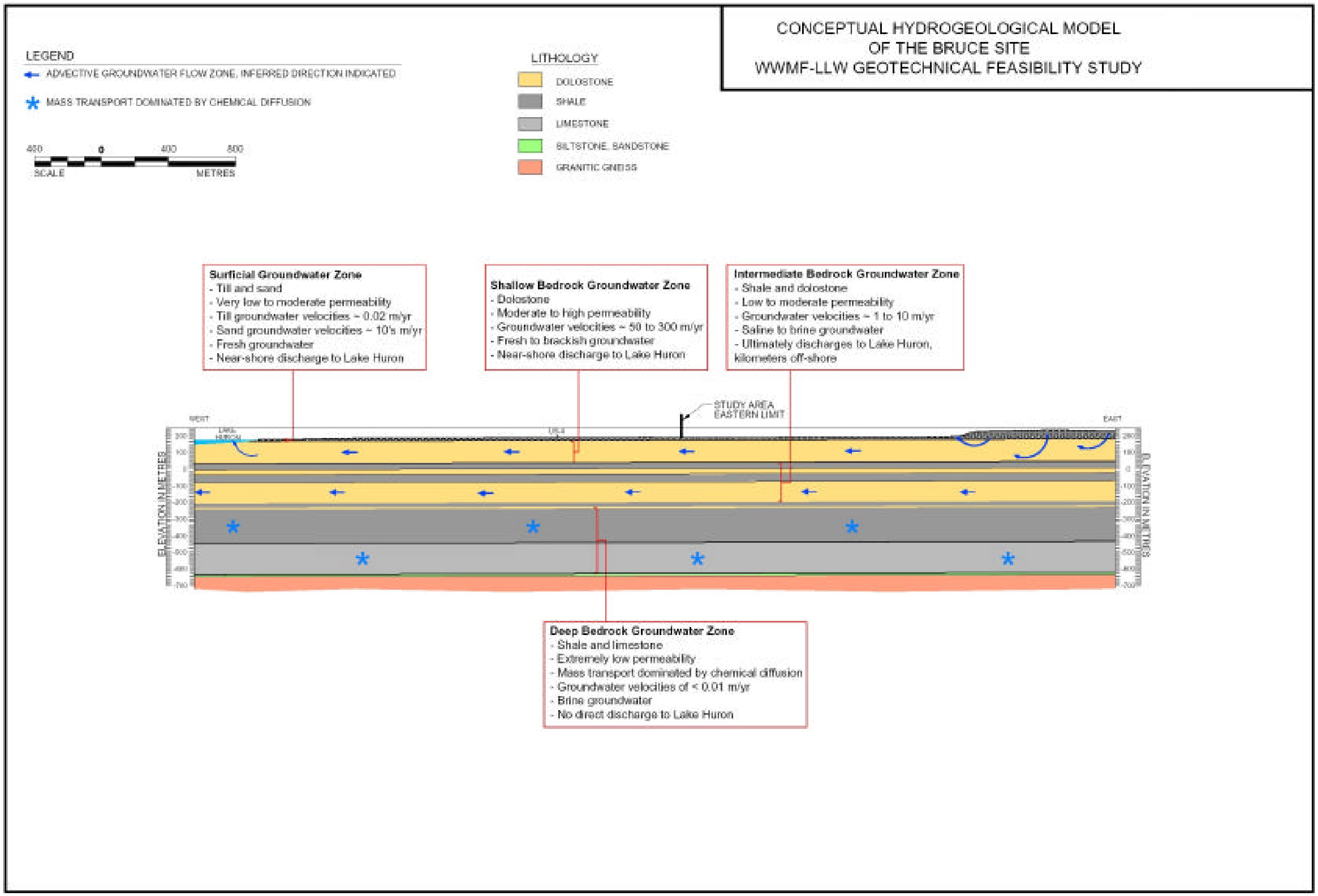

Figure 12: Conceptual Hydrogeological Model of the Bruce Site (Golder Associates, 2003)

The Surficial Deposits (Overburden) Groundwater System - Most of the central area of the Bruce Site is a recharge area for the glacial deposits from which groundwater flows westward to discharge into Lake Huron. Within the glacial deposits, layers of sand and gravel constitute local aquifers while the till layers comprise aquitards.

The Shallow Bedrock Groundwater System – It includes the dolostone sequence of the Amherstburg, Bois Blanc and Bass Island Formations and the top of the Salina Formation. The upper portions of this sequence contain fresh water while at greater depths, sulphur-rich water occurs. Beneath the Bruce Site, the Shallow Bedrock Groundwater system is recharged from upland areas to the east of the site. The direction of groundwater flow is westward towards the lake where it is discharged.

The Intermediate Bedrock Groundwater System – It includes the dolostone sequence of the Salina, Guelph, Lockport and Reynales Formations. The upper portion of the Salina Formation is typically freshwater or sulphur-rich water, whilst the lower dolostone strata can contain either sulphur-rich or saline water. The shales in the Salina Formation act as aquitards between the upper and lower portions of the Intermediate Bedrock Groundwater System. Lake Huron is considered to be the ultimate receptor of groundwater within this system, since the strata outcrop on the lake bed approximately 10 to 20 kilometres off-shore.

The Deep Bedrock Groundwater System – It is associated with the low permeability Ordovician shales and limestones. The groundwater is saline and the movement of pore water is very slow measured in the context of geological time (i.e., mass transport is diffusion dominated).

3.4 THE BIOSPHERE

A summary of the present-day biosphere at the Bruce Site and in its vicinity is given below. More details are provided in Appendix B.

3.4.1 Climate

The present climate is typical of a cool continental location, although the proximity of the large lakes mitigates against extreme conditions. The annual average temperature is 7°C, whilst the average daily temperatures vary from -5°C to 20°C over a year (OPG, 2000). Winds are moderate and predominantly from the south and southwest. Total annual precipitation is about 0.86 m y^{-1} (OPG, 2000). Storms are reasonably frequent and there is a tornado risk.

3.4.2 Topography

Bruce County is characterised by flat semi-open agricultural land to the east, rolling hills, valleys and sandy shores to the lake. The Bruce Site is located about 190 m above sea level, and large areas have been cleared and graded (Figure 13). The generally flat topography, coupled with the poorly conductive subsoil, means that substantial swales (pools) of standing water can form. An abrupt ridge of 1 – 3 m in height (Nipissing Bluff), running roughly north-south, divides the Bruce Site, and similar features (Algonquin Bluff) are found further inland. These ‘bluffs’ correspond to historic lake shorelines and indicate that the lake level has varied substantially in the post-glacial times.

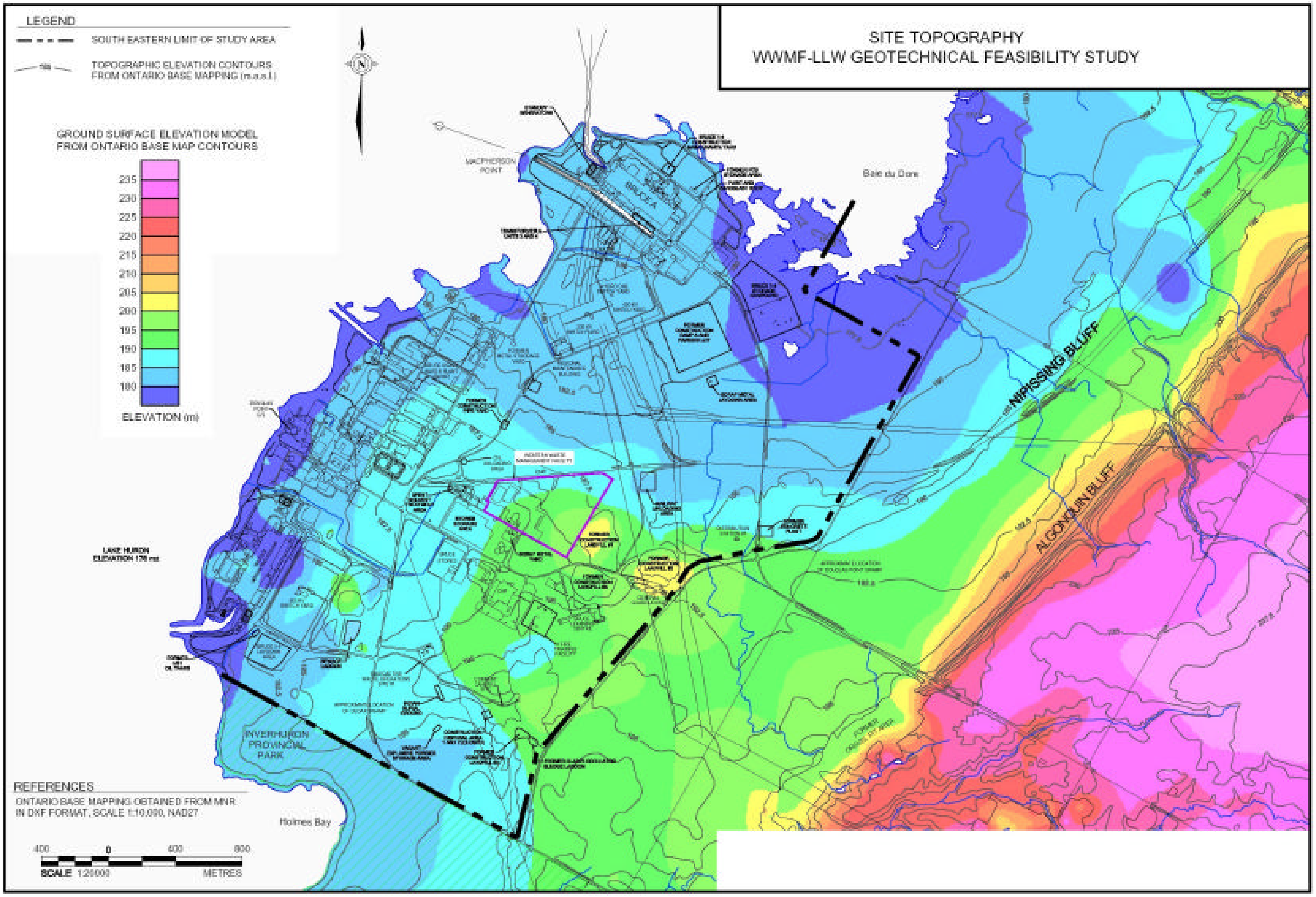

Figure 13: Bruce Site Topography (Golder Associates, 2003)

3.4.3 Surface Water

The dominant surface water feature in the region is Lake Huron (Figure 1), one of the Great Lakes. Lake Huron and the other Great Lakes were formed by glacial ice erosion. They only formed a stable system about 5000 years ago. The lake currently has a total surface area of 5.96×10^{10} m^2 and mean depth of 59 m.

There are no major rivers in the vicinity of the Bruce Site, although there are several surface water features of interest near to the Bruce Site, shown in Figure 14.

The Railway Ditch was originally excavated parallel to a now-disused railway line. It is 2 m to 3 m wide, has a typical water depth of about 0.15 m and a low flow rate. It flows via a wetland (that sometimes becomes blocked by beavers) a total of about 1 km to 'Stream C'. Stream C is a redirected stream of similar size to the Railway Ditch. It flows slowly for 1.4 km into Baie du Dore, a provincially significant wetland with an area of about 9.5×10^5 m^2.

3.4.4 Soil Types

The soil composition in the vicinity of the WWMF site is reported by Patrick and Romano (2001). In general, there is a shallow layer of topsoil, typically about 30 cm, overlying silt till. There are occasional regions of peat-like material. Soil and subsoil is generally firm to stiff and dense. Moisture varies, but the soil is generally moist and often wet or even saturated. To the east of the WWMF site lies an area of wetland. Information from a reference site at Goderich indicates that this is typical for land within a few kilometres of the lake.

3.4.5 Present-day Land Use

Land uses on the Bruce Site are restricted to those associated with the nuclear operations and support activities. The Bruce Site is the county's largest employer, creating 4000 jobs. An industrial park is also located to the east of the Bruce Site, providing a further 160 jobs.

The region around the Bruce Site is mainly used for agriculture, recreation and some residential development. Farmland accounts for around 60% of the land use in the county, with many cattle farmers, as well as farmers of pigs and sheep, and crops such as oats, barley, canola and hay. Local people also hunt wild animals including deer and waterfowl. Farms and rural populations often obtain water from wells. The lake provides water for larger communities, and is used for fishing.

The nearest population centre is Inverhuron, with about 200 permanently occupied dwellings. Larger towns are Port Elgin about 20 km to the northeast and Kincardine, 15 km to the southwest.

Archaeological sites exist in the vicinity showing that it was settled around 2000 years ago by the Iroquois Nation, and occupied by the Ojibway Tribe when Europeans settled in the 1800s. Two areas of archaeological interest exist on the Bruce Site, neither close to the WWMF site.

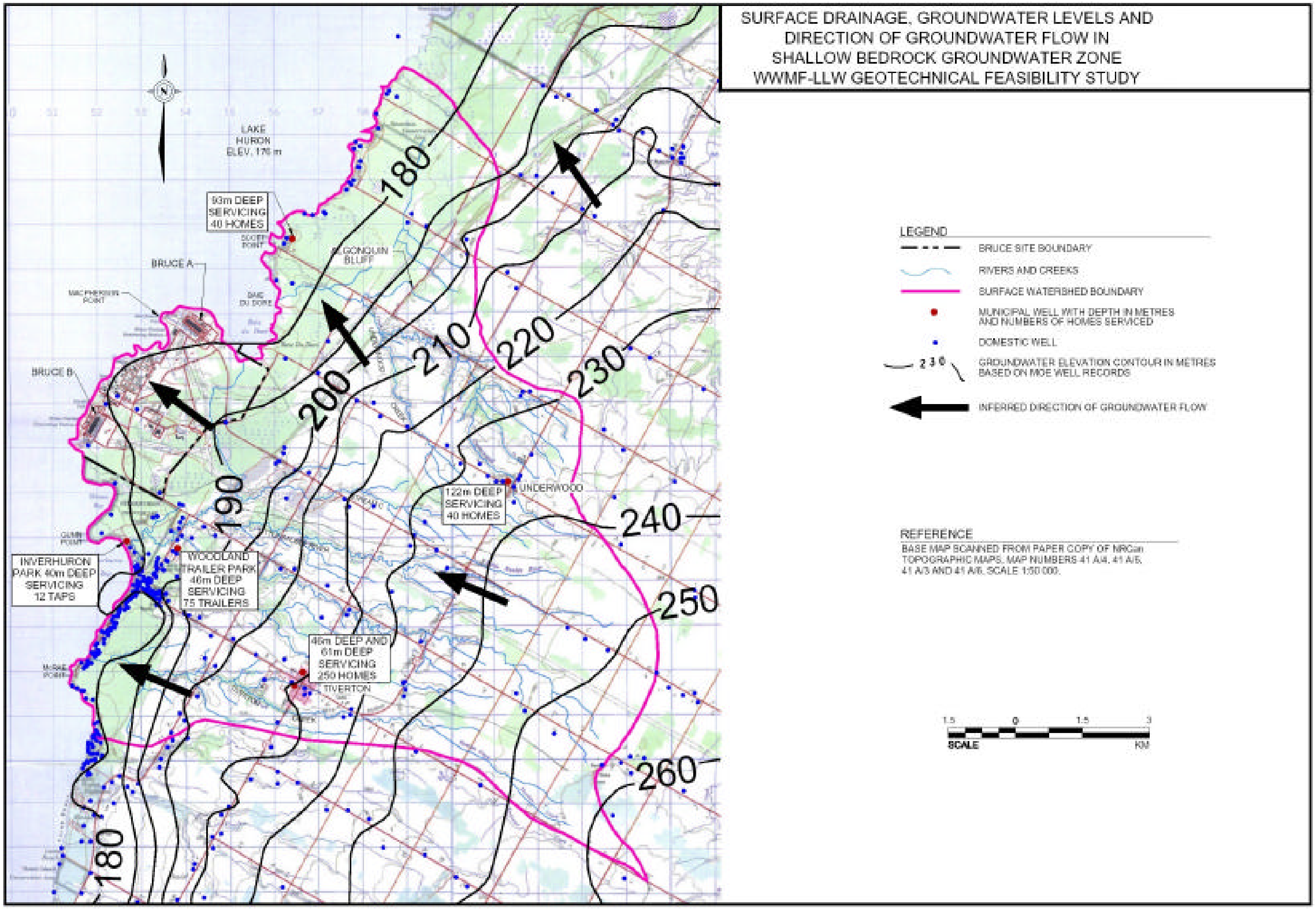

Figure 14: Location of Rivers, Creeks and Municipal Wells in the Vicinity of the Bruce Site (Golder Associates, 2003)

3.4.6 Flora and Fauna

The WWMF site is vegetated with balsam fir, sugar maple and American beech. There is also a meadow and wetland area. There is a wide variety of wildlife in the area, all common for the region. Birds include doves, cuckoos, woodpeckers, pewees, blue-jays, swallows and robins. Mammals that have been observed include deer, porcupine, racoons and beaver. Streams are diversely vegetated with species such as cattails, sedge, pondweed and watercress. Fish species include the Central Mud Minnow, White Sucker, Redbelly Dace, Creek Chub and Spine Stickleback. Larger streams and wetlands contain trout, bass, salmon and carp. Other fauna include frogs, turtles, salamander, water snakes, crayfish, leeches and snails.

3.4.7 Natural Resources

There is some mineral extraction in the region, for sand and gravel. Four disused quarries exist in the controlled development zone around the Bruce Site. Both municipal and domestic users of groundwater exist in the vicinity of the Bruce Site (Figure 14), and in the wider Kincardine Municipality there are approximately 1000 wells (Golder Associates, 2003). Water is drawn principally from the Shallow Bedrock Groundwater System from depths of between 30 and 100 m.

4. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

4.1 INTRODUCTION

For the purposes of this study, a definition of a scenario consistent with that used in IAEA (2002a) has been adopted:

> *A scenario is a hypothetical sequence of processes and events, and is one of a set devised for the purpose of illustrating the range of future behaviours and states of a repository system.*

The aim of a scenario-based approach to postclosure radiological safety assessment is to develop illustrative descriptions of the possible future evolution of the repository system and its surrounding environment. The emphasis is therefore on the identification of representative classes of possible futures, rather than undertaking detailed simulations of projected change. In this way, the wide range of potential future conditions is condensed to an inclusive, yet manageable, set of scenarios, defining a breadth of analysis that allows the importance of key influences and uncertainties (relating to the timing sequence and magnitude of future changes to the repository system) to be explored.

In practice, the development of a robust safety case depends on being able to demonstrate that the selected scenarios and related system models and parameter values provide adequate and comprehensive coverage of the various sources of uncertainty that are inherent in making estimates of postclosure radiological impact. The identification of scenarios inevitably involves expert judgement; however, as IAEA (2002a) notes, it is also important to bring structure and traceability into the process, in order to lend confidence to the selection of scenarios. For this preliminary safety assessment study, the scenarios and associated release, transport and exposure pathways identified for assessment are based largely on Quintessa's experience, taking account of the assessment context, the repository system description, and experience gained from other relevant assessments.

The scenario development procedure used in this preliminary safety assessment has the following main steps.

- Identification of the repository.
- Identification of external FEPs (EFEPs) and their potential relevance to the repository system under study.
- Categorisation of EFEPs to identify contributions to scenario development.
- Definition of scenarios for evaluation through conceptualisation of relationships between EFEPs.

The application of this approach to the current study is described in Appendix C. Its application has resulted in the identification of two scenarios:

- the Reference Scenario; and
- the Human Intrusion Scenario.

These two scenarios are outlined below.

4.2 REFERENCE SCENARIO

At the core of many recent safety assessments is a scenario (the Reference Scenario) that is representative of the projected evolution of the permanent repository and its surrounding environment. This scenario can take into account continuous change prompted by factors that are both internal and external to the repository system and its immediate environment. Such changes are primarily associated with the degradation of the properties of the near field, and evolution of the surrounding environment, caused by climate change and associated changes in human habits and land use.

In light of the discussion in Appendix C, the Reference Scenario adopted for the preliminary safety assessment is one in which change to the repository system (near field, geosphere and biosphere) occurs solely as a result of the internal factors (e.g., degradation of wastes and engineered structures) rather than external factors (e.g., climate change). This is judged to provide a reasonable basis for a preliminary appraisal of safety – particularly in relation to undertaking a comparative assessment of alternative permanent repository concepts – for an assessment period of up to 50,000 years and is consistent with the assessment context (Section 2.6). Indeed, projections undertaken on behalf of OPG (Peltier, 2002) indicate that the Bruce site would be ice free for more than 66,000 years into the future. In future assessments, more systematic consideration can be given to the need (or not) to represent explicitly external factors. In addition to the longer-term effects of climate change (including, ultimately, possible periglacial conditions, followed by glaciation), consideration could be given to the extent to which changes in regional climate might influence the groundwater flow system and lake levels, and the potential safety implications of such changes.

For this preliminary safety assessment, the Reference Scenario considers:

- the gradual release of radionuclides from the repository in liquid, gaseous and, where applicable, solid (e.g., waste and contaminated soil) forms due to the natural processes;
- the subsequent migration and accumulation of radionuclides in the environment; and
- the resulting potential exposure of humans to the radionuclides.

The detailed conceptual models that underlie the Reference Scenario are described in Section 5.2 and Appendix D.2.

4.3 HUMAN INTRUSION SCENARIO

For this preliminary safety assessment, two main categories of disruption are considered for the Human Intrusion Scenario:

- small - representative of the type of disturbance that might be caused by the drilling of boreholes during site investigation; and
- large - representative of large-scale near-surface excavations associated with major construction projects or, potentially, archaeological investigations at the site.

The case for a large excavation is assumed credible for the CAGCV-S and CAGCV-T surface concepts. For the DRCV-S and DRCV-L, the depth of the permanent repository precludes such situations and only borehole intrusion into the wastes is considered.

For the large mode of intrusion, two main exposure situations can be taken into account:

Intruder exposure: describing direct exposure of individuals to essentially undiluted waste materials, for example, in relation to involvement in the activity that would give rise to the intrusion or subsequent actions linked to the event, such as site investigation or collection and examination of samples.

Site occupant exposure: describing exposures of individuals with no direct connection to the intrusion event, but who may nevertheless encounter waste materials incorporated into local surface environmental media as a result of disturbance of the repository (e.g., as a result of occupation of the site in later years).

For the small mode of intrusion, only intruder exposure is considered.

The detailed conceptual models that underlie the Human Intrusion Scenario are described in Section 5.2 and Appendix D.3.

5. FORMULATION AND IMPLEMENTATION OF MODELS AND DATA

5.1 INTRODUCTION

The approach used in the current study for model formulation and implementation is summarised below and in Figure 15.

First, the **general conceptual models** are developed with input from the system description, scenarios and FEP list. The aim is to provide, for each scenario, a high level description of the release, migration and fate of radionuclides from the repository and the associated FEPs. Each scenario has an associated general conceptual model (i.e., there is one for the reference scenario and one for the human intrusion scenario). Each general conceptual model allows different high level options (e.g., repository (surface vs. deep), types of human intrusion (borehole vs. excavation)) to be considered but no consideration is given (at this stage) to potential sources of conceptual model uncertainty or the different calculation cases. For convenience the repository system can be divided into three sub-systems: the repository (the near field); the geology and hydrogeology (the geosphere); and the surface environment (the biosphere). The general conceptual models are justified with logical arguments, documented assumptions, and a clear indication of the uncertainties and how they may be addressed. They are audited against a FEP list to ensure that important issues have not been neglected. The application of this process of general conceptual model development to this preliminary safety assessment is described in Appendix D.

Once each general conceptual model has been developed, there is a need to consider the alternative repository concepts in more detail (e.g., differentiate between the level of engineering of the repositories) (Section 5.2.1) and the various sources of uncertainties for each conceptual model (e.g., exact location of discharge from the geosphere to the biosphere) (Section 5.2.2). This allows the **calculation cases** to be identified (i.e., a list of calculations for which specific conceptual models and mathematical models are to be developed and implemented in and solved by software tool(s)) (Section 5.2.3). Each scenario and general conceptual model can have several associated calculation cases due to the range of associated potential repository concepts and conceptual model uncertainties identified (e.g., the reference scenario has one general conceptual model and eight calculation cases).

Whilst a calculation case relates to a specific scenario and general conceptual model, it does not give a detailed description of the **specific conceptual model** (and associated FEPs) that need to be considered in order to allow the development of the mathematical model. Therefore the next step is to develop a specific conceptual model that explicitly considers the detailed FEPs for each calculation case (Section 5.2.4). This is done by using the higher level conceptual model as a starting point and refining it to take into account the sources of uncertainty and the repository concepts identified for the different calculation cases. Thus each calculation case has its own related specific conceptual model.

Lastly, the specific conceptual models for each calculation case are then used as a prescription for the mathematical models that are required (Section 5.3). The mathematical models themselves indicate the parameters for which data are required. Site-specific data can be obtained from the source of information for the system description. This can be supplemented with other information, e.g., from compilations of data. Data used in this preliminary safety assessment are given in Section 5.4. The mathematical models and associated data are then implemented in a software tool that is used to simulate the migration of radionuclides from the repository via the various pathways and calculate the resulting dose rate and environmental consequences (Section 5.5).

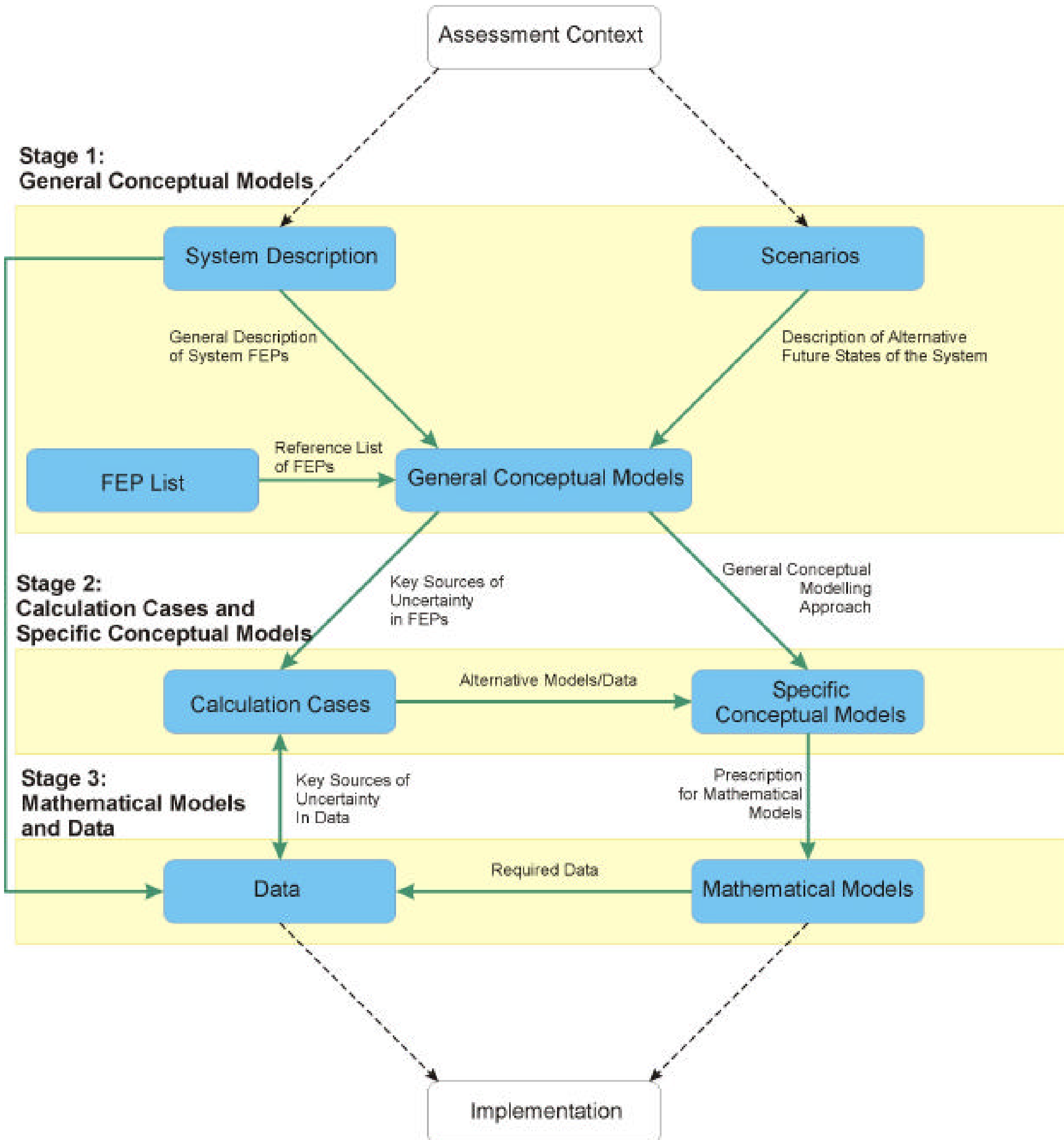

Figure 15: The Model Development Approach Used in the Current Study

5.2 CALCULATION CASES AND SPECIFIC CONCEPTUAL MODELS

The scenario identification process has identified two alternative futures for the repository system that merit investigation (Section 4 and Appendix C). Scenarios and the system description have been used to identify several general conceptual models for consideration in the study (Appendix D). However, these must be further refined into a set of calculation cases for assessment. This allows:

- the analysis of alternative permanent repository concepts, and
- the analysis of key conceptual model uncertainties.

The calculation cases in this section are derived from the general conceptual models with consideration of these two types of issue.

5.2.1 Permanent Repository Concepts Considered in the Preliminary Safety Assessment

The conclusions of the geotechnical assessment by Golder Associates (2003) are identified in Table 5. The Assessment Context for the study identifies the need to consider the permanent repository concepts that are considered to be geotechnically feasible.

In addition to alternative repository locations and designs, OPG is evaluating different degrees of engineering for the repositories (Section 3.2.2). The non-grouting design options envisage an engineered vault (for the CAGCV) or floor slab (DRCV). Wastes are emplaced in the repository without the addition of grout to the waste containers, and without backfill to fill repository void space. For the CAGCV and DRCV, the engineering could, however, be enhanced by the addition of grout to the wastes. For the CAGCV, cementitious backfill could be added to fill the void space between the waste packages. This is referred to as the grouting option.

Therefore, eight alternative permanent repository concepts and associated engineering options require consideration for each identified calculation case:

- CAGCV-S, Non-grouting Case;
- CAGCV-T, Non-grouting Case;
- CAGCV-S, Grouting Case;
- CAGCV-T, Grouting Case;
- DRCV-S, Non-grouting Case;
- DRCV-L, Non-grouting Case;
- DRCV-S, Grouting Case; and
- DRCV-L, Grouting Case

5.2.2 Key Conceptual Model Uncertainties

The conceptual model uncertainties are, by definition, specific to each scenario. Various issues were identified as having potentially important uncertainties during the identification of features and processes, and the development of general conceptual models(see Appendix D). These form the basis of the uncertainties that are considered with alternative calculation cases. It should be noted that not all types of uncertainty are dealt with in defining calculation cases – future uncertainties are dealt with in the identification of scenarios, and parameter/data uncertainties are dealt with in the identification of assessment model data.

5.2.2.1 Reference Scenario

The conceptual model uncertainties identified for the Reference Scenario are largely associated with the future performance of the near-field features and the behaviour of the migrating radionuclides in the groundwater systems. In comparison, the uncertainties associated with the biosphere have been removed to a large extent by assumptions adopted in the assessment context and scenario development and justification process (for example the assumption of constant present-day biosphere features and processes).

CAGCV Concepts

The proximity of the CAGCV concepts to the surface environment means that there are a number of significant conceptual model uncertainties that can be considered in the development of calculation cases. The key issues that have been identified are listed below.

Geosphere Discharge Location: The complicated stratigraphy in the overburden sediments means that there is a substantial degree of uncertainty concerning the presence and connectivity of conductive horizons in the sediments, and hence the flow path for radionuclides in the geosphere. It is most likely that the groundwater path for migrating radionuclides will result in their transport in the Shallow Bedrock Groundwater System and emergence in the near shore lake environment. However this system comes very close to the surface at the lakeshore and discharge to lakeshore sediment might possibly occur, although there is no direct evidence of this occurring at the site. In addition to these 'natural' locations for groundwater discharge, wells could be drilled into the Shallow Bedrock Groundwater System. The calculated dose rates are known to be highly sensitive to the location of groundwater discharge, and so the issue needs to be considered in the calculation cases for the assessment.

Bathtubbing: The presence of low hydraulic conductivity till underneath the CAGCV-T repository means that if the cap, engineered structures and other near-field components degrade to the point at which their hydraulic conductivity is higher than the till, water percolating through the wastes could be diverted horizontally from the base of the repository into surrounding soil and then into a stream. This potential 'short cut' for migrating radionuclides is commonly referred to as 'bathtubbing'. Its occurrence is uncertain, but it is a potentially significant situation as radionuclides can be released into the biosphere more rapidly than would otherwise be the case.

Gas Release: There is unlikely to be significant gas released from the repository due to the relatively inert nature of the wastes. It can be expected that there would be no release of gas until the waste containers fail. It is likely that gases would simply emanate from the cap and be dispersed. However, any building located on the cap could accumulate radioactive gases. Although this is clearly an unlikely situation, it is worthy of assessment to quantify the potential significance of gases such as H-3, C-14 and Rn-222.

Cover Erosion: The physical erosion of the near field is possible in the long term. Initially, the cap and engineered structures would resist surface erosion from wind and water. However, as they degrade the resistance could be lost, and, as the repository stands above the natural topography, the cover materials could gradually be removed by preferential erosion. This would ultimately result in exposing the wastes at the surface after a very long period of time. This situation is potentially important, as solid waste could be released into the biosphere.

DRCV Concepts

The relative homogeneity of the geosphere conditions in which the DRCV concepts could be situated means that there are fewer conceptual modelling uncertainties that need to be considered in the definition of calculation cases. Furthermore, the depth of the concepts means that cover erosion does not need to be considered. In addition, any radioactive gas released from the repository would be subjected to significant dilution and decay during the long travel period prior to it reaching the ground surface. Therefore, the impact of gas releases does not need to be considered.

Shaft Pathway: The very low permeability of the Ordovician shale and limestone, coupled with high saline groundwater regime, imposes a diffusion-controlled environment for mass transport. However, failure to seal the shafts to the DRCV completely and effectively may provide an alternative pathway for some of the radionuclides in the vault to enter into the Intermediate Bedrock Groundwater System via ‘enhanced diffusion’ (due to higher diffusivity of assumed failed shaft sealing materials). This enhanced diffusion of radionuclides in the shaft is expected to affect only a small fraction of radionuclides released from the vault and is best assessed using detailed 3D transport models to determine implications of concentration gradient and effective diffusivity on mass transport. Nevertheless, in this preliminary study, the shaft pathway has been assessed using conservative transport models to provide an upper-bound evaluation of this potential transport pathway.

5.2.2.2 Human Intrusion Scenario

Human intrusion scenarios have a very substantial degree of uncertainty associated with them. However, this is associated with future uncertainty (it is not possible to establish with certainty how the intrusion occurs). For this reason, it is not considered appropriate to develop further calculation cases to explore variants of intrusion scenarios. However, it is appropriate to recognise this uncertainty by undertaking the assessment of intrusion consequences with relatively simplified calculation models (detailed models would not be warranted given the high level of uncertainty intrinsic to the scenarios).

5.2.3 Calculation Cases

A series of calculation cases have been defined for assessment using the considerations described above. These are summarised in Table 7.

5.2.4 Specific Conceptual Models

As noted in Appendix D, the formalised description of specific conceptual models can be accomplished in a variety of ways. In this study, a simple Process Influence Diagram (PID) approach has been chosen. This is based on that described by Chapman et al. (1995), but with the simplification that the only processes illustrated are radionuclide transport mechanisms. The figures show the media and processes that, on the basis of expert judgement and the results of previous assessments, are considered to be key. “Second-order effect” processes (i.e., those that could have a less significant effect on radionuclide concentrations than those presented below) are not considered. Some of the media and processes shown on the figures might be explicitly represented in the computer implementation of the conceptual and mathematical models and might be further discretised (e.g., representation of the lake into seven compartments). Others might be implicitly rather than explicitly represented (e.g., the atmosphere and suspension do not have to be explicitly represented, since they can be represented by assuming a dust loading in the air above the soil).

Radionuclides can be lost by a number of mechanisms from the region of interest (i.e., the area in the vicinity of the release into the biosphere where the radionuclide concentrations can be expected to be highest and the associated dose rates highest). They are no longer of interest in the evaluation of individual dose rates, and can be regarded as being ‘lost’ from the region of interest to ‘other’ locations where radionuclide concentrations are lower and the associated dose rates lower. For the purpose of this preliminary safety assessment and the conceptual models in the following sub-sections, these areas are described as being outside the region of interest.

Table 7: Calculation Cases for Assessment

Scenario	Release Mechanism	Calculation Case Name	Permanent Repository Concept(s)	Potential Exposure Group(s)	Features
Reference Scenario	Liquid	Lake Release	CAGCV-S, CAGCV-T	Fisherman	Contaminated groundwater released to overburden sediments and transported to lake via Shallow Bedrock Groundwater System.
		Lakeshore Release	CAGCV-S, CAGCV-T	Fisherman	Contaminated groundwater released to overburden sediments and transported to lakeshore via Shallow Bedrock Groundwater System.
		Well Release	CAGCV-S, CAGCV-T	Farmer	Contaminated groundwater released to overburden sediments and transported to well via Shallow Bedrock Groundwater System.
		Bathtubbing	CAGCV-T	Site dweller	Contaminated groundwater released directly into soil after degradation of near-field barriers.
	Gas	Gas Release	CAGCV-S, CAGCV-T	Site dweller	Contaminated gas released into a house on the cap after failure of containers or loss of institutional control (whichever is later).
	Solid	Cover Erosion	CAGCV-S, CAGCV-T	Site dweller	Waste exposed at the surface after degradation of near-field barriers and its erosion by wind and water.
	Liquid	Lake Release	DRCV-S, DRCV-L	Fisherman	Contaminated groundwater released by diffusion to Intermediate Bedrock Groundwater System, then transport to off-shore lake sediments.
	Liquid	Shaft Pathway	DRCV-S, DRCV-L	Fisherman	Contaminated groundwater released via shaft and transported via enhanced diffusion to Intermediate Bedrock Groundwater System, then transport to off-shore lake sediments.
Human Intrusion Scenario	Solid	Exploration Borehole	CAGCV-S, CAGCV-T, DRCV-S, DRCV-L	Intruder	Waste retrieved to the surface via shallow (CAGCV) or deep (DRCV) borehole.
		Excavation	CAGCV-S, CAGCV-T	Intruder, Site dweller	Large excavation disrupts waste and spoil from large excavation contaminates surface soils, which are then farmed.

Note: All calculation cases for the CAGCV and DRCV concepts are considered for both grouting and non-grouting options.

5.2.4.1 Specific Conceptual Model for Lake Release, CAGCV Concepts

The specific conceptual model for the Lake Release Calculation Case considers the near-field structures to degrade naturally, until their properties are the same as the surrounding overburden sediments. Both physical and chemical changes are considered, the latter associated with cement degradation. It is assumed that the flow through the repository is controlled by the hydraulic conductivity of the cap, which is assumed to degrade to be the same as the underlying overburden sediments. Consequently, there is no release of contaminated groundwater due to bathtubbing. Flows within the near-field structures are controlled by the relative hydraulic conductivities of the structures and also the relative proportion of each structure that is available for flowing water. This latter property is used to represent the progressive degradation of steel drums – initially none of the waste within the drums is available for transport in water, but the proportion increases linearly with time until all drums have corroded and all waste is available for transport in water. Both factors are considered to determine the distribution of flows via various media, including 'bypass flows' that can occur when excess water flows around waste, for example. The near-field specific conceptual model is illustrated in Figure 16.

Contaminated water from the near field percolates through the overburden sediments, eventually meeting the Shallow Bedrock Groundwater System. It is assumed that the flow is essentially vertical (Figure 17). The overburden sediments are considered to comprise either tills or sand, depending upon the location considered for the CAGCV. The Shallow Bedrock Groundwater System is fractured carbonate rock, and in all materials, transport is by advection and dispersion, with consideration also given to decay and sorption processes.

Contaminated groundwater discharges into the lake water via the lake sediment (Figure 18). Radionuclides are transferred from the lake sediment to the water column by water flow and sediment resuspension. They are transferred from the water column to the sediment by sedimentation. Because these processes are relatively rapid in the timeframe of the assessment, and operate on a large scale, it is not necessary to consider sedimentation and resuspension explicitly, and equilibrium distribution coefficients are used to estimate the sediment concentration. Once in the lake the radionuclides can be dispersed from the immediate area of discharge (resulting in a lowering of their concentrations). Ultimately they leave Lake Huron. This process is shown as the 'flow' transfer from the Lake Water compartment on Figure 18. It is cautiously assumed that part of the lake sediment is exposed and so available for resuspension into the atmosphere. A fishing potential exposure group is considered that is exposed to radionuclides due to ingestion of fish and lake water, inadvertent ingestion of lake sediment, inhalation of lake sediment and external irradiation from lake sediment. A farming potential exposure group could also be considered that makes use of the lake water for domestic and agricultural purposes. However, such a group would receive lower dose rates than the farming group considered in the Well Release Calculation Case (Section 5.2.4.3) due to the greater dilution of radionuclides in the lake, and so the group is not considered for the Lake Release Calculation Case.

5.2.4.2 Specific Conceptual Model for Shore Sediment Release, CAGCV Concepts

The conceptual model for the near field in this calculation case is the same as the lake release case, as shown in Figure 16. The arrangement of the media in the geosphere is also essentially the same; however, contaminated groundwater is assumed to upwell into shore sediments adjacent to the lake. The geosphere conceptual model is therefore the same as Figure 17, with the exception that the release from the Shallow Bedrock Groundwater System is directly into the lakeshore sediments, rather than the submerged lake sediments. The biosphere model is focussed on the lakeshore sediments and the lake. This is illustrated in Figure 19. A fishing potential exposure group is assumed that is exposed via ingestion of fish and lake water, inadvertent ingestion of lakeshore sediment, inhalation of lakeshore sediment and external irradiation from lakeshore sediment. Their habits and exposure pathways are consequently the same as considered for the Lake Release Calculation Case. Again a farming potential exposure group could also be considered that makes use of the lake water for domestic and agricultural purposes. However, such a group would receive lower dose rates than the farming group considered in the Well Release Calculation Case (Section 5.2.4.3) due to the greater dilution of radionuclides in the lake, and so the group is not considered for the Lake Release Calculation Case.

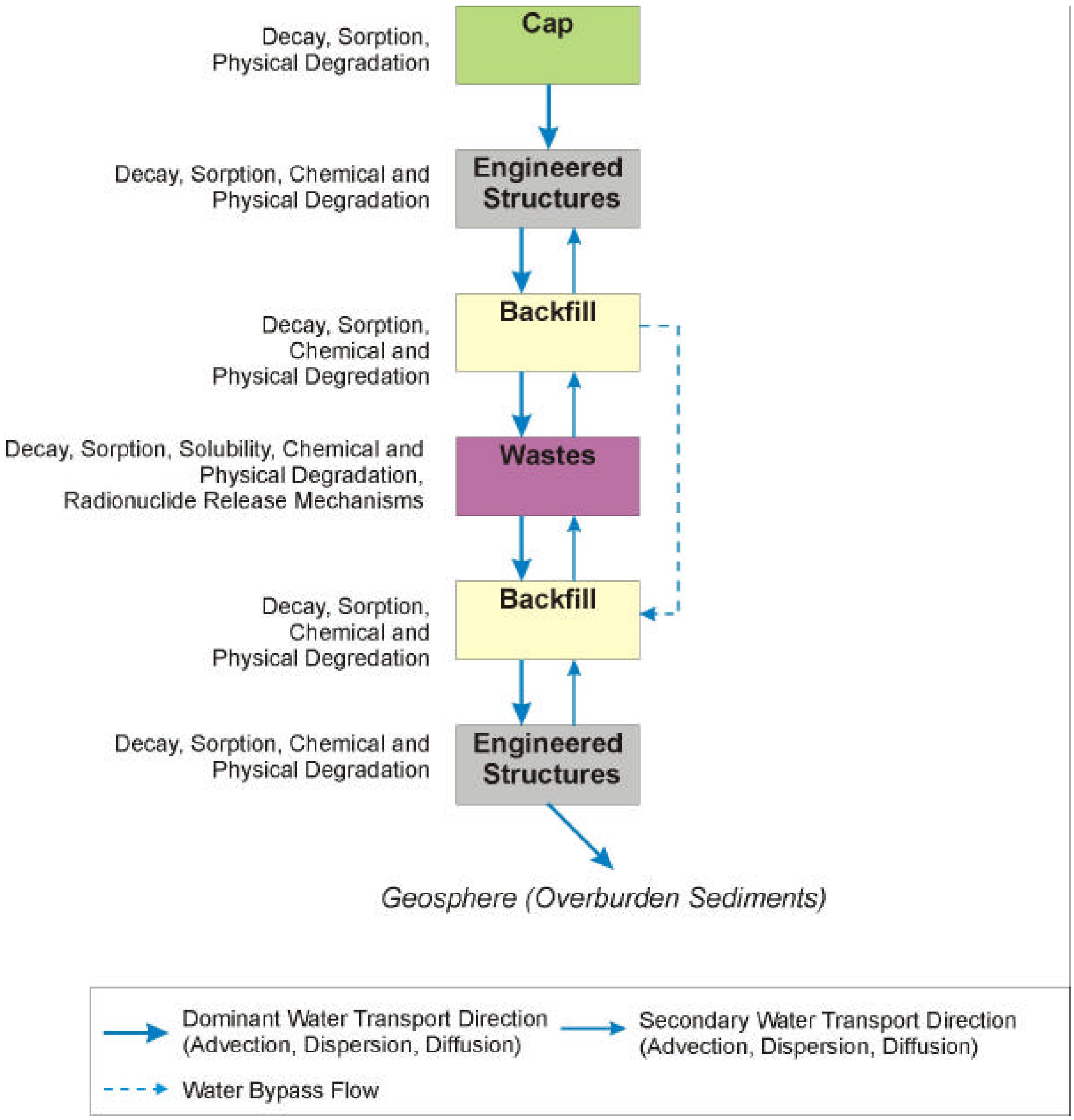

Figure 16: Near-field Conceptual Model for the CAGCV Lake Release Calculation Case

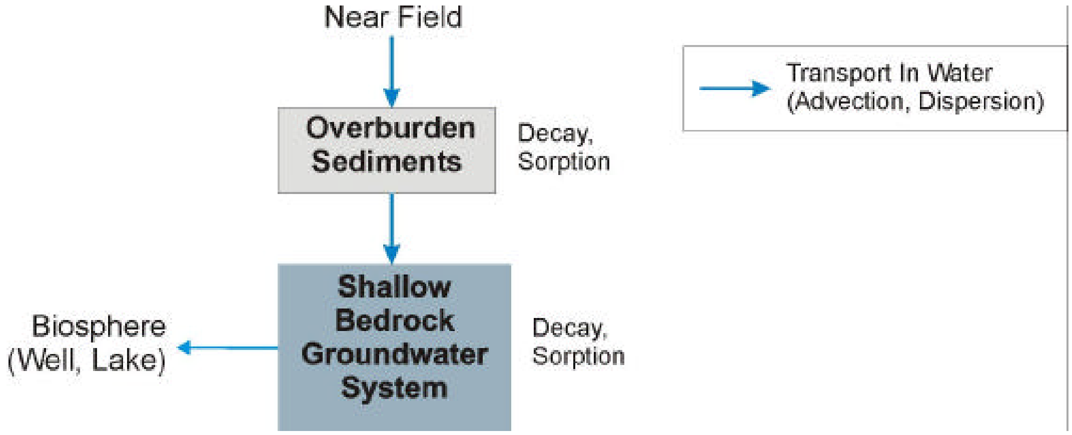

Figure 17: Geosphere Conceptual Model for the CAGCV Lake Release Calculation Case

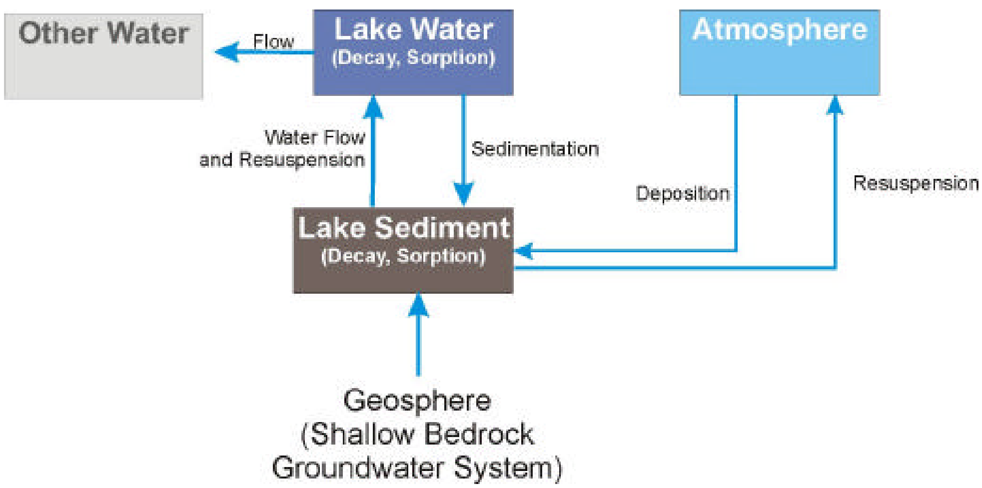

Figure 18: Biosphere Conceptual Model for the CAGCV Lake Release Calculation Case

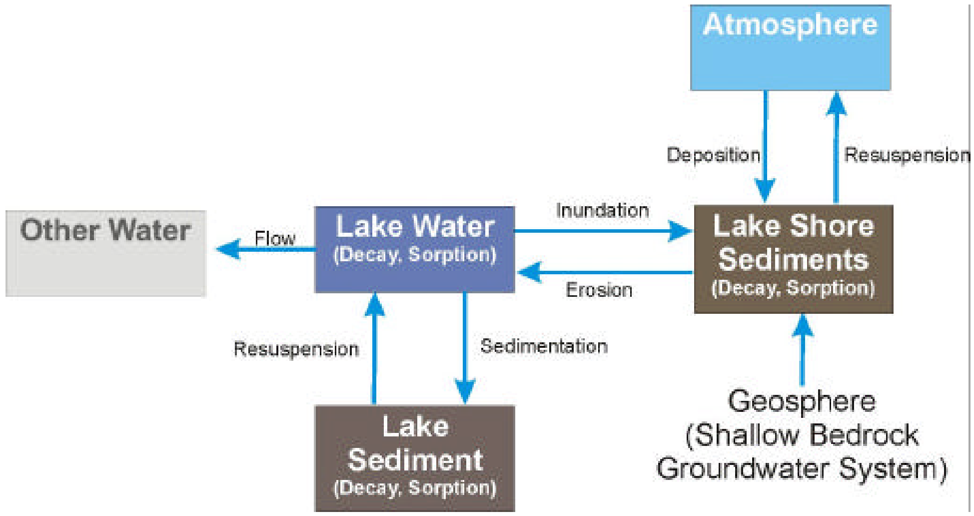

Figure 19: Biosphere Conceptual Model for the CAGCV Lakeshore Release Calculation Case

5.2.4.3 Specific Conceptual Model for Well Release, CAGCV Concepts

The conceptual model for the near field in this calculation case is the same as the lake release case, as shown in Figure 16. The geosphere features are the same as Figure 17, with the exception that contaminated water is assumed to be abstracted from the Shallow Bedrock Groundwater System. It is assumed that water is only abstracted once there is no institutional control over the site. The position of abstraction is conservatively assumed to be downstream from the permanent repository (100 m from the downstream edge of the repository). Therefore, the only difference from Figure 17 is that the release from the Shallow Bedrock Groundwater System is directed to a well rather than the lake.

The different point of release means that the biosphere model requires some amendment, as shown in Figure 20. The well water from the geosphere is used to irrigate the soil and provide drinking water for humans and animals. Radionuclides are lost from the soil due to infiltration, erosion, and resuspension into the atmosphere. However, loss due to resuspension is assumed to be balanced by the gain from deposition from the atmosphere. No surface water systems are considered because it is assumed that irrigation water is only used when necessary and does not run off into streams. The only potential exposure group considered is a farmer that is exposed via ingestion of well water, crops (root and green vegetables and grain) and animal produce (cow's meat, milk, and liver), inadvertent ingestion of soil, inhalation of soil and external irradiation from soil.

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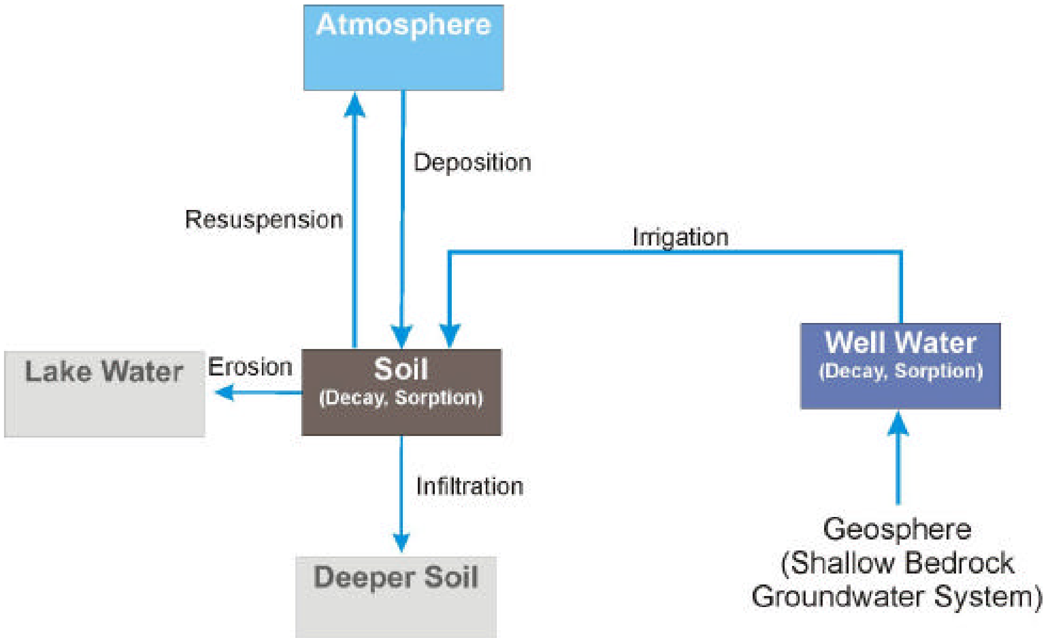

Figure 20: Biosphere Conceptual Model for the CAGCV Well Release Calculation Case

5.2.4.4 Specific Conceptual Model for Bathtubbing, CAGCV-T

This conceptual model considers that the near-field structures (cap, engineered structures and other near-field components) degrade until their hydraulic conductivity is more than the surrounding soils and underlying tills. Consequently, there is a release from the near field into the surrounding soil of excess contaminated infiltrating water, which cannot percolate through the till. This release bypasses the geosphere. Prior to the hydraulic conductivity of the near-field structures being greater than the surrounding soils and underlying tills, the contaminated infiltrating water is assumed to flow into the geosphere, and be transported towards the lake, in the same manner as the Lake Release Calculation Case. Although the degraded structures could also result in a release of gas, this situation is not considered in this calculation case and is addressed separately in the Gas Release Calculation Case for clarity. The conceptual model for the near field is shown in Figure 21.

Contaminated infiltrating water is assumed to emerge from the engineered structures and flow into surface soils. Erosion of contaminated soil and interflow from the soil are also considered. The biosphere conceptual model is shown in Figure 22. The potential exposure group considered is one that lives in the immediate area of the permanent repository (site dweller), once there is no institutional control of the site, and uses the soil to grow crops. This group is exposed via ingestion of crops (root and green vegetables), inadvertent ingestion of soil, inhalation of soil and external irradiation from soil.

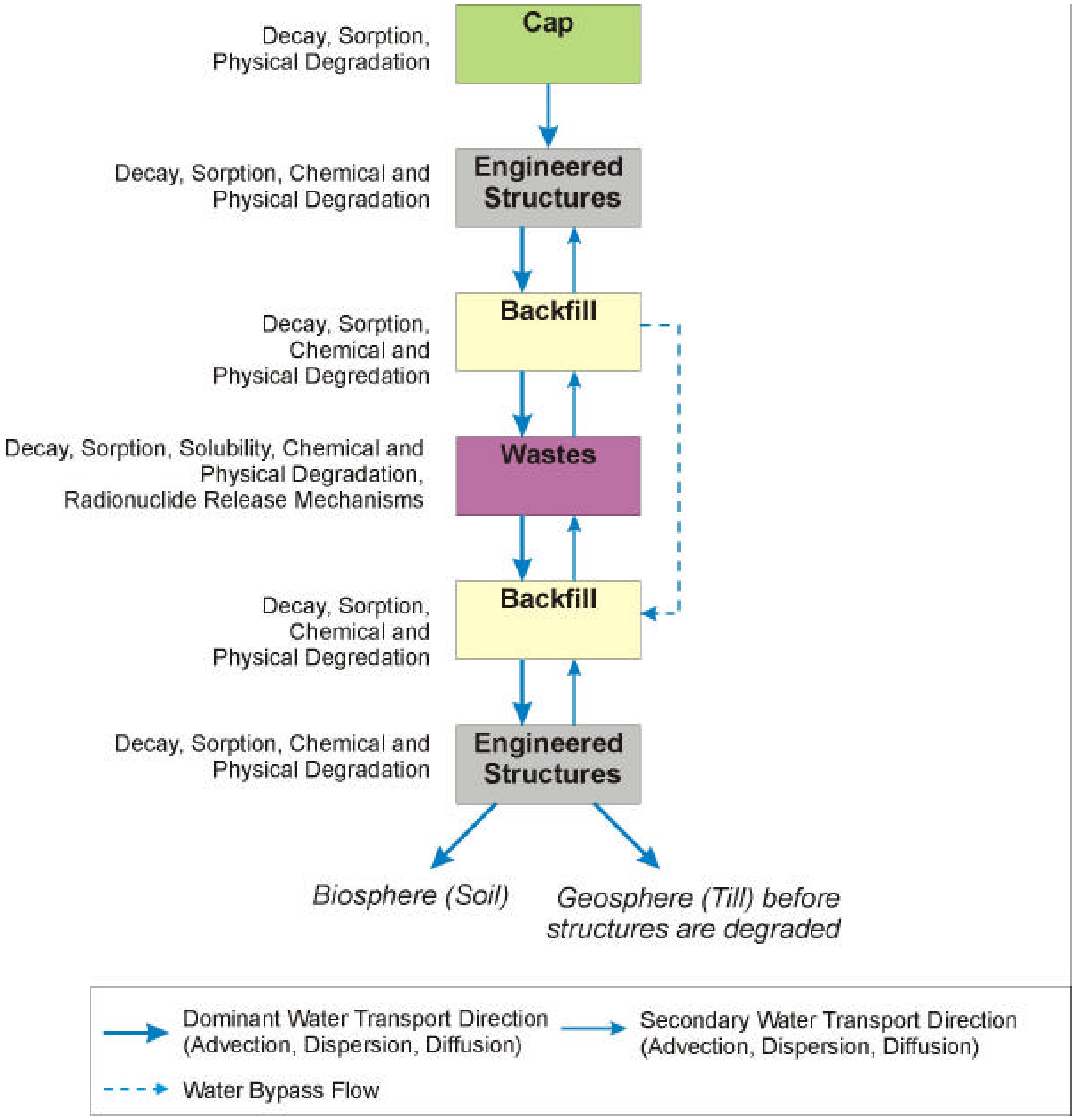

Figure 21: Near-field Conceptual Model for the CAG CV-T Near-Field Release by Bathtubbing Calculation Case

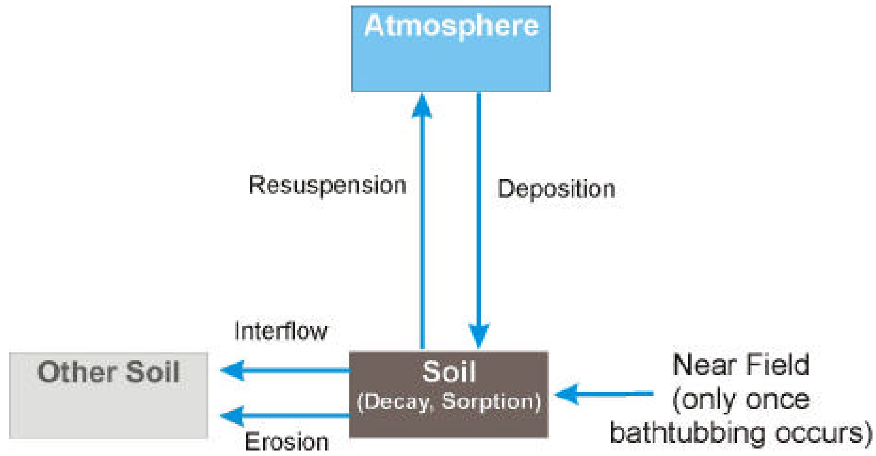

Figure 22: Biosphere Conceptual Model in the CAGCV-T Bathtubbing Calculation Case

5.2.4.5 Specific Conceptual Model for Gas, CAGCV Concepts

The focus of the conceptual model for the gas release is on the potential accumulation of radioactive gases (H-3, C-14 and Rn-222) in a house located on the cap. The effect of the cap is considered by allowing for radioactive decay during gas diffusion through it (this is an important factor to consider for Rn-222) and by representing its reducing thickness through time due to erosion. It is assumed that release of the gases only occurs once the waste containers have physically degraded. Radionuclides may also be released from the near field into the geosphere due to leaching by infiltrating water. Their consequent migration is not explicitly considered in the Gas Release Calculation Case, since the focus of the case is the gas pathway and their dose consequences would be no greater than for the Lake, Lakeshore or Well Release Calculation Cases (Sections 5.2.4.1, 5.2.4.2 and 5.2.4.3). With this approach, there is no 'double counting' of radionuclides (i.e., in this case, a particular atom of C-14 cannot both be released as gas and also in groundwater). The conceptual model is shown in Figure 23. The potential exposure group considered is one that lives in a house built upon the permanent repository (site dweller), after there is no institutional control of the site. This group is exposed from inhalation of the gases.

5.2.4.6 Specific Conceptual Model for Cover Erosion, CAGCV Concepts

The Cover Erosion Calculation Case considers that, after the near-field structures have degraded, they could become subject to natural erosion. Over very long timescales (many tens of thousands of years), this is assumed to result in the removal of all cover materials (the cap and engineered structures). The exposed waste is assumed to be eroded onto the soil that can be used by a farming potential exposure group. Because the rate of erosion of waste onto the soil is assumed to be the same as the rate of erosion of the cover, the soil becomes contaminated over a very long period of time. The release of radionuclides into the underlying geosphere prior to and during the erosion of the repository is also considered; however, these released radionuclides are assumed to leave the domain of interest for this calculation case, and the geosphere itself is not represented explicitly (instead it is considered in the Liquid Release Calculation Cases). Releases by gas are not considered since they are considered in the Gas Release Calculation Case. The resulting near-field conceptual model is shown in Figure 24, and the biosphere model used to consider eroded waste is presented in Figure 25. The potential exposure group considered is one that lives in the immediate area of the permanent repository (site dweller), once there is no institutional control of the site, and uses the soil to grow crops. This group is exposed via ingestion of crops (root and green vegetables), inadvertent ingestion of soil, inhalation of soil and external irradiation from soil.

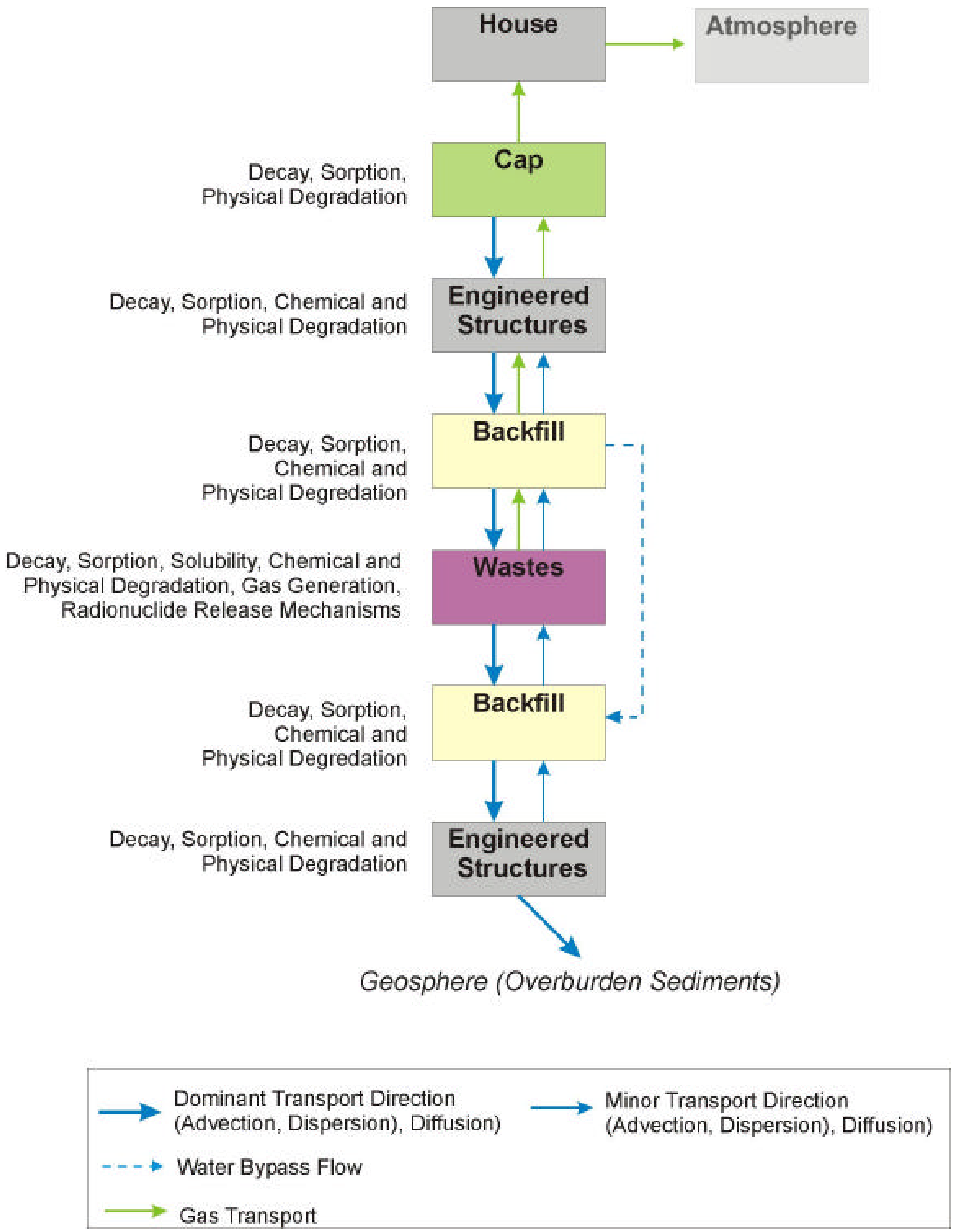

Figure 23: Conceptual Model for the CAGCV Gas Release Calculation Case

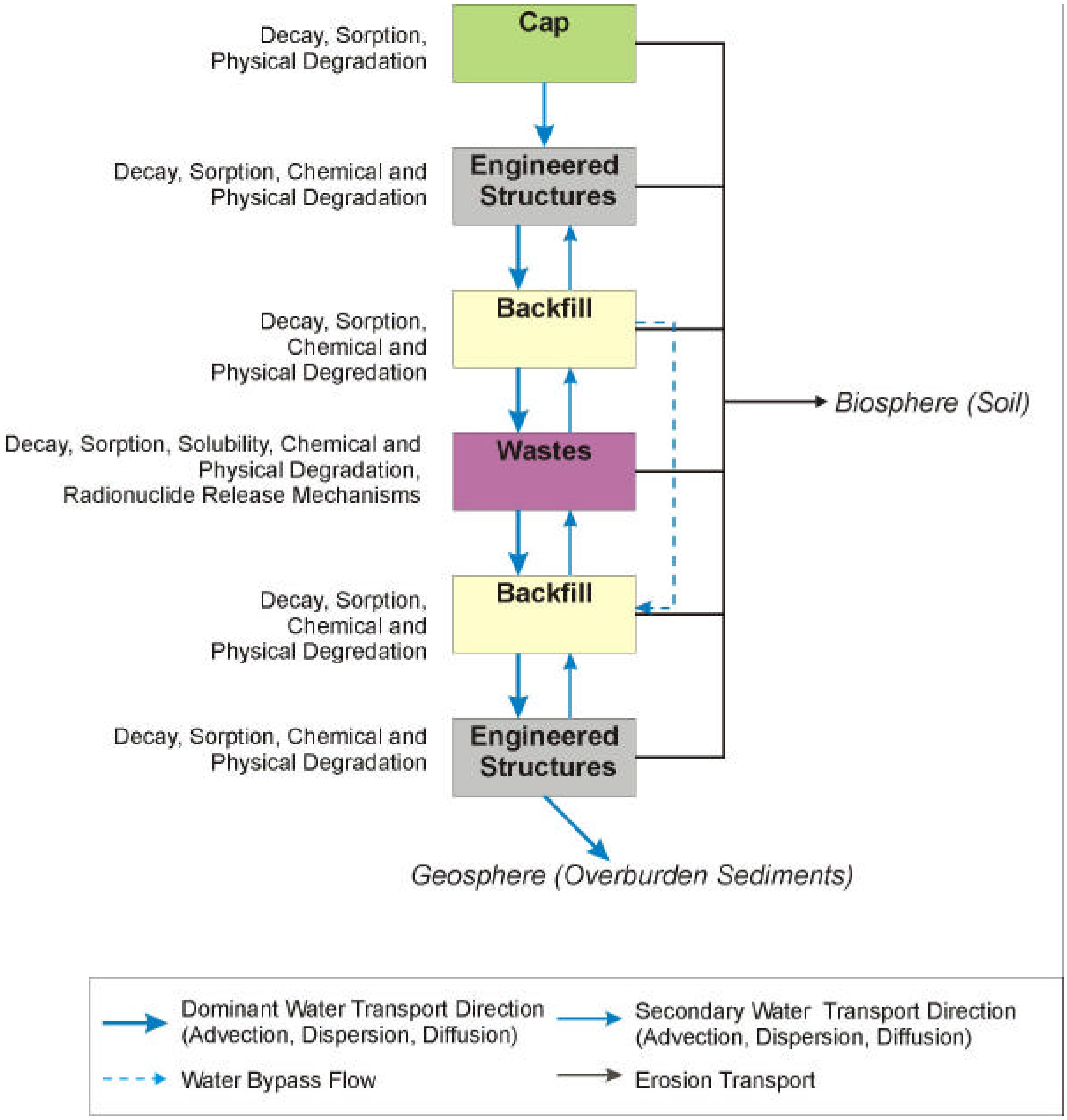

Figure 24: Near-field Conceptual Model for the CAGCV Cover Erosion Calculation Case

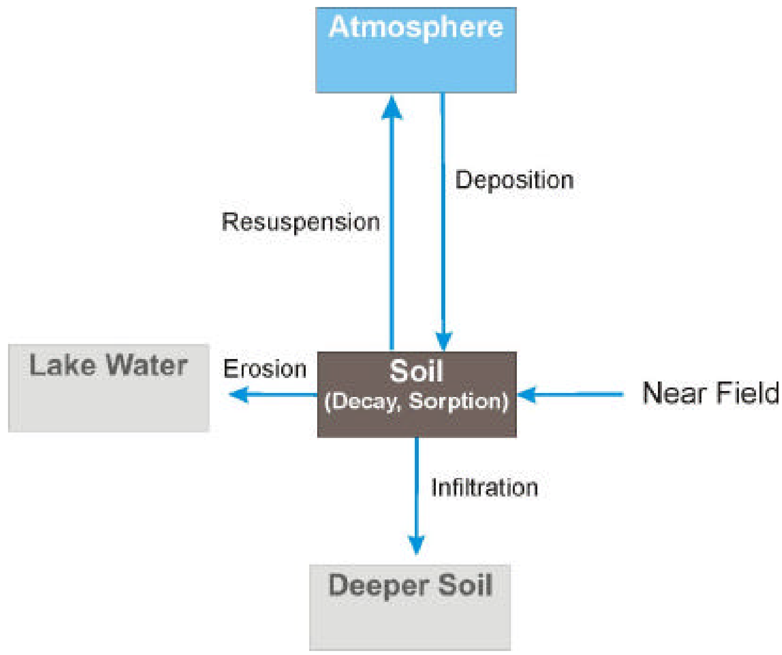

Figure 25: Conceptual Model for the Biosphere in the CAGCV Cover Erosion Calculation Case

5.2.4.7 Specific Conceptual Model for Lake Release, DRCV Concepts

The conceptual model for the Lake Release Calculation Case for the DRCV considers the near-field structures (waste container, engineered structures and, if present, grout) to degrade naturally. However, because of the very low hydraulic conductivity of the rock and the highly saline groundwater regime, potential contaminant migration out of the DRCV repository would be controlled by diffusion following complete re-saturation of the vaults. The conceptual model adopted for the near field of the DRCV is shown in Figure 26.

Radionuclides that diffuse vertically upward from the near field through the limestone and/or shales of the Deep Bedrock Groundwater System would enter the dolostone of the Intermediate Bedrock Groundwater System. As radionuclides would diffuse away from the near field in all directions, only 50 % of the inventory is assumed to be transported vertically upwards towards the dolostone. The radionuclides would then move horizontally by advective and dispersive flow to eventually discharge into the bed of Lake Huron some 10 to 20 km off-shore of the site. During transport, the concentration of radionuclides would be diluted due to mixing with uncontaminated groundwater. The conceptual model adopted is shown in Figure 27. The subsequent transport in the biosphere is assumed to be similar to that for the CAGCV (Figure 18), although the location of the discharge means that the initial dilution conditions would differ. A fishing potential exposure group is considered that is exposed to radionuclides due to ingestion of fish and water, inadvertent ingestion of sediment, inhalation of sediment and external irradiation from sediment. Doses to a farming potential exposure group could be also be evaluated. However, it is anticipated that only relatively mobile radionuclides would reach the biosphere and such radionuclides would not be expected to accumulate significantly in the terrestrial biosphere, even if lake water were to be used for irrigation of crops.

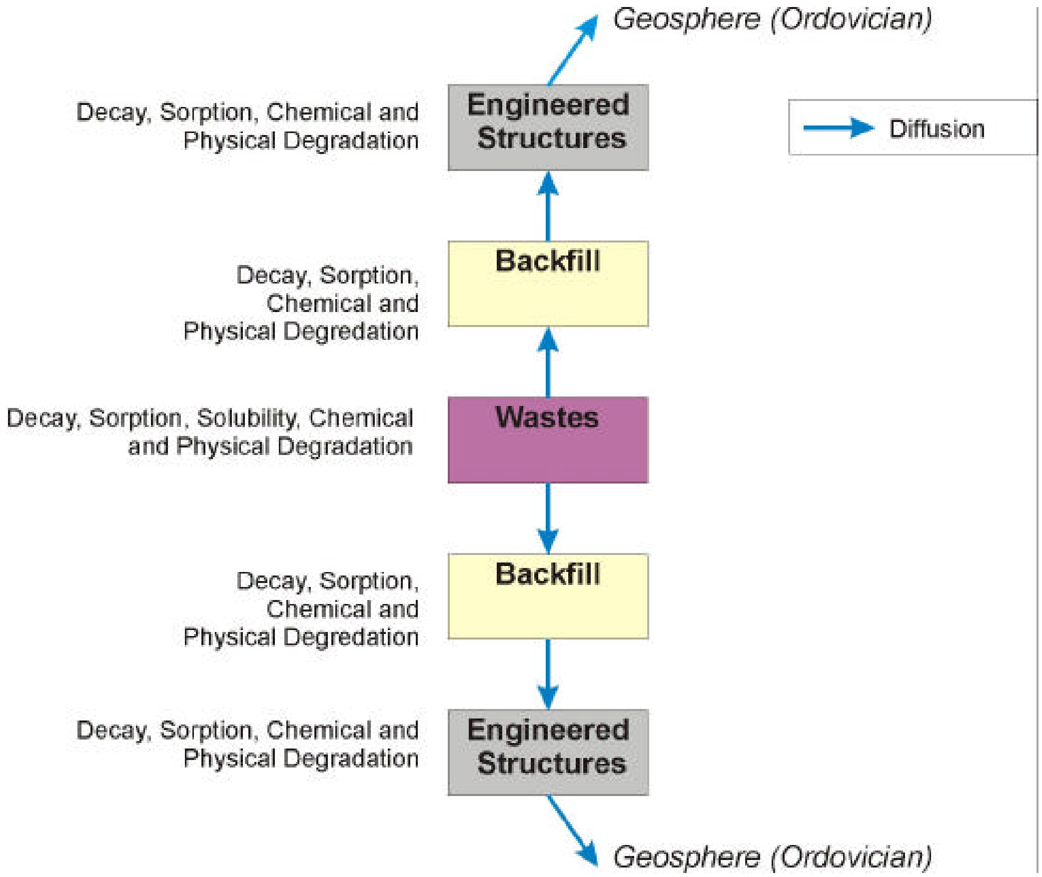

Figure 26: Near-Field Conceptual Model for the DRCV Lake Release Calculation Case

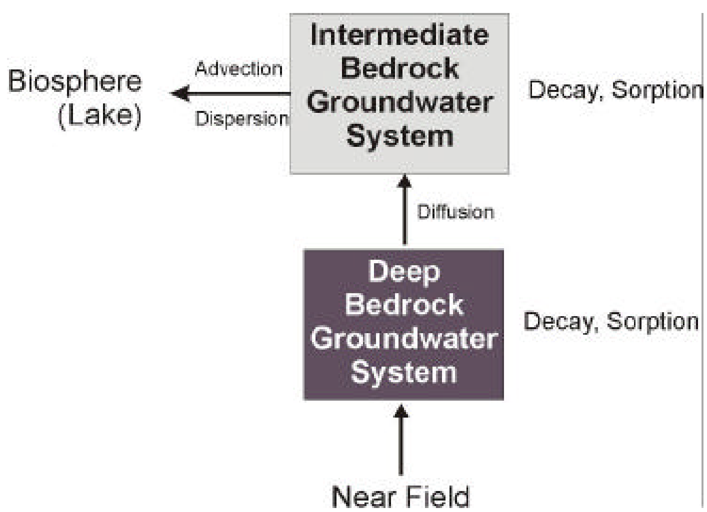

Figure 27: Geosphere Conceptual Model for the DRCV Lake Release Calculation Case

5.2.4.8 Specific Conceptual Model for Shaft Pathway, DRCV Concepts

This calculation case considers the possible degradation of the shaft seal and the consequent availability of a more diffusive transport pathway through the Deep Bedrock Groundwater System. Once the radionuclides reach the Intermediate Bedrock Groundwater System, the conceptual model is the same as for the lake release conceptual model.

The proportion of contaminants that may migrate in this direction is determined by the detailed geometry of the structures in the near field. At present, detailed modelling of the flow and transport of contaminants in the near field has not been undertaken. Therefore, a simple assumption has been made that 10% of the radionuclide inventory may migrate into the lake via this pathway.

5.2.4.9 Specific Conceptual Models for Human Intrusion Scenario

The conceptual models for the two human intrusion calculation cases (exploration borehole and excavation) are unchanged from the general conceptual models discussed in Appendix D.3. For ease of reference these are summarised below.

5.2.4.9.1 Exploration Borehole

The retrieval of waste in exploratory boreholes could occur for either the CAGCV or DRCV concepts once there is no institutional control over the site. Samples would be extracted and examined, and exposures could occur at either stage to an intruder potential exposure group. Exposure mechanisms considered are external irradiation from the waste, inadvertent ingestion of waste material and inhalation of dust.

5.2.4.9.2 Excavation

Large excavations are only relevant to consider for the CAGCV concepts, which are located on the surface. The excavations could be associated with a construction project (e.g., agricultural buildings) or mineral extraction (e.g., sand and gravel pit). Of interest to the assessment are individuals that could be exposed to the waste during the excavation activities (intruder potential exposure group), and individuals that could be exposed to the spoil that is left near the surface (site dweller potential exposure group). For the intruders, exposure mechanisms considered are external irradiation from the waste, inadvertent ingestion of waste material and inhalation of dust. For the site dwellers, who are assumed to grow crops, the exposure pathways are assumed to be ingestion of crops (root and green vegetables), inadvertent ingestion of soil, inhalation of soil and external irradiation from soil. It is assumed that excavation can only occur once there is no institutional control over the site.

5.3 MATHEMATICAL MODELS

An overview of the mathematical approach to representing the conceptual models is given below. Details of the models used are provided in Appendix E.

The basis of the approach is to adopt a compartment modelling approach for the dynamic parts of the system (e.g., radionuclide transport in the geosphere), and scalar models to represent those parts of the system that can be regarded as having a local equilibrium, e.g., the transfer of radionuclides in soil and water to plants.

A compartment modelling approach has been used widely for the representation of radioactive waste repository systems (see for example Chapman et al. (2002) and IAEA (2002b and c)). The approach is to represent features of interest as compartments of a user defined volume, which are assumed to be 'well-mixed' (i.e., have uniform concentrations of radionuclides). These may be assigned a specific spatial location and orientation (e.g., an area of contaminated soil) or may represent some more abstract concept (e.g., all global oceans).

Exchanges between compartments ('transfer processes') are described with first-order linear differential equations. These can be used to represent a wide range of physically-based or empirical transport processes. The mathematical representation of the inter-compartment transfer processes takes the form of a matrix of transfer coefficients that allow the compartment amounts to be represented as a set of first order linear differential equations. For the i^{th} compartment, the rate at which the compartment inventory changes with time is given by:

$$\frac{dN_i}{dt} = \left(\sum_{j \neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t) \right) - \left(\sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right)$$

where *i* and *j* are the two compartments, *N* and *M* are the amounts (Bq) of radionuclides N and M in a compartment (M is the precursor of N in a decay chain), *S(t)* is a time dependent external source of radionuclide *N* (Bq y^{-1}), λ_N is the decay constant for radionuclide *N* (y^{-1}), λ_{ji} and λ_{ij} are transfer coefficients (y^{-1}) representing the gain and loss of radionuclide *N* from compartments *i* and *j* .

The solution of the matrix of equations given above provides the time-dependent inventory of each compartment. Assumptions for compartment sizes allow estimates of the associated concentrations to be made.

Amongst the restrictions of donor controlled compartment models (i.e. compartment models in which each transfer is directly dependent on the amount of the material present in the compartment from which the material is moving) is that they cannot directly be used to solve water flow problems. However, their flexibility allows such conditions to be adequately represented in the model.

Scalar models assume that equilibrium exists instantaneously between two features. A simple radionuclide or elemental 'concentration factor' or 'transfer factor' can then be applied to estimate the concentration in one feature from the other. These factors are generally derived from experimental observations or from more detailed models. The approach is generally used for parts of the biosphere model, and it is also assumed that sorption is instantaneous and reversible.

5.4 DATA

Data for the mathematical models described in Section 5.3 are presented in Appendix F for:

- the radionuclides of interest;
- the near field;
- the geosphere;
- the biosphere; and
- the potential exposed groups.

Where possible, these data are based on site-specific information from the Bruce Site and its vicinity; however, it has been necessary to supplement these with other data in many instances.

Data for the near field draw upon Golder Associates (1998) for the definition of the repository designs in terms of their physical dimensions. Other properties of the construction materials have been obtained from a range of other references, which have considered the detailed properties of the materials that are relevant to Safety Assessment calculations. Much of the work on cement and concrete chemistry is obtained from studies in support of the Swedish SFR permanent repository (e.g., SKB (2001)).

The geological region of interest has been characterised in detail by Golder Associates (2003), and this is the main reference for geosphere data, in terms of the location and hydraulic conductivity of the strata of interest for this preliminary safety assessment. However, these data should also be supplemented with additional information that is required specifically by this study. One of the most important parameters is the elemental distribution coefficient (K_d). The K_d is defined as the ratio of the radionuclide concentration on solid to that in porewater at equilibrium. From this, the proportion available for transport can be calculated. These data are dependent on the type of rock and are always uncertain in safety assessments, unless detailed site-specific measurements are available. For this study, the values have been obtained from several compilations of data, e.g., IAEA (2002b), and Nagra (1994).

The biosphere is a complex arrangement of different environmental media, and consequently a wide range of data is required to describe its features. Information on surface water flows (including data on precipitation and Lake Huron) has been obtained from Bruce Site-specific sources where possible, particularly OPG (2000). Data on soil characteristics are generic, but they have been chosen to reflect the soil types at the Bruce Site, where possible. The plants and animals considered have been chosen to reflect the region. However, radionuclide uptake factors for plants and animals are largely based on a compilation of data derived from experimental observations and other sources (Beak, 2002).

Human characteristics also reflect present day practices around the site. Intake rates and occupancy factors are based on information in Beak (2002), which take account of human habits in Ontario. Factors that convert radionuclide intake or exposure to radiation are based on internationally-accepted compilations of data derived from detailed biokinetic modelling (e.g., ICRP Publication 72 (ICRP, 1996)).

5.5 MODEL IMPLEMENTATION

The mathematical models and data described in Section 5.3 and 5.4 (and their associated appendices) have been implemented in the AMBER compartment modelling code. Details of the implementation are provided in Appendix G.

AMBER is a flexible modelling application that allows the specification of user defined contaminants, parameters, transfers and compartments. It has been developed under Quintessa's quality management system (Quintessa, 2003a and b), which is compliant with the ISO 9001:2000 standard. AMBER has been used in the assessment of a range of proposed and operating LLW repositories (see for example BNFL (2002), Chapman et al (2002), IAEA (2002b and c) and Penfold et al. (2002)). For the current study AMBER v4.4 has been used (Enviros QuantiSci and Quintessa, 2002).

6. PRESENTATION AND ANALYSIS OF RESULTS

The results for the calculation cases identified in Section 5.2.3 and Table 7 are summarised in Table 8. This table gives the peak calculated dose rates for each calculation case considered. Three timeframes of interest are presented: from the assumed end of intstituional control to 1000 years; 1000 to 10,000 years; and beyond 10,000 years. These periods have been chosen because most the repository engineering is expected to provide physical containment in the first thousand years and, beyond 10,000 years, major climate change (e.g., glaciation) could significantly affect the evolution of the repository system.

The results are discussed in the following sub-sections, with a more detailed discussion of results presented in Appendix H. Results for the calculation cases associated with the Reference Scenario are summarised in Section 6.1. Results for the calculation cases associated with the Human Intrusion Scenario are presented in Section 6.2. Consideration was given to the effect of varying the length of the institutional control period.

Before analysing the results in detail, it is important to be aware of a number of caveats.

First, as noted in Section 2.2, the assessment is a preliminary postclosure radiological safety assessment that is designed to give an indication of the safety of the LLW permanent repository concepts at the Bruce Site. It should not be seen as a comprehensive safety assessment. For example, operational safety, non-radiological safety and impacts associated with the development of the repository are not considered, nor are the long-term impacts of non-radiological contaminants in the inventory.

Second, the calculations have been undertaken at a scoping level. Although the near field has been represented in some detail (since one of the purposes of the assessment was to evaluate different repository concepts), there is scope to consider other components of the repository system in more detail. For example, two and three dimensional groundwater flow and transport calculations could be undertaken. In addition, more rigorous consideration could be given to the evaluation of parameter sensitivities through the use of deterministic and probabilistic sensitivity analysis.

Third, the timescales of potential interest extend well beyond 10,000 years and over such timescales results should be seen as being indicative (IAEA, 1994). In addition, environmental change, caused by factors such as major climate change, might be significant over such timescales. As noted in Section 2.7, this preliminary safety assessment does not consider such changes.

Finally, although site-specific data from the Bruce Site and its environs have been used where available, much of the data used in the assessment comes from non-Bruce specific sources. Whilst this is appropriate for certain parameters (for example dose coefficients), for certain other parameters (for example sorption coefficients) the use of site-specific data would be preferable.

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Table 8: Summary of Results for the Calculation Cases Assessed

Scenario	Repository Concept	Level of Engineering	Calculation Case	Peak Dose Rate (mSv y^{-1})		
				300 - 1000 y	1000 - 10,000 y	> 10,000 y
Reference	CAGCV-T	Non-grouting	**Bathtubbing**	0.003	0.3	0.3
			Cover Erosion	0	0	0.001
			Well Release	2×10^{-7}	2×10^{-5}	2×10^{-6}
			Gas	1×10^{-5}	3×10^{-7}	7×10^{-11}
			Shore Release	3×10^{-11}	2×10^{-10}	2×10^{-8}
			Lake Release	2×10^{-10}	8×10^{-11}	2×10^{-11}
Reference	CAGCV-T	Grouting	Bathtubbing	4×10^{-4}	0.003	0.04
			Cover Erosion	0	0	0.007
			Gas	3×10^{-5}	3×10^{-6}	1×10^{-12}
			Well Release	1×10^{-7}	2×10^{-5}	2×10^{-6}
			Shore Release	2×10^{-12}	2×10^{-10}	2×10^{-8}
			Lake Release	4×10^{-13}	8×10^{-11}	2×10^{-11}
Reference	CAGCV-S	Non-grouting	Well Release	5×10^{-4}	0.007	0.001
			Cover Erosion	0	0	4×10^{-4}
			Shore Release	2×10^{-9}	1×10^{-5}	4×10^{-5}
			Gas	1×10^{-5}	8×10^{-9}	0
			Lake Release	1×10^{-9}	8×10^{-6}	8×10^{-6}
Reference	CAGCV-S	Grouting	Cover Erosion	0	0	0.008
			Well Release	1×10^{-5}	2×10^{-6}	4×10^{-5}
			Gas	3×10^{-5}	3×10^{-6}	6×10^{-13}
			Shore Release	5×10^{-11}	2×10^{-10}	1×10^{-7}
			Lake Release	3×10^{-11}	1×10^{-10}	7×10^{-8}
Reference	DRCV-S	Non-grouting	Shaft Pathway	<	1×10^{-15}	5×10^{-14}
			Lake Release	<	2×10^{-15}	4×10^{-14}
Reference	DRCV-L	Non-grouting	Shaft Pathway	<	<	2×10^{-14}
			Lake Release	<	<	2×10^{-14}
Reference	DRCV-S	Grouting	Shaft Pathway	<	<	1×10^{-14}
			Lake Release	<	<	9×10^{-15}
Reference	DRCV-L	Grouting	Shaft Pathway	<	<	5×10^{-15}
			Lake Release	<	<	5×10^{-15}
Human Intrusion	CAGCV-S&T	Non-grouting	Excavation	0.03	0.03	0.004
			Site Dweller	0.01	0.01	0.002
			Borehole	3×10^{-5}	2×10^{-5}	2×10^{-6}
Human Intrusion	CAGCV-S&T	Grouting	Excavation	0.03	0.03	0.02
			Site Dweller	0.02	0.02	0.01
			Borehole	2×10^{-5}	2×10^{-5}	8×10^{-6}
Human Intrusion	DRCV-S&L	Non-grouting	Borehole	3×10^{-5}	2×10^{-5}	3×10^{-6}
Human Intrusion	DRCV-S&L	Grouting	Borehole	2×10^{-5}	1×10^{-5}	6×10^{-6}

Notes:
Emboldened calculation cases exceed the relevant radiological protection criteria given in Section 2.4.1. Calculated dose rates exceeding the criterion for the Reference Scenario (0.3 mSv y^{-1}) are shown in red. For the Human Intrusion Scenario different criteria apply; the facility design must be optimised if dose rates in the range of 1 - 100 mSv y^{-1} are calculated. However no calculated dose rates are in this range.

Dose rates less than 1×10^{-15} mSv y^{-1} are indicated as "<".

An institutional control period of 300 years is assumed for the purposes of this table. The effect of reducing this period to 100 years is minimal (see Section 6.1 and 6.2).

6.1 CALCULATION CASES FOR THE REFERENCE SCENARIO

6.1.1 CAGCV-T, Non-grouting

The CAGCV concept could be located on tills, which have low hydraulic conductivity and thus retard the migration of radionuclides released into the geosphere. The total annual effective radiation dose rates that were calculated for the five calculation cases considered for this concept are presented in Figure 28. This figure also indicates the average annual individual radiation dose rate from natural background radiation in Ontario, which equal to 2 mSv y^{-1} (0.002 Sv y^{-1}) (LaMarre, 2002). The background radiation excludes the contribution from manmade background and medical exposures. Also marked on the figure is the constraint on dose rates from disposed waste recommended by ICRP (2000), 0.3 mSv y^{-1} (3×10^{-4} Sv y^{-1}).

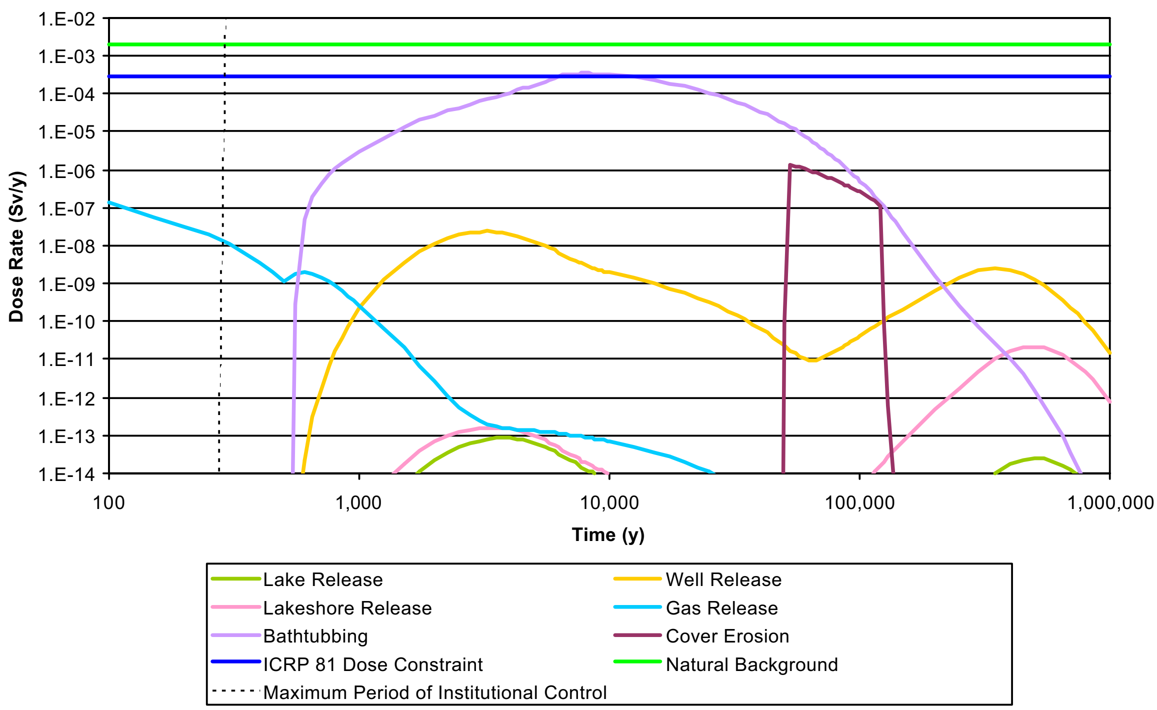

Figure 28: Total Calculated Dose Rates to Potentially Exposed Groups, from Reference Scenario Calculation Cases for the CAGCV-T, Non-grouting Option

It is immediately evident that the Bathtubbing Calculation Case gives rise to the largest dose rates. This calculation case considers the consequences if the near-field structures (including the cap) degrade to the point at which they are more permeable that the underlying tills. Because the tills have such low permeability, this could occur even if the cap contains reworked till, as it would be subject to various processes such as freeze-thaw stresses that could increase its permeability. When the permeability of the cap becomes greater than that of the underlying till, a greater volume of water would be permitted to flow through the repository (per unit area) than could be conducted by the underlying till. The excess contaminated infiltrating water is then assumed to be released directly into soil surrounding the repository. This provides a ‘short cut’ by which contaminants could be released to surface soils without first travelling in the sub-surface till and dolostone. Consequently, high concentrations of radionuclides could accumulate in surface soils near the repository, as there is limited dilution of contaminated porewater from the CAGCV.

The use of these soils by a site-dweller could result in dose rates of about 0.3 mSv y^{-1} (peaking after 8,000 years), which marginally exceeds the ICRP dose constraint. The key pathways are shown in Table 9. The key radionuclide for the Bathtubbing Calculation Case is Nb-94, which accumulates to concentrations of about 200 Bq kg^{-1} in contaminated soil. This radionuclide has energetic gamma emissions, which mean that external irradiation is the dominant pathway.

Table 9: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the CAGCV-T Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Bathtubbing	3.4×10^{-4}	8,000	94	<	-	6	<	-	<	-
Cover Erosion	1.3×10^{-6}	55,000	100	-	<	<	<	-	<	-
Well Release	2.3×10^{-8}	3,250	<	12	-	39	<	49	<	-
Gas Release	1.1×10^{-8}	300	-	-	-	-	-	-	-	100
Lakeshore Release	2.2×10^{-11}	500,000	100	-	<	-	-	<	-	-
Lake Release	8.4×10^{-14}	3,750	<	-	92	-	-	8	-	-

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as “<”. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Anm)” is the ingestion of contaminated animal products; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Ing (Wat)” is the ingestion of contaminated water; “Inh (Dust)” is the inhalation of contaminated dust; “Inh (Gas)” is the inhalation of contaminated gas. ‘-‘ indicates pathway not applicable for the exposure group.

The dose rates calculated for other calculation cases are much lower (at least a factor of a hundred). The next most significant is the Cover Erosion Calculation Case. In this case, radiation doses are associated with the erosion of cover materials, which causes the wastes to be exposed and also become available for erosion onto soil. A person is then assumed to live on the soil. The assumed thickness of cover is 5 m, and erosion waste does not begin until 50,000 years, being complete after 120,000 years. The dose rate is dependent on the concentration of radionuclides remaining in the wastes, and therefore the peak dose rate occurs almost immediately after erosion begins.

It should be noted that the assessment only considers exposure to soil contaminated with eroded waste. If direct exposure to raw wastes (exposed by the absence of the cover) could occur, dose rates could be greater than those calculated. The calculated dose rates for the site dweller in the Excavation Calculation Case indicate the potential magnitude of such exposures.

The next highest dose rates are calculated for the Well Release Calculation Case (four orders of magnitude below the dose rate target). In this case, a farmer is assumed to abstract well water from the contaminated portion of the Shallow Bedrock Groundwater System, and use the water for drinking and to irrigate crops. He is also assumed to live on the contaminated soil and raise cattle. The utilisation of contaminated groundwater close to the repository limits the dilution of radionuclides in the aquifer and the travel time in the geosphere (during which radioactive decay can occur).

This reason, and the greater variety of exposure pathways, indicates why this calculation case gives rise to much higher dose rates than the Lake and Lakeshore Release Calculation Cases, which give rise to very small doses. The lakeshore and lake release pathways have a similar profile, as both consider the release to the lake. The difference is that the former considers discharge of contaminated groundwater at the lakeshore, and the latter under the lake water. Consequently, concentrations of radionuclides in lakeshore sediments are higher for the Lakeshore Calculation Case, resulting in increased dose rates.

Finally, the Gas Release Calculation Case can be seen to be most significant in the first few hundred years after institutional control ceases (this has been assumed to be a period of 300 years, during which radiation exposures are limited by active control of the repository). The initial peak is associated with C-14 and H-3 release, and the much lower, longer term tail is associated with Rn-222. The potential dose rates for the Gas Release Calculation Case have been calculated for periods shorter than the assumed institutional control period. Figure 28 shows that doses reduce by an order of magnitude between 100 and 300 years after closure of the repository.

6.1.2 CAGCV-T, Grouting

The void spaces in the waste and the repository could be filled with cementitious grout prior to the closure of the repository. These additional measures would serve to chemically condition the repository for a longer period, and reduce the rate of physical degradation of key structures that limit water flow through the repository. Results for this ‘grouting’ option are presented in Figure 29.

The grouting of the CAGCV-T concept results in a reduction of the dose rate associated with the Bathtubbing Calculation Case, compared with the non-grouting option. The peak calculated dose rate is 0.038 mSv y^{-1} (3.8 x 10^{-5} Sv y^{-1}) occurring after 37,500 years, about a factor of ten below the ICRP dose constraint of 0.3 mSv y^{-1}.

The reduction in the dose rate, and delay of the timing of the peak, is a consequence of the enhanced retention of key radionuclides such as Nb-94 and C-14 in the near field, compared with the non-grouting option. This is a result of a longer period during which the porewater in the repository is alkaline, due to the larger mass of cement that is present.

It can be seen that the calculated dose rates for the Cover Erosion Calculation Case are increased compared with the non-grouting case. This also reflects the enhanced retention of radionuclides in the repository, which results in potentially higher concentrations in the waste at the time at which it is assumed to be eroded.

The peak calculated dose rate for other calculation cases remains relatively similar to the calculated dose rates for the non-grouting option; however, the enhanced retention of radionuclides in the repository is evident from the longer timescales over which these peak dose rate values are reached.

The key exposure pathways, shown in Table 10, are similar to those for the non-grouting option (Table 9). Once again, external irradiation can be seen to be a key pathway as Nb-94 is the dominant radionuclide for the Bathtubbing and Cover Erosion Calculation Cases.

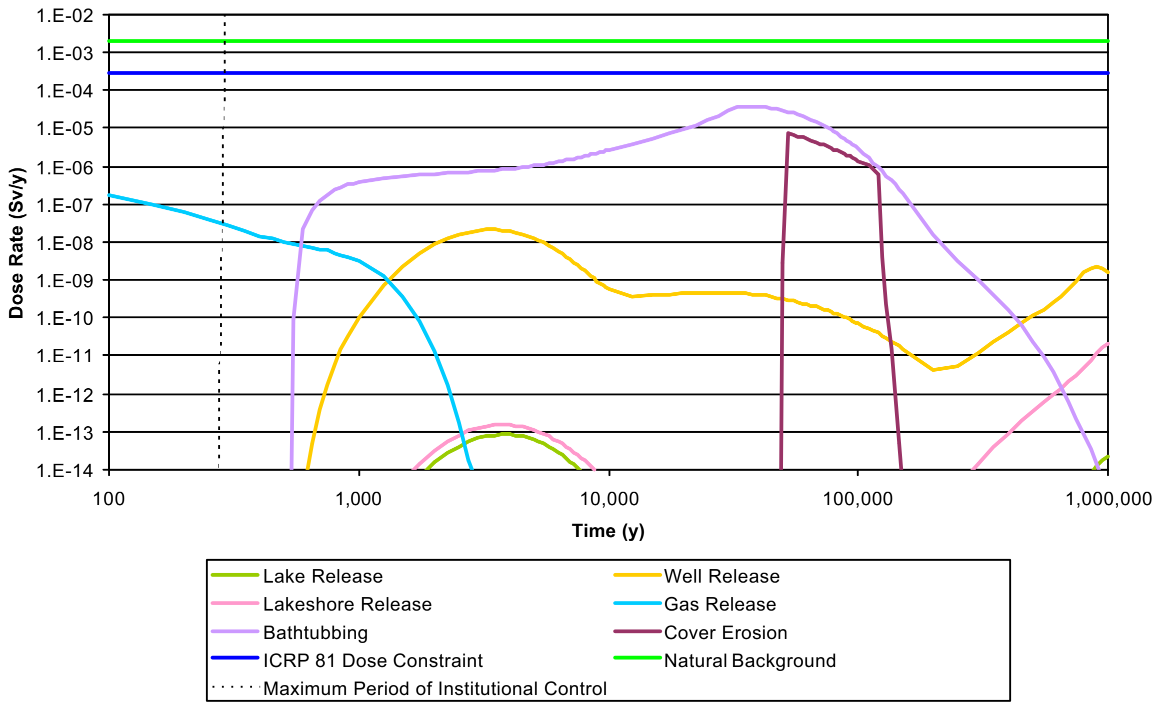

Figure 29: Total Calculated Dose Rates to Potentially Exposed Groups, from Reference Scenario Calculation Cases for the CAGCV-T Grouting Option

Table 10: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the CAGCV-T Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Bathtubbing	3.8×10^{-5}	37,500	98	-	-	2	<	-	<	-
Cover Erosion	7.1×10^{-6}	52,500	99	-	-	1	<	-	<	-
Gas Release	2.7×10^{-8}	300	-	-	-	-	-	-	-	100
Well Release	2.1×10^{-8}	3,500	<	9	<	39	-	52	-	-
Lakeshore Release	2.0×10^{-11}	1,000,000	100	-	<	-	-	<	-	-
Lake Release	8.4×10^{-14}	3750	<	-	92	-	-	8	-	-

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Anm)" is the ingestion of contaminated animal products; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Crop)" is the ingestion of contaminated plants and vegetables; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Ing (Wat)" is the ingestion of contaminated water; "Inh (Dust)" is the inhalation of contaminated dust; "Inh (Gas)" is the inhalation of contaminated gas. '-' indicates pathway not applicable for the exposure group.

6.1.3 CAGCV-S, Non-grouting

The CAGCV concept may also be constructed on sand, which has a much higher permeability than the till. Although the sand is not as effective as the till at retarding the migration of radionuclides released into the geosphere, its permeability is sufficiently high to permit the flow of infiltrating rainwater under any conditions (even if the cap degrades completely). Consequently, the Bathtubbing Calculation Case cannot occur for such a facility.

The results are illustrated in Figure 30, which shows the total dose rate for the calculation cases considered. All calculation cases considered for the concept can be seen to be comfortably below the ICRP dose constraint, with the highest results, of 7.3 μSv y^{-1} (7.3×10^{-6} Sv y^{-1}) being associated with the Well Release Calculation Case. Initially, relatively mobile radionuclides such as C-14, Tc-99 and I-129 dominate the calculated doses. The mobility of these radionuclides also means that the peak in dose rate is sharp (e.g. the peaks at 800 years is associated with Tc-99). Between 1000 and 15,000 years, C-14 is dominant. The profile of the dose rate from C-14 is determined by the timescales for cement degradation, which is complete after 6,000 years for this option.

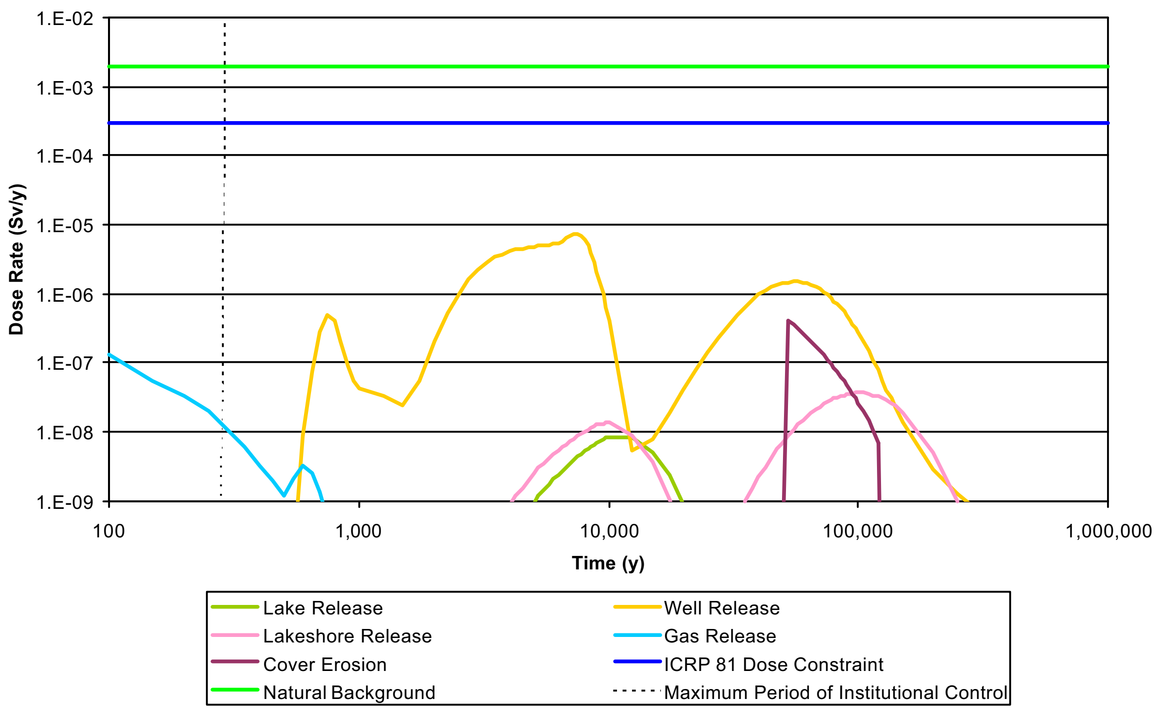

Figure 30: Total Calculated Dose Rates to Potentially Exposed Groups, from Reference Scenario Calculation Cases for the CAGCV-S Non-grouting Option

Table 11: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the CAGCV-S Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Well Release	7.3×10^{-6}	7,500	<	36	-	35	<	29	<	-
Cover Erosion	4.0×10^{-7}	52,500	100	-	-	<	<	-	<	-
Lakeshore Release	3.7×10^{-8}	100,000	100	-	<	-	-	<	-	-
Gas Release	1.1×10^{-8}	300	-	-	-	-	-	-	-	100
Lake Release	8.4×10^{-9}	10,000	<	-	100	-	-	<	-	-

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as “<”. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Anm)” is the ingestion of contaminated animal products; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Ing (Wat)” is the ingestion of contaminated water; “Inh (Dust)” is the inhalation of contaminated dust; “Inh (Gas)” is the inhalation of contaminated gas. ‘-‘ indicates pathway not applicable for the exposure group.

The dose rates for other calculation cases, and the contribution of various pathways to the doses are presented in Table 11. The dose associated with the Cover Erosion Calculation Case can be seen to be about a factor of three lower than for the CAGCV-T concept (non-grouting option), as the release of radionuclides to the geosphere is more rapid because of the more permeable sand associated with this option.

The dose rates for the Lake and Lakeshore Release Calculation Cases can be seen to be higher than calculated for the equivalent concept located on till. This also demonstrates that, although the higher permeability of the sand is beneficial (by precluding the Bathtubbing Calculation Case for this option), it results in less containment of radionuclides, and consequently an increase in dose rate for some Calculation Cases, when compared with the till.

The results for the Gas Release Calculation Case are identical to those for the CAGCV-T non-grouting option, as the performance of the different options is very similar over the first few hundred years.

6.1.4 CAGCV-S, Grouting

The calculated radiation dose rates for the CAGCV-S concept with grouting are presented in Figure 31. It can be seen that for most calculation cases this results in lower calculated dose rates than the non-grouting option for the CAGCV-S concept. This is because the long period of alkaline conditions in the repository (which does not cease until 28,000 years) provides additional retention of radionuclides in the near field. However, the effectiveness of the retention of the radionuclides results in an increase in the calculated dose rate for the Cover Erosion Calculation Case, which is the dominant calculation case for this option. The dose is increased because the concentration of radionuclides in the waste when its erosion begins (50,000 years) is higher than in the non-grouting option. Therefore, although the option of grouting the wastes and voids is beneficial to most calculation cases, from some perspectives it affects performance adversely. Nevertheless, all calculated doses remain well below the ICRP dose criterion (the calculated peak dose rate is 0.0077 mSv y^{-1}, compared with the criterion of 0.3 mSv y^{-1}).

The contribution of various pathways, and a summary of the peak dose rate and time of occurrence are presented in Table 12. The key pathway for the Cover Erosion Calculation Case is external irradiation, and the dominant radionuclide is Nb-94. As noted previously, if direct exposure to the waste is considered, more significant dose rates could be calculated (see Section 6.2) for this calculation case.

The calculated dose rate from the gas release pathway marginally increased from the non-grouting option, as C-14 is less easily leached from the repository by groundwater.

The dose rates associate with the Lake and Lakeshore Release Calculation Cases are substantially lower for the grouting option of the CAGCV-S concept, when compared with the non-grouting option of the concept. This is because some of the key radionuclides, such as

C-14, are retained sufficiently long for radioactive decay to reduce the quantities that are released into the environment.

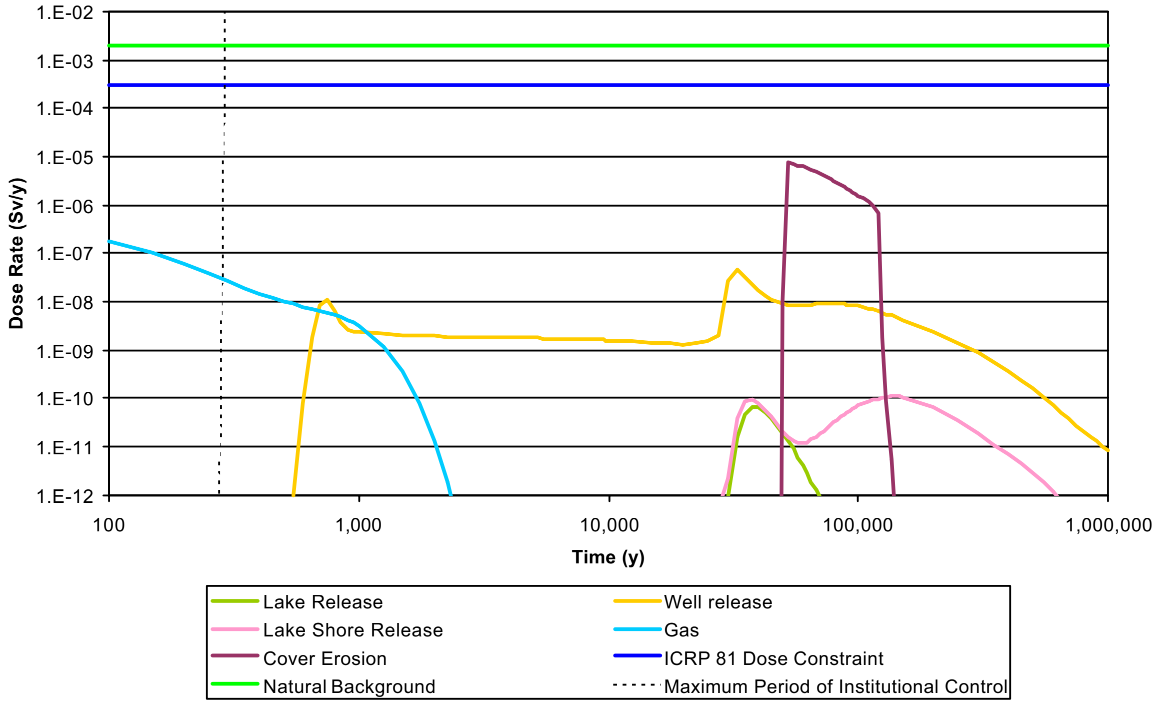

Figure 31: Total Calculated Dose Rates to Potentially Exposed Groups, from Reference Scenario Calculation Cases for the CAGCV-S Grouting Option

Table 12: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the CAGCV-S Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Cover Erosion	7.7×10^{-6}	52,500	100	-	-	<	<	-	<	-
Well Release	4.5×10^{-8}	32,500	<	35	-	35	<	30	<	-
Gas Release	2.7×10^{-8}	300	-	-	-	-	-	-	-	100
Lakeshore Release	1.1×10^{-10}	135,000	100	-	<	-	<	<	<	-
Lake Release	6.6×10^{-11}	37,500	<	-	100	-	<	<	<	-

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Anm)" is the ingestion of contaminated animal products; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Crop)" is the ingestion of contaminated plants and vegetables; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Ing (Wat)" is the ingestion of contaminated water; "Inh (Dust)" is the inhalation of contaminated dust; "Inh (Gas)" is the inhalation of contaminated gas. '-' indicates pathway not applicable for the exposure group.

6.1.5 DRCV-S Concepts

Figure 32 shows the results for the two groundwater release calculation cases considered for the DRCV concept located in shale, without grouting. It is immediately obvious that the calculated dose rates are extremely low, many orders of magnitude below natural background and the ICRP dose constraint. This is due to the extremely effective confinement of the radionuclides by the host rock. In the shales, there is no advective circulation of groundwater, and so radionuclide migration is assumed to be via diffusion only. Even if a more rapid diffusion pathway is present, as assumed in the Shaft Pathway Calculation Case, the results are only affected marginally. This is because for both cases significant retardation, decay and dilution of radionuclides occurs once they enter the overlying Intermediate Bedrock Groundwater System in which they travel for a distance of 15 km before being released into the central basin of Lake Huron. The only point of release that is considered likely is into the lake water, where radionuclides are further diluted.

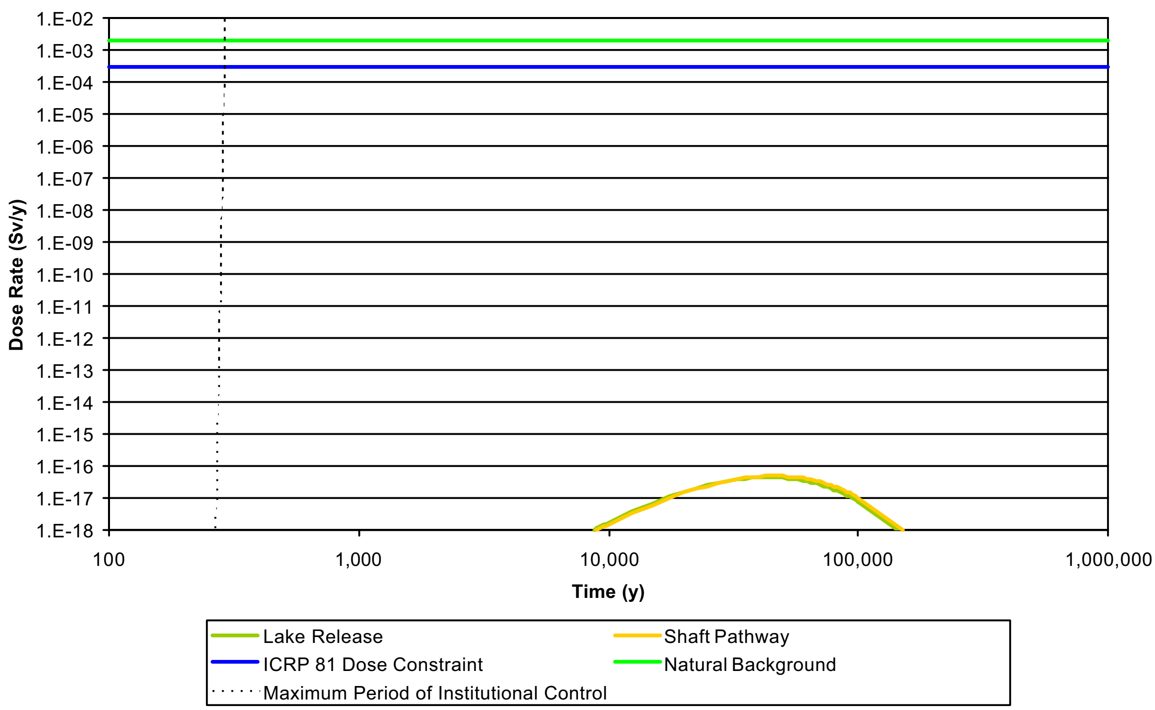

Figure 32: Total Calculated Dose Rates to Potentially Exposed Groups, from Reference Scenario Calculation Cases for the DRCV-S Non-grouting Option

The main pathways by which the potentially exposed group receives a dose rate are indicated in Table 13, which shows that ingestion of fish and water dominate the dose rate. The key radionuclides are I-129 and Tc-99. Table 14 summarises the results that are calculated if the waste and repository are assumed to be grouted. The dose rates are very similar, although in this case Cl-36 also features as a dominant radionuclide (before 100,000 years).

Table 13: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the DRCV-S Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext (Soil)	Ing (Fish)	Ing (Wat)
Shaft Pathway	4.6×10^{-17}	47,500	<	91	9
Lake Release	4.2×10^{-17}	42,500	<	91	9

Note: Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Wat)" is the ingestion of contaminated water.

Table 14: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the DRCV-S Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext (Soil)	Ing (Fish)	Ing (Wat)
Shaft Pathway	1.1×10^{-17}	150,000	<	91	9
Lake Release	9.1×10^{-18}	150,000	<	91	9

Note: Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Wat)" is the ingestion of contaminated water.

6.1.6 DRCV-L Concepts

An alternative location for the DCRV repository is below the shales in a limestone formation. Radionuclides released from a repository in this location would diffuse through the limestone and overlying shales before being released into the dolostone aquifer in the Intermediate Bedrock Groundwater System.

The additional isolation from the aquifer results in an increased time before radionuclides are released into the aquifer, and consequently slightly lower calculated dose rates, as shown in Figure 33. However, the key radionuclides are the same long-lived mobile radionuclides such as Tc-99 and I-129, and therefore the change in the performance of the DRCV in limestone, compared with that in shale, is minor. The only notable difference in the results is that the migration of contaminants via the shaft pathway, if it occurs, results in slightly higher dose rates at very long timescales. Nevertheless, as noted for the DRCV in shale concept, the calculated dose rates are extremely low.

The peak dose rate, and the time of the peak is indicated in Table 15, which also shows that the key pathways are the ingestion of fish and water from the lake. The dose rates are further reduced, and peak values are reached at much later times, if the repository is grouted. The results for the grouting option are presented in Table 16.

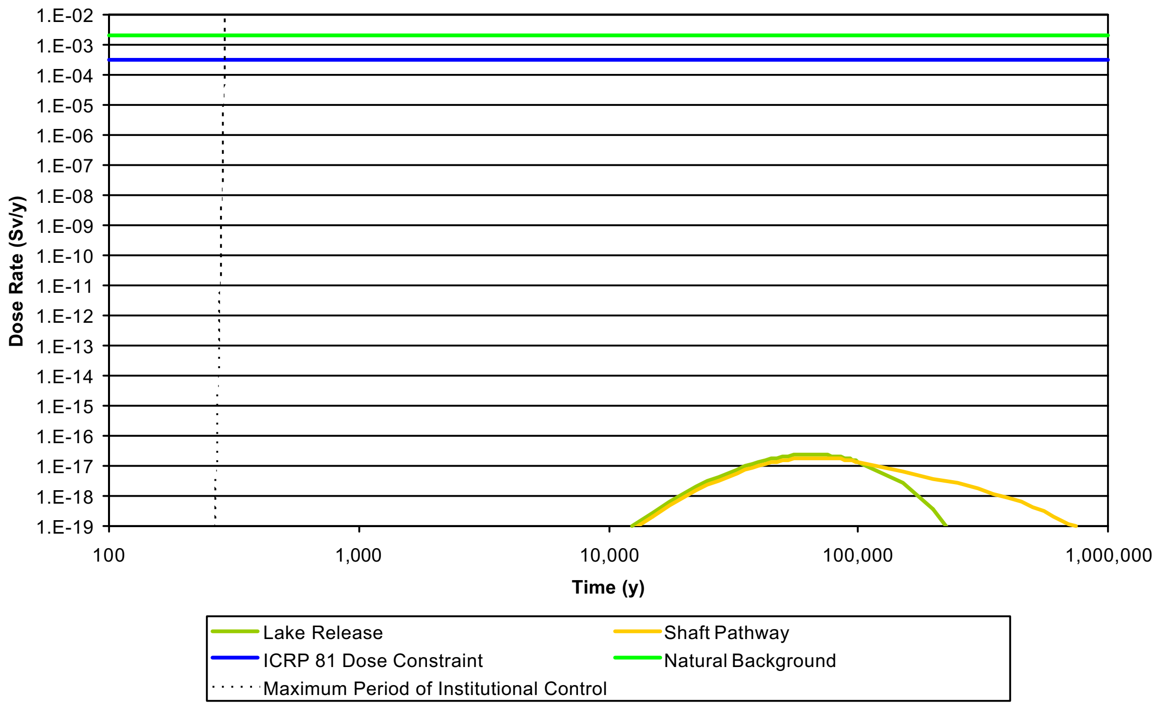

Figure 33: Total Calculated Dose Rates to Potentially Exposed Groups, from Reference Scenario Calculation Cases for the DRCV-L Non-grouting Option

Table 15: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the DRCV-L Non-grouting Option

Calculation Case	**Peak Dose Rate, Sv y^{-1}**	**Time of Peak, y**	**Contribution of Pathway to Peak Dose Rate (%)**		
			Ext (Soil)	**Ing (Fish)**	**Ing (Wat)**
Lake Release	2.7×10^{-17}	65,000	<	91	9
Shaft Pathway	1.8×10^{-17}	67,500	<	91	9

Note: Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Wat)" is the ingestion of contaminated water.

Table 16: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Reference Scenario Calculation Cases for the DRCV-L Grouting Option

Calculation Case	**Peak Dose Rate, Sv y^{-1}**	**Time of Peak, y**	**Contribution of Pathway to Peak Dose Rate (%)**		
			Ext (Soil)	**Ing (Fish)**	**Ing (Wat)**
Lake Release	4.9×10^{-18}	200,000	<	91	9
Shaft Pathway	4.6×10^{-18}	200,000	<	91	9

Note: Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Wat)" is the ingestion of contaminated water.

6.2 CALCULATION CASES FOR THE HUMAN INTRUSION SCENARIO

Human intrusion calculation cases are reported separately from natural release processes, consistent with recent guidance from ICRP (2000) on the consideration of such scenarios. Dose rates are calculated with reference to the residual concentrations in wastes – for the Borehole and Excavation (CAGCV only) Calculation Cases, exposure of the intruder is assumed to be directly to undiluted waste. For the site dweller, following excavation (CAGCV only), excavated waste is assumed to have become mixed with soil that is used for growing some produce.

The calculated dose rate is the dose rate that occurs to an individual member of the relevant exposure group assuming that the intrusion event occurs in the specified year. For example, the calculated dose rate at 1000 years is the dose rate that would be received assuming the intrusion event occurred at 1000 years.

The results are reported for the CAGCV without grouting (Figure 34 and Table 17) and with grouting (Figure 35 and Table 18). No distinction is made between the location on sand and till, as the residual concentrations in the repositories would be similar.

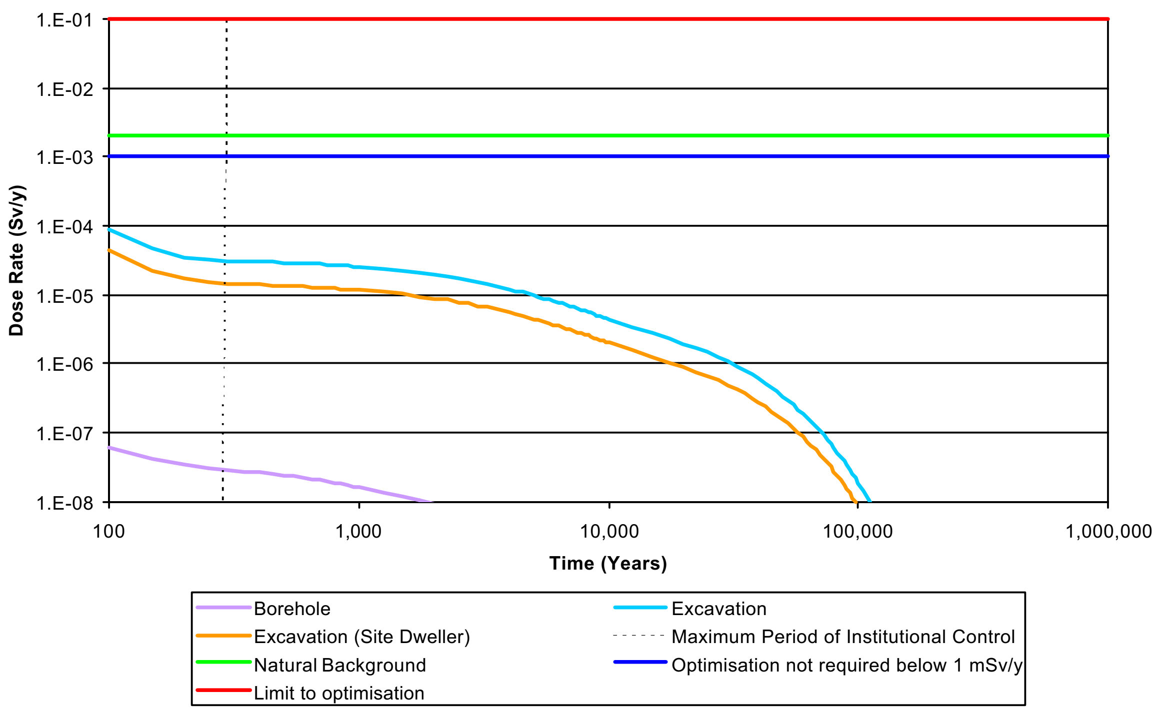

Figure 34: Total Calculated Dose Rates for Human Intrusion, for the CAGCV Non-grouting Option

The results for the CAGCV without grouting show that dose rates are well below the criteria for all calculation cases. Potential dose rates were also calculated for times less than the assumed institutional control period of 300 years, and show that doses are below the 1 mSv y^{-1} criterion even after only 100 years. This result suggests that shorter period of control of the repository could potentially be justified, if necessary.

For the non-grouting option, the calculated dose rates from human intrusion decrease as the concentrations in the repository reduce, due to radioactive decay and the release of radionuclides into the groundwater. The more effective containment of the grouting option result in a less significant reduction of potential doses over time, as the radionuclides are contained in the repository.

Table 17: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the CAGCV Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)			
			Ext	Ing (Crop)	Ing (Soil)	Inh (Dust)
Excavation	3.1×10^{-5}	300	98	-	<	2
Excavation (Site Dweller)	1.4×10^{-5}	300	96	4	<	<
Borehole	2.9×10^{-8}	300	29	-	20	51

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext" is the abbreviation for external irradiation from soil or waste; "Ing (Crop)" is the ingestion of contaminated plants and vegetables; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Inh (Dust)" is the inhalation of contaminated dust. '-' indicates that the pathway not applicable for the exposure group.

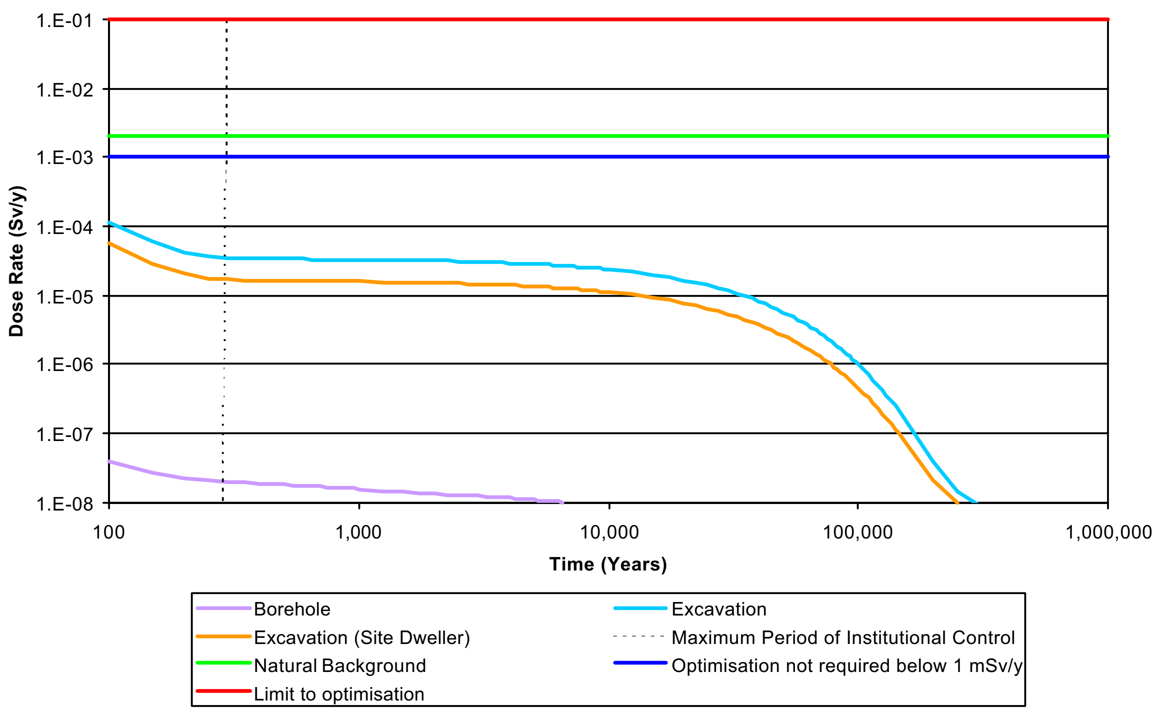

Figure 35: Total Calculated Dose Rates for Human Intrusion, for the CAGCV Grouting Option

The increased isolation of the waste from the surface reduces the range of intrusion events that could affect the wastes. For the DRCV, located 460 to 660 m below the surface, it is only possible to envisage the incidental extraction of borehole samples that contain waste. Larger excavations are not credible, given the low mineral value of the formations under consideration. Human intrusion results for the DRCV concept therefore only consider the Borehole Calculation Case. In this case, even though the radionuclides are effectively retained in the repository over very long periods of time, the limited amounts of waste retrieved means that calculated dose rates are well below the relevant criteria. Figure 36 and Table 19 show the results calculated for the non-grouting option, and Figure 37 and Table 20 show the results calculated for the grouting option. As may be seen, the only difference is that the calculated dose rates remain higher in the grouting case at long timescales, due to the increased retention of the radionuclides. However, the peak dose rate for this option is slightly lower, reflecting the lower average concentrations of radionuclides in the waste due to the addition of uncontaminated cement grout.

Table 18: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the CAGCV Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)			
			Ext	Ing (Crop)	Ing (Soil)	Inh (Dust)
Excavation	3.5×10^{-5}	300	99	-	<	1
Excavation (Site Dweller)	1.7×10^{-5}	300	93	7	<	<
Borehole	2.0×10^{-8}	300	22	-	22	56

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as “<”. Pathways are indicated as follows: “Ext” is the abbreviation for external irradiation from soil or waste; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Inh (Dust)” is the inhalation of contaminated dust. ‘-‘ indicates that the pathway not applicable for the exposure group.

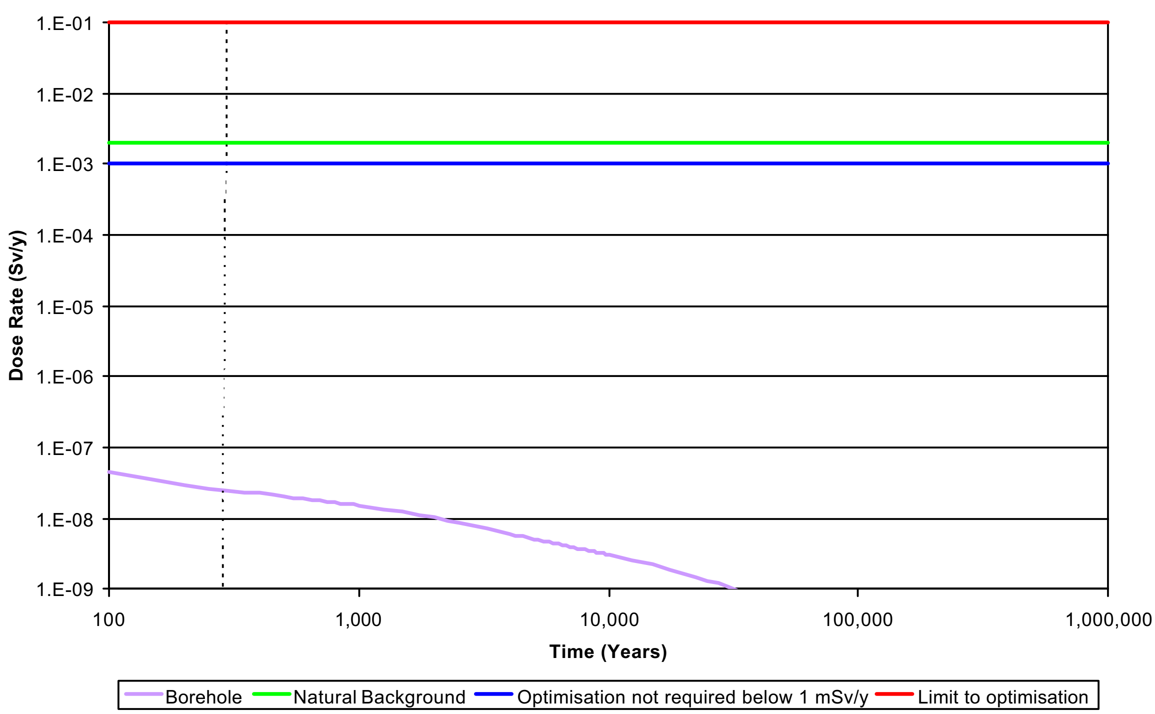

Figure 36: Total Calculated Dose Rates for Human Intrusion, for the DRCV Non-grouting Option

Table 19: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the DRCV Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext	Ing (Soil)	Inh (Dust)
Borehole	2.5×10^{-8}	300	7	26	67

Note: An institutional control period of 300 years is assumed for the purposes this table. Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext" is the abbreviation for external irradiation from soil or waste; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Inh (Dust)" is the inhalation of contaminated dust.

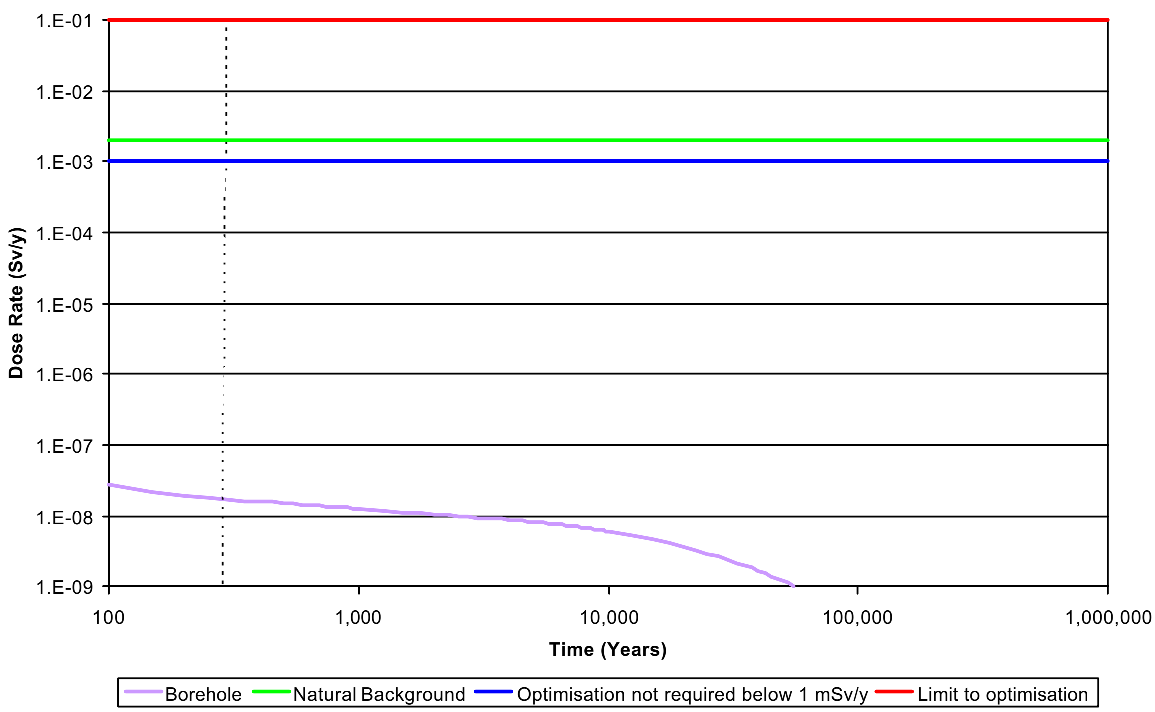

Figure 37: Total Calculated Dose Rates for Human Intrusion, for the DRCV Grouting Option

Table 20: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the DRCV Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext	Ing (Soil)	Inh (Dust)
Borehole	1.7×10^{-8}	300	5	27	68

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % are indicated as "<". Pathways are indicated as follows: "Ext" is the abbreviation for external irradiation from soil or waste; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Inh (Dust)" is the inhalation of contaminated dust.

7. CONCLUSIONS AND RECOMMENDATIONS

The postclosure radiological safety of a range of geotechnically feasible repository concepts for LLW at the Bruce Site has been evaluated using an approach consistent with best international practice. This preliminary safety assessment has demonstrated that the deep repository concepts in shale (DRCV-S) and limestone (DRCV-L), and the surface repository concept on sand (CAGCV-S) should meet the radiological protection criteria adopted for this study, even without grouting of the waste and repository voids. For the surface repository concept on till (CAGCV-T), increased engineering such as grouting of waste and voids needs to be considered in order to reduce the calculated dose rate to below the relevant dose constraint. Whilst grouting has benefits for the surface repository concepts such as reducing and/or delaying dose rates, its benefits for the deep repository concepts are minimal. Although extending the institutional control period from 100 to 300 years has no significant impact on the dose rates for the limiting calculation cases for the Reference Scenario, it does reduce calculated dose rates but only by about a factor of three for Human Intrusion Scenario Calculation Cases. Furthermore, the calculated dose rates at 100 years for the most restrictive calculation case are still more than an order of magnitude below the level above which reasonable efforts should be made to reduce the likelihood of human intrusion or to limit its consequences.

The ability of the repository designs to accept OPG's ILW has been assessed qualitatively. Due to the very low permeability of the host rocks, the deep repository concepts in shale (DRCV-S) and limestone (DRCV-L) are likely to meet the radiological protection criteria adopted for this study for a wide range of ILW, although quantitative analyses would be required to confirm this. The surface repository concept on sand (CAGCV-S) would require additional analyses to ascertain the degree to which the concept could accept ILW.

As emphasised in Section 6, the assessment is a preliminary postclosure radiological safety assessment, and the associated calculations have been undertaken at a scoping level.

This preliminary safety assessment would need to be updated in both its breadth and depth based on future site-specific geotechnical investigations and/or design updates, should it be decided to proceed with a repository at the Bruce Site.

In terms of increasing the breadth of the evaluation of the repository concepts, it could be extended to consider operational issues. Operational issues could include not only radiological safety but also non-radiological safety and impacts associated with the development of the repository.

In terms of increasing the depth of the evaluation of repository concepts, the more detailed consideration could be given to certain aspects of the safety assessment. Issues of particular interest could include the following.

- The relatively simple groundwater flow and transport calculations, which have been undertaken for this preliminary safety assessment, could be supported with more detailed two and three dimensional calculations especially for the Overburden and Shallow Bedrock Groundwater Systems. This in turn would require more detailed characterisation of the physical and chemical characteristics of these systems at the Bruce Site.

- The results presented in Section 6 show that the timescales of potential interest extend well beyond 10,000 years. Over such timescales, environmental change, caused by factors such as major climate change, can be significant and could be addressed in future assessments. For example, a cooling of climate might result in a fall in lake level and the discharge of the Shallow Bedrock Groundwater System to exposed lake sediments rather than submerged lake sediments.

- Although site-specific data from the Bruce Site and its environs have been used where available in this preliminary assessment, much of the data used in the assessment comes from non-Bruce specific sources. Whilst this is appropriate for certain parameters (for example, dose coefficients), for certain other parameters (for example, sorption coefficients) the use of site-specific data would be preferable.

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APPENDIX A: SUMMARY OF GEOLOGICAL HISTORY AND LITHOLOGICAL DESCRIPTIONS FOR THE SEDIMENTARY BEDROCK AT THE BRUCE SITE

CONTENTS

A.1 GEOLOGICAL HISTORY

Unconformably overlying, and derived from, the Precambrian basement is a relatively thin clastic sequence representing the transgression of Cambrian and Middle Ordovician seas over the Precambrian granite-gneiss basement. Following the advance of the Middle Ordovician seas and deposition of the basal clastic deposits, quieter conditions prevailed dominated by limestone deposition. The Ordovician limestones are typically very fine grained, argillaceous to shaly, with consistent thickness and lateral continuity.

Overlying the Middle Ordovician limestones is a thick shale succession comprising the Collingwood, Georgian Bay and Queenston Formations, deposited in the Upper Ordovician from sediments eroded from the contemporary uplift of the ancient Appalachian Mountain area to the east. The Queenston Formation red shales reflect the iron oxide content of the shales caused by exposure of the sediments to the atmosphere during transport and deposition in a marine deltaic environment.

The Manitoulin Formation, a thin (~ 6 m) dolostone of Lower Silurian age represents the transgression of the Silurian seas back into the area as the Michigan Basin continued to subside in response to regional continental tectonics. A further influx of clastic sediment, again from the east, deposited the ~ 30 m thick Cabot Head Formation shale.

The onset of the Middle Silurian is marked by the deposition of thick dolostones of the Reynales, Lockport and the natural gas-bearing Guelph Formations. In the late Silurian, marine waters periodically entered the basin and then evaporated building up alternating beds of dolomite, shale, gypsum and salt to form the Salina Formation. The Salina Formation hosts extensive salt deposits to the south of the Bruce area; however, in the Bruce Site area the deposits were removed by circulating groundwaters during the late Silurian and Devonian times. The sub-erosion of up to 150 m of Salina salts from beneath the Bruce Site has structurally influenced the overlying rock sequence through collapse and differential settlement. This has resulted in warping of the overlying strata, development of vertical fracturing and overall enhancement of formational permeability along bedding horizons and breccia layers extending up through the Devonian sequence.

Following deposition of the Salina Formation, unrestricted carbonate deposition continued within the subsiding basin to the end of the Silurian period with the formation of the Bass Island Formation dolostone. The upper contact of this Formation is a regional discontinuity marking an extended period of time when the entire area became subject to subaerial erosion. The disconformity is represented by a weathering profile several metres thick, recognisable regionally, and associated with weak rock and permeable water bearing strata.

The return of the Devonian seas deposited the cherty dolostone of the Bois Blanc Formation and the overlying dolostone of the Amherstburg Formation, which forms the present erosional bedrock surface at the Bruce Site.

A.2 LITHOLOGICAL DESCRIPTIONS

In the Ordovician, the upper member of the Lindsay Formation comprises fresh, fine grained, thin to medium bedded, nodular textured (10 mm to 50 mm diameter nodules) argillaceous limestone with occasional interbeds of shaly limestone and thin black shale partings. The Sherman Falls Member is less argillaceous, fresh, fine grained micritic limestone with thin interbeds of partly crystalline calcarenitic limestone. A major steeply dipping joint, with a spacing of about 1 m, strikes E-W. Joints are planar or stepped with smooth to rough walls and may contain calcite. The overall rock quality is good. For the most part the Queenston Formation comprises reddish-brown silty mudstone or siltstone with interbeds and nodules of green siltstone. The beds are massive to blocky with some fissile sections and are susceptible to slaking on exposure. Bedding planes associated with thin siltstone beds form discontinuities at spacings of 5 m to more than 10 m. Where they are clay rich they form weak discontinuities surfaces. The Georgian Bay Formation comprises soft, thin to thick bedded grey shale (13 mm to 600 mm) interbedded with grey limestone beds. One steeply dipping joint set, consistent with known regional joint mapping, has been identified in a borehole. The Queenston and Georgian Bay shale Formations show anisotropic deformational behaviour, weather very rapidly and are susceptible to swelling when unconfined.

The description of the properties of shales, dolostones and evaporites of the Salina Formation is based on gypsum and salt mining experience in Southern Ontario. The rocks of the Salina Formation range from thinly to medium bedded (2 cm to 20 cm) medium grained dolostone with vugs (or breccia vugs infilled with gypsum) to strong, massive or medium bedded dolomitic limestones. Solution action is evident in some units and varies from moderate to none in the very strong, fine grained dolostones. The shales and mudstones are very thinly to thinly bedded, with occasional millimetric gypsum infillings, and can be lightly dolomitised. Exposed shale and mudstone tends to slake. Gypsum is the only evaporite mineral present at the Bruce Site and tends to be both weak and massive. Observations of jointing from underground and from core logging suggest that the dominant joint set in the regions are horizontal bedding plane joints. Spacing of these bedding plane joints varies from millimetres in the shales to centimetres in the gypsiferous mudstones.

The dolostones of the Bois Blanc Formation contain chert nodules. Joint frequency is generally greater than in the Amherstburg Formation and therefore joint spacing might be expected to be greater than 1 m.

The Amherstburg Formation comprises hard, fossiliferous, finely laminated, lightly fractured limestones and dolostones. The bedding is horizontal, with some soft thin bituminous seams on bedding partings. Typically, the spacing of bedding partings varies between 0.3 m to 3 m with an average of about 1 to 1.2 m. Vertical joint spacing is 0.6 m to 1 m on average with slightly closer spacing in the upper 7 m and increased spacing at depth to over 1 m at the contact with the Bois Blanc Formation. Joints are tight with minor surface weathering. Localised highly fractured zones, leached zones and vuggy to very vuggy zones are reported from borehole intersections. Rock Quality is classed as “Fair”.

APPENDIX B: DETAILED BIOSPHERE DESCRIPTION

CONTENTS

B.1 CLIMATE

Climate data are reported in Environmental Assessment studies for the Bruce Site submitted by Ontario Hydro (1997) and OPG (2000). Data are largely based on Environment Canada's historical records of observations at Southampton and Wiarton Airport. These data are supplemented with data collected at the Bruce Site from 1994 to 1998.

The regional climate is continental, although the proximity of the large lakes mitigate extreme temperatures and conditions during summer and winter. Storms and heavy snowfall can occur during the winter. Thunderstorms can occur on 20 – 25 days per year, and there is on average 20 – 50 hours of ice storms per year, with freezing rainstorms occurring with similar frequency. One tornado has been recorded within 10 km of the Bruce Site in the last 10 years. Typical tornadoes have a diameter of 150 – 600 m, travel at 50 – 70 km h^{-1} and last for about 20 minutes.

The annual average temperature is 7°C and varies from a mean daily temperature of about -5°C (January and February) to 20°C (July and August). Wind speeds are typically about 15 km h^{-1}, with the wind direction being predominantly from the south and southwest. Within a few km of the lake, 'lake breezes' can occur, directed onshore during the day and 'land breezes' can occur directed offshore at night.

Total annual precipitation is about 0.86 m y^{-1}, of which about 0.17 m y^{-1} falls as snow. Precipitation is generally highest from August to January (0.07 to 0.09 m $month^{-1}$) with lower values from February to July (about 0.05 – 0.07 m $month^{-1}$).

B.2 TOPOGRAPHY

The area in the vicinity of the Bruce Site is characterised by flat semi-open agricultural land to the east, rolling hills, valleys and sandy shores to the lake. The topographic relief of the site itself is subdued, rising from lake level at 176 m above sea level to 195 m at the eastern boundary of the Bruce Site, partially coincident with the Nipissing bluff, a linear feature eroded into the glacial cover by a former shoreline of Lake Huron. The site has an aerial extent of 9×10^6 m^2. Large portions of the Bruce Site have been cleared of vegetation and graded; for example the WWMF site (9×10^6 m^2) varies by less than 2 m in elevation. Some 800 m further inland from the Nipissing bluff an earlier shoreline is represented by the Algonquin bluff which marks an abrupt topographic step in the overburden sediments of some 20 to 30 m.

One consequence of the generally flat topography, coupled with the poorly conductive tills that are located close to the surface is that substantial swales (pools) of standing water form, especially during the spring.

B.3 SURFACE WATER

The dominant surface water feature in the region is Lake Huron (Figure 1), one of the Great Lakes. The Great Lakes were formed by glacial ice erosion, changing as a result of ice sheet melting and isostatic rebound, only forming a stable system about 5000 years ago. The location and characteristics of the lake are therefore likely to change substantially over the period of tens of thousands of years, influencing the present-day shoreline.

The surface of the lake is 176 m above the present sea level and it has a total surface area of 5.96×10^{10} m^2. Its mean depth is 50 – 60 m, and the total water volume is 3.53×10^{12} m^3. The main inflow into the lake is via the Straits of Mackinac (net flow towards Lake Huron of

4.65×10^{10} m^3 y^{-1}) and St. Mary's River (a mean flow rate of about 6.7×10^{10} m^3 y^{-1}). Runoff also accounts for 5.39×10^{10} m^3 y^{-1}, and precipitation is balanced by evaporation. The mean outflow is 1.67×10^{11} m^3 y^{-1} via St. Clair River at the southern end of the lake.

The biological and geochemical properties of the lake are regionalised. For example, some locations display eutrophic conditions, and the south of the lake tends to be warmer than the north. Sediment characteristics are also varied. In the depositional regions they are fine grained. Erosion zones in shallower waters display more varied size distribution including larger gravels. Reported sediment accumulation rates range from 1.3×10^{-4} to 2.1×10^{-3} m y^{-1}.

There are no major rivers in the vicinity of the Bruce Site, the nearest river being the Little Sauble River (Figure 14). However, there are several surface water features of interest near to the WWMF site. Two streams are of interest, the Railway Ditch and 'Stream C', as well as a wetland area that can have pools of open water (standing water also occurs at many other locations on the Bruce Site owing to the poor drainage of the soil) at the east edge of the WWMF site. The wetland is quite thickly vegetated.

The Railway Ditch stream was originally excavated parallel to a now-disused railway line. Its characteristics are described in OPG (2000) and Patrick et al. (2001). The stream is 2 to 3 m wide and has a typical water depth of about 0.15 m (although there are some deeper pools). It is fed by runoff from an area of about 2×10^5 m^2, including the WWMF site. No flow data have been obtained, although it is thought to be low. The stream flows 550 m into the wetland area on the north edge of the WWMF site. It then flows a further 450 m to meet Stream C. The flow to Stream C can sometimes be disrupted when the resident beavers block the wetland outflow culvert.

The Railway Ditch is populated by a variety of fish and amphibians and is generally heavily vegetated. Measured radionuclide concentrations in the water and sediment are below guideline values. Concentrations are higher in vegetation (cattails); however, no guideline values are available for comparison with the measurements. C-14 and H-3 are present in cattails with the highest concentration, of about 6 and 1 Bq g^{-1}, respectively.

Stream C (Figure 14) is a redirected former tributary of the Little Sauble River with plentiful vegetation and aquatic life. The stream has a mean width of 3 m and depths that range from 0.15 to 0.8 m. It flows slowly for 1400 m from the culvert point at the Railway Ditch into Baie du Dore, a provincially significant wetland on the edge of Lake Huron, roughly north of the WWMF site. The Baie du Dore wetland has an area of about 9.5×10^5 m^2 and is composed of three wetland types (46% fen, 4% swamp and 50% marsh) (Ministry of Natural Resources, 2002).

B.4 SOIL TYPES

The soil composition in the vicinity of the WWMF site is reported by Patrick and Romano (2001). In general, there is a shallow layer of topsoil, typically about 30 cm, overlying silt till. There are occasional regions of peat-like material. Soil and subsoil is generally firm to stiff and dense. Moisture varies, but it is generally moist and often wet or even saturated. To the east of the WWMF site lies an area of wetland. Information from a reference site at Goderich indicates that this is typical for land within a few kilometres of the lake.

B.5 PRESENT-DAY LAND USE

The land uses on and around the Bruce Site are described in OPG (2000) and summarised below.

Land uses on the Bruce Site are restricted to those associated with the nuclear operations and associated support activities such as waste management; however, the large area of the site means that about half is covered with open vegetation and woodland. Additional land is owned by OPG and is mainly unoccupied bush and swamp. The Bruce Site is the county's largest employer, creating 4000 jobs. An industrial park is also located to the east of the Bruce Site, providing a further 160 jobs.

The region around the Bruce Site is mainly used for agriculture, recreation and some residential development. Arable farmland accounts for around 60% of the current land use in the county, and the average area per farm is 67 ha (6.7×10^5 m^2). The county has the largest numbers of cattle in Ontario, with on average 43 cows per farm. Pig and chicken farming is also common. About 8 % of all farmers raise cattle for milking, 11 % of farmers raise pigs and 5 % raise sheep. The county is also amongst the top producing counties in Ontario for oats, barley, canola and hay. Local people also hunt wild animals including deer and waterfowl. Farms and rural populations often obtain water from wells (Figure 14). The lake provides water for larger communities. The lake is also used for fishing (commercial, sport and fishing for personal consumption).

Tourism is the second largest industry in Bruce County, being responsible for more than 30 % of retail sales in the county. A Provincial Park, owned by OPG and leased to the Ontario Ministry of Natural Resources (www.ontarioparks.com/inve.html), is located south of the Bruce Site. It is currently only developed to a limited extent; however, a more developed park is located about 10 km to the north at MacGregor Point.

Within 5 km of the Bruce Site there are about 500 permanent and seasonal dwellings. The nearest population centre is Inverhuron, with about 200 permanently occupied dwellings. Larger towns are Port Elgin about 20 km to the northeast (7,000 inhabitants in 1996) and Kincardine, 15 km to the southwest (6,600 inhabitants in 1996).

Archaeological sites exist in the vicinity showing that it was settled around 2000 years ago by the Iroquois Nation, and occupied by the Ojibway Tribe when Europeans settled in the 1800s. Two areas of archaeological interest exist on the Bruce Site, neither close to the WWMF site.

B.6 FLORA AND FAUNA

The flora and fauna of interest are described in Patrick et al. (2001) and OPG (2000). Within the WWMF site more than half the land area is built upon. The remaining land is vegetated by white cedar, dry-fresh sugar maple, mineral cultural meadow and wetland. The dry-fresh sugar maple woodland contains sugar maple and American beech, and also has limited ground cover. The meadow is dominated by species such as brome grass and various asters.

There is a wide variety of wildlife in the area, all being reasonably common for the location. Birds include doves, cuckoos, woodpeckers, pewees, blue-jays, swallows and robins. Wild turkey have been seen. Mammals that have been observed include deer, porcupine, racoon, woodchucks, groundhogs, muskrats, squirrels and beaver. Coyote have been reported to be present, although there have been no recent observations.

Both the Railway Ditch and Stream C are well vegetated with a diverse range of species, none being rare. The dominant species in the Railway Ditch are cattails as well as sedge, pondweed, watercress, water plantain, bulrush and arrowhead. Algae also collect in open pools. Typical fish species in Railway Ditch include the Central Mud Minnow, White Sucker, Redbelly Dace, Creek Chub and Spine Stickleback. Stream C is known to contain trout and bass in addition to these species. A variety of amphibians is also present such as the Green Frog, the Grey Frog, and the Leopard Frog. Other fauna include turtles, salamander, water snakes, crayfish leeches and snails. Wetlands support similar biota. The Baie du Dore is also a significant stopover for migrating birds and provides spawning grounds for salmon, bass and carp.

B.7 NATURAL RESOURCES

Both municipal and domestic users of water exist in the vicinity the Bruce Site. Water is drawn principally from the Shallow Bedrock Groundwater System, mainly the Amherstburg and Bois Blanc Formations (Golder Associates, 2003). There are six water extraction wells within about 7 km of the Bruce Site (Figure 14). As noted in Section 3.3.2, the direction of groundwater flow within the watershed is westward towards Lake Huron and the Bruce Site is essentially down gradient from the various well users. The Bruce Site obtains its own water supplies from Lake Huron via a treatment plant.

Oil was first found in the Canadian part of the Michigan Basin in 1858 at Oil Springs on the west flank of the Algonquin Arch in Ontario. Locally, in southern Ontario the Cambrian sandstones contain natural gas. No significant oil or gas has been found by exploratory drilling in the Bruce area, as there is an absence of oil or gas producing reefs. However, a local non-productive reef was intersected in an exploration well about 5 km south of the Bruce Site. The nearest producing reefs are located in Ashfield and west Wawonosh Townships approximately 30 km south of the Bruce Site.

Salt deposits in Ontario occur principally along the eastern shore line of Lake Huron, Lake St. Clair and St. Clair and Detroit Rivers. Salt has been mined hydraulically at Windsor, Detroit, Sarni, Port Huron, Goderich and Midland Michigan. Solution and conventional mining methods are currently used at the Ojibay mine in Windsor and Goderich. In 1980, solution mining operations were terminated in Port Huron, Michigan. The caverns are now used for storage of natural gas.

Gypsum is mined at Hagersville. The Guelph Formation is a resource for high-purity dolomite and calcined products for use in the iron and steel industry.

Mineral extraction for the construction industry occurs widely in the region, with primarily sand and gravel being extracted. There are 21 licensed pits and quarries within 25 km of the Bruce Site, including four disused quarries in the controlled development zone around the site.

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APPENDIX C: APPROACH USED FOR DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

CONTENTS

C.1 INTRODUCTION

The scenario development procedure used in this preliminary safety assessment has the following main steps.

- Identification of the repository system (Appendix C.2).
- Identification of external FEPs (EFEPs) and their potential relevance to the repository system under study (Appendix C.3).
- Categorisation of EFEPs to identify contributions to scenario development (Appendix C.4).
- Definition of scenarios for evaluation through conceptualisation of relationships between EFEPs (Appendices C.5 and C.6).

C.2 IDENTIFICATION OF THE REPOSITORY SYSTEM

The repository system is defined to consist of near field, geosphere and biosphere components. These have been described in Section 3 and are summarised below.

- The near field. This incorporates all FEPs related to the disposed wastes and associated engineered features of the repository, backfill and final cap. Potentially relevant intrinsic dynamics within the near field include changes to local properties and characteristics associated with the chemical and physical degradation of the waste form, waste container, engineered structures, backfill (if present) and cap (if present).

- The geosphere. This comprises the geological formations in which radionuclides will be transported if they are released from the near field. The domain of interest for surface repositories comprises the principal hydrogeological units of the Overburden and the Shallow Bedrock Groundwater Systems. For the DRCV permanent repository concepts, the geosphere includes the Intermediate and Deep Groundwater Systems. Although the movement of groundwater could be considered a dynamic feature of the geosphere (albeit very slow in some formations), there are no significant sources of change to the flow field or hydrogeochemistry associated with processes that are intrinsic to this component of the repository system. Rather, these features and properties would be expected to evolve in response to other, external changes.

- The biosphere. This includes FEPs related to the migration and accumulation of radionuclides in the accessible environment, as well as pathways of exposure to hypothetical members of potential exposure groups. The domain of the biosphere within the safety assessment is dictated by the need to incorporate those regions of the environment exploited by humans that may receive the most radioactivity as a result of future releases from the repository system. The biosphere is potentially susceptible to highly dynamic change on the timescale of the assessment.

From the perspective of scenario development, it is informative to contrast the development and description of the biosphere with the characterisation of other components of the repository system. For the near field and geosphere, the basic components and properties of the present-day system are determined from documented site characterisation, inventory and engineering design information. Conceptual descriptions of the near field and geosphere, used as a basis for assessment models, are then derived from this information, coupled with assumptions regarding the response of the repository system to external mechanisms for change. For the biosphere, however, important aspects of the surface environment (such as vegetation, soil properties, drainage characteristics, animal populations, and local communities) are strongly influenced by future human behaviour, which is inherently unpredictable. The development of a conceptual description for the biosphere as a basis for safety assessment modelling is therefore guided both by physical considerations, such as landform and the projected location of future releases of radionuclides, and by fundamental assessment assumptions about the influence of local communities on land use and resource exploitation. The role of assessment scenarios in defining the future characteristics of the biosphere is therefore constrained by assumptions relating to the overall context within which the assessment is undertaken.

Outside the repository system is the external system which influences the evolution of the repository system.

A simple illustration of the components involved in this systems approach to scenario development is provided in Figure 38.

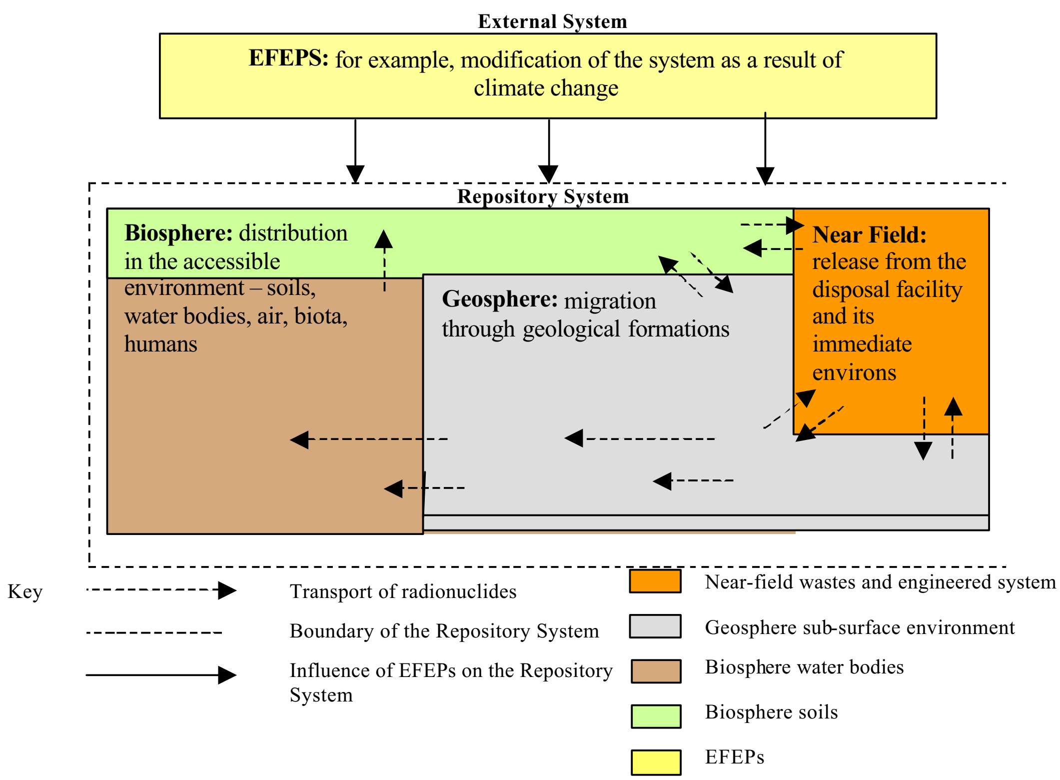

Figure 38: Simple Illustration of the Systems Approach to Scenario Development

C.3 IDENTIFICATION OF EFEPS

The FEPs associated with the external system (i.e., the EFEPs) need to be considered when developing scenarios, since they will influence the evolution of the repository system. By considering the relationships between EFEPs (including mechanisms related to future human actions, climate and earth processes), an understanding is developed of the way in which various mechanisms can operate together, over a range of timescales to modify the properties and characteristics of the repository system.

An internationally-agreed FEP list, intended for application to near-surface repositories, has been used within the IAEA's ISAM project (IAEA, 2002). It provides a high-level differentiation between FEPs internal to the repository system and those external to it (i.e., EFEPs). It therefore provides a useful starting point in identifying EFEPs relevant to the identification and description of scenarios for this safety assessment. In particular, the ISAM list defines a class of 'External Factors' comprising the following main elements:

- repository issues;
- geological processes and effects;
- climatic processes and effects; and
- future human actions.

C.3.1 REPOSITORY ISSUES

According to the ISAM FEP list glossary (IAEA, 2002), FEPs summarised under the heading of 'Repository Issues' relate to decisions on waste allocation, as well as possible events associated with site investigation, operations and closure. Such factors are therefore relevant in determining the assumed condition of the repository at the time of closure. It is recognised that, in principle, there may be various uncertainties regarding its status at this time. Moreover, in relation to a particular project, alternative assumptions regarding repository design may indeed need to be considered as part of the development of a detailed safety case, in order to address optimisation consideration. For the purposes of this preliminary safety assessment, however, such considerations are effectively pre-defined as aspects of the overall assessment context (Section 2) – including, in this case, the decision to make a comparative assessment of four distinct repository concepts. Hence there is no need to take account of "repository issues" (as defined within the ISAM FEP list) in the identification of alternative system states and assessment scenarios for the current study.

C.3.2 GEOLOGICAL PROCESSES AND EFFECTS

The ISAM FEP list identifies a variety of geological processes and effects as being of potential relevance to safety assessment (IAEA, 2002). In the development of a formal safety case, it will be necessary to undertake a systematic review of this category of EFEPs in order to demonstrate that none represents a significant hazard to the long-term safety performance of the permanent repository. For example, this would include a seismic hazard analysis, expressed in terms of the projected return frequency of events occurring close to the site with significant magnitude to disrupt, or distort significantly, the repository system.

One potential impact of strong seismic events on geological repository systems, identified in previous work undertaken for Nirex (Nirex, 1995), is the possibility of disturbance of groundwater flow paths leading to the accelerated release of radionuclides. Such changes in deep groundwater flow paths would be highly unlikely to have a significant effect on radionuclide transport (and hence safety performance) for permanent repositories located at depths of up to only a few tens of metres below the ground surface. However, they could potentially be a relevant consideration in relation to the DRCV-S and DRCV-L repositories. For this preliminary safety assessment, in view of the absence of data on potential fault movements within the Ordovician formations, the possibility of seismically-induced accelerated release has not been investigated further. A further consideration, more relevant to CAGCV-S and CAGCV-T repositories, is the possible threat to the containment integrity of the repository itself, arising from seismically-induced ground disturbance through surface rupture or liquefaction. Strictly speaking, however, it is only the likelihood of very large seismic events (local intensity in the region EMS[4] 10-12), that merits consideration as part of the safety assessment.

The region surrounding the Bruce Site is understood to be geologically quiescent, with no evidence for neotectonic activity or potentially disruptive processes originating within the regional geological environment on the timescale relevant to the safety assessment. There is also no suggestion of any potentially significant ongoing erosive or depositional processes, associated with, for example, topographic variation or land uplift. Of the geological processes and effects identified within the ISAM FEP list (IAEA, 2002), the ones that are most relevant from the perspective of scenario development are therefore those that relate to the response of the geological and hydrogeological system to other external factors, such as potential future ice loading.

C.3.3 CLIMATIC PROCESSES AND EFFECTS

The category of climate-related processes and effects in the ISAM FEP list (IAEA, 2002) incorporates a number of considerations that, ultimately, depend on assumptions relating to global climate change. The treatment of changes in global climate and their expression at a regional scale in terms of the climate and landform evolution is an important aspect of demonstrating overall system understanding as part of the development of a comprehensive safety case. In the past, processes relating to the growth and decay of the Laurentide ice sheet over the North American continent have had an important influence on landform evolution over timescales of tens to hundreds of thousands of years. Whether glacial/interglacial cycling will continue to occur according to the pattern established over the Quaternary period is a matter of debate among climatologists, some of whom suggest that global climate may be so strongly affected by anthropogenic greenhouse gases that anticipated ice sheet growth in the northern hemisphere on timescales of 20,000 and 50,000 years may not now take place and the next glacial maximum could be delayed until as much as 100,000 years after present (see, for example, long-term climate simulations undertaken within the European BIOCLIM research project (http://www.andra.fr/bioclim) and projections carried out on behalf of BNFL (2002)). Nevertheless, the possibility that natural changes in global climate may lead to glaciation of southern Ontario on a period of several tens of thousands of years cannot be discounted.

The consequences of global climate change that are of most interest in the context of descriptions of the evolving permanent repository and its environment are those associated with:

- the potential for disruption by processes relating to ice-sheet growth and decay (including both mechanical disturbance and stream erosion);
- the potential effect of changes in precipitation and seasonal temperature variation on groundwater flow patterns;
- freeze/thaw effects on the near field;
- effects of permafrost and other cold climate processes on groundwater flow as well as features and characteristics of the near-surface environment;
- effects of local climate on the biosphere productivity and the characteristics of human potential exposure groups; and

[4] The structural integrity of an engineered structure includes its capacity to withstand a given intensity of ground movement. At any location, seismic intensity will vary according to local geological factors as well as the distance away from the epicentre of an earthquake. There are several, broadly similar seismic intensity scales in use around the world; the European Macroseismic Scale (EMS) (see http://www.quakes.bgs.ac.uk/hazard/ems1.htm) runs from Level 1 (not felt) to Level 12 (completely devastating). Level 10 corresponds to seismic intensities in which many ordinary buildings would be expected to collapse.

- potential changes in the position of the lake and other surface hydrological features relative to the repository as a result of changes in precipitation and global ice sheet growth, as well as possible isostatic changes (depression and uplift).

Thus far, the possible evolution of the natural environment in the vicinity of the site in response to potential changes in climate has not been considered in detail. However, a generic analysis has been made (in the context of the Canadian Deep Geologic Repository Technical Programme) of the extent of the Laurentide ice sheet associated with global glacial-interglacial cycling, and its possible mechanical, thermal and hydrological effects (Peltier, 2002). The predictability of continuing cyclic glaciation of the North American continent is identified as a key uncertainty in relation to the definition of scenarios for long-term safety assessment of geological repositories.

Reports by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 1996; IPCC, 2001) have noted that the balance of evidence suggests that there is a discernible human influence on global changes in climate during the recent past, and that such changes will continue into the future. This global climate change has been linked to a range of other environmental changes over the last 100 years, including observed increases in global mean sea level as well as reduced volumes of sea ice, snow cover and land area covered by glaciers. Taking account of these considerations, alongside long-term patterns of glacial-interglacial cycling, the following simple description of climate evolution is suggested:

- global warming as a result of anthropogenic greenhouse gases over the next few thousand years, giving rise to local changes in seasonal temperature and precipitation;
- an extended warm interglacial period with elevated temperature and global sea levels;
- eventually cooling to present day and colder climate conditions, over a period of some tens of thousands of years accompanied by falling global sea level, and local changes in seasonal temperature and precipitation; and
- further cooling, ultimately encompassing possible glacial conditions associated with growth of the Laurentide ice sheet.

It is recognised that there are substantial uncertainties in the pattern of climate evolution, but it is possible to envisage a situation in which a warmer global climate persists for several thousand years, but that natural drivers responsible for glacial-interglacial cycling eventually reassert their influence to give rise to global cooling and associated periglacial conditions, followed by ice sheet cover in southern Ontario, on a period of several tens to a hundred thousand years.

C.3.4 FUTURE HUMAN ACTIONS

The potential for future human actions to compromise the isolation capacity of a permanent repository is relevant to demonstrating that a repository site is appropriately located, and some indication of the possible likelihood of disruption can be gained from consideration of the resource and development potential of the site itself and its immediate surroundings (IAEA, 1999). By contrast with the approach taken for natural events and processes, however, the ICRP considers that "*it is not appropriate to include the probabilities of* future human actions *in a quantitative performance assessment that is to be compared with dose or risk constraints*" (ICRP, 2000). Since there can be no scientific basis for forecasting the precise nature, or probability, of future human actions, it is not appropriate to incorporate such probabilities in a quantitative estimate of radiological impact. ICRP (2000) therefore proposes that the significance of conditional doses, determined for stylised exposure situations associated with plausible future human actions that might disrupt the repository system, should be interpreted with reference to radiological protection criteria applied to intervention situations. Such comparisons can then, in turn, be used in support of judgements within the safety assessment regarding the extent to which appropriate action has been taken in the design of the repository to minimise either the likelihood of intrusion or to limit its consequences.

EFEPs identified in the ISAM FEP list (IAEA, 2002) as relating to possible human involvement in future changes to the repository system environment include a variety of factors than can be summarised under the following list, relating to the sequence of stages involved in any future site development:

- define potential site use;
- explore capability of the site;
- develop site;
- utilise development; and
- terminate development.

From the perspective of scenario development, the key considerations in evaluating the potential for inadvertent disturbance of the permanent repository are:

- the motivation for inadvertent disturbance of the repository system (site development, exploitation of natural resources, possible research interests or requirements to exploit subsurface volumes); and
- factors that might deter such actions (administrative and planning controls, possible detection of the hazards, retention of information – through maps, markers, archives or 'folk' memory).

There is a further group of EFEPs that relate to events (such as explosions and crashes) that are potentially capable of disturbing the site and are associated with inadvertent human actions, but are not dependent on site development having occurred. More detailed evaluation of the types of events that would be of principal concern in terms of their potential threats to the integrity of the repository system (and their likelihood) would need to be undertaken as part of a comprehensive analysis. For the purposes of this preliminary assessment, it is assumed that the likelihood of such inadvertent events is sufficiently low to allow their exclusion from the assessment.

C.4 CATEGORISATION OF EFEPS

The ISAM FEP list is not structured according to a strict hierarchy and each main class of FEPs within the list contains a range of phenomena of different types, representing different levels of detail. For example, the EFEP relating to 'Erosion and sedimentation processes' can be disaggregated into separate components relating to spatially extensive denudation processes, more localised erosion, and accretion processes. EFEPs that are carried forward from the preliminary identification therefore need to be considered at a more detailed level in order to assess the potential importance of their individual components to the development of representative scenarios.

It is convenient, at an early stage in the scenario development procedure, to highlight the conceptual difference between 'continuous' and 'intermittent' drivers of change. Gradual change has a cumulative effect that may result in large-scale changes over a long period of time. When uncertainties in the magnitude, spatial scale and sequences of change are taken into account, the continuous EFEPs give rise to a set of futures corresponding to what can be considered the projected natural evolution of the system environment. Exploration of these uncertainties and their implications for the radiological safety performance of the repository system provides a central theme to the analysis undertaken within the safety assessment.

In addition, it is appropriate to explore a range of complementary scenarios, defined by superimposing the effects of EFEPs associated with intermittent events (including future human actions and some major natural events) that are capable of affecting significantly the safety performance of the repository. Projections of the future evolution of the permanent repository and its environment can therefore be thought of as the combination of a gradual sequence of change punctuated by random events.

Scenario descriptions are then developed through an understanding of both continuous and intermittent processes of environmental change and their impact on the repository system. Relevant interactions between the identified EFEPs need to be considered, so that assessment scenarios can be shown to take comprehensive account of all potentially relevant factors responsible for possible sequences of change. A generalised hierarchical decomposition of the EFEPs, such as that illustrated in Figure 39, is helpful in guiding the description of change.

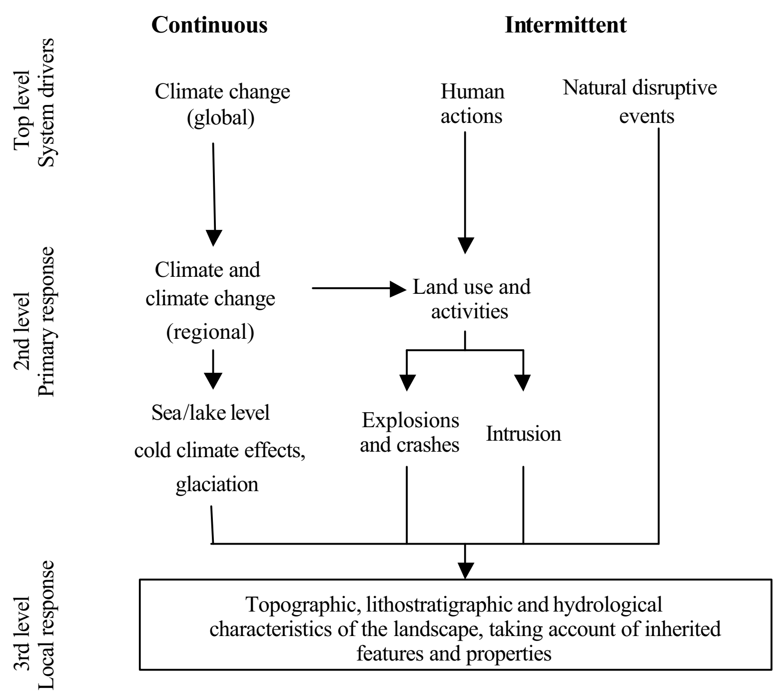

Figure 39: Generalised Hierarchical Representation of Dependencies in the EFEPs

Within this decomposition, it is possible to distinguish three main categories of EFEPs.

- Primary, generic drivers of environmental change (identified as System drivers in Figure 39), including factors such as global climate change, natural disruptive events and social and institutional developments affecting human communities, which operate at the supra-regional, or global, scale and are broadly independent of one another.
- Phenomena operating at a regional scale (Primary response in Figure 39), including factors such as regional climate change and land use.
- Phenomena operating at the scale of the repository system's response to the external system drivers (Local response in Figure 39), including factors such as erosion and human intrusion.

Hence, at the core of the overall assessment, forming the basis for the most detailed exploration of uncertainties associated with models of the safety performance of the repository system, is a scenario that is representative of the projected likely evolution of the permanent repository and its surrounding environment, taking into account continuous change prompted by factors that are both internal and external to the repository system. Such changes are primarily associated with the degradation of the properties of near field, and evolution of the surrounding environment, caused by climate change and associated changes in human habits and land use. This is referred to as the '*central projection*' or '*reference*' scenario. It considers the gradual release of radionuclides from the repository and their migration and accumulation in the environment, in liquid, gaseous and (where appropriate) solid forms. In a comprehensive safety assessment (see, for example, BNFL (2002)), a number of variants of the continuous evolution scenario may need to be considered in order to ensure that the assessment caters for uncertainties in projections of continuous change over the timescale of the assessment.

Potential disruptive events, external to the system, that could occur as a result of intermittent (rather than continuous) sources of change can also be identified. These may be naturally occurring or may be associated with human actions (i.e., disturbance of the repository system linked to future exploitation of the site and/or the surrounding environment).

C.5 REFERENCE SCENARIO

The continuous evolution of the site over a period of more than 10,000 years will be influenced by the evolution of engineered systems and climate evolution. The evolution of engineered systems has been considered in the recent Quintessa study for OPG (Penfold et al., 2002), which investigated possible improvements to near-field modelling and concluded that, over long timescales, the maintenance of high pH cementitious conditions is the dominant consideration affecting safety performance in relation to long-lived radionuclides, with physical aspects of the engineering being more important only in preventing the release of shorter-lived radionuclides in the first few thousand years.

A summary of one possible description of continuous evolution in different timeframes in the post-closure period is provided in Table 21. Possible variants to this description would need to be considered as part of the development of a formal safety case, even if they were not investigated in detail through quantitative calculations, in order to reflect adequate consideration of uncertainties in the timing and magnitude of change. However, the intention within this preliminary safety assessment is to keep the number of calculation cases to a minimum, consistent with the aim of focusing attention on those aspects of system performance that are judged critical to the underlying assessment purpose and context. The evolution pathway described in Table 21 is therefore adopted as the basis for defining the Reference Scenario.

It is notable that many of the most important changes associated with physical degradation of the repository system itself (including the degradation of barriers) are projected to be complete within a timeframe (i.e., the first few thousand years) over which gradual changes in the surrounding environment can be effectively ignored. For the purposes of this preliminary safety assessment, which is focused on a preliminary assessment of the Bruce Site and comparison of alternative permanent repository concepts, a simplified version of the sequence in Table 21 can therefore be defined, in which EFEPs and system dynamics related to long-term environmental change (over tens of thousands of years) are not explicitly represented.

Table 21: Potential Evolution of the Repository System

Timeframe (post closure)	Changes in the System
< 300 y	Institutional controls and monitoring. Human society 'predictable' Some effects of human-induced climate change.
300 – 1000 y	Physical degradation of the near field (CAGCV and DRCV). Possible significant changes in human society Effects of human-induced climate change –possible changes in temperature and precipitation, with associated changes to human habits
1000 – 5000 y	Physical degradation complete Beginning of chemical degradation of near field (CAGCV) Human society cannot be readily anticipated Effects of human-induced climate change – possible changes in temperature and precipitation, with associated changes to human habits
5000 – 10,000 y	Continued chemical degradation (CAGCV) Human society cannot be readily anticipated Continued climate conditions warmer than present.
10,000 – 20,000 y	Chemical degradation of the repository becoming complete (CAGCV) Human society cannot be readily anticipated Potential for climate to return to conditions similar to the present day.
20,000 – 100,000 y	Beginning of chemical degradation of the repository (DRCV) Human society cannot be readily anticipated Potential for site to experience periglacial conditions followed by ice sheet cover.
> 100,000 y	Chemical degradation of the repository complete (DRCV) Human society cannot be readily anticipated Continuing climate cycling

It is acknowledged that such a simplified approach requires justification for why anticipated gradual changes to the system environment have been excluded from the analysis. In this respect the following key points can be noted.

- Whilst the possibility cannot be discounted that natural changes in global climate may lead to glaciation of southern Ontario on a period of several tens of thousands of years, projections undertaken on behalf of OPG (Peltier, 2002) indicate that the site would be ice free for more than 66,000 years in the future. No significant disturbance of the repository by ice sheet effects is therefore anticipated for many tens of thousands of years. If the potential long-term implications of anthropogenic greenhouse gases are taken into account, there is a possibility that glaciation could be delayed even further.

- Cold climate, periglacial conditions are expected to persist for some 10,000 years prior to the arrival of the ice sheet. Nevertheless, for much of the period prior to the next glaciation, it is anticipated that climate conditions would permit some form of agricultural activity to be undertaken in the vicinity of the permanent repository.

- In translating the effects of possible future climate change to descriptions of the local environment, it is typically assumed that human exposure group habits and biosphere conditions should be initially based on present day agricultural land use patterns in the location of interest. Assuming an agricultural biosphere for the entire period represented in the safety assessment is therefore judged to be consistent with the projection of climate evolution presented above, for around 50,000 years after present. It is generally considered that agricultural activity would give rise to higher exposures to individuals living in the vicinity of the repository site than other, less intensive, possible land uses (e.g., recreational, or semi-natural environments).

- An assumption of continuing agricultural land use under present-day conditions is not realistic, but should provide a reasonable description of potential exposures associated with releases from the permanent repository via groundwater or gas transport pathways. Whereas productivity would vary according to seasonal temperatures and precipitation, such effects could be considered, if necessary, via parameter variations in the assessment model for the biosphere.

- The potential implications of climate change on the near field and geosphere over the next 50,000 years can also be largely accounted for through parameter variability, particularly in relation to the balance between evapotranspiration and infiltration, and their joint effects on hydrology and hydrogeology.

For present purposes, the Reference Scenario adopted for the safety assessment is therefore one in which change to the repository system (near field, geosphere and biosphere) occurs solely as a result of the inherent, intrinsic dynamics of the repository system itself (e.g., degradation of wastes and engineered structures, etc.). This is judged to provide a reasonable basis for a preliminary appraisal of safety performance – particularly in relation to undertaking a comparative assessment of alternative permanent repository concepts – for an assessment period of up to 50,000 years. In order to develop a formal safety case, it would be necessary to give more systematic consideration to the need (or not) to represent explicitly within the assessment the implications of projected changes in the repository system and its environment associated with continuous environmental evolution. In addition to the longer-term effects of climate change (including, ultimately, possible periglacial conditions, followed by glaciation), it would be reasonable to consider the extent to which changes in regional climate might have influences on the groundwater flow system and lake levels, and the potential implications of such changes for the assessment of safety performance.

C.6 DISRUPTIVE EVENT SCENARIOS

Intermittent disruptive events can generally be considered to have a finite (and typically small) likelihood of occurring within any given time period during the course of continuous evolution of the repository system and its environment. There are two main sub-classes of these possible disruptive events (Figure 39).

- Natural events – for which there may be some statistical basis or evidence that can be used to make a quantitative estimate of the likelihood of occurrence. An example of such an event is a major seismic event, for which historic records coupled with geological information can be used to estimate the likelihood of occurrence within a given time period.

- Human-induced events – the behaviour of humans is highly unpredictable, even over relatively short timescales, as society evolves. Consequently, although present-day human activities encompass a range of situations in which human actions can be envisaged as leading to disturbance of the wastes or disruption of barriers to environmental release, it can be very difficult to defend any quantitative estimate of the likelihood of occurrence of this class of disruptive situation.

Based on the outline analysis presented in Appendix C.3 above, it is proposed that no formal calculations should be undertaken for the preliminary safety assessment to address the possible implications of natural disruptive events. It is assumed that, for a development of a formal safety case, it will be necessary to demonstrate that the potential for disruption remains very low throughout the assessment period, with only very limited quantitative consideration being given to such events as part of the overall evaluation of potential radiological impacts.

The specific situations that are most appropriate to consider in relation to human-induced events are to some extent influenced by the site and the pattern of human activities in the region. However, the relative likelihood of different types of intrusion is uncertain and it is therefore (consistent with guidance from ICRP (2000)) appropriate to undertake calculations that are somewhat 'stylised'. Although future human actions and some natural disruptive events are potentially capable of causing significant changes to properties of the geosphere and biosphere, the most important risks for analysis within the safety assessment are judged to be those that involve direct disruption of the wastes and engineered system. Moreover, several of the effects of human actions on geosphere and biosphere characteristics (e.g., those arising from changes in land use) are more appropriately addressed as sensitivity analyses in evaluation of the Reference Scenario (Section 4.2) and in the subsequent parameterisation of assessment models for the biosphere, rather than as separate scenario variants in their own right.

Analysis of the ways in which disturbances associated with future human actions might arise, enabling them to be characterised as stylised scenario variants, involves consideration of the various factors associated with possible future development of the site. Representative exposure situations can be identified and corresponding judgements made regarding their perceived likelihood, enabling identification of features associated with the permanent repository (location, waste form, closure engineering, post-closure management period, etc.) that influence the likelihood of disturbances of different magnitudes. This helps to guide the subsequent interpretation of the results of the stylised exposure calculations.

For this preliminary safety assessment, two main categories of disruption are taken into consideration for the human intrusion disruptive event scenario.

- Small: Representative of the type of disturbance that might be caused by the drilling of boreholes during site investigation. Shallow geotechnical boreholes would typically be drilled to prove bedrock, or to a depth of about 10 m to characterise the geotechnical properties of superficial strata. Other boreholes for pumping tests and/or small-scale water supply could extend up to 100 m into bedrock. The volume of samples removed from the site during borehole investigations would typically be a maximum of a few m^3.

- Large: Representative of large-scale excavations associated with major construction projects or, potentially, archaeological investigations at the site. A wide variety of large-scale excavations could be undertaken which can reasonably be taken to extend to depths of some 4 to 6 m, with excavated volumes of around 250 to 15,000 m^3.

If a case can be made that a large excavation is possible in the general vicinity of the permanent repository site, this will be representative of the most significant situations that could occur for the CAGCV-S and CAGCV-T. For the DRCV-S and DRCV-L, the depth of the permanent repository is likely to preclude such situations and it would be appropriate to consider only possible disturbance associated with borehole intrusion into the wastes.

For each of these modes of intrusion, the following main exposure situations can be taken into account.

Intruder exposure: describing direct exposure of individuals to essentially undiluted waste materials, for example in relation to involvement in the activity that gave rise to the intrusion or subsequent actions linked to the event, such as site investigation or collection and examination of samples.

Site occupant exposure: describing exposures of individuals with no direct connection to the intrusion event, but who may nevertheless encounter waste materials incorporated into local surface environmental media as a result of disturbance of the repository (e.g., as a result of occupation of the site in later years).

In each case, consistent with the overall stylised approach to assessment, individual exposures conditional on occurrence of intrusion should be assessed by considering a representative situation that leads to potentially high doses, and exposes an individual to a large number of exposure pathways. For example, in relation to site occupant exposure, an appropriate hypothetical exposure situation is that of an individual who farms on land that has become directly contaminated by wastes exhumed from the repository as a result of the intrusion event.

Although no specific calculations are planned to estimate potential radiological impacts associated with natural disruptive events, it is assumed that interest in the possible radiological consequences of disruption to the permanent repository caused by such events can be effectively addressed on the basis of calculations undertaken for future human actions. In a comprehensive safety case (which may be required at later stage of repository development), it is expected that the emphasis of the analysis for natural disruptive events will be the estimated likelihood of disruption, rather than the radiological implications.

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APPENDIX D: DEVELOPMENT OF THE GENERAL CONCEPTUAL MODEL

CONTENTS

The first stage of the model development approach used in the current study, and shown in Figure 15, is the identification of the general conceptual model for each scenario. This process is described and applied below.

D.1 IDENTIFICATION OF KEY FEATURES, PROCESSES AND INTERNAL EVENTS

A general conceptual model is developed for each defined scenario, recognising that each description of the future evolution of the system has to address different issues; it is not appropriate to address all scenarios in a single general conceptual model. Each general conceptual model is developed principally using the system description and the description of the relevant scenario. These are used to identify the key features, processes and internal events that need to be considered.

D.1.1 FEATURES

The description of the present day system presented in Section 3 is the starting point for the identification of features. Different features can be identified on the basis of different physical characteristics, e.g., soil or rock, groundwater or lake water. The characteristics of most interest are those that are related to the transport processes for radionuclides, to, from or within the features. Therefore some features may be distinguished because of the different processes that apply to them (for example, there may be two identical areas of soil, one subject to contamination by capillary rise and the other not, because of the relative position of the water table).

An important simplification is to ‘average’ the properties of some media so that they can be represented with a single feature – it is often necessary to generalise the description of the physical world in order to render manageable the problem to be addressed in the current preliminary safety assessment. One of the most effective ways to do this is to disregard spatial heterogeneities where they are at a smaller scale than is of interest. For example, if a single exposed person would be equally likely to be exposed to any region of soil in a minimum area A, it might not be necessary to consider separately small areas of soil within A.

Because the identification of features partly depends on the processes that could be associated with them, it is difficult to identify features without giving some consideration to processes; however, they have been documented separately from features (see Appendix D.1.2).

To summarise, the approach to identifying features is to identify them on the basis of:
- their physical characteristics;
- the influence of different transport mechanisms; and
- the spatial averaging implied by the required end points.

D.1.2 PROCESSES

Processes are mechanisms that act continuously over time, or change only slowly (e.g., stream water flow). They influence the transport of radionuclides between the features, and the distribution of radionuclides within features.

All features can consist of solid material, water and gas (or a combination), and so transport processes can occur via any of these forms. For example, radionuclides can be transported in solution with groundwater through rock, contaminated rock can be eroded, and gaseous radionuclides can travel through pores. A range of relevant transport processes is illustrated in Table 22. Processes that can affect the distribution of radionuclides between phases also need to be considered, and some examples are illustrated in Table 23.

Table 22: Examples of Transport Processes in Various Features

	Movement of Gas	Movement of Liquid	Movement of Solid
Atmosphere	Dispersion	Aerosol dispersion	Dust dispersion
Water Bodies	Buoyancy	Bulk water movement	Sedimentation
Unsaturated Soil/Rock	Diffusion	Capillary Rise	Erosion
Saturated Soil/Rock	Diffusion	Advection	Colloid Transport

Table 23: Examples of Processes for the Exchange of Radionuclides Between Phases in Features

From To	Gas	Liquid	Solid
Gas		Condensation	-
Liquid	Volatilisation		Precipitation
Solid	Decay to Gaseous Progeny	Dissolution	

Some transport processes result in very slow radionuclide migration (e.g., erosion of surface soils) with respect to the minimum timescales of interest in the assessment, whereas others can result in rapid radionuclide transport in the given feature (e.g., resuspension of dust). Slow transfers generally need to be represented with a dynamic model, whereas rapid transfers can be approximated by assuming a steady-state equilibrium between the media involved. The biosphere is typically a part of the model when many of the transfer processes can be modelled with equilibrium transfer factors (e.g., IAEA (1994)), whereas the processes associated with the near field and geosphere generally require dynamic representation. Because of the consequences for the mathematical model, it is important to distinguish the situations.

Finally, just as with features, it is important to take account of the spatial averaging that can be applied when identifying processes and internal events of interest. For any given process, natural variability can be expected in terms of the rate at which it applies. The variability should be considered against the natural ‘averaging’ effects of the timescales under consideration (e.g., daily or seasonal variation of rainfall is unimportant, as its influence is mainly of interest over the period of years) and the end points of interest (e.g., if a human exposed group is considered that farms land, then they can reasonably be assumed to spend some time on all parts of the soil).

To summarise, the approach to identifying processes is to identify them on the basis of:
- the potential for migration in solid, liquid or gas in the features in which the radionuclides may be present;
- the potential for the radionuclides to change state in the features in which they may be present;
- the timescales over which the mechanisms operate; and
- the spatial averaging implied by the required end points and timescales.

D.1.3 CONCEPTUAL MODEL DESCRIPTION

The formalised description of conceptual models can be accomplished in a variety of ways. In this study, a simple Process Influence Diagram (PID) approach has been chosen. This is based on that described by Chapman et al. (1995), but with the simplification that the only processes illustrated are radionuclide transport mechanisms. Processes that are internal to features are discussed in the accompanying descriptions. For example, Figure 40 below illustrates some sediment interactions with lake water. Suspended sediment may deposit out, and bed sediment may be resuspended. The bed sediment, over time, may also be buried by freshly deposited sediment. Both lake water and sediment may also move downstream.

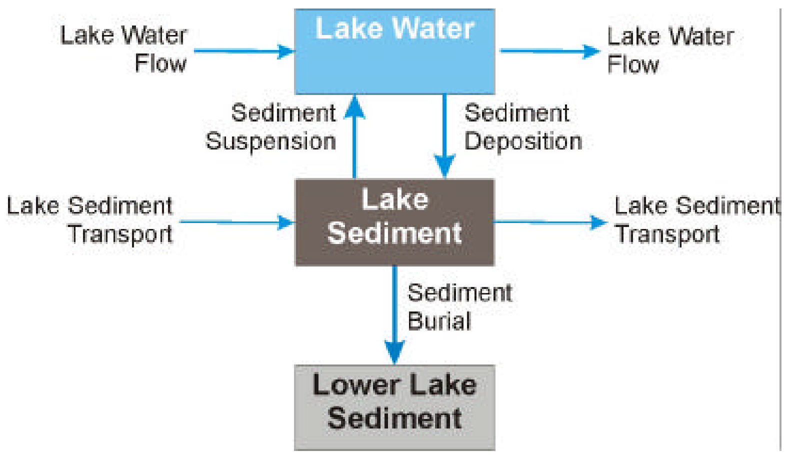


Figure 40: Illustration of a Simplified Process Influence Diagram for Lake Water and Sediment

D.2 REFERENCE SCENARIO

D.2.1 KEY FEATURES OF THE SCENARIO

The key features of the Reference Scenario are described in Section 4.2 and Appendix C.5.

D.2.2 IDENTIFICATION OF FEATURES USING SYSTEM DESCRIPTION INFORMATION

The system description (Section 3) has been used to identify key features for consideration (Table 24), based on the approach described in Appendix D.1. The key features are described and a description of the basis for their identification given below.

Cap: The cap is described in Golder Associates (1998 and 2003), and is only present over the CAGCV concepts. Its purpose is to limit rainwater infiltration through the repository. It contains alternating permeable and impermeable layers of natural and man-made material. Its performance can change with time due to structural degradation and erosion. Radionuclides might become associated with the cap via changes in the water table inside and outside the repository, and by upwards migration of radionuclides. The performance of the cap is a potentially important source of uncertainty to be considered in the definition of calculation cases, as the wastes could become saturated and drain directly into surface soils (‘bathtubbing’) if its hydraulic conductivity increases above that of the underlying till layers for the CAGCV-T concept.

Table 24: Summary of Key Features for the Reference Scenario

Near-field Features	Geosphere Features	Biosphere Features
Cap Waste Backfill Engineered Structures	Overburden sediments (Till and Sand) Devonian and Silurian dolostones Lower Silurian and Upper Ordovician Shale Middle Ordovician Limestone	Well Water Surface Water (stream and wetland) Surface Water (stream and wetland) Sediment Lakeshore Sediment Lake Water Lake Sediment Soil Biota Houses and Buildings Atmosphere

Waste: Three main waste types (ashes, compacted waste, and non-processible waste) are described by Leung and Krochmalnek (2000). These need to be represented for all CAGCV and DRCV concepts. It is appropriate to represent the individual waste types, owing to their different radionuclide inventory and physical/chemical characteristics. The wastes can be either ungrouted or grouted using cement. Waste containers need not be represented explicitly, since radionuclides are not assumed to accumulate to any significant degree on the substrate. Their main function is to prevent water contact with the waste form for some period of time.

Backfill: The backfill material acts to fill voids in the permanent repository. It may or may not be present; if present, a cement-based material would be used (although other options, such as gravel or a sand-bentonite mixture, are possible but not considered in the current study). This can accumulate radionuclides and also potentially provides a low-permeability barrier to water flow. As it may be present either upstream or downstream of the source of radionuclides, the feature should be sub-divided into an upstream and downstream component.

Engineered Structures: The engineered structures for the CAGCV concepts include concrete walls, floors and roofs (Golder Associates, 2003). In the case of the DRCV concepts, the engineered structures only consist of a concrete floor and a concrete plug at the entrance to each vault (Golder Associates, 2003). Depending on the orientation of water flow through the repository, radionuclides can migrate through the floor of the vault (for downwards vertical flow) or the wall of the vault (for horizontal flow), although vertical upward flow might be possible under certain conditions such as significant capillary rise conditions. As with the backfill, it is relevant to consider engineered structures that are upstream or downstream of the source of radionuclides.

Overburden Sediments (Till and Sand): The overburden sediments at the site consist of a complex sequence of surface sands and gravels from former lakeshore beach deposits overlying clayey-silt till with lenses of sand of variable thickness and lateral extent (Golder Associates, 2003). The dominant water flow direction in the sand is downward into the underlying Shallow Bedrock Groundwater System. The dominant water flow direction in the till is also downward (into the underlying Shallow Bedrock Groundwater System), although the till's hydraulic conductivity is lower than the sands. In most circumstances, this is likely to be an advantageous property. However, under some circumstances, if the rate of flow through the permanent repository is greater than the conductivity of the till, contaminated water could be diverted to the surface by bathtubbing (this process is described later).

Devonian and Silurian Dolostones: The Devonian and Silurian carbonate rich rocks of the Amherstburg, Bois Blanc and Bass Island Formations and the top of the Salina Formation form the Shallow Bedrock Groundwater System (Golder Associates, 2003). These comprise hard, lightly fractured dolostones and limestones. They include localised highly fractured and vuggy zones, suggesting that the hydraulic conductivity of the unit is high. These rocks form the main aquifer below the site and are therefore important for radionuclide transport in groundwater that has percolated through the glacial deposits. They can be considered to have relatively homogeneous properties for safety assessment purposes. It is assumed that near-surface flows in the dolostones is reasonably confined to the upper fractured region. The rocks come close to the surface by the lakeshore, and so groundwater discharges could be either to the shore or into the lake.

Lower Silurian and Upper Ordovician Shale: The DRCV-S repository is located 460 m below the site in the Upper Ordovician shale (Queenston Formation) underlying the Lower Silurian dolostones that form the Intermediate Bedrock Groundwater System (Golder Associates, 2003). The Upper Ordovician shale has a very low groundwater circulation, and radionuclide migration is likely to be diffusive to the overlying Lower Silurian dolostones, in which groundwater eventually discharges to Lake Huron 10 to 20 kilometres off-shore.

Middle Ordovician Limestone: The DRCV-L repository is located 640 m below the site in Middle Ordovician limestone (Lindsay Formation) underlying the Upper Ordovician shale and the Lower Silurian dolostones (Golder Associates, 2003). The Middle Ordovician limestone has a very low groundwater circulation, and radionuclide migration is likely to be diffusive through the Upper Ordovician shale to the overlying Lower Silurian dolostones, in which groundwater eventually discharges to Lake Huron 10 to 20 kilometres off-shore.

Well Water: Boreholes, of which there are many in the region, extract water from the Shallow Bedrock Groundwater System for use as drinking water and for farming and industry. Typically, they are sunk into the Amherstburg Formation. It is considered unlikely that deeper wells would be sunk into the Silurian dolostones of the Intermediate Bedrock Groundwater System due to the highly mineralised nature of the water (Golder Associates, 2003).

Surface Water: Two surface water bodies are of potential interest – the Railway Ditch directly to the north of the WWMF site and ‘Stream C’ into which the Railway Ditch discharges (OPG, 2000). In addition, due to the low hydraulic conductivity of the tills that lie very close to the surface, there are numerous areas of wetland around the Bruce Site. Notable locations include the wetland on the eastern edge of the WWMF, through which the Railway Ditch travels, and the Baie du Dore wetland into which Stream C drains, at the edge of the lake to the northeast of the Bruce Site (OPG, 2000). Water from these surface water bodies could be used for domestic and agricultural purposes.

Surface Water Sediment: Water body sediment can interact with the associated water and preferentially accumulate certain radionuclides (e.g., actinides). Sediment characteristics and concentrations may vary; however, it is likely to be appropriate to consider them to be relatively homogeneous, but distinguish between the sediment locations (e.g., those associated with the Railway Ditch or Stream C).

Lakeshore sediment: The distinction between the sandy lakeshore sediment and farmed soils is relevant to consider, because the latter is better able to support vegetation. There is also the possibility of groundwater discharge from the Shallow Bedrock Groundwater System to the lakeshore sediment.

Lake Water: Lake water is generally uniform in characteristics in the vicinity of the Bruce Site, but it can vary over the whole of Lake Huron. The large volume of the lake means that it is necessary to sub-divide the feature for modelling purposes. A zone close to the shore is important, as it can represent the initial mixing of contaminated groundwater discharged from the Shallow Bedrock Groundwater System with lake water, and it may also be used for drinking water or fishing. A zone further off-shore is important for contaminated groundwater discharged from the Intermediate Bedrock Groundwater System. Biota living in the lake may also be consumed and therefore result in exposure from both discharges.

Lake Sediment: Like surface water sediment, lake sediment is likely to preferentially accumulate certain radionuclides. Lake sediment interacts with radionuclides in lake water and so it is necessary to ensure that each lake water compartment has an associated lake sediment compartment. Over time, sediment may accumulate in some locations, resulting in the burial of deposited sediments and associated radionuclides.

Soils: Radionuclides can become associated with soil by a variety of transport mechanisms such as spray irrigation from a contaminated well, surface water or lake water. Soil is the medium often responsible for transport of radionuclides to food and itself may expose individuals to radionuclides. Radionuclides in soil may be sorbed onto soil material or be present in pore water. The precise characteristics of soil might vary around the area of interest, but these can be addressed with spatial discretisation. In general, the soils are thin and underlain by a thin sand/gravel layer overlying the till, the soil being progressively more sandy towards the lakeshore (OPG, 2000).

Biota: The local environment is characterised by a variety of biota as described in OPG (2000). The lake is a source of fish for humans, and although there is no information on the fishing of local streams, this could potentially occur in the future, providing a pathway for contaminated foodstuffs to humans. Both agricultural and natural terrestrial environments are reported in OPG (2000). Human cultivated land is of greatest interest, as it offers the possibility for localised use of soil that could become contaminated. The soil in the region around the Bruce Site is reported to be fertile, and Bruce County is a leading producer of cattle (along with other animals such as sheep, pigs and chickens). It is also noted for production of barley, oats and canola. For this reason, animals and plants associated with natural environments are considered to be of less interest than those associated with farmed land.

Houses and Buildings: Enclosed environments offer the potential for the accumulation of radioactive gases (particularly Rn-222), and are consequently of interest. The buildings around the site are presently industrial; however, there are a number of residential communities nearby. It is possible to envisage a building being constructed on or near a permanent repository at some point in the future, after institutional control of the repository site is no longer in place.

Atmosphere: The general surface atmosphere does not provide a feature in which radionuclides can accumulate to high concentrations, owing to its dispersive effects. However, humans, animals and plants interact with the atmosphere, and therefore it offers an alternative pathway of interest from soil and water to biota and directly to humans.

D.2.3 IDENTIFICATION OF PROCESSES USING SYSTEM DESCRIPTION AND SCENARIO INFORMATION

The processes of interest have been identified taking into account the system description information (see Section 3). As has been noted in Appendix D.1.2, there are three broad categories of processes and internal events that are of interest. The first group includes all those processes that affect the distribution of radionuclides in different phases (solid, liquid, gas) within a given medium. The key processes are listed below.

Sorption: Sorption and desorption can be described using an empirical relationship that defines the distribution of radionuclides between solid and liquid in a medium that contains both. It is generally based on observations and therefore covers a range of detailed physical and chemical processes that act to retard radionuclides. Consideration of sorption enables the quantity of radionuclides available for transport by solid or liquid flow mechanisms to be determined. Sorption data are usually derived for equilibrium conditions and in certain situations (e.g., the very rapid flow in rock fractures) equilibrium sorption might not be established.

Decay: All radionuclides decay and some produce radioactive progeny that need to be considered. For the purposes of this preliminary safety assessment, it is assumed that all progeny with a half-life of greater than 25 days are explicitly modelled. Those with a half-life of less than or equal to 25 days are assumed to be in secular equilibrium with the parent.

Solubility: The sorption process is considered to be applicable when there are low concentrations of radionuclides. At higher concentrations, solubility limits the amount of an element in solution (given the chemical composition of the water, the chemical form of the element and the concentration of organics) and can therefore control their dissolution into the liquid phase. Because it is only relevant with relatively high concentrations of radionuclides, solubility is likely to require consideration in the near field only.

Chemical effects: Chemical effects (such as changes in pH and Eh conditions) in a medium can influence the chemical form and therefore the partitioning of radionuclides between phases. Whilst the chemistry is unlikely to affect the bulk velocity of solids, liquids or gases, it can affect the distribution of radionuclides. The consequences may therefore be manifest primarily in terms of the degree of sorption exhibited by a particular element. This issue is principally of interest where there is scope for chemical conditions to change, such as may occur in the near field. Near-field degradation processes are discussed further below.

Gas Generation: Gas generation in the near field may occur by a variety of mechanisms, e.g., the oxidation of metals or radioactive decay. Collectively, they can act to generate radionuclides in a gaseous phase from matter in the solid or liquid phase. Gas generation could also affect a repository system that is well sealed, as gas pressure may build up and cause engineered structures to crack and fail. However, this is considered to be unlikely for the design concepts described in Golder Associates (1998 and 2003) which are not considered to be sufficiently tight to cause a build-up of gas pressure sufficient to cause failure of the engineered structures.

Other processes that have been identified as being of interest can be categorised as being associated with radionuclide transport between features. These processes therefore generally describe bulk movements of water, solid material or gas between various media (porous solids or liquids, principally). Many of these processes are fundamentally advective, diffusive or dispersive processes.

Surface Water Transport: The characteristics of the overburden sediments appear to be such that it is likely that substantial quantities of surface water flow horizontally either on the ground surface or in the shallow layer of loose sand and gravel deposits overlying the till. Surface water is principally associated with rainfall and hence uncontaminated by radionuclides from the permanent repository (although there may be irrigation using potentially contaminated water). However, it can provide a mechanism for transporting radionuclides in surface soils into other media, and therefore is an important consideration. Periodic flooding of terrestrial water courses can result in significant volumes of water infiltrating soil and provides a mechanism for the transport of radionuclides in the surface water to the soil. Bulk water flows in the terrestrial environment are important mechanisms that redistribute radionuclides in the biosphere. These are driven by the local and regional hydrology. Bulk water flows in the lake environment are driven by lake currents.

Infiltration: The advective flow of water infiltrating from the surface is necessary to consider in all unsaturated media, and results in vertically downward advective transport of radionuclides in solution. Advection is affected by the characteristics of the medium through which it flows, including its capacity for sorption. As infiltration is principally of interest for overburden sediments, it is considered appropriate to represent the process in terms of transport through a porous medium.

Upward Advective Transport: In some circumstances, vertical advective flow can be directed upwards in unsaturated media, leading to some transport of radionuclides in the direction opposite to infiltration transport. This general process can be driven by a variety of mechanisms - chiefly the variation of the water table location over seasons, capillary rise during dry periods, and inhomogeneities in media that can lead to the deflection of water in an upwards direction due to contrasts in hydraulic conductivity. The net result of these various processes can generally be characterised by assuming some net upwards flow, and the process can be an important pathway for contaminated groundwater to be directed to surface soils from near surface permanent repositories.

Saturated Flow – Advection: Saturated flow can occur in a variety of features, some in which the flow is predominantly via the pores, some in which flow is predominantly via fractures and bedding planes. For transport predominantly via the pores, advective and dispersive transport will require consideration. If groundwater movement is very slow, such as in the Ordovician Shales, diffusive transport may be significant (see below). Saturated flow in porous media is most appropriate to consider for saturated overburden sediments, and may also be an adequate basis for representing transport in the Shallow and Intermediate Bedrock Groundwater Systems. The flow in fractures and conductive bedding planes is different in character to porous medium transport. For example, the influence of the bedding planes and fracture network is to constrain the flow direction to some degree. The characteristics of radionuclide sorption may differ, and processes such as matrix diffusion may be significant. Saturated flow in fractured media is most appropriate to consider for Shallow and Intermediate Bedrock Groundwater Systems, although it may be acceptable to approximate the transport of radionuclides with an equivalent porous medium approach.

Saturated Flow – Dispersion: The dispersion of a plume of contaminated water in a saturated medium is a result of the inhomogeneities in the medium, compared with the length over which transport is being observed. There are a variety of different paths available to the moving water, with the net result that over a defined pathlength, a distribution of water travel times may be observed. The process is important in influencing the time profile of radionuclides following transport in such a medium.

Diffusion: Diffusion processes are most significant when flow rates are low, and advection does not dominate the transport process. Radionuclides may then migrate according to the concentration gradient existing from one location to another. The transport process is potentially important in undegraded near-field materials and the Ordovician shale and limestone, where the groundwater flow rate is very low.

Colloidal Transport: Colloids are fine particles that can migrate in a fluid stream in porous or fractured materials, without being effectively filtered out. They provide a mechanism by which the transport of strongly sorbed elements can be transported more rapidly than in water alone.

Bioturbation: Radionuclides in solid material may be redistributed in soil by natural mixing processes. Bioturbation occurs in healthy soils and is associated with the movement of animals (e.g., worms) and plant roots in the surface layers of soil. It is consequently only relevant for the first metre or so of soil. There is no dominant direction of mixing (towards or away from the surface), so the general effect is to act to slowly equilibrate the concentrations of radionuclides in soil. Human induced mixing of the soil (e.g., by ploughing annually) also acts to mix surface layers of soil, altering the distribution of radionuclides deposited on its surface, or migrating upwards from below.

Resuspension and Sedimentation: Soil dust can be suspended into atmosphere and dispersed with the action of the wind on the soil surface. Suspended particles ultimately settle out as a result of gravitational effects (sedimentation). Resuspension and sedimentation of solid material can also occur in aquatic environments, as a result of the action of shear forces on sediments. Over a long period, the processes of resuspension and sedimentation can lead to net erosion of some surface features and the redistribution of contaminated soil or sediments over a wide area. This aspect of the movement of solid material is considered as the process of erosion (see below).

Erosion: Erosion is considered to include all mechanisms by which solid material is transported from one surface medium to another. The resuspension/sedimentation process described above results in erosion; however, erosion may also occur by the movement of solid material by surface water, or the ‘rolling’ of particles over surfaces, without suspension. Soil and other material can also be redistributed by the movement of animals. The process of erosion, therefore, is taken to represent the gradual movement of solid material from one location to another, as distinct from the temporary suspension of solid material in atmosphere or water, which is addressed by resuspension and sedimentation.

Water Abstraction: The natural surface and subsurface hydrology can be altered by the emplacement of a well into an aquifer of sufficient size. The abstracted water can then be used to supplement rainfall for agricultural purposes, and for domestic and industrial purposes. The process provides a rapid pathway for transporting potentially contaminated water in sub-surface systems to the surface. It could also alter significantly the local hydrology, e.g., by increasing the hydraulic gradient near a well due to its drawdown effects. Water obtained from surface water bodies and lakes can also be used in similar ways.

Uptake by Biota: Radionuclides in soil can be transferred to plants via uptake by roots, interception by leaves and/or direct contamination of plant surfaces (some portion of the radionuclides may also be subsequently removed, e.g., by washing). Animals can eat contaminated plants, soil and/or water.

Gaseous Transport: Corrosion and biological processes can generate bulk gas in wastes (i.e., not dissolved in any water present). Contaminated gas may escape via gas permeable regions in the cap, the exhalation rate driven by gas pressure and variations in atmospheric pressure and wind speed.

Ingestion of Contaminated Media: Humans can be envisaged to ingest a variety of contaminated media. Residents of the site could ingest contaminated animals and crops if contaminated soil were to be farmed. The soil itself could be ingested inadvertently. If drinking water were obtained from a well, surface water, or lake, this could also be contaminated.

Inhalation of Contaminated Media: Radionuclides may be present in the air that could be inhaled by a resident on the site. For example, contaminated soil can be suspended by the action of the wind and subsequently inhaled. It could also be inhaled if raised when ploughing soil. Gaseous radionuclides could also be inhaled if released from the permanent repository. In this case, the most significant exposure situation is likely to be associated with their accumulation and inhalation in indoor air.

External Irradiation by Contaminated Media: People in the proximity of contaminated media can be irradiated by them if no shielding is present. Most media of interest in this scenario are subject to contamination over a significant area, and so the exposure geometry should reflect this.

A final category of processes of interest is those that are associated with changes in the characteristics of the system over time. Changes that occur as a result of external factors, such as long-term climate change, are not considered in this preliminary safety assessment (see Section 2.6).

Physical Degradation of Man-made Structures: Repository structures are designed to limit water flow through the repository environment, as well as having other roles. However, over assessment timescales, the physical integrity of these man-made structures will not persist, and consequently the flow of water through these structures can change. This influences the characteristics of radionuclide retention in the repository. Other consequences of such a change can be to alter the surface water balance and introduce additional radionuclide transport pathways – for example, a 'short cut' pathway may be introduced for a surface permanent repository if the hydraulic conductivity of its barriers becomes greater than the hydraulic conductivity of underlying soil and rock (the Bathtubbing Calculation Case).

Chemical Degradation of Manmade Structures: Cementitious materials used in repository structures can play an important role in retarding radionuclide release, by causing water in the repository to become highly alkaline. However, over time the cement structures degrade and the constituents (alkali metal hydroxides, portlandite, and calcium silicate hydrate phases) dissolve and are removed, resulting in the return of the pH to conditions similar to groundwater. The enhanced radionuclide retention effects are then lost. Consequently, it is important to consider the duration and characteristics of the chemical regime that results from cementitious structures.

D.2.4 DESCRIPTION OF THE GENERAL CONCEPTUAL MODEL

The conceptual model for the Reference Scenario has been developed from the basic features, processes and internal events described above. These have been assembled to create a network of environmental media of interest, and interactions between them. Interactions about which there is some uncertainty as to their nature or effects have been included alongside those that are regarded as certain. Model uncertainties are dealt with subsequently through the identification of calculation cases and specific conceptual models (Section 5.2).

D.2.4.1 Overall System Model

Radionuclides released from the wastes can migrate through and between the near field, geosphere and biosphere due to a range of processes. A high level description of these processes is initially given below. A more detailed description is then provided in the subsequent sections on the near field, geosphere and biosphere.

Radionuclides can be transported from the near field in solid materials if the repository cover is subject to erosion (CAGCV-S and CAGCV-T only). It is also possible that colloidal material in groundwater may be a pathway for the transport of radionuclides sorbed onto the colloids; however, this is considered likely to have a minor effect and there are limited data available. Other forms of natural disruption (e.g., by glaciation) have been excluded from consideration by the assessment context (Section 2.6).

Radionuclides may leave the repository dissolved in water by a number of routes. For a repository on the surface, such as the CAGCV-S and CAGCV-T, infiltrating rainfall will initially be limited due to the physical integrity of the engineered structures. However, ultimately it can be expected to percolate through the repository. Radionuclides can enter the fluid by a variety of mechanisms, and be transported down, under the action of gravity, into the underlying geosphere. There is also the possibility that, should the performance of the cap to the point at which they are more conductive than the lithology on which the repository is placed, infiltrating water could flow horizontally into soils in the biosphere rather than down into the geosphere (the 'bathtubbing' effect). For a repository located below the surface in low permeability saturated rock (i.e., the DRCV-S and DRCV-L repositories), once the repository is resaturated, radionuclides would diffuse through the waste, backfill and engineered structures into the surrounding geosphere.

Gas may be generated by radioactive decay and processes such as the corrosion of ferrous materials. In the CAGCV-S and CAGCV-T, degradation of the engineered structures can result in pathways by which gas, generated in the repository, can be transported into the biosphere. The greater distance from the surface of the DRCV concepts means that it must migrate (and disperse) through the rock before reaching the surface.

Radionuclides that reach the geosphere can migrate through it in groundwater. Colloids may again be present, but are unlikely to constitute a significant transport mechanism. Therfore, the transport of colloids is not considered in this study. The location and arrangement of strata play the key role in the determining the flowpaths by which radionuclides can be transported from the near field to the geosphere. Physical (e.g., hydraulic conductivity) and chemical (e.g., sorption) characteristics can also determine the rate of transport of radionuclides. The nature of the rock may also mean that particular types of transport need to be considered (e.g., flow is different in porous media compared with fractured rock). Ultimately, however, all groundwater can be regarded as having some potential route to the biosphere.

The biosphere is the part of the system in which the key end points are evaluated – radiation doses to the exposure groups. Of interest in the biosphere are the locations in which radionuclides can accumulate and expose humans. For this reason, biota (plants and animals, terrestrial and lacustrine) should be considered. There is a wide range of mechanisms for radionuclide transport around the region of the biosphere that is of interest (where concentrations of radionuclides can be highest) and they are readily identifiable. The different features – such as soils, sediments, water bodies, plants – can also be readily identified. Consequently, it is possible to construct a relatively detailed model of the biosphere. Human exposures in the biosphere can occur by the ingestion of contaminated foods and other media, the inhalation of dust and gas and external irradiation. Dose rates are assessed for the average member of the hypothetical exposure group that is likely to receive the highest exposures from the given contamination of the environment. A local farmer and fisherman, both living on the site and eating local produce, are considered.

Radionuclides can be lost by a number of mechanisms from the region of interest (i.e., the area in the vicinity of the release into the biosphere where the radionuclide concentrations can be expected to be highest and the associated dose rates highest). They are no longer of interest in the evaluation of individual dose rates, and can be regarded as being 'lost' from the region of interest to 'other' locations where radionuclide concentrations are lower and the associated dose rates lower. For the purpose of this preliminary safety assessment and the conceptual models in the following sub-sections, these areas are described as being outside the region of interest.

The general conceptual model for the overall system for the Reference Scenario is summarised in Figure 41.

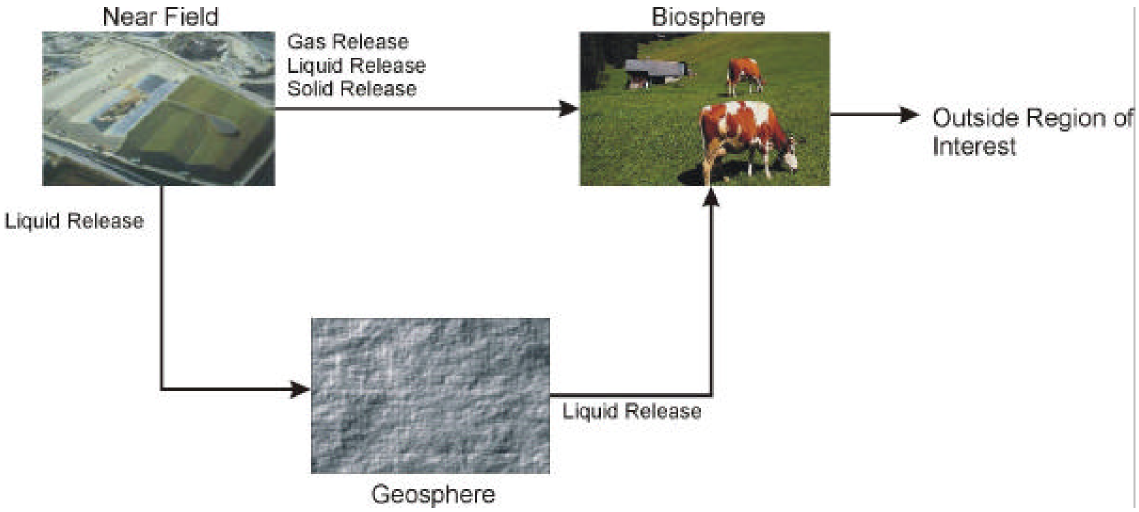


Figure 41: General Conceptual Model for the Overall System for the Reference Scenario

(Note: Releases directly from near field to biosphere are not relevant for DRCV-S and DRCV-L)

D.2.4.2 The Near Field

The objective is to model the retention in and release of radionuclides from the permanent repository in water, gas and solid material.

From the perspective of radionuclide release from the near field, the key physical components of the permanent repository are:

- the waste form;
- the waste container;
- the backfill (only present for the grouting option); and
- the engineered structures (i.e., concrete walls, floor and roof of each vault, and the engineered cap).

These are usually considered to be the main components of the near field (e.g., see the Swedish assessment of SFR (Chapman et al., 2002)). Consideration of these features allows any spatial and/or temporal differences in the chemical and physical conditions between these components of the near field to be represented. Additional discretisation of these features may be required in the mathematical model in order to appropriately represent processes such as dispersion and diffusion. Also, the non-processible wastes (significant proportion of metals) have distinctive characteristics that need to be represented.

In the permanent repository, groundwater can flow sequentially through the near-field features. Prior to the failure of the steel containers, flow occurs through the engineered structures, the backfill (if present); it would not infiltrate into the waste container. However, once the containers start to fail, water would enter the container and contact the waste form, allowing radionuclides to be released.

To represent the migration of radionuclides in water through the near field and their eventual release to the geosphere and biosphere, it is necessary to distinguish between features that are ‘upstream’ and ‘downstream’ of the waste (in terms of the dominant direction of water flow), as transport processes can operate differently in each direction. This is especially significant for the CAGCV-S and CAGCV-T, in which transport against the dominant flow direction (for example due to capillary rise) could lead to radionuclides being released directly to the biosphere.

The general near-field conceptual model configuration for the CAGCV and DRCV concepts is illustrated in Figure 42 and Figure 43, respectively.

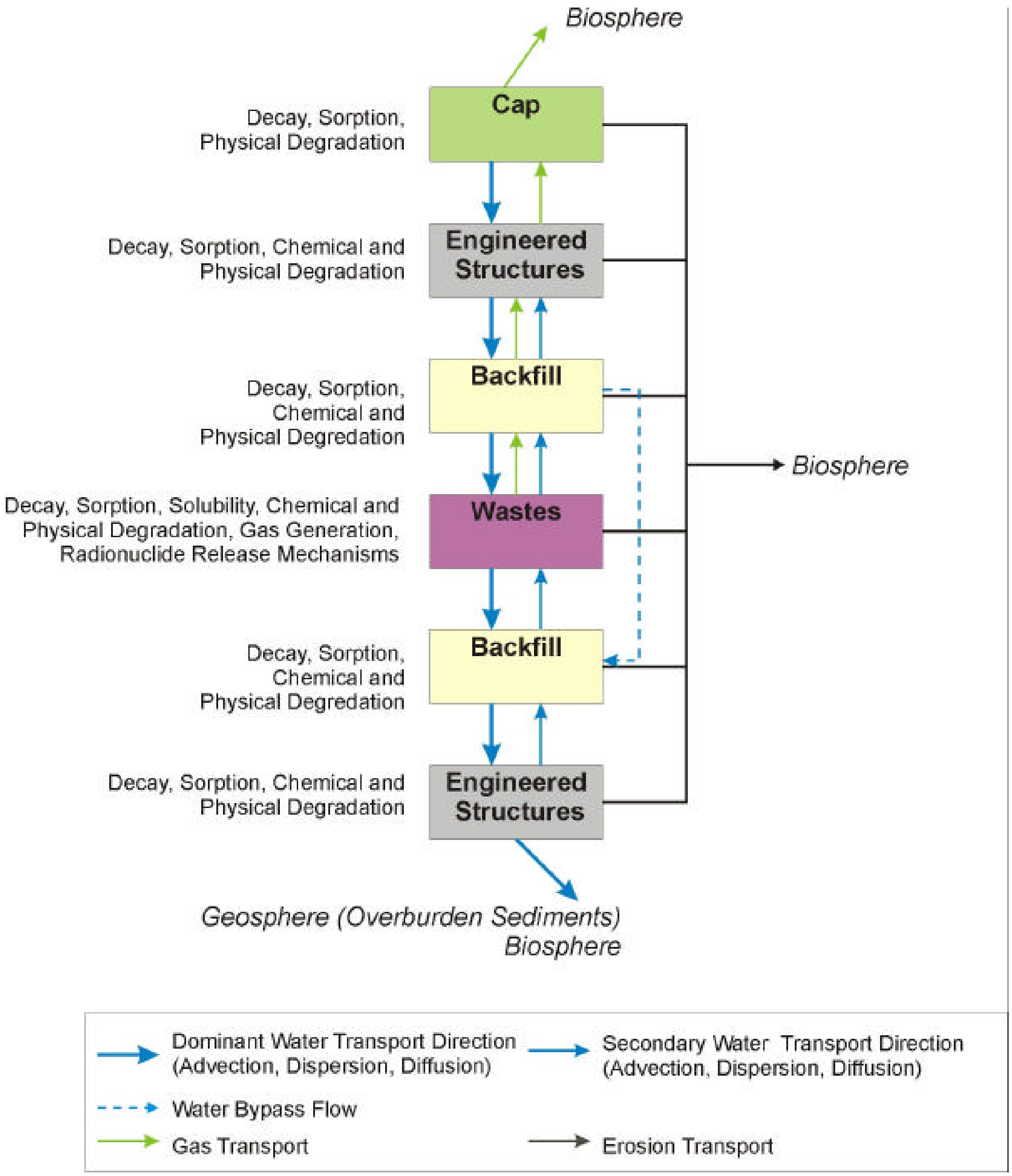


Figure 42: General Conceptual Model for the Near Field (CAGCV-S and CAGCV-T) for the Reference Scenario

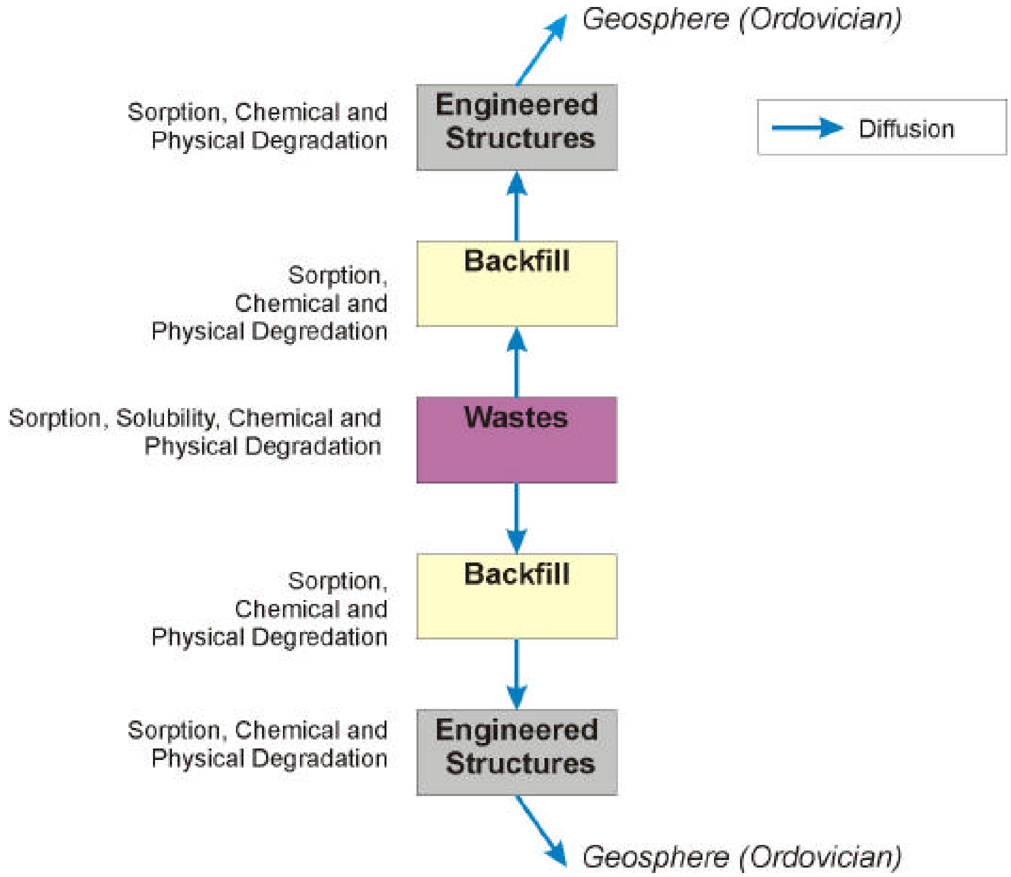


Figure 43: General Conceptual Model for the Near Field (DRCV-S and DRCV-L) for the Reference Scenario

The physical and chemical changes in the permanent repository are potentially important, These changes need to be represented with time-dependent properties, as waste and structures degrade. In principle, it would be possible to use detailed process models for physical degradation of concrete/cement and steel and geochemical models for chemical changes, with microbiology represented if considered to be significant. However, these are resource intensive and not considered to be appropriate for this preliminary safety assessment. Instead, the effects of these detailed processes can be represented – and if they prove to be important, the subsequent studies can investigate them in more detail.

The physical changes to consider include the degradation of the waste form, waste container, backfill (if present), engineered structures (vault roof, walls and floor) and cap. The main physical aspect of interest is changes to the hydraulic conductivity, but changes to the porosity might also need to be considered. An oxidising chemical environment is considered to be relevant to the CAGCV concepts, whereas the DRCV concepts are assumed to be in a reducing environment. The key changes in the chemical environment are related to the cement/concrete components of the permanent repository. These degrade in three stages, associated with the dissolution of the cement component, with each stage having a characteristic pH value for cement porewater:

- Stage 1 (fresh concrete) – K and Na hydroxides dominate pore water and the pH lies between about 13.3 and 12.5;

- Stage 2 (hardened, non-degraded concrete) – Ca hydroxide dominates pore water and the pH is around 12.5; and
- Stage 3 (degraded concrete) – Ca silicates dominate pore water and pH falls gradually to that of the groundwater.

The duration of these stages is largely dependent on the integrated water flow through the permanent repository. Berner (1990) describes how the number of complete cycles of porewater removal from the repository can be used to estimate the duration of these stages.

In addition to the release of radionuclides in water, gas generated in the repository may migrate from the near field into the biosphere. Gas may be generated by radioactive decay (the decay of Ra-226 to Rn-222 is mainly of interest). It may also be generated by chemical reactions in the near field, e.g., the corrosion of ferrous metals. Compacted wastes and some non-processible wastes already contain organic materials such as plastics. Therefore, in addition to metal wastes and metal containers, gases such as methane and carbon dioxide can be generated from microbial degradation of organic materials. Waste containers and engineered structures will contain the gas for some period of time, however these can be expected to degrade eventually. Gas can then be released. In the case of the CAGCV concepts, a relatively short path can be envisaged (through the cap), and so radioactive decay and dispersion of the gas may not be significant. However, for DRCV concepts, these processes are likely to render gas insignificant as an issue and so it is not considered further for the DRCV concepts.

Radionuclides may also be released into the biosphere as solid material if the physical degradation of the engineered structures, cap and other near-field features renders them prone to erosion. This situation is relevant to the CAGCV concepts on timescales of about 10^4 - 10^5 years, although glacial and tectonic processes could ultimately result in deeper repositories being brought to the surface on timescales of millions of years or more – considered to be too long to warrant consideration in this preliminary safety assessment. Although not certain, general surface erosion could act on the CAGCV-S and CAGCV-T repositories, which stand above the existing landscape, eventually removing the cover materials and exposing the waste. Other natural disruptive events could also have similar consequences (such as glacial disruption), but these are outside the scope of this study.

D.2.4.3 The Geosphere

The general geosphere conceptual models for the CAGCV and DRCV concepts are very different due to their different geological setting. For the CAGCV concepts, the geological systems of interest are the overburden sediments and the Shallow Bedrock Groundwater System (see Section 3.3.2). For the DRCV concepts, depending on location, the Ordovician shales and limestones are of interest, with the overlying dolostones of the Intermediate Bedrock Groundwater System (see Section 3.3.2). General conceptual models for the CAGCV and DRCV concepts are therefore considered separately. Both have been developed with information from Golder Associates (2003).

General Geosphere Conceptual Model for the CAGCV Concepts

The key issue for the geosphere conceptual model is groundwater flow in the identified features. This is characterised by advection, dispersion, sorption and dilution. The chemical characteristics of the strata determine the relative mobility of radionuclides due to sorption; however, this issue is effectively addressed with the definition of features. The advective and dispersive transport characteristics are associated with the direction and arrangement of groundwater flow paths. The physical characteristics of the strata (hydraulic conductivity and porosity) determine this. Most of the east and central area of the site is a recharge area from which groundwater within the overburden sediments and upper portion of the bedrock flows westward (and probably north westwards) to discharge into Lake Huron. Surface water interactions are discussed in terms of the biosphere component of the system. The water flow paths for the CAGCV-S and CAGCV-T are discussed below and illustrated in Figure 44 and Figure 45, respectively. For reasons of flexibility, the vault dimensions given in these figures are associated with higher waste volume than those assumed in this study.

For the CAGCV-S, the contaminated water migrates vertically down through the unsaturated overburden of sandy silt and silty sand and upper portion of the bedrock until it reaches the groundwater table. Radionuclides then move laterally through the bedrock and discharge into the near-shore area of Lake Huron.

For the CAGCV-T, the contaminated water migrates vertically down through the till and upper portion of the bedrock. Radionuclides then move laterally through the bedrock and discharge into the near-shore area of Lake Huron. If the rate of flow through the repository exceeds the hydraulic capacity of the till, then part of the contaminated water would be diverted laterally at the till surface and would emerge at the edge of the repository into the biosphere.

The general conceptual model that has been developed to take account of these flow paths is illustrated in Figure 46.

General Geosphere Conceptual Model for the DRCV Concepts

The deep geosphere conceptual model is also dominated by the characteristics of groundwater flow in the identified features. In this case, however, diffusion is also of interest, as well as advection, dispersion and sorption. The general flow paths for the DRCV concepts are shown in Figure 47.

The Ordovician shales and limestones of the Deep Bedrock Groundwater System are considered as possible host formations for a DRCV permanent repository concept. These strata are expected to be of very low permeability with very low groundwater flow rate and circulation. The porewater is typically brine. Because of the very low hydraulic conductivity of the rock and the highly saline groundwater regime, potential contaminant migration out of DRCV concepts would be controlled by chemical diffusion following complete re-saturation of the vaults. Radionuclides which diffuse vertically upwards from the DRCV repositories would enter the dolostones of the Intermediate Bedrock Groundwater System (see Section 3.3.2). Flow in the dolostones is horizontal towards Lake Huron where it discharges under the lake bed some 10 to 20 km off-shore of the Bruce Site. An alternative conceptual model is for more rapid diffusive transport of radionuclides from the near field to the Intermediate Bedrock Groundwater System via the DRCV access shaft, which acts as a conduit (despite being backfilled at closure).

The general conceptual model is illustrated in Figure 48.

D.2.4.4 The Biosphere

As has been noted in the description of the overall system model, the conceptual model of the biosphere has the potential to be the most complex, owing to the variety of release mechanisms and locations from the geosphere into the biosphere, and the variety of biosphere features, processes, and their potentially heterogeneous characteristics. General biosphere conceptual models for liquid, gas and solid releases are presented below.

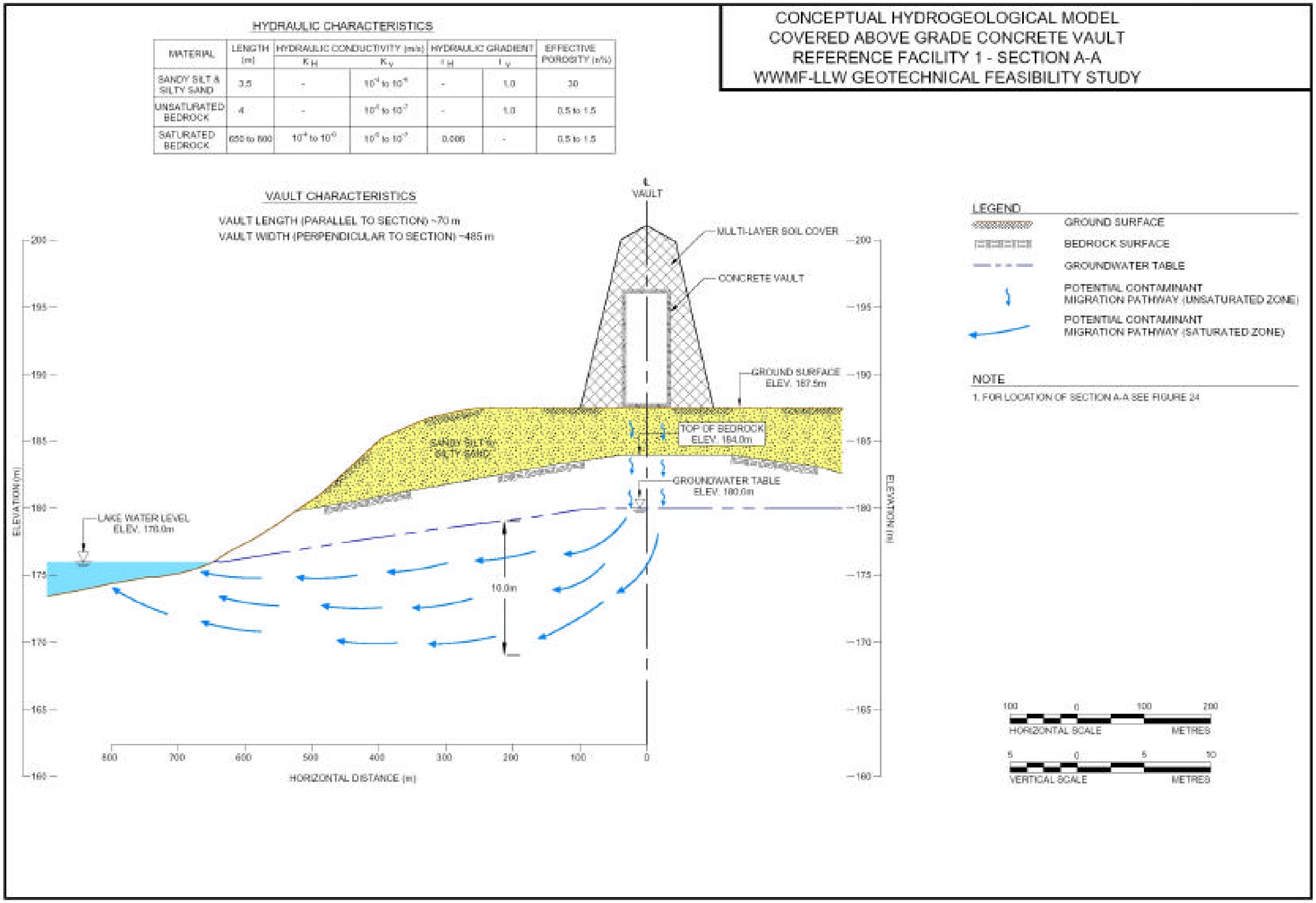
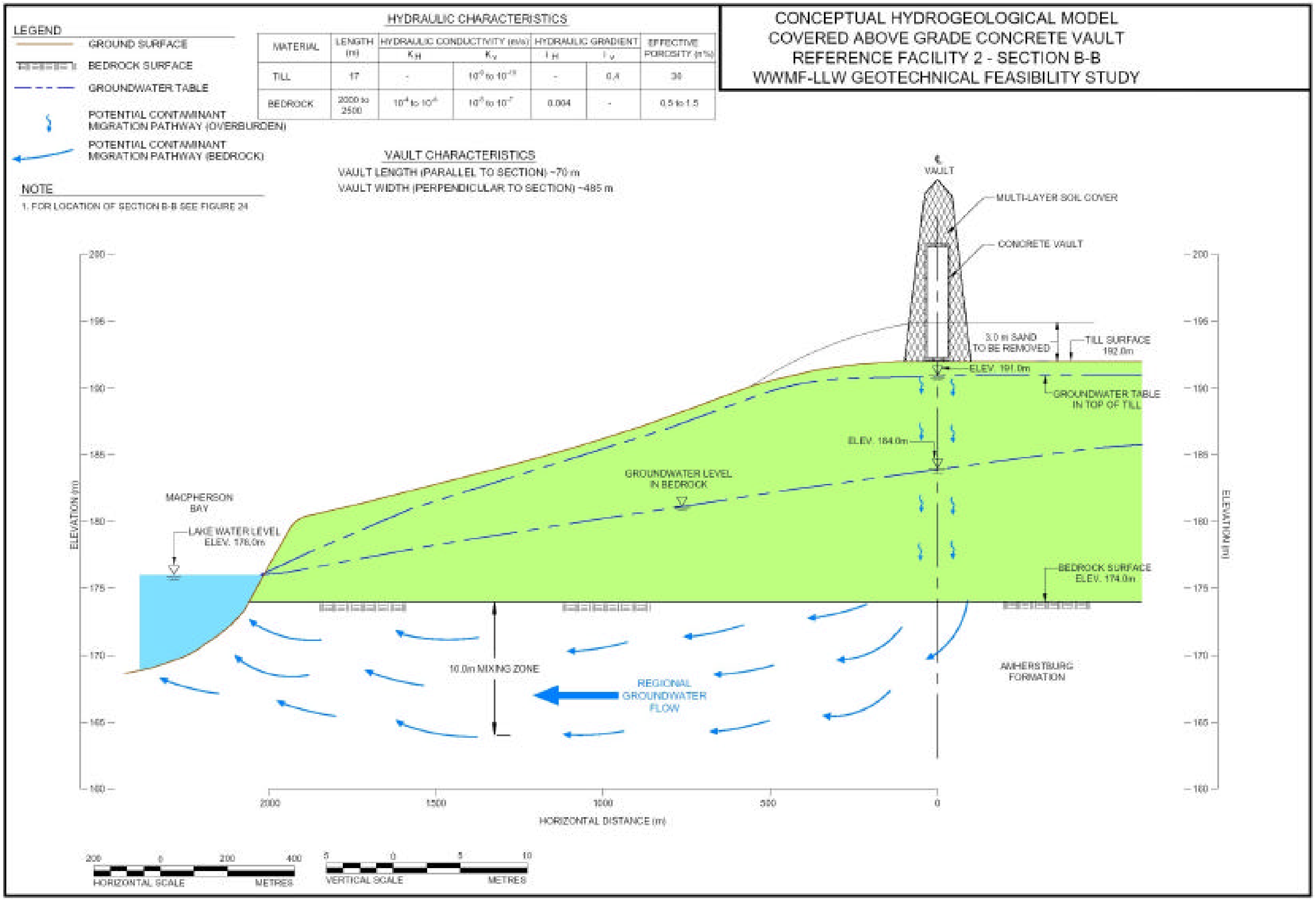


Figure 44: Water Flow Path for the CAVGCV-S (Golder Associates, 2003)



MATERIAL	LENGTH (m)	HYDRAULIC CONDUCTIVITY (m/s) K_H	K_V	HYDRAULIC GRADIENT i_H	i_V	EFFECTIVE POROSITY (n%)
TILL	17	-	10^{-9} to 10^{-10}	-	0.4	30
BEDROCK	2000 to 2500	10^{-4} to 10^{-6}	10^{-5} to 10^{-7}	0.004	-	0.5 to 1.5

Figure 45: Water Flow Path for the CAVGCV-T (Golder Associates, 2003)

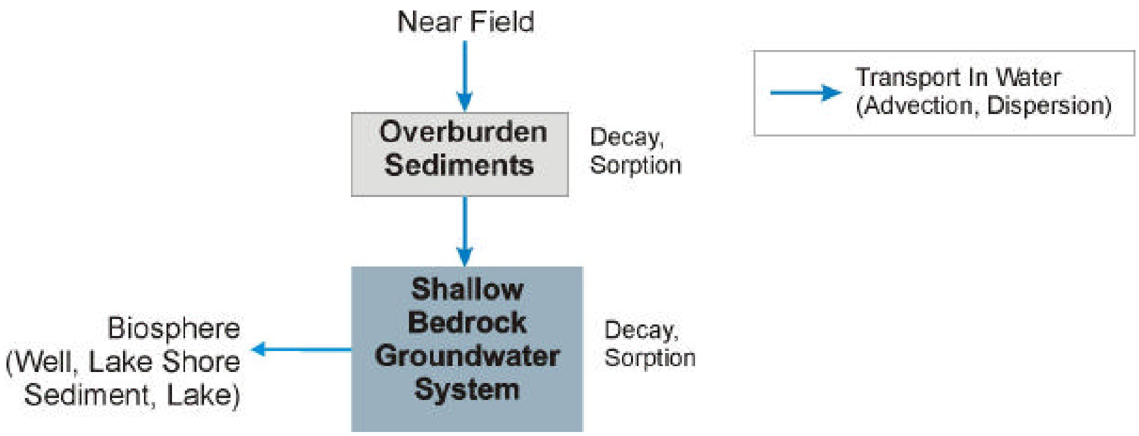


Figure 46: General Conceptual Model for the Geosphere (CAGCV-S and CAGCV-T) for the Reference Scenario

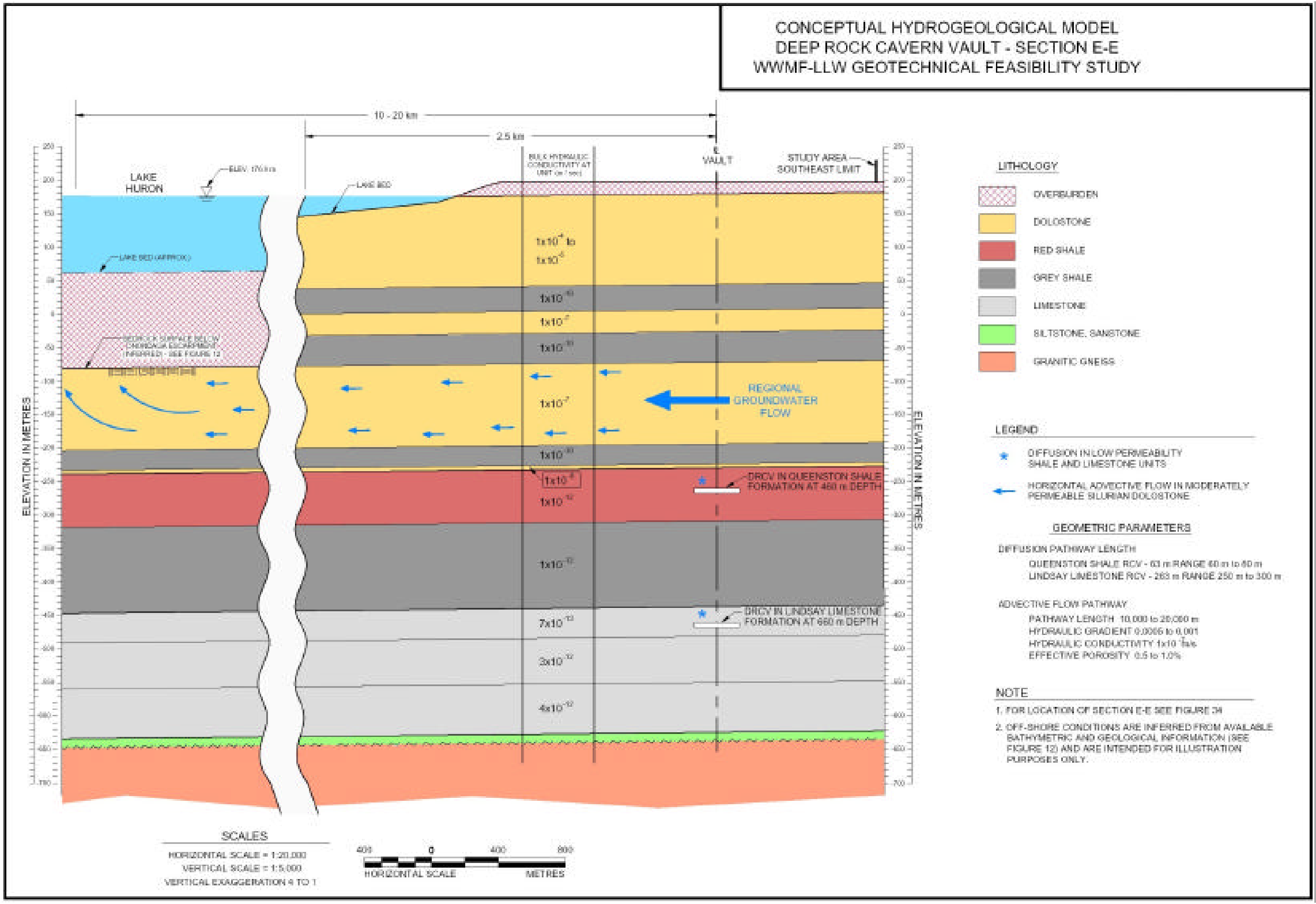


Figure 47: Water Flow Path for DRCV Concepts (Golder Associates, 2003)

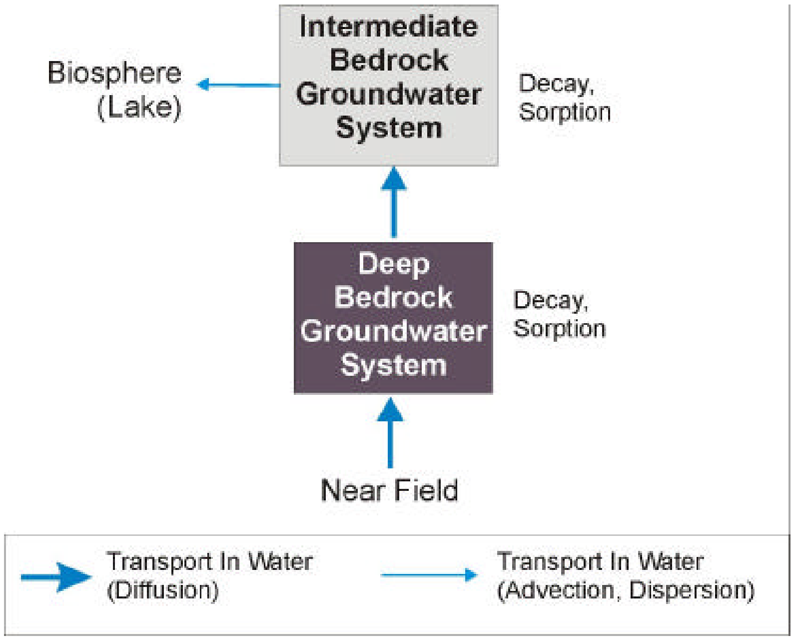


Figure 48: General Conceptual Models for the Geosphere (DRCV-S and DRCV-L) for the Reference Scenario

Liquid Release

The key features into which radionuclides may be released are fundamental in determining the location of interest for safety assessment purposes, as radionuclide concentrations in and around these locations are likely to be the highest in the accessible environment. The features that have been identified as potential initial receptors for liquid releases are:

- soils in the vicinity of the repository (releases from the CAGCV-T concept only due to the bathtubbing effect);
- well water (releases from the CAGCV concepts only);
- lakeshore sediments (releases from the CAGCV concepts only); and
- lake sediment.

Note that the greater proximity of the CACGV to the biosphere results in a greater number of potential locations at which radionuclides can be released into the biosphere.

Subsequent migration of the radionuclides in the biosphere would result in the contamination of further media.

- Lake water could become contaminated due to the discharge of contaminated groundwater into it via lake sediment or from surface water. As the lake is very large, consideration needs to be given to the discretisation of the water body and associated sediment, and the flows of water (and potentially sediment) within it.
- Surface water and associated sediment could become contaminated due to interflow and erosion from contaminated soil. However, radionuclides concentrations are likely to be reduced in comparison with those in the soil due to dilution with uncontaminated water. Furthermore the surface water courses at the Bruce Site are small and they all eventually drain into Lake Huron. Therefore, surface water and associated sediment are not represented in Figure 49; instead, it is assumed that interflow and erosion from the contaminated soil enters the lake water directly.

- Soils in the vicinity of the repository could be used for agriculture and could become contaminated by water that is used for irrigation (in addition to being directly contaminated by bathtubbing for the CAGCV-T concept). Present-day practice is to obtain irrigation water from shallow boreholes rather than the lake or other surface water sources. Radionuclides in soil may be sorbed in the soil or percolate back into the groundwater, but the low permeability of the subsoil at the site is also likely to lead to significant run-off for radionuclides in solution, potentially also transporting soil particles.
- Biota (plants and animals) could become contaminated from the contaminated soils and water bodies. For clarity, they are not explicitly represented in Figure 49 because they can be associated with all surface media.
- The atmosphere could become contaminated due to the resuspension of radionuclides sorbed onto soil and exposed sediment.

Human exposure to the features in Figure 49 can occur by a variety of pathways (Figure 50). The potential exposure groups, who would be exposed to the greatest number of these pathways and are considered to be suitable for assessment, are farmers and fishermen that live locally and derive food from the contaminated biosphere media.

A local farmer could obtain water from a well for direct human and animal consumption and for irrigating crops, whilst a fisherman that lived by the lake would be expected to use it as a source of water and fish. It is considered unlikely that surface and lake water would be used for irrigation, based on current practices. All radionuclides in soil and water can be assimilated by plants and animals that are ingested by humans, and also expose humans by external irradiation. Resuspension by wind or mechanical disturbance can also result in making soil particles airborne, which can subsequently be inhaled by humans.

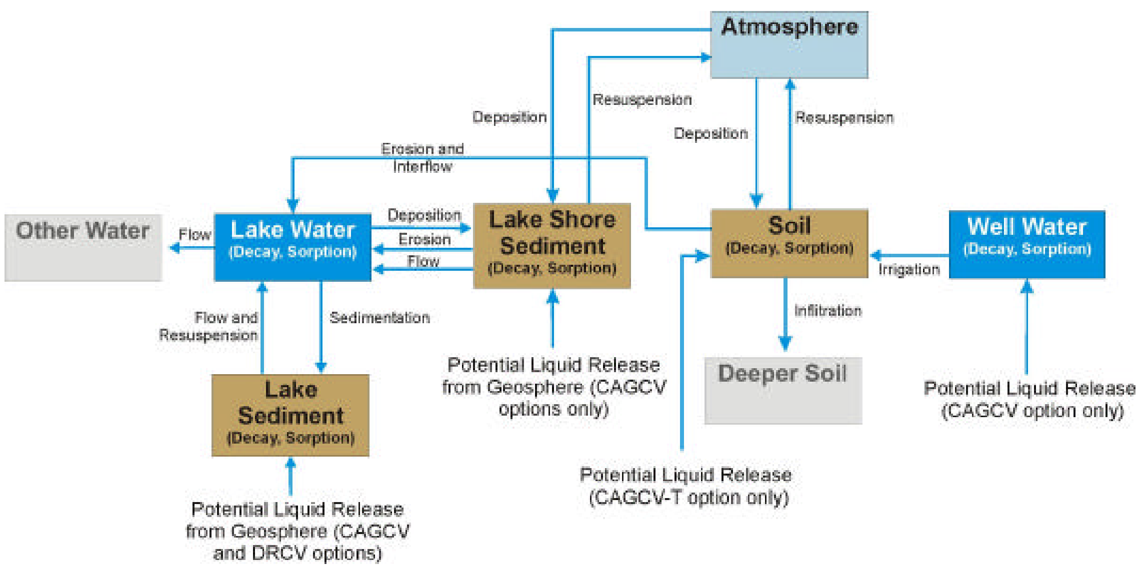


Figure 49: General Conceptual Model for Liquid Release to the Biosphere (All Permanent Repository Concepts)

In the case of the contamination of the soil due to bathtubbing, the localised nature of the contamination means that it is more appropriate to consider a site dweller potential exposure group that grows some crops over the relatively small area of contamination. This group is exposed to radionuclides due to ingestion of crops and soil, inhalation of dust and external irradiation from the contaminated soil.

Gas Release

Gas could be released from the CAGCV concepts to a house built on top of the permanent repository resulting in exposure of house dwellers by inhalation (the contribution to dose rate from external irradiation is considered to be small by comparison, as long as the cap remains intact) (see Figure 51).

Solid Release

In the long term, erosion of the cover of the CAGCV concepts could result in the contamination of soil and the subsequent contamination of crops due to various uptake processes (such as root uptake). Exposure of site dwellers is assumed to occur via ingestion of crops and soil, inhalation of resuspended soil, and external irradiation (IAEA, 2002a) (Figure 52). It is assumed in this preliminary safety assessment that the area of contamination is not large enough to support the growing of crops for the raising of animals.

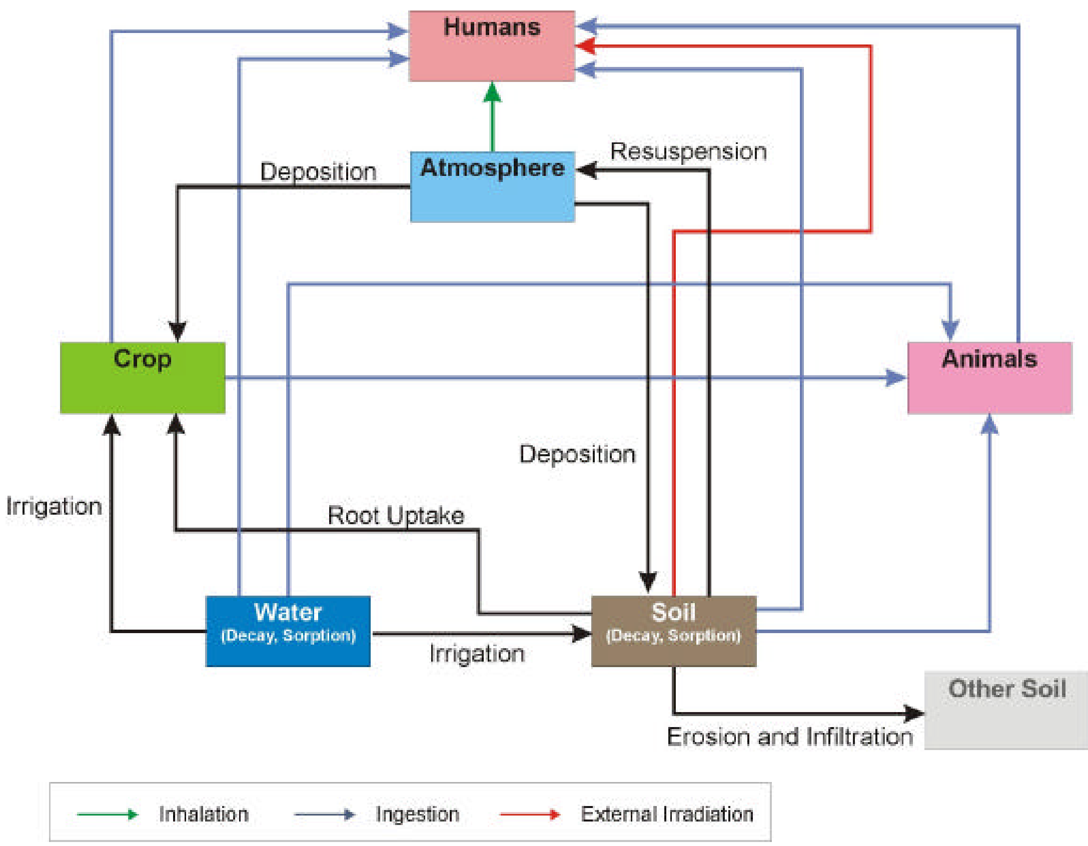


Figure 50: General Conceptual Model for Human Exposure for the Reference Scenario (Liquid Release)

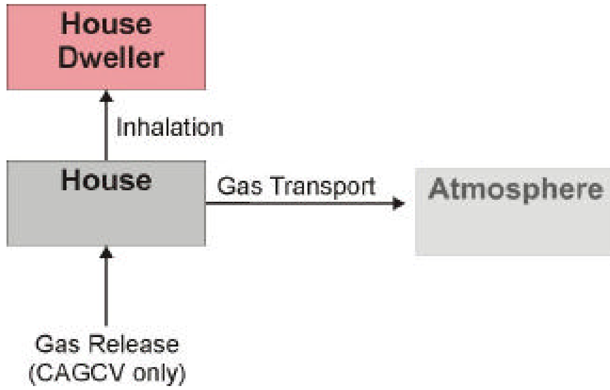


Figure 51: General Conceptual Model for the Reference Scenario Gas Release to the Biosphere and Subsequent Human Exposure (CAGCV Concepts)

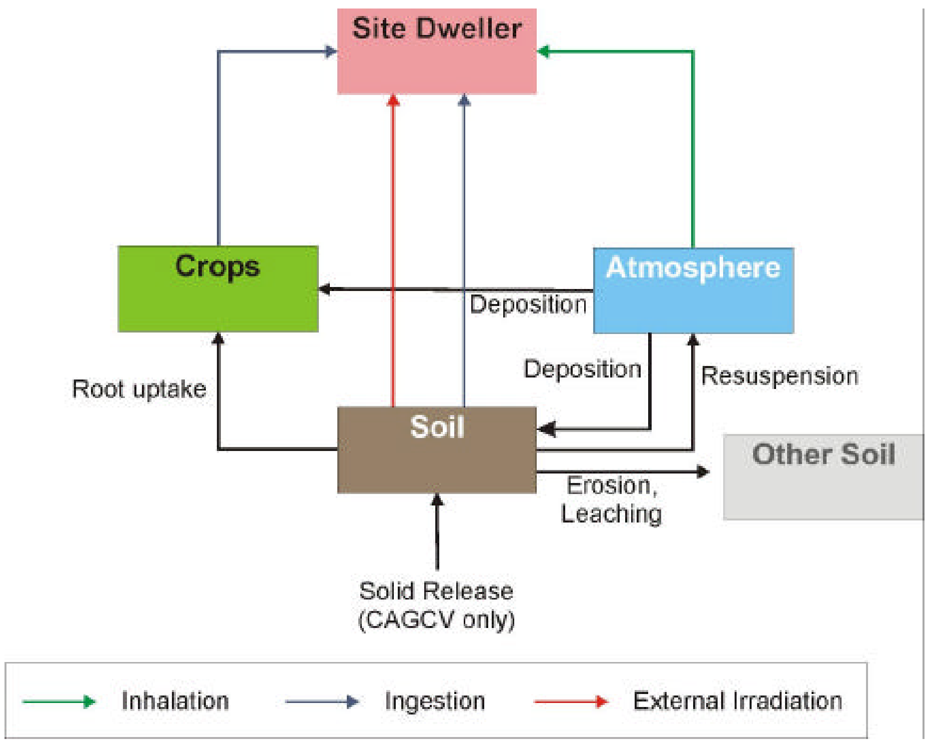


Figure 52: General Conceptual Model for the Reference Scenario for Solid Release to the Biosphere and Subsequent Human Exposure (CAGCV Concepts)

D.2.5 FEP AUDIT

An audit of the features and processes identified in the general conceptual models for the Reference Scenario has been undertaken. These have been compared with the ISAM FEP list (IAEA, 2002b). Although not a highly detailed FEP list, this is a standard reference list considered to be an appropriate reference for auditing the model. The ISAM FEPs that are addressed with the identified features and processes in the general conceptual models are presented in Table 25. This is followed by a summary of the FEPs that are not explicitly covered in the models, given in Table 26.

Table 25: Comparison of the Features and Processes for the Reference Scenario with the ISAM FEP List

Feature/Process	FEP References
Features	
Cap (CAGCV concepts only)	2.1.05
Waste	2.1.01, 2.1.02, 2.1.03
Backfill	2.1.04
Engineered Structures	2.1.05
Overburden sediments	2.2.01, 2.2.02, 2.2.05, 2.3.03
Shallow Bedrock Groundwater System	2.2.01, 2.2.05, 2.3.03
Intermediate Bedrock Groundwater System	2.2.03, 2.2.05
Deep Bedrock Groundwater System	2.2.01, 2.2.02, 2.2.05
Soil	2.3.01, 2.3.02
Surface Water	2.3.04
Surface Water Sediment	2.3.04
Well Water	2.3.03
Lake Water	2.3.04
Lake Sediment	2.3.04
Biota	2.3.08, 2.3.09
Houses and Buildings	2.4.07
Atmosphere	2.3.07, 2.3.10
Processes and Internal Events	
Sorption	2.1.09, 2.2.08, 2.3.01, 2.3.03
Solubility	2.1.09, 2.3.02
Chemical effects	2.1.09, 2.2.08, 3.2.05
Gas Generation	2.1.09, 2.1.12
Surface Water Transport	2.3.04, 2.3.10, 2.3.11, 3.2.07
Infiltration	2.1.08, 2.2.05, 2.2.07, 2.3.10, 2.3.11, 3.2.07
Vertical Upward Transport	2.1.08, 2.2.05, 2.2.07, 2.3.11, 3.2.07
Bioturbation	2.3.13, 3.2.06, 3.2.11
Resuspension and Sedimentation	2.3.10, 2.3.12, 3.2.08
Erosion	2.3.04, 2.3.12, 3.2.08
Saturated Flow – Advection	2.1.08, 2.2.05, 2.2.07, 3.2.07
Saturated Flow – Dispersion	2.1.08, 2.2.05, 2.2.07, 3.2.07
Diffusion	2.1.08, 2.2.05, 2.2.07, 3.2.07
Colloidal Transport	2.1.08, 2.2.05, 2.2.07, 3.2.04
Water Abstraction	2.2.05, 2.2.07, 3.2.07
Uptake by Plants and Animals	2.3.13, 3.2.13
Gaseous Transport	2.1.12, 2.2.05, 2.2.11, 3.2.09, 3.2.10
Ingestion of Contaminated Media (Humans)	2.4.01, 2.4.02, 2.4.03, 2.4.05, 2.4.06, 2.4.08, 2.4.09, 2.4.10, 2.4.11, 3.3.01, 3.3.02, 3.3.04, 3.3.05, 3.3.06
Inhalation of Contaminated Media (Humans)	2.4.01, 2.4.02, 2.4.04, 2.4.05, 2.4.07, 2.4.08, 2.4.09, 2.4.10, 2.4.11, 3.3.02, 3.3.03, 3.3.04, 3.3.05, 3.3.06, 3.3.08
External Irradiation by Contaminated Media (Humans)	2.4.01, 2.4.02, 2.4.04, 2.4.05, 2.4.07, 2.4.08, 2.4.09, 2.4.10, 2.4.11, 3.3.02, 3.3.03, 3.3.04, 3.3.05, 3.3.06
Physical Degradation of Man-made Structures	2.1.02, 2.1.03, 2.1.05, 2.1.07
Chemical Degradation of Man-made Structures	2.1.02, 2.1.05, 2.1.08, 2.3.05

Table 26: ISAM FEPs Not Addressed in the General Conceptual Models for the Reference Scenario

ISAM FEP Number and Short Name	Justification for Not Addressing the FEP
0.- Assessment Context FEPs	Issues of assessment context have already been addressed (see Section 2)
1.- External Factors FEPs	External factors are discussed in relation to the definition of scenarios (see Section 4 and Appendix C)
2.1.06: Other engineered features materials, characteristics and degradation processes	No other engineered features of significance were identified.
2.1.10: Biological/biochemical processes and conditions (in near field)	The waste has a relatively low content of organic material (much being incinerated prior to emplacement in the permanent repository) and the potential for such processes is considered to be low.
2.1.11: Thermal processes and conditions (in near field)	There are no significant heat sources in the near field (cement curing is not considered significant).
2.1.13: Radiation effects (in near field)	The radionuclide concentrations are too low for significant radiation effects in structures such as radiolysis.
2.1.14: Nuclear criticality	The radionuclide concentrations are too low for criticality to be possible.
2.1.15: Extraneous materials	No extraneous materials of interest have been identified.
2.2.04: Discontinuities, large scale (in geosphere)	No faults or other large-scale geological discontinuities have been identified (preferential flow paths are, however, addressed).
2.2.06: Mechanical processes and conditions (in geosphere)	No mechanical processes of interest have been identified, e.g., the site is in low relief with no potential for landslides.
2.2.09: Biological/biochemical processes and conditions (in geosphere)	No significant biological presence (e.g., microbes) has been identified in the geosphere.
2.2.10: Thermal processes and conditions (in geosphere)	There are no notable thermal sources in the geosphere.
2.2.12: Undetected features (in geosphere)	There is no evidence of other potentially important features in the geosphere.
2.2.13: Geological Resources	*This issue is considered in the Human Intrusion Scenario*
2.3.05: Coastal features	The site is inland, however lake 'coastal' features such as the lakeshore have been considered.
2.3.06: Marine Features	The site is inland.
2.3.14: Animal/plant intrusion leading to vault/trench disruption	Erosion of the cover is considered for the CAGCV concepts, and the effects of animal/plant intrusion would be similar. This FEP is not relevant for the DRCV concepts.
3.2.12: Human-action-mediated transport of contaminants	*This issue is considered in the Human Intrusion Scenario*
3.3.07 Non-radiological toxicity/effects	Non-radiological toxicity and effects have been excluded from consideration in this preliminary study by the Assessment Context (Section 2.2).

D.3 HUMAN INTRUSION SCENARIO

D.3.1 KEY FEATURES OF THE SCENARIO

The key features of the scenario are summarised in Section 4.3 and Appendix C.6.

D.3.2 IDENTIFICATION OF FEATURES USING SYSTEM DESCRIPTION INFORMATION

The system description (Section 3) has been used to identify key features for consideration in the assessment of human intrusion situations, which have been listed in Table 27.

Table 27: Summary of Key Features for the Human Intrusion Scenario

Near-field Features	Geosphere Features	Biosphere Features
Cap Waste Backfill Engineered Structures	Overburden sediments and Bedrock	Soil Biota Houses and Buildings Atmosphere

Cap: The cap, described in Golder Associates (1998 and 2003), is only present for the CAGCV concepts. Here, it has an important role in protecting the permanent repository from disruption. Initially, features such as anti-intrusion layers (e.g., cobbles, which are difficult to excavate) and markers can be expected to have an important role in deterring intrusion. However, over time, they can be expected to physically degrade. If intrusion were to occur even after the cap had physically degraded, the cap could be expected to influence the consequences of the intrusion by diluting the concentration of the excavated wastes.

Waste : The main waste types are described by Leung and Krochmalnek (2000). The Human Intrusion Scenario considers situations in which exposure could occur by intrusion into the waste in the permanent repository. Unlike the Reference Scenario, therefore, radionuclides released from the permanent repository by other mechanisms such as leaching and gas release are not of interest. Wastes with high concentrations, or that are very heterogeneous are potentially important to consider, as are any materials that, if retrieved, could be considered artefacts of interest or value.

Backfill: Backfill material has a limited role in the Human Intrusion Scenario. Its main influence is the potential diluting effect of backfill with disrupted wastes, and its potential role in retaining radionuclides in the permanent repository for long periods of time.

Engineered Structures: A consequence of the 'concentrate and contain' philosophy is that the radionuclides in the waste are retained for an extended period of time and can present a greater hazard to intruders in the future. Consequently, features such as engineered structures that are designed to contain radionuclides in the waste can act to increase potential dose rates associated with the human intrusion pathway. However, like the cap, for some period engineered structures can act as a deterrent to intrusion. Even in a degraded state, they would offer some minor dilution to any disrupted waste.

Overburden sediments and bedrock: The overburden sediment and bedrock overlying a deeper repository provides a natural physical barrier to intrusion. Intrusion into a deep repository is only expected in association with mineral prospecting or mineral extraction. As has been noted in the description of the system, deep boreholes and wells are extremely unlikely, although not entirely impossible to envisage, as the geological formations do not have properties of potential interest.

Soil: Any disrupted material may become incorporated with soil – for example, if a building is constructed, spoil may be used for landscaping, or to fill in depressions. The consequence is that waste materials could become mixed directly with soils. Contaminated soil can provide a number of exposure pathways, including direct irradiation, inhalation and ingestion of soil, and could be farmed.

Biota: Contaminated soil could be farmed for animal and plant produce, which could subsequently be ingested by people. Very heavy loadings of excavated waste in soil would not be expected, as the waste and structural materials would reduce the fertility of the soil. Also, it is general practice in the present day to restore mounds of spoil with fresh (possibly imported) topsoil. Nevertheless some direct use of contaminated soil can be envisaged for safety assessment purposes.

Houses and Buildings: Enclosed environments offer the potential for the accumulation of radioactive gases (particularly Rn-222), and are consequently of interest. The buildings around the site are presently industrial; however, there are a number of residential communities. It is therefore possible to foresee a range of possible buildings on the site; although once the use of the site for nuclear purposes has ceased, it is most likely that it would revert to agricultural use. The frequency and character of potential buildings is important in determining the likelihood that human intrusion could occur, as the depth of potential excavations is a key factor for the disruption of the CAGCV concepts. Once built, if on contaminated land, the enclosed environment of a house or other building offers the possibility for the accumulation of contaminated gas released from waste. Potential buildings are not relevant to the much deeper DRCV concepts.

Atmosphere: The general surface atmosphere does not provide a feature in which radionuclides can accumulated to high concentrations, owing to its dispersive effects. However, humans, animals and plants interact with the atmosphere, and therefore it offers an alternative pathway of interest from soil/waste into biota and directly to humans.

D.3.3 IDENTIFICATION OF PROCESSES USING SYSTEM DESCRIPTION AND SCENARIO INFORMATION

The processes of interest for the Human Intrusion Scenario are principally identified by considering the scenario itself and the initiating events, as the present-day system does not inform greatly on the potential mechanisms by which permanent repositories may be disrupted. However, broader information, such as geotechnical investigation and construction practices do assist in determining the key processes (even if the main information that they provide is associated with the likelihood of the scenario occurring).

The processes and events of interest are those that determine the nature of the disruptive event – the amount of waste extracted, any dilution with engineered structures, etc., the afteruse of the extracted material, and potential exposure pathways associated with the disruption. They are consequently quite different in character from the processes considered in relation to the Reference Scenario. Specifically, in Human Intrusion Scenario, external events (related to future human actions) are considered, consistent with the assessment context (Section 2).

Physical Degradation of Man-made Structures: Permanent repository structures are designed to deter intrusion with anti-intrusion layers and markers. These can be expected to reduce the likelihood for a period of time. However, on timescales of hundreds to thousands of years these cannot be relied upon to offer resistance to intrusion.

Decay: All radionuclides decay and some produce radioactive progeny that need to be considered. For the purposes of this preliminary safety assessment, it is assumed that all progeny with a half-life of greater than 25 days are explicitly modelled. Those with a half-life of less than or equal to 25 days are assumed to be in secular equilibrium with the parent.

Contaminant Transport from the Near Field: Radionuclides in wastes would be transported from the near field by a variety of mechanisms noted in the discussion of the general conceptual model for the Reference Scenario (Appendix D.2). This process could result in the reducing residual concentrations of radionuclides in the permanent repository, and is therefore relevant to consider in human intrusion calculations. However, it should be noted that conservative assumptions for these processes for the Reference Scenario (favouring radionuclide release) would be optimistic for the Human Intrusion Scenario, and vice versa.

Site Investigation: Investigation of the site could occur in conjunction with a wide range of possible future uses for the land. With respect to the disturbance of the CAGCV concepts, the overburden sediments could be subject to investigation for the suitability of the site for constructions. The resource potential is limited; however, there are a number of quarries in the vicinity of the site and investigation for this purpose is assumed to be possible. There is also notable archaeological heritage in the region and this could instigate an investigation. With respect to the disturbance of the DRCV concepts, the Ordovician shales and limestones are unlikely to be of interest as a groundwater resource due to their low hydraulic conductivity and highly mineralised water. Nevertheless, natural gas is extracted in the region, and exploratory boreholes may be drilled for this purpose that reach a sufficient depth to disrupt the DRCV concepts. Golder Associates (2003) note that three exploration boreholes have been put down to the Precambrian basement within 5 km of the site.

Construction/Excavation: Construction or excavations for resource use is only relevant to the CAGCV concept, as the deeper DRCV repositories are located in strata from which material would not be extracted. Constructions may occur on the surface that result in sufficient disruption to a depth sufficient to affect the wastes in the CAGCV repositories – i.e., several metres. Typical residential housing could reach such depths if a basement were constructed. Industrial buildings, such as agricultural storage tanks or a gas station, would also be expected to excavate to sufficient depth to affect a CAGCV repository. The result of such an excavation would be the disruption of the near field and the possibility that some waste would be brought to the surface. There are many possible subsequent uses of excavated material, amongst them simple land-spreading and landscaping. Both of these practices would contaminate soil with waste material.

Uptake by Biota: Radionuclides transferred to soil by excavations or other disruptions could ultimately be transferred to plants by uptake from roots and direct contamination of plant surfaces (some portion of the radionuclides may also be subsequently removed, e.g., by weathering and washing). Animals could eat contaminated plants, soil and water. Human exposure pathways are most likely if the disruption of the repository is followed immediately with an agricultural use; however, even if not, the site could revert to agricultural use at some point in the future.

Resuspension: Dust can be suspended into the atmosphere by mechanical disturbance (e.g., excavation or drilling) or the action of the wind on the soil surface. Suspended particles ultimately settle out as a result of gravitational effects (sedimentation); however, when airborne they can be inhaled by humans. In intrusion situations, the suspended material could be undiluted waste.

Ingestion of Contaminated Media: Humans can be envisaged to ingest a variety of contaminated media. Residents of the site could ingest contaminated animal and crop produce if contaminated soil were to be farmed. The soil itself could also be ingested inadvertently. Intruders into waste may inadvertently ingest contamination on hands.

Inhalation of Contaminated Media: Radionuclides may be present in the air that could be inhaled by a resident on the site or an intruder. For example, for the intruder, waste can be suspended by mechanical disturbance and subsequently inhaled. For the site dweller, it could be inhaled if raised when ploughing contaminated soil after excavation.

External Irradiation by Contaminated Media: People in the proximity of contaminated media could be irradiated by them if no shielding is present. For small sources like borehole samples, the external irradiation geometry can be approximated to a point source. Contaminated soil is likely to be spread over a wider area, and exposure geometry should reflect this.

D.3.4 DESCRIPTION OF THE GENERAL CONCEPTUAL MODEL

The conceptual model for the Human Intrusion Scenario has been developed using the identified features, processes and events described in the preceding sub-section. The characteristic element of the general conceptual model is the presence of an initiating event associated with possible future human actions that has the potential to disrupt the wastes.

D.3.4.1 Overall System Model

The system can be considered to consist of the source of radioactivity (the near field) and the receptor environment (the biosphere). The biosphere is contaminated with solid material (including waste) from the geosphere by a disruptive event, the nature of which has been discussed in the scenario description (Section 4.3 and Appendix C.6).

The release of radionuclides into the geosphere, and thence to the biosphere, is considered but only in terms of the reduction of radionuclide concentrations in the waste that could be disrupted. It is assumed that the concentrations of radionuclides in soil as a result of migration are much lower than would arise if the soil were contaminated directly with waste. In addition, migration of radionuclides in soil contaminated by waste will only act to reduce the concentrations in soil, decreasing the potential radiation dose rate. Moreover, it can cautiously be assumed that exposures to the soil can occur immediately after the intrusion event. Therefore, losses of radionuclides by migration from the near field and biosphere are therefore shown as transfers to outside the region of interest in Figure 53.

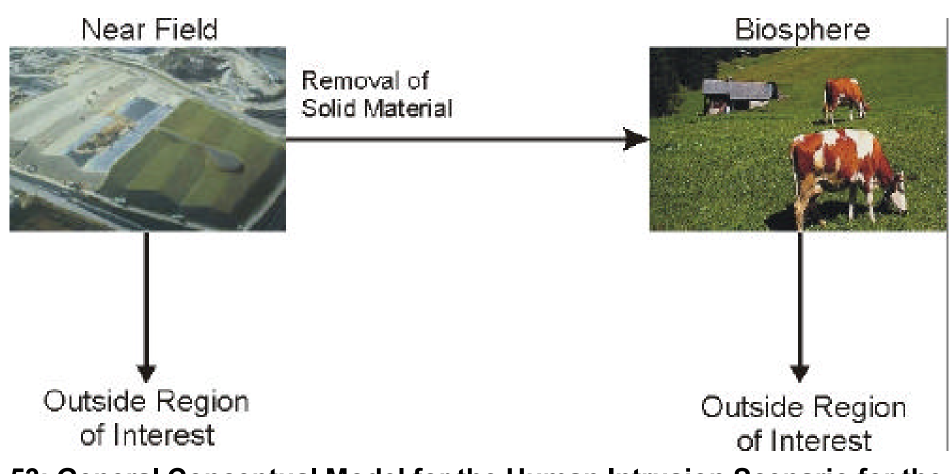


Figure 53: General Conceptual Model for the Human Intrusion Scenario for the Overall System

D.3.4.2 General Conceptual Model for Exploration Boreholes

The retrieval of waste in exploratory boreholes could occur for either the CAGCV or DRCV concepts, although the borehole drilling mechanism could be very different owing to the different depths involved. However, the quantity and form in which radioactive material could be brought to the surface is likely to be sufficiently similar for them to be assessed with a single general conceptual model. Samples would be extracted and examined, and exposures could occur at either stage. In the longer term, samples would probably be stored. People could receive exposures directly from the waste at any of these stages, with the exposure mechanisms including external irradiation from a small source, inadvertent ingestion and inhalation of dust (drilling activities only).

Figure 54 illustrates the general conceptual model. In this figure, 'waste' indicates waste extracted from the permanent repository by the borehole; processes prior to this event (e.g., radionuclide migration in groundwater) are not shown.

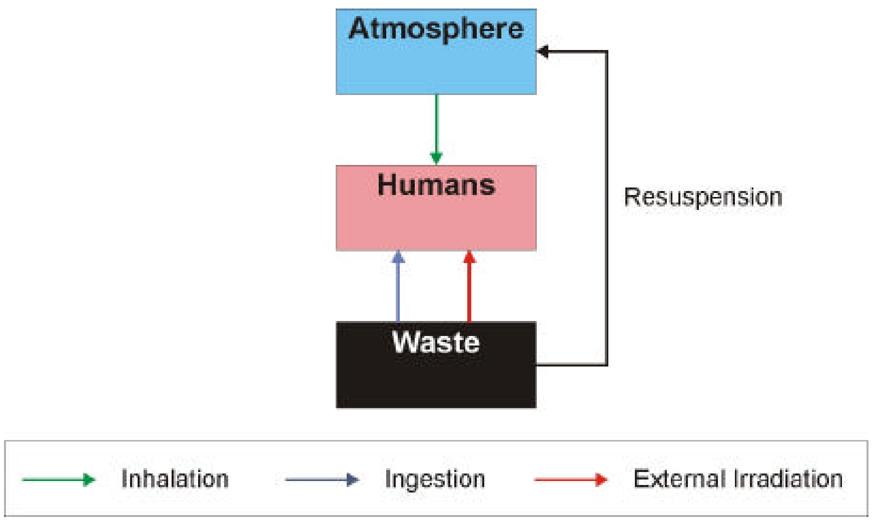


Figure 54: General Conceptual Model for the Human Intrusion Scenario (Exploration Borehole)

D.3.4.3 General Conceptual Model for Large Excavations

Large excavations are only relevant to consider for the CAGCV concepts, which are located on the surface. The excavations could be associated with a construction project (e.g., agricultural buildings) or mineral extraction (e.g., sand and gravel pit). However, given the intrinsic uncertainties with the scenario, it is considered sufficient to assess both situations with a single general conceptual model. This is appropriate because both situations involve mechanical extraction of potentially large quantities of material (including waste), which could then be treated as spoil and left on the surface.

Of interest to the assessment are individuals that could be exposed to the waste during the excavation activities, and individuals that could be exposed to the spoil that is left near the surface. For those involved in the excavation, exposure mechanisms to consider include external irradiation from a small source, inadvertent ingestion and inhalation of dust (excavation activities only). Those potentially exposed after the excavation could be site dwellers who grow crops (IAEA, 2002c), in which case they would be exposed by these pathways as well as the ingestion of contaminated foodstuffs. It is assumed that the area of contamination is not large enough to support the growing of crops for the raising of animals. The general conceptual model for excavation of the waste is the same as the conceptual model for the excavation borehole (although the parameterisation of the pathways would be different), and is therefore shown in Figure 54. A site dweller growing crops on soil contaminated with the excavated spoil would be exposed by alternative pathways, as discussed above. The general conceptual model for this situation is the same as the Reference Scenario solid release illustrated in Figure 52.

D.3.5 FEP AUDIT

An audit of the general conceptual models for the Human Intrusion Scenario has been undertaken in the same manner as for the Reference Scenario. Model assumptions have been compared with the ISAM FEP list (IAEA, 2002b). The ISAM FEPs that are addressed with the features and processes are presented in Table 28. This is followed by a summary of the FEPs that are not included, given in Table 29.

Table 28: Comparison of the Features and Processes for the Human Intrusion Scenario with the ISAM FEP List

Feature/Process	FEP Reference
Features	
Cap	2.1.05
Waste	2.1.01, 2.1.02, 2.1.03
Backfill	2.1.04
Engineered Structures	2.1.05
Overburden sediments and Bedrock	2.2.03
Soil	2.3.02
Biota	2.3.13
Houses and Buildings	2.4.07
Atmosphere	2.3.07, 2.3.10
Processes	
Physical Degradation of Man-made Structures	2.1.07, 2.1.08, 2.1.09
Contaminant Transport from the Near Field	2.1.12, All 3.2.-.
Site Investigation	1.4.02, 1.4.03, 1.4.08, 1.4.09, 3.2.12
Construction/Excavation	1.4.02, 1.4.06, 1.4.08, 1.4.09, 3.2.12
Uptake by Plants and Animals	3.2.13
Resuspension	3.2.10
Ingestion of Contaminated Media (Humans)	2.4.01, 2.4.02, 2.4.03, 2.4.05, 2.4.06, 2.4.08, 2.4.09, 2.4.10, 2.4.11, 3.3.01, 3.3.02, 3.3.04, 3.3.05, 3.3.06
Inhalation of Contaminated Media (Humans)	2.4.01, 2.4.02, 2.4.04, 2.4.05, 2.4.07, 2.4.08, 2.4.09, 2.4.10, 2.4.11, 3.3.02, 3.3.03, 3.3.04, 3.3.05, 3.3.06, 3.3.08
External Irradiation by Contaminated Media (Humans)	2.4.01, 2.4.02, 2.4.04, 2.4.05, 2.4.07, 2.4.08, 2.4.09, 2.4.10, 2.4.11, 3.3.02, 3.3.03, 3.3.04, 3.3.05, 3.3.06

Table 29: ISAM FEPs Not Addressed in the General Conceptual Models for the Human Intrusion Scenario

ISAM FEP Number and Short Name	Justification for Not Addressing the FEP
0.- Assessment Context FEPs	Issues of assessment context have already been addressed (see Section 2)
1.- External Factors FEPs (with the exception of those associated with future human actions)	External factors are discussed in relation to the definition of scenarios (see Section 4 and Appendix C)
2.1.06: Other engineered features materials, characteristics and degradation processes	No other engineered features of significance were identified.
2.1.10: Biological/biochemical processes and conditions (in near field)	The waste has a relatively low content of organic material (much being incinerated prior to emplacement in the permanent repository) and the potential for such processes is considered to be low.
2.1.11: Thermal processes and conditions (in near field)	There are no significant heat sources in the near field (cement curing is not considered significant).
2.1.13: Radiation effects (in near field)	The radionuclide concentrations are too low for significant radiation effects in structures such as radiolysis.
2.1.14: Nuclear criticality	The radionuclide concentrations are too low for criticality to be possible.
2.1.15: Extraneous materials	No extraneous materials of interest have been identified.
2.2 – Geological Environment Factors	These are not considered in the Human Intrusion Scenario and the geosphere is only relevant as a barrier to intrusion.
2.2 – Surface Environment Factors	The only surface environment factor that is considered relevant is the soil into which excavated radionuclides become mixed.
3.3.07 Non-radiological toxicity/effects	Non-radiological toxicity and effects have been excluded from consideration in this preliminary study by the Assessment Context (Section 2.2).

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APPENDIX E: MATHEMATICAL MODELS

CONTENTS

Page

Definition of Symbols used in this Appendix

Symbol	Definition	Unit
α_T	Transverse dispersion length	m
β	Fraction of the volume of a material through which water is flowing	unitless
$â_{UnDeg}$	Initial portion of the inventory that is available for transport in flowing water through the medium	unitless
$â_{Deg}$	Final portion of the inventory that is available for transport in flowing water through the medium	unitless
σ^2	Variance of the plume shape in the relevant transverse direction	m^2
Äh	The hydraulic gradient	unitless
Äx	Distance downstream	m
Δ^{ij}	Representative diffusion length between the two compartments	m
λ_{Diff}	'Forward' diffusive transfer	y^{-1}
λ_{Eros}	Transfer rate from soil compartment to a neighbouring soil (or other surface) compartment	y^{-1}
λ_{Flow}	Rate of transfer of contaminants due to water flows through a water body	y^{-1}
λ^{ij}_{Flow}	Advective transfer in water from compartment *i* to compartment *j*	y^{-1}
λ_{Rn}	Rn-222 decay rate	y^{-1}
λ_{Soil}	Transfer rate from soil compartments	y^{-1}
λ_{ST}	Transfer coefficient for sedimentation and remobilisation from water to sediment	y^{-1}
λ_V	Rate of ventilation of the space	y^{-1}
$\lambda_{Weather}$	Removal rate of irrigation water from the crop by weathering processes	y^{-1}
ε	Degree of saturation of the medium	unitless
ε_{Rn}	Emanating fraction for the material	unitless
κ	Capacity of the compartment	m^3
κ_C	Capacity of the compartment for the colloid phase	m^3
κ_L	The capacity of the compartment in the absence of sorption on to solids	m^3
κ_S	Capacity of the compartment for the solid phase	m^3
μ_{crop}	Interception fraction for irrigation water on the crop	unitless
ρ	Density	kg m^{-3}
ρ_{Cov}	Density of the cover	kg m^{-3}

τ_{gas}	Timescale over which gas production is assumed to take place	y
θ_{Flow}	Flowing porosity	unitless
θ_{Total}	Total porosity	unitless
Ö	Flux of contaminants in gas into the house	Bq m^{-2} y^{-1}
Φ_{gas}	Flux of contaminants in gas to the surface	Bq m^{-2} y^{-1}
Φ_{Rn}	Flux of radon gas	Bq m^{-2} y^{-1}
A	Cross-sectional area at right angles to the direction of flow	m^2
A_h	Floor area of the enclosed space	m^2
A^{tot}	Total surface area of compartments adjoining the donor compartment	m^2
a	Total number of moles of an element that can be in in a given compartment at any one time	mol
B	Person's average breathing rate whilst on a particular exposure material	m^3 y^{-1}
c_{Aero}	Concentration of dust in air	kg m^{-3}
C_{Anm}	Concentration of radionuclides in an animal product	Bq kg^{-1} fresh weight
C_{Aq}	Concentration of radionuclides in an aquatic foodstuff	Bq kg^{-1} fresh weight
C_{Coll}	Concentration of colloids in flowing water	kg m^{-3}
C_{crop}	Concentration of radionuclides in a crop	Bq kg^{-1} fresh weight
C_{EM}	Average radionuclide concentration in a particular exposure material	Bq m^{-3}
C_{gas}	Mean concentration of a radioactive gas in indoor air	Bq m^{-3}
C_L	Concentration of radionuclides in the liquid phase	Bq m^{-3}
C_{Past}	Concentration of radionuclides in pasture	Bq kg^{-1} fresh weight
C_{Ra}	Concentration of radium-226 in the source	Bq kg^{-1}
C_S	Concentration of radionuclides in the solid phase	Bq kg^{-1}
c_{Soil}	Amount of soil that adheres to plant surfaces	kg kg^{-1} fresh
C_W	Radionuclide concentration in the liquid phase of the compartment from which irrigation water is taken	Bq m^{-3}
$\overline{C}_s$	Average concentration over the whole of the solid	Bq kg^{-1}
CF_{Anm}	Element-dependent concentration factor for the animal	y kg^{-1} fresh weight

CF_{Aq}	Element-dependent concentration factor for the aquatic foodstuff	m^3 kg^{-1} fresh weight
CF_{Crop}	Element-dependent concentration factor for the crop	kg kg^{-1} fresh weight
CF_{Past}	Element-dependent concentration factor for the pasture	kg kg^{-1} fresh weight
CM_{EM}	Average radionuclide concentration in a particular exposure material	Bq kg^{-1} dry weight
D_c	Depth of cover	m
D_d	Diffusion length for radon in the material	m
D_{Eff}	Effective diffusion coefficient	m^2 y^{-1}
Dil	Dilution factor	unitless
D_{llel}	Depth of the donor compartment in the direction perpendicular to the erosion	m
DC_{ExtPt}	Dose factor for exposure to small objects	Sv y^{-1} Bq^{-1}
DC_{ExtSl}	Dose factor for exposure to contaminated soil	Sv kg y^{-1} Bq^{-1}
DC_{Gas}	Dose factor for inhalation of gas	Sv m^3 y^{-1} Bq^{-1}
DC_{Ing}	Dose factor for ingestion	Sv Bq^{-1}
DC_{Inh}	Dose factor for inhalation	Sv Bq^{-1}
d_{Irr}	Annual depth of irrigation water applied to the crop	m y^{-1}
E_{ExtObj}	Dose rate from exposures to small objects	Sv y^{-1}
E_{ExtSed}	Dose rate from external irradiation	Sv y^{-1}
E_{IngAnm}	Annual effective dose rate arising from the consumption of animal product	Sv y^{-1}
E_{IngAq}	Annual effective dose rate arising from the consumption of aquatic product	Sv y^{-1}
$E_{IngCrop}$	Annual effective dose rate arising from the consumption of contaminated crops	Sv y^{-1}
E_{IngSed}	Annual effective dose rate arising from the consumption of soil and sediment	Sv y^{-1}
E_{IngWat}	Annual effective dose rate from the consumption of contaminated water	Sv y^{-1}
$E_{InhDust}$	Annual effective dose rate from exposure to contaminated dust	Sv y^{-1}
E_{InhGas}	Annual effective dose rate from exposure to the gas	Sv y^{-1}
$f_{âCong}$	Fraction that has been congruently released at time *t*	y
f_{Beta}	Describes the transition of the values from undegraded to degraded state for medium	unitless
f_{gas}	Total fraction of the inventory of the contaminant which is assumed to be released as gas	unitless

$f_{PhysDeg}$	Describes the transition of the values from undegraded to degraded state for medium	unitless
f_{Prep}	Soil removed by food preparation	kg kg^{-1} fresh
f_{Trans}	Fraction of activity transferred from external to internal plant surfaces	unitless
I	Inventory of the radionuclide in question	Bq
I_{Anm}	Ingestion rate of animal foodstuffs by humans	kg (fresh) y^{-1}
I_{APast}	Total annual intake of pasture by animals	kg y^{-1}
I_{Aq}	Ingestion rate of aquatic foodstuffs by humans	kg y^{-1}
I_{ASed}	Total annual intake of soil by animals	kg y^{-1}
I_{AWa}	Total annual intake of water by animals	m^3 y^{-1}
I_{AWat}	Rate of drinking of contaminated water by animals	m^3 y^{-1}
I_{Crop}	Total annual intake of a crop by humans	kg y^{-1}
I_{Sed}	Total annual intake of soil by humans	kg y^{-1}
I_{Wat}	Consumption rate of drinking water by humans	m^3 y^{-1}
K	Hydraulic conductivity	m y^{-1}
K_d	Distribution (sorption) coefficient between the solid and liquid phases, which is element-dependent;	m^3 kg^{-1}
K_{deg}	Degraded hydraulic conductivity	m y^{-1}
K_{undeg}	Undegraded hydraulic conductivity	m y^{-1}
L	Characteristic length in the direction of flow	m
M_{obj}	Mass of the object	kg
O	Fraction of a year spent by a person on each exposure material	unitless
O_{anm}	Fraction of a year spent by an animal on a contaminated area	unitless
O_H	Fraction of a year spent by a person in a dwelling	unitless
Q^{ij}	Appropriate flux of water between compartments *i* and *j*	m^3 y^{-1}
Q_{Bath}	Volume of water that is released from the repository due to bathtubbing	m^3 y^{-1}
Q_{Flow}	Volumetric flow of the water	m^3 y^{-1}
Q_{Poss}	Total possible volume of flowing water for each compartment	m^3 y^{-1}
q_{corr}	Corrosion rate in congruent releases	m y^{-1}
q_{Eros}	Soil erosion rate	m y^{-1}
$q_{In}(t)$	Time-dependent flow rate of water	m y^{-1}
q_{Poss}	Potential Darcy velocity	m y^{-1}
q_{soil}	Soil erosion rate	m y^{-1}

R	Retardation coefficient	Unitless
r	Characteristic radius	m
S_{Cong}	A Boolean flag which should be set to have value 1 for those materials for which congruent release is considered	Unitless
Sol	Solubility limit of the compartment	mol m^{-3}
t	Time	y
$t_{BetaEnd}$	Time at end of change in proportion of medium contacted by flowing water	y
$t_{BetaStart}$	Time at start of change in proportion of medium contacted by flowing water	y
$t_{CemDegEnd}$	End of the chemical degradation period	y
$t_{CemDegStart}$	Start of the chemical degradation period	y
V	Total volume	m^3
V_h	Total volume of the enclosed space	m^3
W	Hypothetical 'radionuclide' with a infinite half-life, representing 1 m^3 of water	m^3 y^{-1}
W_d	The width of the plume width at a distance Δx downstream	m
W_0	The initial value of the plume width	m
Y_{Crop}	Yield of the crop	kg fresh weight of crop m^{-2}

E.1 PROPERTIES OF FEATURES AND COMPARTMENTS

Features are considered to be materials with a particular set of physical and chemical properties (e.g., density, sorption coefficient) in a particular location. Compartments are related to features and may represent directly the feature, or sub-divide it. Compartments and features can both be considered to have characteristic media associated with them, e.g., ‘sandy soil’ or ‘concrete’.

E.1.1 MEDIA

Various different media of interest in the near field can be identified from the features that are defined for the conceptual models. The key media are strongly related to the features that have been identified, and comprise:

- waste forms (ashes, compacted waste, and non-processible waste, which may be grouted or not);
- backfill (none or cement);
- engineered structures (including caps, which consist of alternating layers of materials, topped with soil);
- soil;
- lakeshore sediments;
- lake water and associated sediments;
- overburden sediments (sand and till);
- Shallow Bedrock Groundwater System;
- Intermediate Bedrock Groundwater System; and
- Deep Bedrock Groundwater System.

Each of these media is assumed to incorporate solid and liquid phases (there will be no solid phase if the porosity is unity). Gas space is taken to be the volume of a medium that is not solid or liquid, rather than being represented explicitly in the model. The following properties need to be specified for each medium in order to represent its main physical and chemical characteristics of interest:

- grain density, ρ (kg m^{-3});
- flowing porosity[5], θ_{Flow} (-);
- total porosity, θ_{Total} (-);
- degree of saturation when partially saturated, ε (-);
- the fraction of the volume of a material through which water is flowing, β (-);
- the hydraulic conductivity, K (m y^{-1});
- distribution (sorption) coefficient between the solid and liquid phases, K_d (m^3 kg^{-1}), which is element-dependent;
- elemental solubility, Sol,(mol m^{-3}) (only considered for the wastes);
- the effective diffusion coefficient, D_{Eff} (m^2 y^{-1}); and
- the concentration of colloids or other suspended solids in the liquid phase, C_{Coll} (kg m^{-3}).

Figure 55 illustrates that this approach allows the model to consider situations in which only part of a medium may be available for flow. This can be used to represent the presence of preferential flow pathways and allows fracture flow to be approximated (see for example Chapman et al. (2002)). It can also represent the gradual degradation of an otherwise (effectively) impermeable barrier in the near field (e.g., intact steel containers).

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[5] $\theta_{Flow} = \beta\ \theta_{Total}$

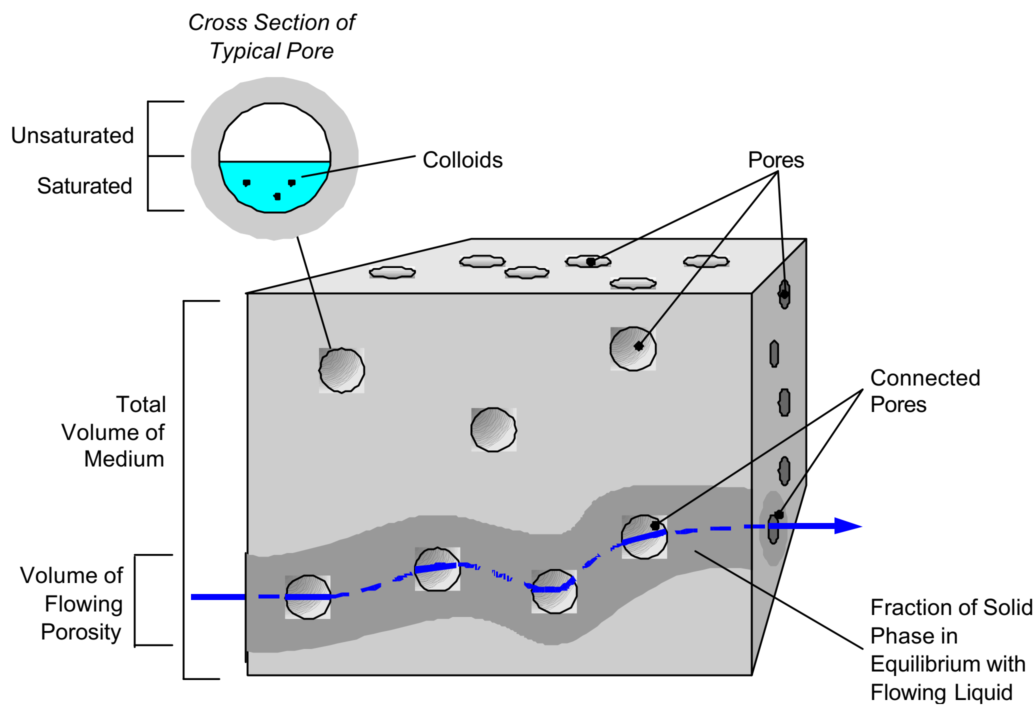

Figure 55: Key Properties Associated with Water Flow in Saturated and Partially Saturated Media

As has been noted, the evolution of the properties of the near field is considered in this study. The main properties that can represent the changing conditions, for the purposes of radionuclide transport modelling, are K_d, *Sol*, β and K.

E.1.2 COMPARTMENTS

Compartments are a subset of each medium and are related to the physical location of the features of interest. Consequently, compartments are also assigned properties that give them spatial dimensions. As has been noted, some compartments can correspond to abstract locations, for which it is not sensible to define a given length, height and depth. Therefore, the fundamental quantity is that of the total volume (V, m^3), and also surface area of the interface between compartments that is perpendicular to the flow (A_{Perp}, m^2), as well as a characteristic length in the direction of flow (D_{llel}, m, which can be determined from the ratio of V and A_{Perp}). Where helpful, explicit lengths, widths and heights can also be considered. Height is assumed to be the vertical dimension, length is the distance in the horizontal plane in the direction of water flow, and width is the distance in the horizontal plane, perpendicular to the direction of water flow. Some compartments can change size with time (e.g., waste that is being eroded). To avoid numerical calculation problems, these compartments must always have a small positive value for D_{llel}, which is set at 1 cm.

As water flow is fundamental to the transport of radionuclides in the models being considered, the volume flow rate (Q, $m^3\ y^{-1}$) and flow rate (q, $m\ y^{-1}$) are considered to be basic properties of compartments. Since AMBER has not been designed to model flow directly, these values are specified in a variety of ways.

The actual volume flow rate, Q_{Actual}, is derived from the possible (theoretical) Darcy velocity of groundwater, q_{Poss}. For unsaturated surface soils, this is the rate of infiltration (precipitation minus evapotranspiration and runoff). For saturated rocks it is assumed to be the product of the hydraulic conductivity and hydraulic gradient. This is multiplied by the saturation, å, beta factor, â, and perpendicular area, A_{Perp}.

In cases where it is necessary to calculate flows as a function of time (the near field), the actual volume flow rate, Q_{Actual}, is limited by the possible (theoretical) flow through the compartment. However, the volume flowing through the compartment may be less, as it is limited by the conductivity of 'upstream' compartments. In addition, if flow of water trying to enter a compartment is greater than the maximum flow that can pass through the compartment, the remainder can 'bypass' it by flowing around the compartment (as long as there is sufficient capacity for the bypass flow).

This information forms the basis of calculating radionuclide concentrations in the relevant compartments. However, the result also depends on some more detailed assumptions about the properties of its medium, which include the following:

- all pores (whether flowing or not) have the same degree of saturation;
- the fraction of the solid phase in contact with flowing water varies with the degree of saturation, i.e., it is given by $\varepsilon\beta$; and
- the concentration of radionuclides on colloids is the same as that in the solid phase, and only colloids in the flowing porosity are considered.

With these assumptions, the total amount of a radionuclide in any given compartment, I (Bq) can be written in terms of the concentration in the liquid phase, C_L (Bq m^{-3}) and in the solid phase, C_S (Bq kg^{-1}):

$$I = V\,[\varepsilon\theta_{Flow}C_L + \varepsilon\beta\rho(1-\theta_{Total})C_S + \varepsilon\theta_{Flow}C_{Coll}\,C_S] \tag{1}$$

Here ε is the degree of saturation of the medium and C_{Coll} is the concentration of colloids in flowing water (kg m^{-3}). The linear equilibrium assumption between the solid and liquid phases means that:

$$C_S = K_d\,C_L \tag{2}$$

Combining Equations 1 and 2 enables an expression for the concentrations in the liquid phase to be written.

$$C_L = \frac{I}{\kappa} \tag{3}$$

The denominator of Equation 3 is referred to as the capacity κ (m^3) of the compartment which can be written as:

$$\kappa = \kappa_L + \kappa_S + \kappa_c \tag{4}$$

where

$$\kappa_L = V\varepsilon\theta_{Flow} \tag{5}$$

$$\kappa_S = V\varepsilon\beta\rho(1-\theta_{Total})K_d \tag{6}$$

$$\kappa_c = V\varepsilon\theta_{Flow}K_d\,C_{Coll} \tag{7}$$

κ_L can be thought of as the capacity of the compartment in the absence of sorption on to solids (K_d = 0). If it is assumed that suspended solids/colloids move at the same velocity as the water, then a retardation coefficient, R (-), can be defined:

$$R = 1 + \frac{\beta\rho(1-\theta_{total})K_d}{\theta_{flow}(1+K_d\,C_{Coll})} \tag{8}$$

$$= \frac{\kappa}{\kappa_L + \kappa_c} \tag{9}$$

When considering the radiological consequences of radionuclide concentrations in the solid phase, rather than the concentration in that part of the solid that is contaminated, the average concentration over the whole of the solid may be more relevant:

$$\overline{C}_s = \beta\,\varepsilon\,K_d\,C_L \tag{10}$$

Equilibrium transfer factors can then be applied to the calculated concentrations to determine concentrations in other materials.

E.1.3 CHEMICAL AND PHYSICAL EVOLUTION

E.1.3.1 Chemical Evolution of Properties

The chemical evolution of the near field is dealt with by altering parameters that can be strongly dependent on the chemical conditions in the permanent repository. The chemical conditions are assumed to be dominated by the effects of cementitious materials, and their degradation in three distinct stages. For the parameters of interest, characteristics values may be specified at the beginning of each stage of cement degradation. The parameters of interest are:

- solubility; and
- sorption (distribution) coefficient.

Other parameters may be relevant, such as those associated with the physical changes that result from the leaching of the cement matrix. However, it is assumed that the timescale of physical degradation is shorter than that associated with chemical changes (for example, BNFL (2002) estimates that chemical degradation will take place over a period of greater than 100,000 years in the Drigg repository).

The mathematical modelling approach is to represent linearly changing K_d and solubility values over the period of Stage 1, constant values in Stage 2, and then linear changes over Stage 3 to a final value that is representative of the local host geologic medium. This is illustrated in Figure 56 for K_d and mirrors the pattern of changes in pH during the cement degradation, which is likely to be a key factor in determining the mobility of most radionuclides that can be considered ‘trace elements’ (i.e., not solubility limited). It is also appropriate for inorganic C-14, whose mobility is determined by bulk chemistry of the system. For inorganic C-14 the key process retaining the radionuclide in the near field is its reduced mobility due to its incorporation in immobile calcite during (at least) the first two stages of cement degradation. Organic C-14, and C-14 in non-alkaline cementitious environments can be regarded as effectively ‘mobile’ throughout the period of assessment. Nevertheless, it must be acknowledged that there remains some uncertainty concerning the behaviour of C-14 (and other radionuclides) during the chemical degradation of cement.

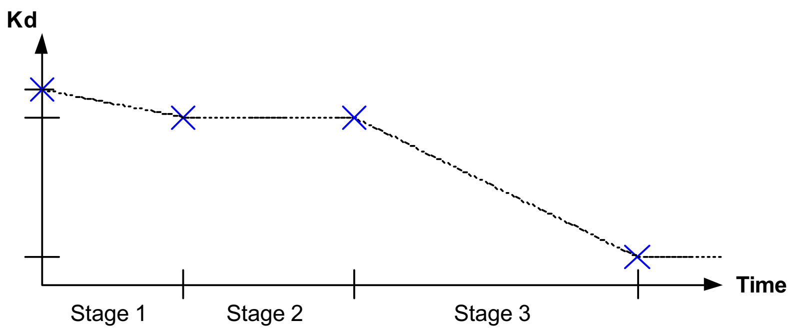

Figure 56: Interpolation of Values to Represent Chemical Conditions Associated with Cement Degradation

The approach to representing these changes mathematically is as follows. For those stages in which changes take place linearly, the interpolation of values is undertaken by defining a normalised value that ranges linearly from 0 to 1 over the interval. This value is then applied to the parameter values specified at the beginning and end of the period to determine an intermediate value. This approach is implemented with the following equations.

The interval itself is indicated with $b_{CemDeg}(n)$ which is 1 during the interval and 0 otherwise.

$$b_{CemDeg}(n,t) = 1 \qquad t_{CemDegStart}(n) \le t < t_{CemDegEnd}(n) \tag{11}$$

$$b_{CemDeg}(n,t) = 0 \qquad otherwise \tag{12}$$

A value between 0 and 1 is linearly interpolated at time t between the start ($t_{CemDegStart}$, y) and end ($t_{CemDegEnd}$, y) of the period.

$$f_{CemDeg}(n,t) = \frac{t - t_{CemDegStart}(n)}{t_{CemDegEnd}(n) - t_{CemDegStart}(n)} b_{CemDeg}(n) \tag{13}$$

The value of K_d or solubility at a given time t during a stage of degradation n, where n is 1, 2 or 3 (e.g., $K_d(n,t)$) is then calculated by interpolating between the values specified for the beginning of the stage, and the beginning of the following stage.

$$K_d(n,t) = \Big(\big(1 - f_{CemDeg}(n,t)\big)K_d(n) + f_{CemDeg}(n,t)\, K_d(n+1)\Big) b_{CemDeg}(n,t) \tag{14}$$

For the transition during the final stage of chemical degradation, $K_d(n+1)$ is replaced by the final value of K_d, K_{dFinal}, that applies after the cement has degraded. This value then applies at all times t $t_{CemDegEnd}$ (Stage 3).

The duration of concrete degradation stages is user defined (specified by the parameters $t_{CemDegStart}(n)$ and $t_{CemDegEnd}(n)$) and is dependent on the flux of water through the system. The integrated volume of water flowing through the repository can be determined by defining a hypothetical 'radionuclide', W, with an infinite half-life, which represents 1 m^3 of water. This is necessary because AMBER does not intrinsically have a concept of the flow of bulk materials in the system, so W is used as a 'marker'. A source of radionuclide W ($S(W,t)$, m^3 y^{-1}) is introduced at the upstream flow boundary of the system to represent the inflowing water, and assigned the boundary condition flux, i.e.

$$S(W,t) = q_{In}(t)\, A \qquad (15)$$

where $q_{In}(t)$ is the time-dependent flow rate of water (m y^{-1}) and *A* is the cross-sectional area (m^2) at right angles to the direction of flow. The total number of exchanges of cement/concrete porewater can then be related to the stages of cement degradation (e.g., see Berner (1990)). It is assumed that the first stage of degradation (loss of KOH and NaOH phases) is complete after 80 porewater exchange cycles, stage 2 ($Ca(OH)_2$ dissolution) is complete after about 1000 cycles, and the final stage (CSH leaching) is concluded after 7450 cycles.

E.1.3.2 Physical Evolution of Properties

The physical evolution of the near field encompasses the development of small and large cracks in concrete structures, the failure of structures and increases in the hydraulic conductivity of materials as a result of these and other processes. In order to provide sufficient functionality to represent this range of effects, two ways of representing the physical evolution of the near field are defined.

The first approach can be used to represent processes that act to change the fraction of the inventory in a compartment that is available for transport by flowing water. For example, if metal drums have a given uniform failure rate between times t_1 and t_2, the fraction of the inventory that is available for leaching can be described as a linear function from 0 to 1 over the interval.

The second approach that is available allows physical changes in hydraulic conductivity to be described over a given interval. This approach may be more suitable to represent the gradual physical degradation of concrete, as a result of the formation of micro-fractures due to structural effects and processes like rebar corrosion. It should be noted that physical changes in the porosity of materials is not modelled. A review of near field modelling approaches (Penfold et al., 2002) showed this parameter to be less significant than others, and therefore changes in porosity are considered to be a second-order effect.

The method of implementing the first of these models is as follows. The parameter *â* is introduced to describe, in general terms, the proportion of any given medium, *m*, (and therefore the fraction of its inventory) that may be contacted by flowing water. This value can be changed from 0 to 1 (i.e., none of the medium is wetted by flowing water, to flow in all the medium) over a user-defined period of time between $t_{BetaStart}$ and $t_{BetaEnd}$, both in units of y. A function f_{Beta} describes the transition of the values from physically undegraded to degraded state for medium m:

$$f_{Beta}(m,t) = 0 \qquad t < t_{BetaStart} \qquad (16)$$

$$f_{Beta}(m,t) = 1 \qquad t \quad t_{BetaEnd} \qquad (17)$$

$$f_{Beta}(m,t) = \frac{t - t_{BetaStart}(m)}{t_{BetaEnd}(m) - t_{BetaStart}(m)} \qquad \textit{otherwise} \qquad (18)$$

The value of *â(m,t)* is determined using the function as follows.

$$\beta(m,t) = (1 - f_{Beta})\, \beta_{UnDeg}(m) + f_{Beta}(m,t)\, \beta_{Deg}(m) \qquad (19)$$

The values of $â_{UnDeg}$ *(m)* and $â_{Deg}$ *(m)* may be set to any value between 0 and 1 to represent the initial and final portion of the inventory that is available for transport in flowing water through the medium m. It should be noted that $\hat{a}(m,t)$ is only applied to advective transfers, and diffusive transfers are unaffected by the fraction of the medium in which water flows.

The alternative method for representing physical degradation is by changes in the hydraulic conductivity of the relevant media. This can be represented by the definition of 'undegraded' and 'degraded' values for hydraulic conductivity, and a period over which the actual hydraulic conductivity of media should change from one value to the other. A simple linear interpolation is made between the values. The start ($t_{PhysStart}$, y) and end ($t_{PhysEnd}$, y) of the period can be specified separately for different media, as can the degraded and undegraded hydraulic conductivities, K_{Deg} and K_{UnDeg} (both in m y^{-1}).

A function $f_{PhysDeg}$ describes the transition of the values from undegraded to degraded state for medium m:

$$f_{PhysDeg}(m,t) = 0 \qquad t < t_{PhysStart} \qquad (20)$$

$$f_{PhysDeg}(m,t) = 1 \qquad t \quad t_{PhysEnd} \qquad (21)$$

$$f_{PhysDeg}(m,t) = \frac{t - t_{PhysStart}(m)}{t_{PhysEnd}(m) - t_{PhysStart}(m)} \qquad \text{otherwise} \qquad (22)$$

The value of $K(m,t)$ can be determined using the function as follows.

$$K(m,t) = (1 - f_{PhysDeg})\ K_{UnDeg}(m) + f_{PhysDeg}(m,t)\ K_{Deg}(m) \qquad (23)$$

E.2 DYNAMIC RADIONUCLIDE TRANSPORT PROCESSES

E.2.1 GENERAL PROCESSES CONSIDERED

Radionuclide transport is mainly represented with dynamic transfer processes (first order linear differential equations). The following dynamic transport processes are included in the model directly:

- advection of radionuclides in flowing groundwater;
- dispersion of radionuclides in flowing groundwater;
- diffusion of radionuclides through saturated media;
- bulk erosion of solids; and
- flow of liquids.

Radionuclide release from the waste can occur by various methods and is described in the following section. Radionuclide uptake in the biosphere, sedimentation/remobilization, suspension in air and gas migration and accumulation are dealt with using equilibrium transfers, as described later. These can be represented in this way because the assessment timescales of interest are greater than those associated with the processes. Consequently, equilibrium conditions can be assumed to exist between compartments representing the source and receptor (i.e., water and sediment, or waste and air).

All transfers from waste form compartments have the potential to be limited by solubility. This is only considered in waste form compartments, where concentrations of radionuclides are highest. The limit on the availability, a (in mol), of all isotopes of a particular element for transport is applied by considering the solubility limits for the compartment (Sol (t), mol m^{-3}) and the capacity κ (m^3).

$$a = Sol\ \kappa \qquad (24)$$

a defines the total number of moles of an element in a given compartment at any one time. This is the upper limit to the amount of an element that is available for transport. The remaining amount of the element that could desorb (according to the specified K_d) but would exceed this limit is assumed to be precipitated but not sorbed, and is not transported. Such 'precipitated' radionuclides may be available for dissolution if either the solubility limits change, or the concentration of the element in the compartment decreases to a point where the theoretically dissolved amount (*a*) is lower than the maximum available amount.

E.2.2 ADVECTION IN GROUNDWATER

A general expression for an advective transfer in water from compartment *i* to compartment *j* can be written as λ^{ij}_{Flow} (y^{-1}):

$$\lambda^{ij}_{Flow} = \frac{Q^{ij}\ (1 + C^{i}_{Coll}\ K^{i}_{d})}{\kappa^{i}} \qquad (25)$$

where Q^{ij} is the appropriate flux of water ($m^3\ y^{-1}$) between compartments *i* and *j* (which may be the product of some flow rate in m y^{-1} and the surface area perpendicular to the flow, A in m^2). The $C_{Coll}\ K_d$ component of the equation represents the transport of a portion of radionuclides sorbed to colloids, the concentration of which is C_{Coll} (kg m^{-3}).

The flow of water, Q^{ij} is either assumed or calculated with a simple water balance model. Codes such as AMBER are primarily intended to represent radionuclide transport and therefore have a limited ability to represent the governing equations for water flow. Calculations are generally related to the assumed hydraulic conductivity and hydraulic gradient. The water balance model is discussed in greater detail in Appendix G.3.2. For each compartment in which groundwater flows, the potential Darcy velocity (m y^{-1}) can be calculated with:

$$q_{Poss} = K\ \ddot{A}h \qquad (26)$$

where *Äh* is the hydraulic gradient (-).

The total possible volume of flowing water for each compartment (Q_{Poss}, $m^3\ y^{-1}$), without a change in the saturation, is then:

$$Q_{Poss} = q_{poss}\ A\ \hat{a}\ \mathring{a} \qquad (27)$$

where *A* is the area (m^2) of the face through which water flows, *â* is the fraction of each compartment through which water can flow and *å* is the degree of saturation. As noted above, where it is necessary to ensure that the water flows assumed are self-consistent, the various values of Q_{Poss} for adjacent compartments can be compared.

E.2.3 DISPERSION IN GROUNDWATER

The dispersion of radionuclides in the direction of groundwater movement (longitudinal dispersion) is not represented explicitly as a mathematical model. This is because when a flow path is split up into a number of equally sized compartments in the direction of groundwater flow, the mathematical representation as a series of well-mixed compartments introduces dispersion. The effective Peclet number (a measure of dispersion) is twice the number of compartments in the flow path (see discussion in Appendix B of Penfold et al. (2002)). Where the compartments are not of the same size, the effective Peclet number is dominated by the largest compartment.

Contaminant dispersion at right angles to the direction of groundwater movement is not represented explicitly as a process because the compartment dimensions can be defined to represent the increase in plume dimensions due to lateral spreading. Spreading of a plume transverse to the advective direction can be represented by:

$$\frac{d\sigma^2}{dx} = 2\alpha_T \tag{28}$$

where α_T is the transverse dispersion length (m), and σ^2 is the variance of the plume shape in the relevant transverse direction (m^2). The transverse dispersion length is considered to be some fraction of the overall pathlength. If the plume profile is taken to be uniform, i.e., a top-hat function of width W_d, then σ^2 has a value of $W_d^2/4$. Whence from Equation 28 one obtains:

$$W_d^{\,2} = W_o^2 + 8\alpha_T \Delta x \tag{29}$$

where W_0 is the initial value of the plume width (m), and W_d is its value a distance Δx downstream (m).

E.2.4 DIFFUSION

If the flux of radionuclides between two compartments is diffusive, then that flux can be approximated with:

$$\Phi^{ij} = \frac{A^{ij} D_{Eff} (C_L^i - C_L^j)}{\Delta^{ij}} \tag{30}$$

where A^{ij} (m^2) is the cross-sectional area relevant to the transport, D_{Eff} ($m^2\,y^{-1}$) is the effective diffusion coefficient for the donor compartment, C_L^i and C_L^j (Bq m^{-3}) are the radionuclide concentrations in the liquid phase in the donor and receiving compartments, and Δ^{ij} (m) is a representative diffusion length between the two compartments, generally taken to be the distance between the mid-points of the compartments in the direction of the diffusive flux. A ‘forward’ diffusive transfer can then be expressed as:

$$\lambda_{Diff}^{ij} = \frac{A^{ij} D_{Eff}}{\kappa^i \Delta^{ij}} \tag{31}$$

with a corresponding ‘backward’ diffusive transfer in the reverse direction. For details concerning the representation of diffusion using compartment models are given in Appendix B of Penfold et al. (2002).

E.2.5 BULK EROSION OF SOLIDS

The wind and water can result in the erosion of surface soils and sediments. This process can result in the transport of contaminated solid material. The transfer rate from soil compartment to a neighbouring soil (or other surface) compartment is taken to be given by:

$$\lambda_{Eros} = \frac{q_{Eros}}{D_{llel}} \quad (32)$$

where q_{Eros} is the soil erosion rate (m y^{-1}), *and* D_{llel} is the depth of the donor compartment in the direction perpendicular to the erosion (m). This simple representation assumes that contaminants in both the solid and liquid phases can be transported by this process.

In the Cover Erosion Calculation Case, the erosion of the waste is principally of interest, as the concentrations in the eroded waste will be very much greater than those in the cap and engineered structures. The delay before the erosion of the waste commences can simply be calculated by dividing the total thickness of the cover materials (i.e., the cap and the engineered roof of the vault in m) by the erosion rate q_{Eros}.

E.2.6 FLOW OF LIQUIDS

The rate of transfer of contaminants due to water flows through a surface water body (e.g., lake) is simply the ratio of the volumetric flow of the water Q_{Flow} (m^3 y^{-1}) and the total volume of water in the donor compartment V (m^3).

$$\lambda_{Flow} = \frac{Q_{Flow}}{V} \quad (33)$$

E.3 RADIONUCLIDE RELEASES FROM WASTE

There are various approaches to modelling radionuclide releases from waste. The most common approaches include:

- instant release (where the radionuclides in the waste form are available for transport by advection or diffusion as soon as the waste is contacted by flowing water);
- fractional release rate/leach rate (where the radionuclides in the waste are gradually released over a defined period of time, at a uniform rate, e.g., to represent container failure);
- congruent release (where the radionuclides in the waste are gradually released, the rate and period of time being determined by some rate of corrosion/dissolution of the host material, and its geometry); and
- diffusive release (where the radionuclides in the waste form are available for transport by diffusion only).

These releases can be modelled using the general functionality described in the preceding section, and the approach is described below for each type of release in turn. For the current study, the instant release model (Appendix E.3.1) and diffusive release model (Appendix E.3.4) are used consistent with Penfold et al. (2002). The diffusive release model is applied to all repository concepts, whilst the instant release model is applied to the CAGCV concepts once engineered structures have degraded sufficiently to allow flow through the repository.

E.3.1 INSTANTANEOUS RELEASE

Instantaneous release of radionuclides from waste assumes that, once flowing water contacts the waste, all radionuclides are immediately available for dissolution from the waste matrix, from where they may be subject to advection and diffusion transport into the surrounding materials (backfill, engineered structures, etc.). The proportion of the radionuclides that are available for transport is dependent on the distribution coefficient (K_d,

$m^3\ kg^{-1}$) and solubility limit (*Sol*, mol m^{-3}) of the waste form. This type of release may be represented in the following way.

- The radionuclide inventory of the waste form of interest (*I*, Bq) is assigned to the relevant waste form compartment.
- The fraction of waste available for flow, *â*, should be set to unity for both 'undegraded' and 'degraded' materials (i.e., all the inventory is available for transport in flowing water).
- If diffusive releases are required, a non-zero value of the effective diffusion coefficient D_{Eff} ($m^2\ y^{-1}$) can be specified.
- The hydraulic conductivity of the waste *K* (m y^{-1}) can be changed, if required, using the method described above.

E.3.2 FRACTIONAL RELEASE RATE

A fractional release rate assumes that the inventory of radionuclides gradually become available for transport by flowing water, over a user specified period from t_{Start} to t_{End} years, at a uniform rate per year (i.e., 1/($t_{End} - t_{Start}$) per year). It can be appropriate to represent a uniform degradation rate of steel waste containers, for example. Such a release can be represented in the following way.

- The radionuclide inventory of the waste form of interest (*I*, Bq) is assigned to the relevant waste form compartment.
- The fraction of waste available for flow, *â*, should be set to zero for 'undegraded' and 1 for 'degraded' materials. A timescale should be set by specifying the times that the material is fully undegraded and fully degraded, in $t_{â}$ (years).
- If diffusive releases are required before and during the period of release, a non-zero value of the effective diffusion coefficient D_{Eff} ($m^2\ y^{-1}$) can be specified.
- The hydraulic conductivity of the waste *K* (m y^{-1}) can be changed, if required, using the method described above.

As has been discussed, diffusive releases may be considered before and during this period, or not, by setting the effective diffusion coefficient D_{Eff} ($m^2\ y^{-1}$). The fractional release model assumes no sorption on or solubility constraint within the waste form.

E.3.3 CONGRUENT RELEASES

Congruent release is a more physically based form of fractional release. In this case, the rate of release at time *t* is not uniform, but dependent on the geometry of the materials considered. It is especially appropriate for representing the release of radionuclides dispersed within a largely impermeable matrix, e.g., activation products in steel, or vitrified liquid waste.

A simple cylindrical geometry has been assumed, from which a release occurs according to the corrosion rate (assumed to be uniform), q_{corr} (m y^{-1}). If the cylinder (e.g., a steel rod) has characteristic radius of *r* (m), the fraction that has been released at time *t* (y) is:

$$f_{\beta Cong}(t) = 1 - \frac{(r - q_{Corr}\ t)^2}{r^2} \qquad q_{Corr}\ t \quad r \qquad (34)$$

$$f_{âCong}(t) = 1 \qquad \textit{otherwise} \qquad (35)$$

In order to specify such a form of release, the following approach is used.

- The radionuclide inventory of the waste form of interest (*I*, Bq) is assigned to the relevant waste form compartment.
- The fraction of waste available for flow, *â*, should be set to zero for 'undegraded' and 1 for 'degraded' materials.
- The parameter S_{Cong} (a Boolean flag, which has value 1 or 0) should be set to be 1 for those materials for which congruent release is considered, and relevant values of r and q_{Corr} should be assigned.
- If diffusive releases are required before and during the period of release, a non-zero value of the effective diffusion coefficient D_{Eff} ($m^2\ y^{-1}$) can be specified.
- The hydraulic conductivity of the waste *K* ($m\ y^{-1}$) can be changed, if required, using the method described above.

E.3.4 DIFFUSIVE RELEASE

A diffusive release of radionuclides can occur when none of the inventory is available to flowing water. Diffusion may occur through the waste form (and possibly through the container) into the surrounding material. A solely diffusive release is represented by setting the fraction of the waste available for flow to zero.

E.4 REPRESENTATION OF SPECIFIC TRANSPORT PROCESSES

There are several situations in which the general processes for representing dynamic radionuclide transport, described in Appendix E.2, are modified to represent specific transport processes. The approach and assumptions are summarised below.

E.4.1 BATHTUBBING

The volume of water that is released from the repository due to bathtubbing (Q_{Bath}, $m^3\ y^{-1}$) is calculated by considering the volume of water flowing through the repository at a given time, compared with the capacity for the underlying material (sand or till) to conduct the water. The excess (if there is an excess) is assumed to be released at the base of the repository. There, the water flows through the soil, with a total flow rate equal to Q_{Bath} plus infiltrating rainfall (calculated from the rate of infiltration, q_{Inf}, $m\ y^{-1}$, and the perpendicular surface area of the soil, A_{Perp} m^2). This water is assumed to drain eventually to Lake Huron (see Appendix D.2.4.4); this transfer is represented using Equation 25 given in Appendix E.2.2. Radionuclides are also lost from the soil due to erosion; this process is represented using Equation 32 given in Appendix E.2.5. The concentration of a radionuclide in the soil is calculated using the equations given in Appendix E.1.2.

E.4.2 WELL WATER

The radionuclide concentration in well water is assumed to be equal to the concentration of porewater in the geosphere at the point at which the well intercepts the plume. However, the transfer of contaminants to surface soils by irrigation is represented with a dynamic transfer model. The rate of the transfer is equal to the depth of irrigation water that is applied, q_{Irr} $m\ y^{-1}$, and the area that is irrigated, A_{Perp} m^2, for the soil in question. Losses from the soil and radionuclide concentrations in the soil are calculated using the same equations as for the Bathtubbing Calculation Case.

E.4.3 EROSION OF THE COVER

The cover (cap and near-field structures) are assumed to be eroded at the same rate as surface soils, q_{Eros} m y^{-1}, for the Gas Release and Cover Erosion Calculation Cases. Its depth at any given time t is its initial depth D_c minus q_{Eros} x t. The depth of the cover cannot be negative. The transfer of contaminants to surface soils by erosion is represented by Equation 32 given in Appendix E.2.5. Losses from the soil and radionuclide concentrations in the soil are calculated using the same equations as for the Bathtubbing and Well Release Calculation Cases.

E.5 BIOSPHERE TRANSFERS AND EXPOSURE MODELS

The biosphere transfers and exposure models are described below. These are consistent with Beak (2002).

These general equations are applied to calculate effective dose rates for all potentially exposed groups considered. However, different exposure groups are considered to be exposed to different sources of contamination (Table 30). Consequently, the concentration of contaminants in soil (CM_{EM}, Bq kg^{-1}) or water (C_W, Bq m^{-3}) can relate to different areas of soil or water, depending on the calculation case.

Table 30: Soil and Water Compartments Considered for Different Calculation Cases

Calculation Case	Concept(s)	Potential Exposure Group	Source of Contaminated Soil	Source of Contaminated Water
Lake Release	CAGCV	Fisherman	Shore Sediments	Lake Release Zone
Lakeshore Release	CAGCV	Fisherman	Shore Sediments	Lake Release Zone*
Well Release	CAGCV	Farmer	Irrigated Soil	Well water
Bathtubbing	CAGCV-T only	Site dweller	Soil through which bathtubbing water flows	-
Gas Release	CAGCV	Site dweller	-	-
Cover Erosion	CAGCV	Site dweller	Soil onto which waste is eroded	-
Lake Release	DRCV	Fisherman	Shore Sediments	Central Basin of Lake
Shaft Pathway	DRCV	Fisherman	Shore Sediments	Central Basin of Lake
Exploration Borehole	CAGCV & DRCV	Intruder	Waste**	-
Excavation	CAGCV	Intruder and Site dweller	Waste**	-

Note:
***In this case, the release of contaminants is not directly to lake water, but to a near-shore lake water compartment, which is used for assessing fishing and water ingestion dose rates.
** For the intruder a dilution factor of 1.0 is assumed (i.e., no dilution), whilst for the site dweller a factor of 0.1 is assumed.

E.5.1 EXTERNAL IRRADIATION

The effective dose rate from external irradiation depends on the concentration of contaminants in the material and the geometry of the source. For exposure to contaminated soil, sediments or rock, a semi-infinite plane of contamination is assumed. The dose rate, E_{ExtSed} (Sv y^{-1}) is then:

$$E_{ExtSed} = C_{EM}\ O\ Dil\ DC_{ExtSl} \tag{36}$$

where C_{EM} (Bq m^{-3}) is the average radionuclide concentration in a particular exposure material (*'EM'* could be soil or lakeshore sediments, for example) and the Occupancy (*O*, unitless) is the fraction of a year spent by a person on each exposure material. *Dil* is a dilution factor that is only used in the Excavation Calculation Case for the Human Intrusion Scenario to take account of the mixing of waste with other materials such as soil or engineered structures. For the calculation of doses to the site dweller potential exposure group it is set to 0.1; for the intruder potential exposure group it is set to 1. The dose factor, DC_{ExtSl} (Sv m^3 y^{-1} Bq^{-1}) is radionuclide-dependent.

For exposures to small objects, such as borehole samples considered in the Human Intrusion Scenario, a different approach is used. The effective dose rate, E_{ExtObj} (Sv y^{-1}) is:

$$E_{ExtObj} = CM_{EM}\ O\ M_{obj}\ DC_{ExtPt} \tag{37}$$

The dose factor used in this equation, DC_{ExtPt} (Sv y^{-1} Bq^{-1}), relates to a point source. The mass of the object considered is M_{obj} (kg) and the radionuclide concentration, CM_{EM}, is in Bq kg^{-1}.

E.5.2 INGESTION OF SOIL AND SEDIMENT

Contaminated soil or sediment could be ingested inadvertently, giving rise to radiation dose rates. The general equation for calculating the dose rates, E_{IngSed} (Sv y^{-1}) is given below.

$$E_{IngSed} = CM_{EM}\ O\ I_{Sed}\ DC_{Ing} \tag{38}$$

The dose rate is calculated from the product of the concentration in the material in the contaminated area, the occupancy in the contaminated area and the ingestion rate of soil and sediment from all areas (I_{Sed}, kg y^{-1}). DC_{Ing} is the dose factor for ingestion (Sv Bq^{-1}).

E.5.3 INGESTION OF CROPS

Soil contaminated with radionuclides could be used to grow crops. The concentration in the crop is calculated with (JNC, 2000):

$$C_{Crop} = (CF_{Crop} + (1 - f_{Prep})c_{Soil})\ CM_{EM} + \mu_{Crop} d_{Irr} C_W \frac{(1 - f_{Prep}) + f_{Trans}}{Y_{Crop}\ \lambda_{Weather}} \tag{39}$$

The equilibrium soil-to-plant concentration factor, CF_{Crop} (kg kg^{-1} fresh weight) is dependent on the element and crop type. Soil is assumed to adhere to plant surfaces, the quantity being c_{Soil} (kg kg^{-1} fresh), although it can also be removed by food preparation, the fraction lost being f_{Prep}. The final term accounts for interception of contaminated irrigation water by the plants. μ_{crop} is the interception fraction for irrigation water on the crop (unitless), whilst d_{Irr} is the annual depth of irrigation water applied to the crop (m y^{-1}). The radionuclide concentration in the compartment from which irrigation water is taken is given by C_W (Bq m^{-3}). f_{Trans} is the fraction of activity transferred from external to internal plant surfaces (unitless), Y_{Crop} is the yield of the crop (kg fresh weight of crop m^{-2}) and $\lambda_{Weather}$ is the removal rate of irrigation water from the crop by weathering processes (y^{-1}).

Pasture is assumed not to be irrigated, and there are no food preparation losses:

$$C_{Past} = (CF_{Past} + c_{Soil})\ CM_{EM} \tag{40}$$

The effective dose rate arising from the consumption of contaminated crops, $E_{IngCrop}$ (Sv y^{-1}), is calculated by summing over all crops consumed using:

$$E_{IngCrop} = \sum_{Crop} C_{Crop}\ I_{Crop}\ DC_{Ing} \tag{41}$$

where C_{Crop} is the concentration of radionuclides in a crop (Bq kg^{-1} fresh weight), and I_{Crop} is the total annual intake of a crop by humans (kg (fresh weight) y^{-1}).

E.5.4 INGESTION OF ANIMAL PRODUCTS

Animals may also be raised on the land being considered. Potential dose rates associated with the consumption of meat, offal and milk obtained from these animals is accounted for with the following equations.

The concentration of contaminants in animal products, C_{anm} (Bq kg^{-1}), is calculated with:

$$C_{anm} = CF_{Anm}\ (O_{anm}\ C_{Past}\ I_{APast} + O_{anm}\ CM_{EM}\ I_{Ased} + I_{Awat} C_W) \tag{42}$$

Here, the concentration factor for the relevant animal product is CF_{Anm} (y kg^{-1}). The first term refers to the intake of pasture grazed by the animal when it is present outside in a contaminated area (for duration O_{anm}). I_{APast} (kg y^{-1}) is the total annual intake of pasture. Animals also ingest soil; the total annual intake rate of I_{ASed} (kg y^{-1}) is multiplied by the occupancy in a contaminated area. The final term allows for animals to drink contaminated water with concentration C_W (Bq m^{-3}) at a rate I_{AWat} (m^3 y^{-1}).

The effective dose rate arising from the consumption of contaminated animal products, E_{IngAnm} (Sv y^{-1}), is calculated in a similar manner to those for crops by summing the contribution from each animal product:

$$E_{IngAnm} = \sum_{Anm} C_{Anm}\ I_{Anm}\ DC_{Ing} \tag{43}$$

where C_{Anm} is the concentration of radionuclides in the animal product (Bq kg^{-1} fresh weight), and I_{Anm} (kg (fresh weight) y^{-1}) is the ingestion rate of the animal product.

E.5.5 INGESTION OF AQUATIC FOOD

Fish may be obtained from the lake. The concentration of contaminants in any aquatic animal or plant (C_{Aq}, Bq kg^{-1} fresh weight), is calculated with:

$$C_{Aq} = C_W\ CF_{Aq} \tag{44}$$

where C_W is the radionuclide concentration (Bq m^{-3}) in the lake water and CF_{Aq} is the element-dependent concentration factor for the foodstuff (m^3 kg^{-1}).

The effective dose rate which could result from the ingestion of these foods is given by summing over all aquatic foodstuffs:

$$E_{IngAq} = \sum_{Aq} C_{Aq}\ I_{Aq}\ DC_{Ing} \tag{45}$$

where I_{Aq} (kg y^{-1}) is the ingestion rate of aquatic foodstuffs.

E.5.6 INHALATION OF CONTAMINATED DUST

Soils and sediments can become suspended in air by natural or mechanical disturbance, and then be inhaled. This pathway is only considered for humans, and is not extended to animals, because they are already considered to ingest a large amount soil directly. A simple model is applied to derive the concentration of contaminants in air, the dust-loading approach; a constant concentration of soil is assumed to be in suspension in air. The effective dose rate $E_{InhDust}$ (Sv y^{-1}) can then be calculated based on the occupancy and breathing rate of a person for each of the exposure material.

$$E_{InhDust} = CM_{EM}\, O\, c_{Aero}\, B\, DC_{Inh} \tag{46}$$

In this expression, parameters are as before with the addition of c_{Aero} and B. c_{Aero} is the concentration of dust in air in (kg m^{-3}) and B is the person's average breathing rate whilst on a particular exposure material (m^3 y^{-1}).

E.5.7 INGESTION OF WATER

The annual effective dose rate from the consumption of contaminated water, E_{IngWat} (Sv y^{-1}), is given by the following:

$$E_{IngWat} = DC_{Ing}\, C_w\, I_{Wat} \tag{47}$$

where C_W is the radionuclide concentration in the liquid phase of the compartment from where the drinking water is sourced (Bq m^{-3}); and I_{Wat} is the consumption rate of drinking water (m^3 y^{-1}).

E.5.8 INHALATION OF GAS

Various gases may be released as a result of corrosion, microbial action and other processes. The flux of contaminants in gas to the surface, Φ_{gas} (Bq m^{-2} y^{-1}), can be taken as:

$$\Phi_{gas} = \frac{I\, f_{gas}}{\tau_{gas} A} \tag{48}$$

where I is the inventory of the radionuclide in question (Bq) and τ_{gas} is the timescale over which gas production is assumed to take place in (y). A is the area over which the gas is produced (m^2) and f_{gas} is the total fraction of the inventory of the contaminant which is assumed to be released as gas.

The expression assumes a uniform rate of gas generation. In addition, this approach does not deplete radionuclide concentrations in other media and therefore conservatively 'double counts' contaminants which could be released in gas.

A different approach is necessary when considering Rn-222 releases, as the characteristics of radon emanation and transport in media must be considered in greater detail due to the short half-life of the radioactive gas. Consistent with UNSCEAR (1988), the flux of Rn-222 gas (Φ_{Rn}, Bq m^{-2} y^{-1}) is given by:

$$\Phi_{Rn} = C_{Ra} \lambda_{Rn} \varepsilon_{Rn} \rho_{Cov} D_d \tanh \frac{D_C}{2 D_d} \quad (49)$$

C_{Ra} is the concentration of Ra-226 in the repository (Bq kg^{-1}). λ_{Rn} and ε_{Rn} are the Rn-222 decay rate (y^{-1}) and the emanating fraction for the material (unitless). D_c is the depth of cover (m) and ρ_{Cov} its density (kg m^{-3}). D_d is the diffusion length for Rn-222 in the material (m). The same approach can be applied to Rn-220, a gaseous radioactive progeny of Th-228 (sometimes referred to as 'thoron'). However, Rn-220 has a short half-life in comparison with Rn-222 (55 seconds, compared with 3.8 days) and accumulated concentrations are very much lower than for Rn-222.

Gaseous contaminants such as Rn-222 can accumulate in enclosed spaces overlying their source, such as a house, to much higher concentrations than in outside air, where they are dispersed very rapidly. Therefore, only indoor air is considered when calculating potential dose rate due to inhalation of gases. The mean concentration of a radioactive gas in indoor air, C_{gas} (Bq m^{-3}), is given by:

$$C_{gas} = \ddot{O} A_h / (\lambda_v V_h) \quad (50)$$

where $\ddot{O}$ (Bq m^{-2} y^{-1}) is the flux of the radionuclide into the house, A_h (m^2) and V_h (m^3) are the floor area and total volume of the enclosed space and λ_v is the rate of ventilation of the space (y^{-1}).

The annual effective dose rate from exposure to the gas (Sv y^{-1}) is calculated from:

$$E_{InhGas} = C_{gas} O_H B DC_{Gas} \quad (51)$$

The fraction of time spent in the dwelling is given by O_H and DC_{Gas} is a dose factor for the inhalation of gas (Sv Bq^{-1}).

E.6 REFERENCES

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APPENDIX F: DATA

CONTENTS

F.1 RADIONUCLIDE DATA

The radionuclides considered in this assessment have been selected from those presented in OPG's reference waste inventory. The radionuclide inventory is given in Leung and Krochmalnek (2000), and is presented earlier in Table 4. The radionuclide inventory considered for this study assumes a 'high waste generation scenario' at repository closure, and does not consider the emplacement of any decommissioning waste in the permanent repository.

All radionuclides specified in the OPG LLW inventory have been considered in this study with the exception of Ru-106, Ag-108m, Sb-125 and europium isotopes. These radionuclides have not been considered, because they have very short half-lives or are present at very low concentrations compared with other radionuclides. Table 31 gives details of these radionuclides, their half lives and total estimated activity.

Table 31: Radionuclides Not Considered in the Safety Assessment

Radionuclide	Half Life (y)	Estimated Total Activity at 2035 (Bq)	Fraction of Total Activity in Inventory[A]
Ru-106	1.01	$1.0x10^{9}$	$2x10^{-6}$
Ag-108m	127	$2.5x10^{7}$	$2x10^{-3}$
Sb-125	2.77	$2.5x10^{9}$	$5x10^{-6}$
Eu-152	13.3	$5.0x10^{8}$	$1x10^{-7}$
Eu-154	8.80	$2.6x10^{9}$	$2x10^{-7}$
Eu-155	4.96	$1.7x10^{8}$	$2x10^{-6}$

Note: (A) All the radionuclides contribute less than 0.1 % of the total activity of all radionuclides in OPG's reference inventory.

The remaining radionuclides presented in Table 4 have been considered in this study. In addition to these radionuclides, it is necessary to consider the radioactive progeny that can be formed by decay of some of the radionuclides. Table 32 presents the decay schemes relevant to consider in this study. This illustrates the additional radionuclides, such as Pb-210, that need to be considered, as they are decay products of radionuclides that require emplacement in the permanent repository. Some decay products are very short-lived with respect to the Safety Assessment timescales (e.g., with half lives of only a few days). These radionuclides can be assumed to be in secular equilibrium with their parent radionuclide if their half-life is less than 25 days. The radionuclides to which this applies are presented in Table 33.

Table 34 shows the full list of radionuclides considered in this study (radionuclides that are disposed, and their progeny, not including those in secular equilibrium). This table also presents the half-lives and decay constants for these radionuclides.

Table 32: Radionuclide Decay Schemes Adopted for the Safety Assessment

Radioactive decay						
Am-243	Pu-239	U-235	Pa-231	Ac-227		
Pu-238	U-234	Th-230	Ra-226	Pb-210	Po-210	
Pu-241	Am-241	Np-237	Pa-233	U-233	Th-229	
Pu-242	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210
Cm-244	Pu-240	U-236	Th-232	Ra-228	Th-228	

Note:
Short-lived radioactive progeny (e.g., with half-life of a few tens of days) have been assumed to be in secular equilibrium with their long lived parent (see Table 33).

Table 33: Radionuclides with Progeny in Assumed Secular Equilibrium

Radio-nuclide	Progeny Assumed to be in Secular Equilibrium
Sr-90	Y-90
Sn-126	Sb-126m, (0.14) Sb-126
Cs-137	(0.946) Ba-137m
Pb-210	Bi-210
Ra-226	Rn-222, Po-218, (0.9998) Pb-214, (0.0002) At-218, Bi-214, (0.9998) Po-214
Ra-228	Ac-228
Th-228	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (0.3593) Tl-208, (0.6407) Po-212
Th-229	Ra-225, Ac-225, Fr-221, At-217, Bi-213, Tl-209, (0.9784) Po-213, (0.0216) Tl-209, Pb-209
Ac-227	(0.0138) Fr-223, (0.9862) Th-227, Ra-223, Rn-219, Po-215, Pb-211, Bi-211, (0.9972) Tl-207, (0.0028) Po-211
U-235	Th-231
U-238	Th-234, (0.9980) Pa-234m, (0.0033) Pa-234
Pu-241	(2.45×10^{-5}) U-237
Am-243	Np-239

Note: Branching ratios for radioactive progeny have been indicated in brackets, preceding the radionuclide. If none is indicated, the branching ratio is 1.

Table 34: Radionuclide Half-Lives, Decay Rates and Associated Decays

Radionuclide	Half-life (y)	Decay Constant (y^{-1})
H-3	1.23×10^{1}	5.64×10^{-2}
C-14	5.73×10^{3}	1.21×10^{-4}
Cl-36	3.01×10^{5}	2.30×10^{-6}
Fe-55	2.70×10^{0}	2.57×10^{-1}
Co-60	5.27×10^{0}	1.32×10^{-1}
Ni-59	7.50×10^{4}	9.24×10^{-6}
Ni-63	9.60×10^{1}	7.22×10^{-3}
Se-79[B]	1.10×10^{6}	6.30×10^{-7}
Zr-93	1.53×10^{6}	4.53×10^{-7}
Sr-90[A]	2.91×10^{1}	2.38×10^{-2}
Nb-94	2.03×10^{4}	3.41×10^{-5}
Tc-99	2.13×10^{5}	3.25×10^{-6}
Sn-126[A,C]	2.10×10^{5}	3.30×10^{-6}
I-129	1.57×10^{7}	4.41×10^{-8}
Cs-134	2.06×10^{0}	3.36×10^{-1}
Cs-135	2.30×10^{6}	3.01×10^{-7}
Cs-137	3.00×10^{1}	2.31×10^{-2}
Sm-151	9.00×10^{1}	7.70×10^{-3}
Pb-210[A]	2.23×10^{1}	3.11×10^{-2}
Po-210	3.79×10^{-1}	1.83×10^{0}
Ra-226[A]	1.60×10^{3}	4.33×10^{-4}
Ra-228[A]	5.75×10^{0}	1.21×10^{-1}
Th-228[A]	1.91×10^{0}	3.63×10^{-1}
Th-229[A]	7.34×10^{3}	9.44×10^{-5}
Th-230	7.70×10^{4}	9.00×10^{-6}
Th-232	1.41×10^{10}	4.92×10^{-11}
Ac-227[A]	2.18×10^{1}	3.18×10^{-2}
Pa-231	3.28×10^{4}	2.11×10^{-5}
Pa-233	7.39×10^{-2}	9.38×10^{0}
U-233	1.59×10^{5}	4.36×10^{-6}
U-234	2.45×10^{5}	2.83×10^{-6}
U-235[A]	7.04×10^{8}	9.85×10^{-10}
U-236	2.34×10^{7}	2.96×10^{-8}
U-238[A]	4.47×10^{9}	1.55×10^{-10}
Np-237	2.14×10^{6}	3.24×10^{-7}
Pu-238	8.77×10^{1}	7.90×10^{-3}
Pu-239	2.41×10^{4}	2.88×10^{-5}
Pu-240	6.54×10^{3}	1.06×10^{-4}
Pu-241	1.44×10^{1}	4.81×10^{-2}

Table 34: Radionuclide Half-Lives, Decay Rates and Associated Decays

Radionuclide	Half-life (y)	Decay Constant (y^{-1})
Pu-242	3.76×10^{5}	1.84×10^{-6}
Am-241	4.32×10^{2}	1.60×10^{-3}
Am-243	7.38×10^{3}	9.39×10^{-5}
Cm-244	1.81×10^{1}	3.83×10^{-2}

Note: All data are taken from ICRP (1983) unless stated. (A) indicates those radionuclides with progeny in secular equilibrium (see Table 33). (B) indicates half live based on Chunsheng et al. (1997). (C) indicates half life based on Haas et al. (1996).

F.2 NEAR FIELD

F.2.1 DIMENSIONS

F.2.1.1 Covered Above Ground Concrete Vault

The CAGCV concept is described by Golder Associates (1998 and 2003), and this design is assumed for both the CAGCV on sand or till. It has 34 vaults with internal dimensions of 17 m wide, 27 m long and 7 m high. Each vault has an internal volume of approximately 3200 m^3. The vaults are arranged in two parallel rows of 17 vaults of each side of a central access aisle, which is 9 m wide, 320 m long and 7.5 m high.

It is assumed that the cap covering the repository is multi-layer, with the majority of the material being excavated sediments. It is assumed that it is 4.1 m thick (Golder Associates, 2003).

The total volume of the vaults is taken as 109,000 m^3; however, the waste form volume is only 89,000 m^3 (Leung and Krochmalnek, 2000). The backfill can fill the void space of 20,000 m^3. The central access aisle (24,000 m^3) could also be backfilled.

The thickness of the waste form is 7 m in the direction of water flow (vertical). The thickness of the void for backfill is estimated to be 0.9 m using Golder Associates (1998), and the engineered structure is also 0.9 m thick. The backfill void and engineered structure are assumed to be present with similar thickness both ‘upstream’ (above) and ‘downstream’ (below) the waste.

The area of waste forms perpendicular to the direction of flow has been calculated by dividing the total waste volume by the thickness, which gives 12,700 m^2. The proportion of the total volume that is ash, compacted and non-processible is 3.4%, 15.2% and 81.4% respectively. This implies that the area of each waste form, perpendicular to the direction of flow, is 430 m^2, 1930 m^2, and 10,340 m^2 respectively.

The total area of backfill is the internal width and length of the vault (27 m x 17 m) multiplied by all 34 vaults, or 15,600 m^2. The area available for ‘bypass flows’ (i.e., flow through backfill or engineered structures, not going through the waste) is the difference between these two values, i.e., 2900 m^2. The area of the engineered structures also allows for the thickness of walls (i.e., the area of each vault is 28.8 m x 18.8 m), and is 18,400 m^2, implying an area for bypass flows of 2800 m^2.

The volume of the waste, with the assumed length and area, is 89,000 m^3. The nominal volume of backfill in the vaults is simply the difference between the total volume of the vaults (27 m x 17 m x 7 m x 38 vaults) and the volume of waste, which is 20,000 m^3, plus the volume of the access aisle (24,000 m^3). The total volume of engineered structures is calculated from the above dimensions, assuming that the thickness of concrete is 0.9 m. This implies a total volume of 53,000 m^3 for the 34 vaults.

These data are summarised in Table 35.

Table 35: Dimensions Assumed for the CAGCV

Near-field Component	Length *L*, m (parallel to the flow direction)	Area *A*, m^2 (perpendicular to flow)	Bypass flow area A_{Bypass}, m^2 (perp. to flow)	Volume *V*, m^3
Waste Form	7	12,700	-	89,000
Backfill	0.9	15,600	2900	44,000
Engineered Structures	0.9	18,400	2800	53,000
Cap	4.1	18,400	-	-

Note:
The area of each individual waste form, perpendicular to the direction of flow, is 430 m^2 (ash), 1930 m^2 (compacted), 10,340 m^2 (non-processible).

F.2.1.2 Deep Rock Cavern Vault (DRCV)

The DRCV described by Golder Associates (1998), and the same design is assumed for the potential repository in Ordovician shales or limestone. It has 14 vaults with internal dimensions of approximately 10 m wide, 7 m high and 120 m long. There are no engineered structures other than the concrete floor of each vault and the concrete plug at the end of each tunnel. Backfill can surround the waste forms (it is assumed that 10% of the volume of each tunnel could be backfilled if required). As the direction of water flow is along the long axis of the tunnel, the effective 'length' of the waste is 216 m, and 24 m of backfill.

The internal volume of each vault is approximately 8400 m^3. The vaults are arranged in two parallel rows of 7 vaults of each side of a central access tunnel, which is 8 m wide, 5 m high and 160 m long, with an internal volume of 6400 m^3. The total internal volume of the DRCV repository is about 123,000 m^3 (including the central access tunnel).

The horizontal cross sectional area of the repository is calculated from the dimensions given above assuming a 15 m separation of adjacent vaults, which gives a total footprint of 38,400 m^2. The total cross-sectional area of vaults is 10 m x 120 m x 14 vaults = 16,800 m^2. The total cross sectional area of the backfill assumed to be the same as the cross sectional area of the vaults, in the horizontal plane. The cross sectional area of the waste assumes that it is on average 6 m high and has a total volume of 89,000 m^3 (89,000 / 6 = 14,800 m^2).

In addition, a shaft is assumed to be associated with the repository in one calculation case. This is assumed to have dimensions of 5 m x 5 m in the horizontal plane.

The dimensions are summarised in Table 36.

Table 36: Dimensions Assumed for the DRCV

Near-field Component	Length *L*, m (in vertical plane)	Area *A*, m^2 (in horizontal plane)	Volume *V*, m^3
Waste Form	6	14,800	89,000
Backfill	1	16,800	34,000
Shaft	From repository to Dolostone	25	-

Note: The product of the length and area give about 117,000 m^3 (the value without the central access tunnel); however, the central access tunnel is included in the total volume. Using the percentage of the total waste volume occupied by each waste type, noted for the CAGCV above, the area of each individual waste form, in the horizontal plane, is 500 m^2 (ash), 2300 m^2 (compacted), 12,000 m^2 (non-processible).

F.2.2 PHYSICAL CHARACTERISTICS

The density, porosity and degree of saturation (relevant to the CAGCV only) have been based on information from Golder Associates (1998), Dolinar et al. (1996), SKB (2001), Allard et al. (1991) and Leung and Krochmalnek (2000). No reliable data were available on possible colloid concentrations, and therefore the transport of radionuclides by this method was not modelled.

In addition to wastes, concrete and grout are considered as materials in the assessment. Concrete is structural material, including the addition of aggregate materials and other, such as structural reinforcing bars made of steel. Grout is a fluid cement that can be used to fill voids in waste and in repository vaults.

Compacted waste and ashes wastes that are ungrouted are assigned a grain density of 1500 kg m^{-3} and a porosity of 0.5 (compacted waste) or 0.3 (ash). Non-processible wastes that are ungrouted are assumed to have a grain density of 7500 kg m^{-3} (approximately that of solid steel) and a porosity of 0.9. The degree of saturation is based on the value for gravel in Golder Associates (1998), with the exception of ashes, for which the degree of saturation is assumed to be the same as cementitious grout.

Where wastes are grouted, there is a large ratio of grout to waste. The proportion of cement (by volume) in normal concrete is 15% (SKB, 2001). Taking account of the ratio of raw waste volume (assumed to be around 50% void space) to the total waste volume, the cement fraction is 0.075 for all wastes except non-processible waste, for which the greater porosity yields a value of 0.14. Wastes are assumed to have the same properties of concrete, although with higher porosity of 0.3 (based on SKB (2001)). It is assumed that the degree of saturation for all grouted waste in the CAGCV is 0.75.

The grain density, porosity and degree of saturation of cementitious grout backfill are taken to be the same as the grout for the waste form, described above. If no backfill is used, the void space is assumed to be filled with air and water.

Concrete density is 2400 kg m^{-3} (Golder Associates, 1998), with the proportion of cement (by volume) taken to be 15% (SKB, 2001). The porosity of concrete, 0.125, is the mean value for the range presented by Allard et al. (1991). It is assumed that the degree of saturation in the CAGCV is 0.75.

The selected values are presented in Table 37.

Table 37: Summary of Selected Parameter Values for Density, Porosity, Degree of Saturation, Fraction of Cement and Effective

Material	Grain Density (kg m^{-3}) ñ	Porosity è	Degree of Saturation^{A} å	Fraction of Cement f_{Cement}
Ungrouted Waste (ash)	1500	0.3	0.75	0
Ungrouted Waste (non-processible)	7500	0.9	0.14	0
Ungrouted Waste (compacted)	1500	0.5	0.14	0
Grouted Waste (ash)	2400	0.3	0.75	0.075
Grouted Waste (non-processible)	2400	0.3	0.75	0.14
Grouted Waste (compacted)	2400	0.3	0.75	0.075
Grout Backfill	2400	0.3	0.75	0.075
Concrete Engineered Structures	2400	0.125	0.75	0.15

Note: (A) Values for CAGCV only. When the repository is in the saturated region, it is assumed to resaturate instantaneously after closure, and the degree of saturation is taken as unity.

F.2.3 HYDROLOGICAL CHARACTERISTICS

The conceptual designs specified by Golder Associates (1998) provide specifications of the hydraulic conductivity of various construction materials. Based on this, it is assumed that ungrouted non-processible and compacted unconditioned waste have a hydraulic conductivity of 32 m y^{-1}. Ashes and grouted wastes are assumed to have the same hydraulic properties as cement grout, discussed below.

Nagra (1994) specify a range for the hydraulic conductivity for structural concrete and cement of 3x10^{-3} to 0.3 m y^{-1}, depending on the degree of degradation. It is assumed that grout has the characteristics of degraded cement instantaneously, whereas concrete degrades from over a period of time, the hydraulic conductivity changing linearly from an undegraded to degraded value. Undegraded low permeability concretes are considered to have a hydraulic conductivity of about 3 x 10^{-5} m y^{-1} in Golder Associates (1998). The value assumed in this study is 3.2 x 10^{-4} m y^{-1} (i.e., between the values suggested by Nagra (1994) and Golder Associates (1998)). Degraded concrete and cement grout has a hydraulic conductivity of 0.32 m y^{-1}.

The timescale for the physical degradation of low-permeability structural concrete is based on the work by Dolinar et al. (1996). It is assumed that reinforcement corrosion is the most significant mechanism for concrete degradation. The duration can be estimated by considering the time that chlorine ions would take to diffuse into the concrete at a sufficient depth to come into contact with rebar (and neglecting the function of rebar coating). On this basis, the repository concrete structures were assumed not to begin to fail until 500 years after construction, and then to take a further 1000 years to completely degrade. This approach is similar to that adopted in other studies (e.g., BNFL (2002)).

It is assumed that the hydraulic gradient is unity for the CAGCV and the same as exists in the host rock for the DRCV (considered below in Appendix F.3.1).

The effective diffusivity for compacted and non-processible ungrouted waste is assumed to be 0.02 m^{2} y^{-1}, based on values for sand and gravel presented in Savage and Stenhouse

(2002). The effective diffusivity for cementitious materials and concrete is taken as $8x10^{-5}$ m^2 y^{-1}, from values suggested by Dolinar et al. (1996). Cement values are assumed for ashes and grouted waste.

The selected data values are presented in Table 38.

Table 38: Summary of Selected Parameter Values for Hydraulic Conductivity

Material	Hydraulic Conductivity		Degradation timescale	Effective Diffusivity
	Undegraded K_{Undeg}, m y^{-1}	Degraded K_{Deg}, m y^{-1}	$t_{PhysDeg}$, y	D_{Eff} m^2 y^{-1}
Ungrouted Waste (ash)	0.32	0.32	-	$8x10^{-5}$
Ungrouted Waste (non-processible)	32	32	-	0.02
Ungrouted Waste (compacted)	32	32	-	0.02
Grouted Waste (ash)	0.32	0.32	-	$8x10^{-5}$
Grouted Waste (non-processible)	0.32	0.32	-	$8x10^{-5}$
Grouted Waste (compacted)	0.32	0.32	-	$8x10^{-5}$
Grout Backfill	0.32	0.32	-	$8x10^{-5}$
Concrete Engineered Structures	$3.2x10^{-4}$	0.32	500 (start)-1500 (end)	$8x10^{-5}$

Note: Concrete engineered structures are assumed to be present for CAGCV only.

Hydrological conditions can be altered by the evolution of other aspects the near field – principally the degradation of the cap for the CAGCV and the corrosion of containers in the CAGCV and DRCV.

Few studies have made a detailed analysis of the potential behaviour and performance of LLW repository caps, although BNFL (2002) has presented some detail for a medium-engineered cap envisaged for the Drigg repository in the UK. The approach used by BNFL recognises that a profiled cap has an important role in shedding water even if low permeability layers within it have degraded. The assumptions for this study are based on BNFL's work, and are implemented using the â parameter with values of 0.1 and 0.6 for $â_{Undeg}$ and $â_{Deg}$ (i.e., 10% of infiltration can penetrate the cap initially, rising to 60%).

These values multiply the theoretical hydraulic conductivity and gradient to determine the Darcy flow through the cap. For the CAGCV on till, the cap is assumed to have the same theoretical hydraulic conductivity as the till (0.02 m y^{-1}, see below), except in the Bathtubbing Calculation Case. In this case, the theoretical hydraulic conductivity is assumed to be much higher, and the maximum flow of water through the cap, q_{Cap}, is assumed to be equal to the rate of infiltrating water. Because the surficial sediments in the potential location of the CAGCV on sand have much greater hydraulic conductivity than the tills, the maximum flow of water through the cap for this concept is also assumed to be equal to the rate of infiltrating water.

Waste containers that are not lidded or sealed would allow contact with ingressing water immediately, and hence the potential for radionuclide release. This is the case for most of the non-processible waste bins. However, lidded and/or sealed containers such as drums would stop water contacting waste for some period of time, before they become corroded. Reported corrosion rates are of the order of 10^{-7} – 10^{-5} m y^{-1} (considering conditions ranging from anaerobic conditions in saturated concrete to aerobic environments in unsaturated conditions) (Höglund and Bengsston, 1991). The theoretical lifetime of an OPG metal drum is therefore 260 – 26,000 y. Whilst the latter value represents idealised conditions, it certainly illustrates that water may not fully contact all the wastes for at least several hundred years.

It is therefore assumed that the fraction of waste contacted by water rises from 0 to 100% over 250 years for ungrouted waste with no chemical conditioning (achieved by changing the â value from 0 – 1). For waste packages in cementitious environments, the lower corrosion rates are reflected with a maximum lifetime of 2500 years.

The data relating to cap degradation and waste package corrosion are given in Table 39.

F.2.4 GEOCHEMICAL CHARACTERISTICS

Sorption in cementitious environments can change as the chemical conditioning of the cement evolves over time. Cement degrades chemically according to three characteristic stages associated with the dissolution of the alkali metal hydroxides (Stage 1), the calcium hydroxide (Stage 2) and calcium silicate hydrates, or CSH, (Stage 3). The pH conditions are relatively constant (about pH 11) in stages 1 and 2, but decrease to neutral conditions at the end of Stage 3. The sorption reflects the alkalinity of the porewater, and therefore a different value of sorption applies during stage 3, compared with stages 1 and 2 (note that references that present separately values for sorption in stages 1 and 2 consistently quoted the same value for each stage). Sorption of certain elements is also different in oxidizing conditions, compared with reducing conditions. It has been assumed that water flowing through the CAGCV is oxidizing, and reducing for the DRCV.

The timescales for the stages are determined from the integrated number of porewater exchange cycles for the cementitious materials (i.e., the flux of water through these materials). Berner (1990) explored this issue and suggested that:

- Stage 1 (loss of KOH and NaOH phases) is complete after 80 porewater exchange cycles;
- Stage 2 ($Ca(OH)_2$ dissolution) is complete after about 1000 cycles; and
- Stage 3 (CSH leaching) is concluded after 7450 cycles.

The duration of the stages is determined by calculating the number of porewater cycles in AMBER. This is achieved by monitoring the integrated flow of water through the repository. Transitions from K_d values for different stages are assumed to be linear between the derived timescales. The calculated values are shown in Table 40.

Various databases are available on the sorption of elements in cementitious systems. The most recent and comprehensive compilations are provided by Bradbury and colleagues (Bradbury and Sarott (1995); Bradbury and van Loon (1998)) and Krupka and Serne (1998). These sources of data are used to determine appropriate values for use in this study, taking account of suggestions made by Savage and Stenhouse (2002). Representative values are presented in Table 41, alongside sorption coefficients for ungrouted wastes (Kozak, et al. 2000). It is assumed that at the end of Stage 3 the K_d is the same as that for the ungrouted waste.

Solubility limits are typically unimportant for radioactive waste in a near-surface repository, as the concentrations of radionuclides are generally well below solubility limits. However, in some circumstances they may be significant for certain radionuclides, such as uranium and plutonium isotopes. Solubility limits need only be considered for the wastes, as concentrations of radionuclides elsewhere in the modelled environment would be much lower. The most recent compilation of solubility data been developed by JNC (2000). These data have been presented in Table 42, supplemented with information from Krupka and Serne (1998).

Table 39: Summary of Selected Parameter Values for Cap and Waste Package Degradation

Medium	â value for undegraded material, $\hat{a}_{Undeg}$	â value for degraded material, $\hat{a}_{Undeg}$	Maximum flow rate through cap (m y^{-1}) q_{Cap}	Timescale of degradation, t_{Beta} (beginning – end in y)
Cap degradation				
- CAGCV-S	0.1	0.6	Infiltration rate (see Appendix F.4.1)	0 – 500
- CAGCV-T	0.1	0.6	0.02	0 – 500
- CAGCV-T (bathtubbing)	0.1	0.6	Infiltration rate (see Appendix F.4.1)	0 – 500
Corrosion of Waste Package:				
- Ungrouted	0	1	See Table 38	0 – 250
- Grouted	0	1	See Table 38	0 – 2500

Note: â is the fraction of the total volume of material that is available for flowing water to travel through. For all other media considered it is assumed to be 1 at all times. The cap is assumed to be present for the CAGCV only.

Table 40: Timescales for Cement Degradation

Repository Concept/ Calculation Case	Engineering	Stage 1 End (y)	Stage 2 End (y)	Stage 3 End (y)
CAGCV-S	Non-grouting	600	1000	6000
CAGCV-T	Non-grouting	3000	22,000	150,000
CAGCV-T (Bathtubbing)	Non-grouting	600	1000	6000
CAGCV-S	Grouting	710	4000	28,000
CAGCV-T	Grouting	8100	94,000	700,000
CAGCV-T (Bathtubbing)	Grouting	710	4,000	28,000
DRCV-S, DRCV-L	Non-grouting	-	-	-
DRCV-S, DRCV-L	Grouting	>1,000,000	>1,000,000	>1,000,000

Note: '-' indicates that, because no cementitious materials are present for the option, no chemical conditioning of the repository is considered. For the grouting options for the DRCV, '> 1,000,000' indicates that alkaline conditions are assumed to exist for the whole of the assessment period.

Table 41: Distribution Coefficients for the Near Field, in $m^3 kg^{-1}$

Element	Ungrouted Waste, K_d	Cementitious Materials, Oxidizing K_d		Cementitious Materials, Reducing K_d	
		Stage 1 and 2	Stage 3	Stage 1 and 2	Stage 3
H	0	0	0	0	0
C	0	0.5	0.01	0.5	0.01
Cl	$1x10^{-6}$	0.001	0	0.001	0
Fe	$1x10^{-3}$	0.1	0.01	0.1	0.01
Co	$1x10^{-4}$	0.1	0.01	0.1	0.01
Ni	$5x10^{-3}$	0.1	0.01	0.1	0.01
Se	$5x10^{-4}$	0	0	0	0
Sr	$1x10^{-4}$	0.1	0.01	0.1	0.01
Zr	0.05	5	1	5	1
Nb	0.05	0.5	1	0.5	1
Tc	0	0	0	1	1
Sn	0.1	0.5	1	0.5	1
I	0	0.02	0.001	0.02	0.001
Cs	0.001	0.001	0.005	0.001	0.005
Sm	0.001	0.5	0.5	0.5	0.5
Pb	0.001	0.5	0.1	0.5	0.1
Po	0.005	0.5	0.1	0.5	0.1
Ra	0.005	0.05	0.05	0.05	0.05
Ac	0.5	5	1	5	1
Th	0.01	5	1	5	1
Pa	0.5	0.5	0.1	0.5	0.1
U	$5x10^{-5}$	1	0.1	5	1
Np	$1x10^{-4}$	2	0.2	5	1
Pu	0.01	5	1	5	1
Am	0.001	5	1	5	1
Cm	0.001	5	1	5	1

Table 42: Solubility Limit Data for the Near Field

Element	Solubility Limit (mol m^{-3}) Stage 1, *Sol*	Solubility Limit (mol m^{-3}) Stage 2, *Sol*	Solubility Limit (mol m^{-3}) Stage 3, *Sol*
H	Unlimited	Unlimited	Unlimited
C	$7x10^{-5}$	0.07	0.01
Cl	Unlimited	Unlimited	Unlimited
Fe	0.2	0.03	0.002
Co	0.2	0.03	0.002
Ni	0.2	0.03	0.002
Se	Unlimited	Unlimited	Unlimited
Sr	0.1	0.1	0.1
Zr	Unlimited	Unlimited	Unlimited
Nb	Unlimited	Unlimited	Unlimited
Tc^{A}	Unlimited / $4x10^{-5}$	Unlimited / $4x10^{-5}$	Unlimited / $4x10^{-5}$
Sn	Unlimited	Unlimited	Unlimited
I	Unlimited	Unlimited	Unlimited
Cs	Unlimited	Unlimited	Unlimited
Sm	Unlimited	Unlimited	Unlimited
Pb	Unlimited	Unlimited	Unlimited
Po	Unlimited	Unlimited	Unlimited
Ra	0.001	0.001	0.001
Ac	$3x10^{-6}$	$4x10^{-6}$	$4x10^{-6}$
Th	$6x10^{-7}$	$7x10^{-7}$	$8x10^{-7}$
Pa	$2x10^{-5}$	$2x10^{-5}$	$2x10^{-5}$
U^{A}	0.1 / $1x10^{-5}$	0.1 / $1x10^{-5}$	0.1 / $1x10^{-5}$
Np^{A}	$9x10^{-3}$ / $5x0^{-6}$	$9x10^{-3}$ / $5x10^{-6}$	$9x10^{-3}$ / $5x10^{-6}$
Pu	$1x10^{-7}$	$1x10^{-7}$	$1x10^{-7}$
Am	$2x10^{-6}$	$3x10^{-6}$	$9x10^{-6}$
Cm	$2x10^{-6}$	$3x10^{-6}$	$9x10^{-6}$

Note:

A Where two values are given, the first corresponds to oxidizing conditions and the second to reducing conditions. Cm has been assumed to have the same solubility as Am.

F.2.5 RELEASE OF SOLIDS AND GASES

As well as releases of radionuclides in groundwater, two calculation cases consider release of radionuclides in solid material (the Cover Erosion Calculation Case) and as gas (the Gas Release Calculation Case).

Radionuclides are assumed to be released by surface erosion of the CAGCV repository in the Cover Erosion Calculation Case. The general surface erosion rate that has been adopted is $1x10^{-4}$ m y^{-1} (Kozak et al., 2000). The release is modelled as a delay (for the period that the cap and vault are eroded), followed by erosion at this rate of the horizontal surfaces of the repository. Eroded waste is then assumed to be deposited onto soil surrounding the repository with a width of 100 m. Whilst the erosion occurs, the cap depth is assumed to reduce.

The model for releases of H-3 and C-14 in gas is relatively simple. It has been assumed that the radionuclides are released with a characteristic timescale of 100 y, once waste containers are breached. f_{gas} is assumed to be 1 for the Gas Release Calculation Case. For Rn-222, a diffusion model is assumed. The radon diffusion coefficient is assumed to be 5×10^{-7} m^2 s^{-1} (UNSCEAR, 2000), and the diffusion distance is the depth of the cap (it is assumed to reduce with erosion, as above). The radon emanation fraction is 0.2 and assumed bulk density of the cap is 1600 kg m^3 (UNSCEAR, 2000). H-3, C-14 and Rn-222 are all assumed to accumulate in a house overlying the cap in the Gas Release Calculation Case. The house is assumed to have a volume of 250 m^3, floor area of 100 m^2 and air exchange rate of 1 h^{-1} (UNSCEAR, 2000).

F.3 GEOSPHERE CHARACTERISTICS

The geological formations of interest to the Safety Assessment have been studied for their suitability for LLW repository by Golder Associates (2003), and this work is the primary reference used to determine the data for use in the model. The data of interest are all associated with modelling radionuclide transport in these formations, which is either advective-dispersive or diffusive. Using the formulations described in Appendix E, these data are:

- hydraulic conductivity in m y^{-1};
- hydraulic gradient in m m^{-1};
- dispersion length in m;
- the fractional volume of material through which water flows (i.e.,β);
- the porosity (total and flowing porosity);
- degree of saturation for unsaturated materials;
- the grain density in kg m^{-3};
- elemental distribution coefficients in m^3 kg^{-1};
- the concentration of colloids in kg m^{-3}; and
- effective diffusion coefficient in m^2 y^{-1}.

In addition to the properties, it is necessary to define the physical dimensions of the paths that radionuclides could follow when migrating from the repository concepts, as identified in the descriptive conceptual hydrogeological models for the selected repository designs.

F.3.1 PHYSICAL CHARACTERISTICS

There are four groundwater systems of interest to this study, described in Golder Associates (2003):

- the Overburden Groundwater System, which includes overburden sediments (the weathered till (O-WT), unweathered till (O-UT) and sand (O-S) all need to be represented explicitly);
- the Shallow Bedrock Groundwater System, in which the dolostones are of interest (SB-D);
- the Intermediate Bedrock Groundwater System, in which Silurian dolostones are of interest (IB-D); and
- the Deep Bedrock Groundwater System, in which various shale formations (DB-S), and limestones (DB-L) are considered.

The physical characteristics associated with the rocks of interest in these groundwater systems are presented in Golder Associates (2003), and summarised in Table 43 (using the abbreviated terminology given above). No reliable data were available on colloid concentrations, and therefore the transport of radionuclides by colloid was not considered in the study.

Table 43: Physical Characteristics of Geological Materials

Parameter	Geological material						
	O-WT	O-UT	O-S	SB-D	IB-D	DB-S [B]	DB-L [B]
Hydraulic conductivity (m y^{-1})	0.02	0.006	300	300	3	$3x10^{-5}$	$3x10^{-5}$
Hydraulic gradient (-)	0.4	0.4	1	0.004	$8x10^{-4}$	na	na
Total porosity (-)	0.3	0.3	0.3	0.1	0.08	0.1	0.02
Flowing porosity (-)	0.3	0.3	0.3	0.01	0.008	0.01	0.002
Grain density (kg m^{-3}) [A]	2600	2600	2600	3000	2800	2900	2700
Effective diffusion coefficient (m^2 y^{-1}) [B]	0.02	0.02	0.02	0.005	0.003	0.005 (C)	0.003 (C)
Longitudinal dispersivity/Total path length (-)	0.1	0.1	0.1	0.1	0.1	-	-

Note:

The abbreviations are as follows: O-WT, O-UT and O-S refer to the weathered till, unweathered till and sands in the Overburden Groundwater System; SB-D refers to the dolostones in the Shallow Bedrock Groundwater System; IB-D refers to the dolostones in the Intermediate Bedrock Groundwater System; DB-S and DB-L refer to the Deep Bedrock Groundwater System (shale and limestones respectively).

A Grain density has been obtained using the total porosity and dry density given in Golder Associates (2002).

B Diffusive transport in rocks is only considered for the Ordovician Shale/Limestone Groundwater System.

C The calculation case in which the shaft seal is incomplete or faulty (the Shaft Pathway Calculation Case) considers a diffusive pathway via the shaft for 10% of the inventory. The shaft is assumed to have a diffusion coefficient of 0.02 m y^{-1} (the same as sand/gravel).

Generally, central values have been selected where ranges are presented in Golder Associates (2003). Where the range is less than one order of magnitude the arithmetic mean is taken, and the geometric mean is used for ranges greater than this (unless otherwise indicated in Golder Associates (2003)). Other issues considered in the development of these data are indicated below.

In the Overburden Groundwater System, the hydraulic conductivity of the weathered till has been taken to be the upper value of the range presented, with the geometric mean taken for the unweathered till.

The anisotropy of the hydraulic conductivities noted for the dolostones in the Shallow Bedrock Groundwater System (Amherstburg formation) has not been represented directly, but it is accounted for in the assumed vertical mixing of the plume which is assumed to occur over a vertical distance of 10 m.

Golder Associates (2003) quote a chloride-matrix effective diffusion coefficient. This is only used for transport in the Deep Bedrock Groundwater System. Diffusion from the source occurs in all directions. This is not modelled explicitly – rather it is assumed that 50 % of the inventory may diffuse in an upwards direction towards the overlying aquifer.

The possible incomplete sealing of the shaft is represented by considering a more diffusive pathway to the overlying aquifer for a portion of the wastes (10% is assumed). The exact hydrological characteristics of an incomplete shaft seal are highly uncertain. Therefore, the effective diffusion coefficient of the more diffusive pathway is taken to be the same as that of the sand/gravel.

F.3.2 GEOCHEMICAL CHARACTERISTICS

The general geochemical conditions are given in Golder Associates (2003). For safety assessment modelling, the key values of interest are equilibrium sorption coefficients, K_ds, (Table 44).

The only distribution coefficients presented in Golder Associates (2003) have been obtained from general compilations of such values. Site-specific values are not available. The values selected for the assessment reflect general rock types, but it has not been possible to distinguish details. Data have been taken from Golder Associates (2003), supplemented with Thibault et al. (1990).

F.3.3 FLOW PATHS

The physical dimensions of the flow paths considered in the Safety Assessment are derived from the conceptual hydrogeological models described by Golder Associates (2003), and the calculation cases identified in this study. The details are presented below for the CAGCV and the DRCV. For the CAGCV concepts, four possible groundwater flow paths are considered – release to the lake, shore sediments, via a well, or by bathtubbing. The flow path is described for each separately below. For the DRCV concepts, only two cases are considered – release under 'normal' conditions to the lake, or transport via a degraded shaft, then release to the lake. The flow path considerations are very similar, and are discussed together for the DRCV in shales or limestone.

F3.3.1 CAGCV (Lake Release)

The definition of the flow path dimensions for the CAGCV Lake Release Calculation Case draws on the conceptual model presented by Golder Associates (2003), with minor modifications to take account of the specific assumptions for the Calculation Case. The Calculation Case envisages the possibility of flow both directly through till (CAGCV-T), and through sand (the CAGCV-S), to the Shallow Bedrock Groundwater System.

In the first flow path, flow is directly downwards through 17 m of till to the Shallow Bedrock Groundwater System, followed by discharge into the Lake. It has been assumed that the first 3 m of till is weathered. The flow path via the sand envisages flow through 3.5 m of sand and 4 m of unsaturated carbonate. This then joins the Shallow Bedrock Groundwater System and flows to the lake. The weathered till is found further from the lakeshore than the sand, and this is reflected in the horizontal flow path lengths shown in Table 45.

F.3.3.2 CAGCV (Lakeshore Release)

This calculation case envisages that the radionuclides are released to the lakeshore sediments rather than the lake water. It is therefore simply assumed that the flow path in the Shallow Bedrock Groundwater System is 200 m shorter (i.e., the point of discharge is 200 m inland rather than at the shore). The potential point of discharge is not known, and this value is chosen as being representative of the location at which such a discharge could occur. Other aspects of the flowpaths remain the same, as shown in Table 46.

Table 44: Assumed Equilibrium Distribution Coefficients for the Geosphere (m^3 kg^{-1})

Element	Sand (O-S)	Till (O-UT, O-WT)	Dolostone and Limestone (SB-D, IB-D, DB-L)	Shale (DB-S)
H	0	0	0	0
C	0.005	0.02	0.005	0.001
Cl	0	0	0	0
Fe	0.22	0.8	0.22	0.165
Co	0.06	1.3	0.06	0.55
Ni	0.4	0.3	0.5	0.65
Se	0.15	0.5	0.15	0.74
Sr	0.015	0.02	0.015	0.11
Zr	0.6	2.2	0.6	3.3
Nb	0.16	0.16	0.16	0.9
Tc	0.0001	0.0001	0.0001	0.001
Sn	0.13	0.45	0.13	0.67
I	0	0	0	0
Cs	0.28	4.6	0.28	1.9
Sm	0.245	0.8	0.245	1.3
Pb	0.27	16	0.27	0.55
Po	0.15	0.4	0.15	3
Ra	0.5	36	0.5	9.1
Ac	0.45	1.5	0.45	2.4
Th	3.2	3.3	3.2	5.8
Pa	0.55	1.8	0.55	2.7
U	0.035	0.015	0.035	1.6
Np	0.005	0.025	0.005	0.055
Pu	0.55	1.2	0.55	5.1
Am	1.9	9.6	1.9	8.4
Cm	4.0	18	4.0	6.0

Notes:

The abbreviations are as follows: O-WT, O-UT and O-S refer to the weathered till, unweathered till and sands in the overburden Groundwater System; SB-D refers to the dolostones in the Shallow Bedrock Groundwater System; IB-D refers to the dolostones in the Intermediate Bedrock Groundwater System; DB-S and DB-L refer to the Deep Bedrock Groundwater System (shale and limestones respectively). The K_d values for sand and till relate to oxidizing conditions and those for limestone and shale relate to reducing conditions.

Table 45: Definition of the Flow Path for the CAGCV Lake Release Conceptual Model

Geosphere Medium	Flow Direction	Path length (m)	Depth (m)	Width (m)
CAGCV-T: Till – Shallow Bedrock Groundwater System				
Weathered Till (O-WT)	V	3	-	-
Unweathered Till (O-UT)	V	14	-	-
Dolostones (SB-D)	H	2000*	10	320**
CAGCV-S: Sand – Shallow Bedrock Groundwater System				
Sand (O-S)	V	3.5	-	-
Dolostones (SB-D)	V	4	-	-
Dolostones (SB-D)	H	725*	10	320**

Note:
*When modelled, the total flow path is increased by 67 m to account for the width of the CAGCV repository (67 m) parallel to the direction of groundwater flow in the Shallow Bedrock Groundwater System.
**The width given here is the initial plume width, which is increased to account for dispersion in downstream compartments. An expression for the plume spreading is included in Appendix E.2.3.

Table 46: Definition of the Flow Path for the CAGCV Shore Release Conceptual Model

Geosphere Medium	Flow Direction	Path length (m)	Depth (m)	Width (m)
CAGCV-T: Till – Shallow Bedrock Groundwater System				
Weathered Till (O-WT)	V	3	-	-
Unweathered Till (O-UT)	V	14	-	-
Dolostones (SB-D)	H	1800*	10	320**
CAGCV-S: Sand – Shallow Bedrock Groundwater System				
Sand (O-S)	V	3.5	-	-
Dolostones (SB-D)	V	4	-	-
Dolostones (SB-D)	H	525*	10	320**

Note:
*When modelled, the total flow path is increased by 67 m to account for the width of the CAGCV repository (67 m) parallel to the direction of groundwater flow in the Shallow Bedrock Groundwater System.
**The width given here is the initial plume width, which is increased to account for dispersion in downstream compartments. An expression for the plume spreading is included in Appendix E.2.3.

F.3.3.3 CAGCV (Well Release)

The Well Release Calculation Case considers the possibility that a well abstracts contaminated water from the Shallow Bedrock Groundwater System. The location of the well is obviously hypothetical, and therefore the distance from the repository is essentially arbitrary. For the purposes of this assessment, it is assumed that the well is located 100 m downgradient of the repository.

The repository itself is approximately 67 m wide, and therefore, depending upon the location of the waste, the distance to the well in the Shallow Bedrock Groundwater System may either be 100 or 100 + 67 m (i.e., the downstream or upstream edge of the repository). In this case, dispersion of the plume is cautiously not considered, reflecting the short distance of the well from the site. It should be noted that the discretisation of the geosphere means that concentrations are averaged in the modelled compartments, and therefore reflect the average concentration in the plume, at a given point downgradient of the repository.

The assumed parameter values are presented in Table 47.

Table 47: Definition of the Flow Path for the CAGCV Well Conceptual Model

Geosphere Medium	Flow Direction	Path length (m)	Depth (m)	Width (m)
CAGCV-T: Till – Shallow Bedrock Groundwater System				
Weathered Till (O-WT)	V	3	-	-
Unweathered Till (O-UT)	V	14	-	-
Dolostones (SB-D)	H	100*	10	320**
CAGCV-S: Sand – Shallow Bedrock Groundwater System				
Sand (O-S)	V	3.5	-	-
Dolostones (SB-D)	V	4	-	-
Dolostones (SB-D)	H	100*	10	320**

Note:
*When modelled, the total flow path is increased by 67 m to account for the width of the CAGCV repository (67 m) parallel to the direction of groundwater flow in the Shallow Bedrock Groundwater System.
**The width given here is the initial plume width, which is increased to account for dispersion in downstream compartments. An expression for the plume spreading is included in Appendix E.2.3.

F.3.3.4 CAGCV (Bathtubbing)

If the CAGCV cap materials degrade to the point at which they have a higher hydraulic conductivity than the underlying till, the 'bathtubbing' phenomenon may occur (this is only possible for the CAGCV on till - the hydraulic conductivity of the sand is sufficiently high for this situation not to occur). Excess water percolating through the repository is released horizontally into soil and then into a stream. Therefore, no geosphere media are required in the model.

F.3.3.5 DRCV in Shale (All Calculation Cases)

Radionuclides are released from DRCV in shale and travel by diffusion to the overlying Intermediate Bedrock Groundwater System, where they travel by advective transport to Lake Huron. Golder Associates (2003) present information on the likely flow paths, which is used to determine the data used in this study and presented in Table 48. Note that the depth of the dolostone indicated in this table is a nominal value, based on the depth of the Intermediate Bedrock Groundwater System. The flow path via the shaft is also indicated. The proportion of contaminants that could travel by this route would be dependent upon the detailed characteristics of the materials in the repository and their orientation, and would require detailed modelling to ascertain. Such information is not available at present, and therefore the simple assumption has been made that 10 % of the radionuclide inventory may be transported via the shaft.

Table 48: Definition of the Flow Path for the Lake Release Conceptual Model for the DRCV in Ordovician Shales

Geosphere Medium	Flow Direction	Path length (m)	Depth (m)	Width (m)
Shales (DB-S)	V	60	240	160
Shaft	V	60	5	5
Dolostone (IB-D)	H	15,000	120	160*

Note:
*The width given here is the initial plume width, which is increased to account for dispersion in downstream compartments. An expression for the plume spreading is included in Appendix E.2.3. The shaft pathway is only considered for the Shaft Pathway Calculation Case.

As diffusion of radionuclides from the repository would be in all directions, it has been assumed, simply, that 50% are directed upwards along the assigned pathlength (i.e., the remainder diffuse in the opposite direction).

F.3.3.6 DRCV in Limestone (All Calculation Cases)

Radionuclides are released from DRCV in limestone and travel by diffusion through the shales to the overlying Intermediate Bedrock Groundwater System, where they travel by advective transport to Lake Huron. The potential radionuclide flow paths for this case are an extension to those described for the shales. The assumptions are presented in Table 49.

Table 49: Definition of the Flow Path for the Lake Release Conceptual Model for the DRCV in Ordovician Shales

Geosphere Medium	Flow Direction	Path length (m)	Depth (m)	Width (m)
Ordovician Limestone (OL)	V	30	240	160
Ordovician Shales (OS)	V	230	240	160
Shaft	V	260	5	5
Silurian Dolostone (SD)	H	15,000	120	160*

Note:
* The width given here is the initial plume width, which is increased to account for dispersion in downstream compartments. An expression for the plume spreading is included in Appendix E.2.3. The shaft pathway is only considered for the Shaft Pathway Calculation Case.

F.4 BIOSPHERE CHARACTERISTICS

F.4.1 SURFACE WATER

The surface water balance at the Bruce site is substantially influenced by the presence of the low hydraulic conductivity tills near the surface. OPG (2000) presents data on the typical rates of precipitation, which is supplemented by Beak (2002) and information on run-off, presented in Sharma (1997).

The annual rate of precipitation is assumed to be 0.9 m y^{-1}, of which 20% falls as snow (OPG 2000). In addition, it is assumed that irrigation water is used for crops during summer months, at a total rate of 0.3 m y^{-1} (this is based on IAEA (2002), and is the mean of the range in Beak (2002)). Direct surface run-off has been measured as 0.2 m y^{-1} (Sharma, 1997). Evapotranspiration is assumed to be 0.5 m y^{-1} (Beak, 2002).

The hydraulic conductivity of the tills is assumed to limit downwards flow to 0.006 m y^{-1} (Golder Associates, 2003), whereas the sand does not limit vertical flow. For the till, the balance of the precipitation is assumed to flow by interflow (in the sand/gravel underlying the soil, but above the till) to enter the general surface water system and discharge into Lake Huron. For the sand, all infiltration acts as recharge.

The general near-surface water balance that has been developed using these assumptions is shown in Figure 57.

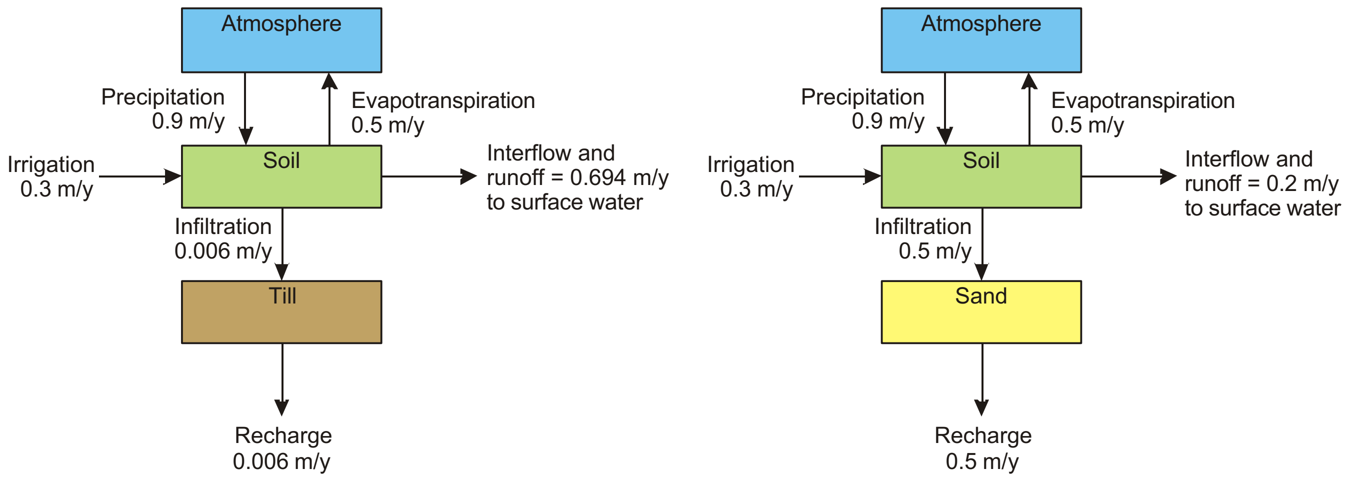

Figure 57: Assumed Near-Surface Water Balance (with Irrigation)

Recharge enters the overburden geosphere system as described in Appendix F.3.

The surface water is considered to be uncontaminated, except in the case of bathtubbing in which contaminated infiltrating water is released to soil. This is considered in the Bathtubbing Calculation Case. Excess water from bathtubbing flows through soil, as interflow, into a stream and then into the lake.

The characteristics of the lake are based on its discretisation into seven compartments for modelling purposes. These model compartments are illustrated in Figure 58, and the properties presented in Table 50.

Specific sedimentation and gaseous evasion rates have been recommended for carbon in Davis et al. (1993). However, net sedimentation and evasion of carbon (and other radionuclides) has cautiously been neglected (the significance of such effects for long-term safety are much less significant than the dilution that occurs in the lake).

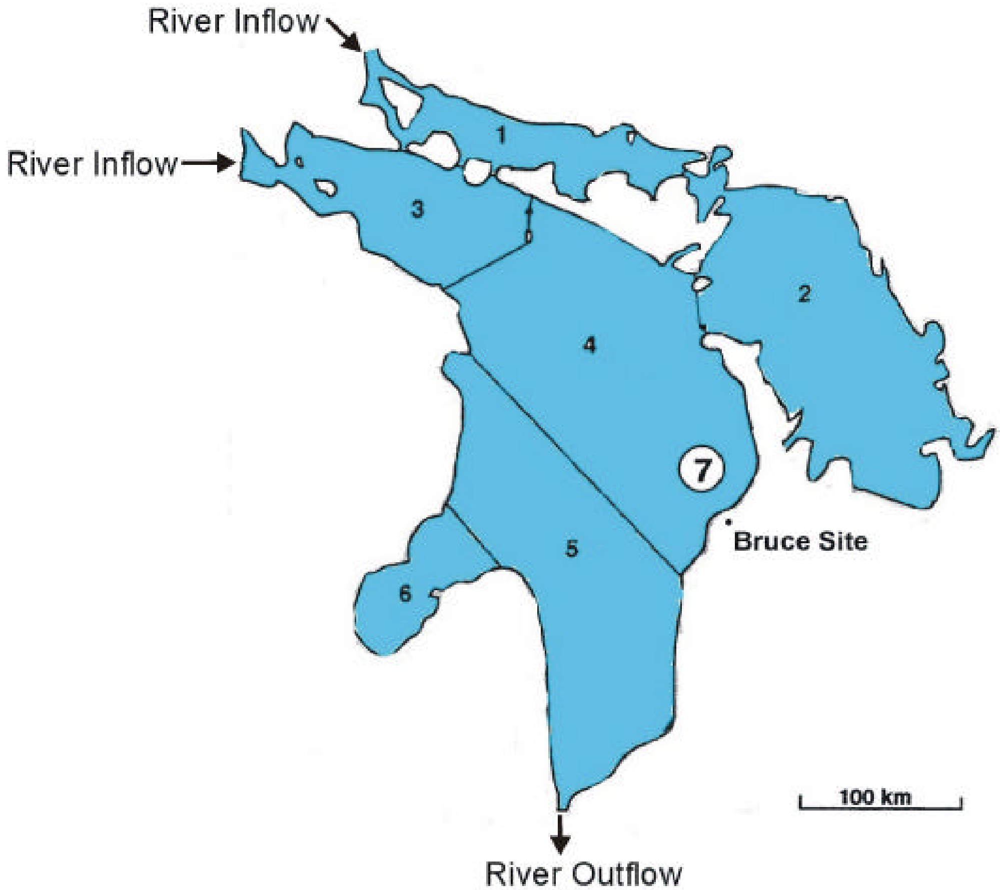

Figure 58: Discretisation of Lake Huron for Assessment Modelling

F.4.2 SOILS AND SEDIMENTS

Surface soil and sediment is assumed to have a uniformly mixed depth of 0.3 m as a result of ploughing, with the exception of soil that is considered in the Bathtubbing Calculation Case. This is assumed to be uniformly contaminated to a depth of 2 m by the interflow of contaminated groundwater released directly from the repository. The area of soil considered is 200 m x 100 m for the Well Release Calculation Case and 100 m x 100 m for the Cover Erosion and Bathtubbing Calculation Cases. The area of sediments assumed to be contaminated in the Lakeshore Release Calculation Case is a length of 200 m and width of the plume (approximately 320 m).

It is assumed that farmed land is rotated, therefore the ploughing assumption is applied to land used for grazing cattle as well as that on which crops are grown. The dry bulk density of the soil is assumed to be 1500 kg m^{-3}, and its water-filled porosity is 0.2 (Beak, 2002) with a total porosity of 0.3. A general surface erosion rate of $1x10^{-4}$ m y^{-1} is assumed (Kozak et al., 2000).

Soils are assumed to be generally silty in character, and the sorption coefficients assumed in the calculations are presented in Table 51. These data have been obtained from Thibault et al. (1990).

Lake sediments are assumed to become contaminated by mixing with contaminated lake water. The lakeshore sediments can also become contaminated by a direct discharge in the Lakeshore Release Calculation Case. In other calculation cases, the lakeshore sediments are conservatively assumed to have the same radionuclide concentration as the lake sediments in the region of the discharge of contaminated groundwater.

Table 50: Properties of Lake Compartments

Segment Number	Name	Interfaces with Segment Number	Volume of Compartment (m^3)	Area of Interface (m^2)	Volume of Exchanges ($m^3\ y^{-1}$)	Precipitation Runoff ($m^3\ y^{-1}$)
1	North Channel	2	8.8×10^{10}	1.8×10^{4}	5.7×10^{9}	9.44×10^{9}
		3		1.0×10^{5}	3.2×10^{10}	
2	Georgian Bay	1	6.7×10^{11}	1.8×10^{4}	5.7×10^{9}	2.20×10^{10}
		4		2.4×10^{5}	7.6×10^{10}	
3	Mackinac Basin	1	3.9×10^{11}	1.0×10^{5}	3.2×10^{10}	2.59×10^{9}
		4		4.9×10^{6}	1.6×10^{12}	
4	Central Basin	2	1.7×10^{12}	2.4×10^{5}	7.6×10^{10}	4.58×10^{9}
		3		5.1×10^{6}	1.6×10^{12}	
		5		7.4×10^{6}	2.3×10^{12}	
		7 (CAGCV)		3.6×10^{3}	1.1×10^{10}	
		7 (DRCV)		3.8×10^{3}	1.2×10^{9}	
5	South Basin	4	6.6×10^{11}	7.4×10^{6}	2.3×10^{12}	9.55×10^{9}
		6		1.5×10^{6}	4.7×10^{11}	
6	Saginaw Bay	5	4.9×10^{10}	1.5×10^{6}	4.7×10^{11}	5.83×10^{9}
7	Discharge Zone(CAGCV)	4	2.2×10^{4}	3.6×10^{3}	1.1×10^{10}	0
7	Discharge Zone(DRCV)	4	3.8×10^{4}	3.6×10^{3}	1.2×10^{9}	0
	River Inflow	1			6.7×10^{10}	
	River Inflow	3			4.65×10^{10}	
	Outflow from Lake	5			1.67×10^{11}	

Note:
The size of the discharge zones is based on the width of the plume (assumed to be the size of the repository perpendicular to the direction of groundwater flow. i.e., 320 m for the CAGCV and 160 m for the DRCV). The length of the discharge area is assumed to be 100 m in each case. A near-shore velocity scaling factor is applied to the discharge for the CAGCV, which increases the mean dispersive transport velocity in the lake from 3.16×10^{5} m y^{-1} (assumed for all other exchanges) to 3.16×10^{6} m y^{-1} for the CAGCV discharge zone.

Table 51: Assumed Equilibrium Sorption Coefficients for Silty Soil and Lake Sediment

Element	Soil ($m^3 kg^{-1}$)	Sediment ($m^3 kg^{-1}$)	Element	Soil ($m^3 kg^{-1}$)	Sediment ($m^3 kg^{-1}$)
H	0	0	Cs	5	3
C	0.02	$5x10^{-4}$	Sm	0.8	0.8*
Cl	$6x10^{-4}$	$6x10^{-4}$*	Pb	20	20*
Fe	0.8	2	Po	0.4	0.4*
Co	1	0.6	Ra	40	40*
Ni	0.3	0.3*	Ac	2	2*
Se	0.5	0.5*	Th	3	3*
Sr	0.02	0.1	Pa	2	2*
Zr	2	6	U	0.02	0.3
Nb	0.6	10	Np	0.03	0.04
Tc	$1x10^{-4}$	0.001	Pu	1	0.5
Sn	0.5	1	Am	10	20
I	0.005	0.001	Cm	20	40

Note:
Data for soil are from Thibault et al. (1990). Data for sediment are from Beak (2002) except those marked "*", which are values for silt from Thibault et al. (1990). All parameter values rounded to one significant figure.

F.4.3 PLANTS

Data describing the radionuclide uptake into plants, and their characteristics, have largely been obtained from Beak (2002).

Table 52 gives soil to plant equilibrium concentration factors for the three main crop groups considered in this assessment, together with information for uptake by animal's pasture. These data represent the root uptake of contaminants from soil.

For crops, irrigation with potentially contaminated water must be considered. Additional data are required to take account of the interception and translocation of elements deposited onto crop surfaces. These data are presented in Table 53, and have been obtained from Kozak et al. (2000) and Little et al. (1999), as this pathway is not considered in detail in Beak (2002).

In addition, soil contamination of plant surfaces is considered. These and other data required to calculate the concentration of radionuclides in plants are presented in Table 54. These data have been obtained from Beak (2002) where possible, and supplemented with information from Kozak et al. (2000).

Table 52: Soil to Plant Concentration Factors (in Bq kg^{-1} fresh wt per Bq kg^{-1} dry soil)

Element	Cereal	Pasture	Root Vegetables	Green Vegetable	References
H	5.0×10^{0}	5.0×10^{0}	5.0×10^{0}	5.0×10^{0}	C
C	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	C
Cl	5.0×10^{0}	5.0×10^{0}	5.0×10^{0}	5.0×10^{0}	B
Fe	4.3×10^{-3}	4.3×10^{-3}	1.1×10^{-3}	5.0×10^{-4}	A
Co	6.9×10^{-3}	4.8×10^{-2}	6.3×10^{-3}	1.1×10^{-2}	A
Ni	5.0×10^{-2}	2.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	B
Se	1.0×10^{0}	1.0×10^{0}	1.0×10^{0}	1.0×10^{0}	B
Sr	1.3×10^{-1}	1.3×10^{-1}	1.1×10^{-1}	2.0×10^{-1}	A
Zr	2.8×10^{-3}	2.8×10^{-3}	6.7×10^{-4}	3.2×10^{-4}	A
Nb	2.5×10^{-2}	2.5×10^{-2}	6.1×10^{-3}	2.9×10^{-3}	A
Tc	7.1×10^{-1}	4.8×10^{0}	6.2×10^{-1}	3.7×10^{-1}	A
Sn	3.5×10^{-1}	3.5×10^{-1}	8.6×10^{-2}	4.1×10^{-2}	A
I	3.6×10^{-4}	2.4×10^{-3}	3.2×10^{-4}	5.4×10^{-4}	A
Cs	8.6×10^{-3}	5.6×10^{-2}	7.1×10^{-3}	1.3×10^{-2}	A
Sm	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	B
Pb	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	B
Po	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	B
Ra	4.0×10^{-2}	4.0×10^{-2}	4.0×10^{-2}	4.0×10^{-2}	B
Ac	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	B
Th	5.9×10^{-4}	4.0×10^{-3}	5.0×10^{-4}	9.0×10^{-4}	A
Pa	3.3×10^{-2}	3.3×10^{-2}	8.0×10^{-3}	3.8×10^{-3}	A
U	1.5×10^{-3}	9.5×10^{-3}	1.3×10^{-3}	2.2×10^{-3}	A
Np	1.6×10^{-3}	1.1×10^{-2}	1.4×10^{-3}	2.5×10^{-3}	A
Pu	1.7×10^{-5}	1.3×10^{-4}	1.7×10^{-5}	2.9×10^{-5}	A
Am	7.7×10^{-5}	5.1×10^{-4}	6.5×10^{-5}	1.2×10^{-4}	A
Cm	0.0×10^{0}	2.6×10^{-5}	2.1×10^{-6}	5.0×10^{-6}	A

Notes:

A Data from Beak (2002)
B Data from Kozak et al. (2000)
C Data from Little et al. (1999)

Table 53: Translocation Fraction and Processing Losses for Crops (both unitless)

Element	Root Vegetables		Green Vegetables		Grain	
	Trans-location	Prep. Losses	Trans-location	Prep. Losses	Trans-location	Prep. Losses
H	2.0×10^{-2}	0	2.3×10^{-2}	0.9	1.0×10^{-2}	0.85
C	4.0×10^{-1}	0	5.8×10^{-1}	0.9	1.6×10^{-1}	0.85
Cl	1.9×10^{-1}	0	1.9×10^{-1}	0.9	8.8×10^{-2}	0.85
Fe	2.2×10^{-1}	0	2.3×10^{-1}	0.9	1.0×10^{-1}	0.85
Co	1.7×10^{-1}	0	1.8×10^{-1}	0.9	8.0×10^{-2}	0.85
Ni	3.9×10^{-2}	0	3.7×10^{-1}	0.9	1.6×10^{-1}	0.85
Se	6.8×10^{-2}	0	3.0×10^{-1}	0.9	1.3×10^{-1}	0.85
Sr	1.4×10^{-1}	0	2.0×10^{-1}	0.9	1.2×10^{-1}	0.85
Zr	5.3×10^{-1}	0	1.3×10^{-1}	0.9	5.6×10^{-2}	0.85
Nb	5.3×10^{-1}	0	5.2×10^{-1}	0.9	5.6×10^{-2}	0.85
Tc	1.1×10^{-1}	0	2.8×10^{-1}	0.9	1.2×10^{-1}	0.5
Sn	2.2×10^{-1}	0	2.2×10^{-1}	0.9	1.0×10^{-1}	0.85
I	7.4×10^{-2}	0	6.1×10^{-1}	0.9	2.8×10^{-1}	0.85
Cs	3.0×10^{-1}	0	1.9×10^{-1}	0.9	8.8×10^{-2}	0.5
Sm	2.0×10^{-2}	0	7.6×10^{-2}	0.9	4.8×10^{-2}	0.85
Pb	2.2×10^{-1}	0	2.2×10^{-1}	0.9	1.0×10^{-1}	0.85
Po	2.2×10^{-1}	0	2.2×10^{-1}	0.9	1.0×10^{-1}	0.85
Ra	9.9×10^{-2}	0	1.8×10^{-1}	0.9	8.0×10^{-2}	0.85
Ac	2.9×10^{-1}	0	4.5×10^{-1}	0.9	2.0×10^{-1}	0.85
Th	2.9×10^{-1}	0	3.8×10^{-2}	0.9	1.3×10^{-1}	0.85
Pa	2.9×10^{-1}	0	4.5×10^{-1}	0.9	2.0×10^{-1}	0.85
U	4.3×10^{-2}	0	3.6×10^{-1}	0.9	1.6×10^{-1}	0.85
Np	2.9×10^{-1}	0	4.5×10^{-1}	0.9	2.0×10^{-1}	0.9
Pu	4.3×10^{-2}	0	3.6×10^{-1}	0.9	1.6×10^{-1}	0.9
Am	2.9×10^{-1}	0	2.8×10^{-1}	0.9	1.3×10^{-1}	0.9
Cm	1.1×10^{-1}	0	2.7×10^{-1}	0.9	2.1×10^{-1}	0.9

Notes:

Translocation fractions are obtained from a compilation of data presented in Kozak et al. (2000), and data are not presented for pasture as it is not assumed to be irrigated. Food preparation loss data have been obtained from Little et al. (1999), and only apply to the surface contamination on the crops.

Table 54: Other Parameters Describing Radionuclide Uptake In Plants

Parameter	Green Vegetables	Root Vegetables	Grain
Interception factor (unitless)[A]	0.3	0.3	0.05
Yield (kg m^{-2})[B]	4.9	2.1	0.5
Weathering rate (y^{-1}) – all elements except Np, Pu and Am	18	18	8.4
Weathering rate (y^{-1}) –Np, Pu and Am	50	18	50
Soil contamination (unitless)	0.002	0.0012	0.0034

Note:

A Interception factor is the fraction of the total area irrigated that is intercepted, rather than the canopy cover only (as quoted by Beak (2002)) and therefore values are taken from Kozak et al. (2000).

B Yield data relate to fresh weight and are from Beak (2002) for Bruce and Durham counties, and relate to cabbage (green vegetables), potatoes (root vegetables) and the mean value from oats, barley, winter wheat and grain corn (grain).

C Weathering rates and soil contamination data are taken from Kozak et al. (2000).

D Soil contamination is given in terms of dry mass of soil by mass of fresh plant.

E Data are not required for pasture as, with the exception of soil contamination, the data in Table 54 are related to irrigation. Soil contamination is not considered for pasture because the direct ingestion of soil by grazing animals is considered explicitly.

F.4.4 ANIMALS

The approach to calculating radionuclide uptake into animals makes use of the approach and data described in Beak (2002). However, the expressions for radionuclide transfer used in this assessment are slightly different, and some conversion of units has therefore been applied where required. In addition, Beak (2002) does not contain data for Cl, Ni, Se, Sm, Pb, Po, Ra and Ac. Parameter values for these elements have therefore generally been derived from Kozak et al. (2000).

The basic elemental transfer factors for animals are presented in Table 55. In this study, only a representative animal (a cow) has been considered.

Additional assumptions are required to take account of ingestion of potentially contaminated soil and water by animals. These data are presented in Table 56.

Radionuclide uptake by fish is modelled using equilibrium concentration factors, which are presented in Table 57.

Table 55: Transfer Factors for Cows

Element	Cow Milk ($y\ l^{-1}$)	Beef Meat ($y\ kg^{-1}$)	Beef Liver ($y\ kg^{-1}$)
H	3.8×10^{-5}	4.9×10^{-5}	4.9×10^{-5}
C	4.1×10^{-5}	1.8×10^{-4}	1.8×10^{-4}
Cl	4.7×10^{-5}	1.2×10^{-4}	1.2×10^{-4}
Fe	4.4×10^{-7}	3.1×10^{-5}	1.1×10^{-2}
Co	2.6×10^{-6}	6.3×10^{-6}	2.7×10^{-4}
Ni	2.7×10^{-6}	8.2×10^{-5}	8.2×10^{-5}
Se	1.1×10^{-5}	1.5×10^{-3}	1.5×10^{-3}
Sr	5.5×10^{-6}	5.8×10^{-6}	8.2×10^{-7}
Zr	8.7×10^{-9}	5.5×10^{-8}	2.7×10^{-8}
Nb	1.3×10^{-7}	5.5×10^{-7}	2.7×10^{-8}
Tc	1.9×10^{-6}	2.6×10^{-6}	1.1×10^{-4}
Sn	3.0×10^{-6}	3.0×10^{-5}	6.0×10^{-5}
I	2.3×10^{-5}	2.7×10^{-5}	5.5×10^{-6}
Cs	2.0×10^{-5}	1.0×10^{-4}	8.2×10^{-5}
Sm	5.5×10^{-8}	1.4×10^{-6}	1.4×10^{-6}
Pb	8.2×10^{-7}	2.7×10^{-5}	2.7×10^{-5}
Po	8.2×10^{-7}	1.1×10^{-5}	1.1×10^{-5}
Ra	3.6×10^{-6}	3.6×10^{-6}	3.6×10^{-6}
Ac	1.1×10^{-9}	4.4×10^{-7}	4.4×10^{-7}
Th	6.2×10^{-8}	3.3×10^{-7}	1.7×10^{-4}
Pa	1.4×10^{-8}	3.1×10^{-8}	3.0×10^{-6}
U	1.2×10^{-6}	1.2×10^{-6}	1.9×10^{-6}
Np	1.1×10^{-8}	1.0×10^{-6}	5.5×10^{-5}
Pu	1.6×10^{-9}	5.8×10^{-8}	5.5×10^{-5}
Am	3.0×10^{-9}	4.4×10^{-8}	5.5×10^{-5}
Cm	2.6×10^{-9}	5.3×10^{-8}	5.5×10^{-5}

Note:

Data have been converted to $y\ kg^{-1}$ and $y\ l^{-1}$ from Beak (2002), with the exception of values for H, C, Cl, Ni, Se, Sm, Pb, Po, Ra and Ac, which are obtained from Kozak et al. (2000). For the Kozak et al. (2000) data transfer factors are not given for beef offal, so the rates for cow meat are assumed.

Table 56: Various Parameters for Uptake In Animals

Parameter	Beef Cattle	Dairy Cattle
Consumption rate (soil, kg y^{-1})	520	800
Consumption rate (fresh pasture, kg y^{-1})	5600	8400
Consumption rate (water, m^3 y^{-1})	11	55
Stocking Density (m^{-2})	$1x10^{-4}$	$1x10^{-4}$

Note:
All Data from Beak (2002). Stocking density is the average area of pasture required to support an individual animal.

Table 57: Concentration Factors for Fresh Water Fish

Element	Concentration Factor (m^3 kg^{-1})	Reference	Element	Concentration Factor (m^3 kg^{-1})	Reference
H	0.001	B	Cs	5.7	A
C	50	B	Sm	0.03	B
Cl	0.017	B	Pb	0.3	C
Fe	0.52	A	Po	0.1	A
Co	0.055	A	Ra	0.05	C
Ni	0.1	C	Ac	0.03	C
Se	0.2	C	Th	0.1	A
Sr	0.0014	A	Pa	0.01	C
Zr	0.014	A	U	0.01	A
Nb	0.3	A	Np	0.03	A
Tc	0.02	A	Pu	0.03	A
Sn	3	A	Am	0.03	A
I	0.017	A	Cm	0.03	A

Note:
A Data obtained from Beak (2002)
B Data obtained from Kozak et al. (2000)
C Data obtained from IAEA (2002)

F.5 HUMAN EXPOSURE GROUP CHARACTERISTICS

F.5.1 DESCRIPTION OF POTENTIAL EXPOSURE GROUPS

Potential exposure groups for the safety assessment are hypothetical, rather than being based on the characteristics of humans living at the present day in the vicinity of the site. Their habits are defined cautiously. This is consistent with advice from ICRP (2000) that recognises the need to consider potential exposure groups with habits that could lead to high dose rates.

The exposure pathways that need to be considered include those presented in Section 5.2.4. Potential exposure groups relate to the scenarios and calculation cases being considered, by maximising exposure via the relevant pathways. Table 58 shows the potential exposure groups assumed for the calculation cases being considered. Further potential exposure groups with habits more representative of typical people could be added subsequently, however the initial calculations are aimed at evaluating the potential safety impacts of the repository concepts. The potential exposure group definitions are considered to be the same for all concepts being considered. In all cases adults are considered; infants and children could subsequently be considered; however, adult's high consumption rates and wide range of activities mean that their age group would give results that are representative of those likely for other age groups.

Table 58: Potential Exposure Groups Considered for the Different Calculation Cases

Calculation Case	Concept(s)	Potential Exposure Group
Lake Release	CAGCV & DRCV	Fisherman
Lakeshore Release	CAGCV	Fisherman
Well Release	CAGCV	Farmer
Bathtubbing	CAGCV-T only	Site dweller
Gas Release	CAGCV	Site dweller
Cover Erosion	CAGCV	Site dweller
Shaft Pathway	DRCV	Fisherman
Exploration Borehole	CAGCV & DRCV	Intruder
Excavation	CAGCV	Intruder and Site dweller

F.5.1.1 Farmer

The subsistence farmer potential exposure group is assumed to live in a house close to the repository and to farm land on and around the potential points of discharge of contaminated groundwater. The potential exposure group is assumed to obtain all their dietary needs from the farmed land, which is of sufficient size to support such needs.

A guide on the typical size of farms can be obtained from OPG (2000), which implies that typical commercial farms in the region occupy about 67 hectares. However, a subsistence farmer could occupy a much smaller area of land – for example, typical intake rates and yields of foodstuffs suggest that sufficient food for a group of four adults could be obtained from an area of $2x10^4$ m^2. This area is taken to be a conservative reference assumption. Water abstraction rates for irrigation, drinking and other uses would amount to approximately $1x10^4$ m^3 y^{-1} (IAEA, 2002).

F.5.1.2 Fisherman

For the release to lake water and shore sediments, a fisherman is considered, who lives close to the site but obtains a greater proportion of food from the lake than the farmer. The fisherman is assumed to live close to shore sediments, and spend a considerable time on the lake (fishing) or on the shore (mending nets). The lakeshore sediments can constitute a source of external irradiation, inhalation exposure and inadvertent ingestion exposure. Their habits can be inferred from those of aboriginal communities in Ontario. They are not assumed to ingest contaminated vegetables or terrestrial animals, as the radionuclide releases are in a location in which agricultural soil is unlikely to become substantially contaminated. However, they are assumed to obtain all their drinking water from the lake.

The concentration in all lakeshore sediments is assumed to be the same as the average concentration of sediments in the region of release to lake water, for the Lake Release Calculation Case.

For the Lakeshore Release Calculation Case, contaminated groundwater is assumed to be discharged to the lakeshore. The area is assumed to be 200 m long by 320 m wide (the approximate width of the plume).

F.5.1.3 Site Dwellers

Site dwellers are assumed to live on the site but not farm it for all foodstuffs, although they are assumed to grow vegetables in the garden. It is assumed that 50 % of their green and root vegetables are obtained from their garden. This corresponds to about 100 m^2 of vegetable garden to support four adults. They are assumed to frequent a total area of 100 m by 100 m.

This potential exposure group is considered for all calculation cases in which there is the potential for inadvertent exposure to directly contaminated soil or radioactive gases released from it. It is characterised by long-duration occupancy of a small area of contaminated soil, and indoors residence (where gas can accumulate).

The calculation cases for which this exposure group is considered includes the Bathtubbing, Cover Erosion and Gas Release Calculation Cases. In the first two, the failure or removal of the cap results in a release of contaminated liquid or solid from the near field directly to soil. The area of soil is assumed to be an 'annulus' of width 100 m surrounding the repository, as illustrated in Figure 59. Cautiously, only a fraction (a 100 m by 100 m area) of the whole area of soil that could be contaminated is assumed to be contaminated. It is assumed that the site dweller lives on this contaminated area. This cautious approach has been adopted to reflect the potential for the surrounding soil to become inhomogeneously contaminated (e.g., by the release of bathtubbing water from a particular location at the base of the repository).

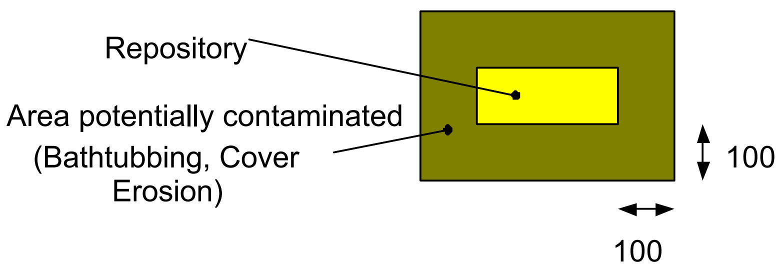

Figure 59: Assumed Area of Potentially Contaminated Soil for Bathtubbing and Cover Erosion Calculation Cases

F.5.1.4 Intruders

Human intrusion exposure scenarios consider the potential disruption of the repository by intruders. The potential exposure groups should therefore directly represent their habits and characteristics. However, the potential intrusion scenario is very uncertain (i.e., it is not possible to envisage the number of boreholes that could be drilled, or the size of building that may be constructed).

Therefore, the following 'stylised' assumptions are considered, consistent with the recommendations of ICRP (2000). For the exploration borehole intruder, a person retrieves and examines borehole cores that have penetrated the waste. Consistent with Wuschke (1996), it is assumed that samples are taken and inspected for a total of 40 hours. Each sample has a mass of 5 kg.

Digging and construction activities are assumed to disrupt a substantial portion of the waste. It is assumed that a large building is constructed which requires a person to be working at the site for a substantial fraction of the year (assumed to be 1000 h).

A person that lives on soil contaminated with excavated waste is also considered. They are assumed to have the same habits described under 'site dweller' above. No specific area of contaminated land is designated – rather is assumed that the excavated waste is diluted in soil to an average concentration of 10 % (the assumptions for the excavated volume would imply that $1.7x10^4$ m^2 could be contaminated to a depth of 0.3 m). This is considered to be the highest concentration of excavated material that could be included in soil without adversely affecting its fertility, and therefore gives a cautious indication of the significance of the potential exposures.

F.5.2 INGESTION RATES AND EXPOSURE DURATIONS

The ingestion rates have been based on Beak (2002), which contains recommended default intake rates for a range of foodstuffs. Intake rates for the farmer use the conservative values presented, and assume all foodstuffs are contaminated (rather than the fraction given by Beak (2002)). A smaller set of foodstuffs is considered in these calculations than presented in Beak (2002). Cow meat, milk and offal are considered as representative animal food products, whilst the main vegetable classes only are considered – green vegetables, root vegetables and grain. The farmer is assumed to spend all his time on the potentially contaminated soil, being outdoors for, on average, 30 % of the time (about 7 h d^{-1}). This is cautiously higher than the 20% suggested in Beak (2002), but is consistent with Kozak et al. (2000) and is considered compatible with the cautious assumptions for the potential exposure group.

For clarity in the potential exposure group assumptions, the farmer is not considered to ingest contaminated lake fish. Instead a 'fisherman' potential exposure group is considered for those situations in which a release to the lake is the focus (the Lake and Lakeshore Release Calculation Cases). The intake rates for this potential exposure group make use of information on aboriginal communities, which suggests that fish intake rates could be as high as 1.4 kg d^{-1} over a whole year. The fisherman is assumed to reside on in the vicinity of the site, residing on potentially contaminated shore sediments and fishing at sea (20% of time).

The site dweller potential exposure group has been chosen to enable a cautious assessment of potential exposures from smaller areas of contaminated soil than considered for the farmer. The exposed person is only assumed to obtain vegetables from the contaminated soil, and ingestion rates are obtained from Beak (2002). Their exposure time is also adjusted to represent the typical values suggested in Beak (2002), although it should be noted that the person is assumed to spend all their time on the site.

Soil ingestion and inhalation rates are based on the values assumed in Kozak et al. (2000) and IAEA (2002) respectively. Dust concentrations for intruders are based on Wuschke (1996).

The intruder potential exposure groups are only assumed to be exposed during work activities, for which the exposure durations are outlined above.

The assumptions are summarised in Table 59. This also presents the estimated energy intake of contaminated foods (in kcal/d) that is implied by the assumptions.

Table 59: Occupancy Factors and Ingestion Rates of Contaminated Material for the Potentially Exposed Groups Considered in the Safety Assessment

Foodstuff	Farmer	Fisherman	Site Dweller*	Intruder (Exploration Borehole)	Intruder (Excavation)
Cow Meat (kg y^{-1})	66	-	-	-	-
Cow Liver (kg y^{-1})	2.8	-	-	-	-
Cow Milk (l y^{-1})	280	-	-	-	-
Green Veg. (kg y^{-1})	250	-	91	-	-
Root Veg. (kg y^{-1})	110	-	41	-	-
Grain (kg y^{-1})	90	-	-	-	-
Fish (kg y^{-1})	-	520	-	-	-
Soil/sediment (kg h^{-1})	$1.3x10^{-5}$	$1.3x10^{-5}$	$1.3x10^{-5}$	$1.3x10^{-5}$	$1.3x10^{-5}$
Water (m^3 y^{-1})	0.84	0.84	-	-	-
Inhalation rate (m^3 h^{-1})	0.95	0.95	0.95	1.8	1.8
Dust concentration (kg m^{-3})	$2x10^{-8}$	$2x10^{-8}$	$2x10^{-8}$	$1x10^{-7}$	$1x10^{-7}$
Duration indoors (h y^{-1})	6136	6136	7013	-	-
Duration outdoors (h y^{-1})	2630	2630	1753	40	1000
Location of residence	Contam. soil	Contam. shoreline	Contam. soil	-	-
Area habituated (m^2)	20000	100	100	-	-
Energy intake of contaminated foods (kcal d^{-1})	3700	1800	430	-	-

Note:
*Applicable for the Gas, Bathtubbing, Cover Erosion and Excavation Calculation Cases. The total area of contaminated soil for the Bathtubbing and Cover Erosion Calculation Cases is assumed to be 100 m x 100 m, and that the total area contaminated in the Excavation Calculation Case is not used in the calculations – instead it is assumed that the soil used by the site dweller contains 10% waste. For the Gas Release Calculation Case, only the inhalation exposure pathway is considered.

F.5.3 DOSIMETRY

Dose rates to exposed individuals have been calculated for ingestion, inhalation and external irradiation (Table 60). Dose factors for ingestion and inhalation are derived from recommended values calculated by ICRP (1996), and where necessary include contributions from short-lived progeny.

Dose conversion factors for external irradiation from a semi-infinite plane of contaminated soil have been obtained from USEPA (2002), as this allows a consistent set of data to be used for all radionuclides (Beak (2002) do not present data for all radionuclides considered in this assessment). A shielding factor of 0.4 is also applied for irradiation whilst indoors, shielded by a building from contaminated soil (CSA, 1987).

Table 60: Dose Coefficients for Ingestion and Inhalation, and Dose Factors for External Irradiation

Radionuclides	Ingestion [B] (Sv Bq^{-1})	Inhalation [B] (Sv Bq^{-1})	External, Soil [C] (Sv y^{-1} per Bq m^{-3})	External, Point (Sv y^{-1} Bq^{-1})
H-3	1.80×10^{-11}	4.50×10^{-11}	0.00×10^{0}	0.00×10^{0}
C-14	5.80×10^{-10}	2.00×10^{-9}	1.86×10^{-15}	2.60×10^{-19}
Cl-36	9.30×10^{-10}	7.30×10^{-9}	4.20×10^{-13}	2.13×10^{-17}
Fe-55	3.30×10^{-10}	3.80×10^{-10}	$0.00\text{x}0^{0}$	3.44×10^{-19}
Co-60	3.40×10^{-9}	1.00×10^{-8}	2.60×10^{-9}	3.50×10^{-13}
Ni-59	6.30×10^{-11}	1.30×10^{-10}	$0.00\text{x}0^{0}$	4.19×10^{-17}
Ni-63	1.50×10^{-10}	4.80×10^{-10}	0.00×10^{0}	0.00×10^{0}
Se-79	2.90×10^{-9}	1.10×10^{-9}	2.58×10^{-15}	3.02×10^{-17}
Sr-90[A]	3.07×10^{-8}	3.75×10^{-8}	6.89×10^{-12}	2.79×10^{-16}
Nb-94	1.70×10^{-9}	1.10×10^{-8}	1.54×10^{-9}	2.20×10^{-13}
Tc-99	6.40×10^{-10}	4.00×10^{-9}	1.83×10^{-14}	1.67×10^{-18}
Sn-126[A]	5.07×10^{-9}	2.85×10^{-8}	1.88×10^{-9}	2.79×10^{-13}
I-129	1.10×10^{-7}	3.60×10^{-8}	1.61×10^{-12}	1.78×10^{-19}
Cs-137	1.30×10^{-8}	4.60×10^{-9}	5.40×10^{-10}	7.84×10^{-14}
Sm-151	9.80×10^{-11}	4.00×10^{-9}	1.14×10^{-16}	4.48×10^{-18}
Pb-210[A]	6.91×10^{-7}	1.19×10^{-6}	1.26×10^{-12}	5.42×10^{-17}
Po-210	1.20×10^{-6}	3.30×10^{-6}	8.33×10^{-15}	1.19×10^{-18}
Ra-226[A]	2.80×10^{-7}	3.53×10^{-6}	1.79×10^{-9}	2.39×10^{-13}
Ra-228[A]	6.90×10^{-7}	2.63×10^{-6}	9.56×10^{-10}	1.30×10^{-13}
Ac-227[A]	1.21×10^{-6}	5.67×10^{-4}	3.16×10^{-10}	5.38×10^{-14}
Th-228[A]	1.43×10^{-7}	4.32×10^{-5}	1.63×10^{-9}	2.17×10^{-13}
Th-229[A]	6.13×10^{-7}	8.58×10^{-5}	2.50×10^{-10}	4.30×10^{-14}
Th-230	2.10×10^{-7}	1.40×10^{-5}	1.81×10^{-13}	5.25×10^{-17}
Th-232	2.30×10^{-7}	2.50×10^{-5}	7.70×10^{-14}	2.42×10^{-17}
Pa-231	7.10×10^{-7}	1.40×10^{-4}	2.98×10^{-11}	4.83×10^{-15}
Pa-233	8.70×10^{-10}	3.90×10^{-9}	1.59×10^{-10}	2.84×10^{-14}
U-233	5.10×10^{-8}	3.60×10^{-6}	2.14×10^{-13}	3.79×10^{-17}
U-234	4.90×10^{-8}	3.50×10^{-6}	5.81×10^{-14}	1.67×10^{-17}
U-235[A]	4.73×10^{-8}	3.10×10^{-6}	1.17×10^{-10}	2.24×10^{-14}
U-236	4.70×10^{-8}	3.20×10^{-6}	3.00×10^{-14}	3.22×10^{-18}
U-238[A]	4.84×10^{-8}	2.91×10^{-6}	2.65×10^{-11}	3.46×10^{-15}
Np-237	1.10×10^{-7}	2.30×10^{-5}	1.17×10^{-11}	2.95×10^{-15}
Pu-238	2.30×10^{-7}	4.60×10^{-5}	1.97×10^{-14}	1.04×10^{-18}
Pu-239	2.50×10^{-7}	5.00×10^{-5}	4.45×10^{-14}	7.04×10^{-18}
Pu-240	2.50×10^{-7}	5.00×10^{-5}	1.90×10^{-14}	1.02×10^{-18}
Pu-241[A]	4.80×10^{-9}	9.00×10^{-7}	2.89×10^{-15}	6.64×10^{-19}
Pu-242	2.40×10^{-7}	4.80×10^{-5}	1.68×10^{-14}	1.14×10^{-18}
Am-241	2.00×10^{-7}	4.20×10^{-5}	6.28×10^{-12}	2.98×10^{-15}
Am-243[A]	2.01×10^{-7}	4.10×10^{-5}	1.37×10^{-10}	2.98×10^{-14}

Table 60: Dose Coefficients for Ingestion and Inhalation, and Dose Factors for External Irradiation

Radionuclides	Ingestion [B] (Sv Bq^{-1})	Inhalation [B] (Sv Bq^{-1})	External, Soil [C] (Sv y^{-1} per Bq m^{-3})	External, Point (Sv y^{-1} Bq^{-1})
Cm-244	1.50x10^{-7}	3.10x10^{-5}	9.03x10^{-11}	0.00x10^{0}

Note:

A Dose coefficients and factors contain contributions from short-lived progeny (with half-life of less than 25 days)

B Ingestion and inhalation dose coefficients taken from ICRP (1996) using the default lung absorption class that is recommended. Where no default absorption class is recommended, the highest value is used as a cautious assumption.

C Dose coefficients for external irradiation from soil are taken from US EPA Federal Guidance Report 12 (USEPA, 2002) using values for soil contaminated to an infinite depth. No data are available for irradiation by water, therefore the values for soil are assumed.

Dose conversion factors for external irradiation from a point source objects (considered in the calculations of dose rates for borehole samples) are obtained by multiplying the mean gamma energy of emissions for a given radionuclide (in MeV) by 1.4x10^{-13} Sv y^{-1} per Bq MeV^{-1} (Smith et al., 1988). Emissions data are taken from ICRP 38 (ICRP, 1983). Photons with individual energies below 50 keV have not been included because the equation used to calculate the dose coefficient from a point source substantially over-estimates the dose rate below this value, and the contribution to effective dose equivalent, given the existence of other exposure pathways, would in any event be very small. Where ICRP 38 does not record a radionuclide as having photon energies above the threshold of 50 keV, Browne and Firestone (1986) This reference includes low intensity internal bremsstrahlung emissions, which may nevertheless be quite energetic and were not included in ICRP 38.

The dose coefficients for Rn-222 and progeny is obtained from UNSCEAR (2000), and the value assumed is 9x10^{-9} Sv m^{3} h^{-1} Bq^{-1}. Values for other radioactive gases are taken from Beak (2002); the value for H-3 (as HTO) is 2.0x10^{-11} Sv Bq^{-1}, whilst the value for C-14 (as CO_2) is 1.2x10^{-11} Sv Bq^{-1}.

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APPENDIX G: MODEL IMPLEMENTATION

CONTENTS

G.1 APPROACH TO MODEL SPECIFICATION IN AMBER

The models and data described in Appendix E and F have been implemented in version 4.4 of the AMBER compartment modelling code (Enviros QuantiSci and Quintessa, 2002). This is a flexible modelling application that allows the specification of user defined contaminants, parameters, transfers and compartments. AMBER uses numerical approach to solving the ordinary differential equations that describe transfers between compartments. The solution method is described in Byrne and Hindmarsh (1975). The verification of the solution is discussed in Robinson et al. (2001).

The contaminants of interest (radionuclides) are specified with a name and radioactive decay rate. Contaminants can decay to other contaminants, with the result that decay chains can be represented. It is assumed that the amounts of contaminants in any given compartment are very much lower than amounts of other materials present in that compartment, and they do not affect its characteristics. It is also assumed that the contaminants are uniformly distributed in any one compartment.

Parameters are of two main types. ‘Standard’ parameters that are required for the model to calculate the amounts of contaminants in any compartment as a function of time (the basic results calculated by AMBER). ‘Observer’ parameters (e.g., concentration) are used to calculate quantities derived from the calculated compartment amounts. All parameters can be defined as having a single value, or as an array of one or two dimensions (e.g., sorption coefficient and porosity). Array characteristics are referred to as parameter ‘multiplicity’ in AMBER. Multiplicity can be assigned over items such as the set of contaminants, the set of compartments, or additional user defined ‘name sets’.

Contaminant transfers between compartments are specified in a simple manner. Each transfer represents a first-order linear donor-control transfer of contaminants. Its value can be assigned directly (as a number), or as a standard parameter. All transfers have multiplicity of contaminants (i.e., transfer rate values can be different for different contaminants). The donor and receptor compartments must also be specified for each transfer.

Compartments in AMBER are simply treated as model elements that can contain contaminants. They do not, by default, have any physical characteristics, although these are routinely assigned with user-defined parameters. The only property compartments are required to have is a name. However, it is also possible to specify initial amounts of contaminants in the compartment, assumed to be present at the beginning of the simulation (i.e., the initial inventory of radionuclides).

The main issues for model implementation in AMBER are the definition of compartments, transfers and parameters that implement the defined conceptual models, mathematical models and data, and these issues are discussed in this Appendix.

G.2 GENERAL MODELLING STRUCTURE

G.2.1 ORGANISATION OF CASE FILES

In order to minimise the number of separate files that are used for calculations, the range of calculation cases identified for the study has been implemented as three separate AMBER ‘case’ files (each defining a model). These are as follows:

- CAGCV-T, which contains the models to represent all calculation cases for the CAGCV concepts located on till (lake release, lakeshore release, well release, bathtubbing, gas release, cover erosion and human intrusion);

- CAGCV-S, which contains the models to represent all calculation cases for the CAGCV concepts located on sand (lake release, lakeshore release, well release, gas release, cover erosion and human intrusion); and
- DRCV, which contains the models to represent all calculation cases for the DCRV concept in shale or limestone (lake release, shaft pathway or human intrusion for each repository concept).

Such an approach has the benefits of avoiding the replication of data needed in several calculation cases (e.g., inhalation dose coefficients), which can introduce transcription errors. It also enables the models to be described with consistent and coherent assumptions.

The model can be run for any particular calculation case by setting a parameter to indicate the desired calculation case. This parameter takes a value of ‘1’ for the selected calculation case and 0 for others, and can then be used to define transfers or data values that are specific to the calculation case.

G.2.2 ORGANISATION OF COMPARTMENTS, TRANSFERS AND PARAMETERS

Compartments in each model is organised into a near field, geosphere (or far field) and biosphere component. ‘Standard’ parameters are also assigned a prefix that indicated which part of the model they relate to:

- NF_… indicates the parameter applies exclusively to the near-field model;
- FF_… indicates the parameter applies exclusively to the far-field model;
- B_… indicates the parameter applies exclusively to the biosphere model; and
- G_… indicates the parameter is general, and used in several parts of the model (e.g., density).

In addition, observers are prefixed with O_….

A number of user-defined ‘namesets’ have been specified that allow parameters to be specified efficiently. A nameset has been defined for any set of items that can have a common parameter – e.g., breathing rate can be specified for each exposure group, so exposure group is defined as a nameset. The full list of namesets considered in each AMBER case file is given in Table 61.

G.2.3 METHOD OF MODIFYING THE CASE FILE FOR SPECIFIC CALCULATION CASE

Because several calculation cases are represented in a single AMBER model case file, it is necessary to enable the model to be modified easily to reflect the specific conceptual model for the calculation case. However, many aspects of the model remain the same.

This is achieved by using a user-defined parameter to specify the calculation case of interest (called G_CalcCase). Another parameter is also used to ‘switch’ values for other parameters on and off as appropriate. The ‘switch parameter’ is named ‘G_F_CalcCase’ and has multiplicity by calculation case. The user specifies the desired calculation case, for which this parameter takes a value of 1 (i.e., the values of parameters associated with the desired calculation case are switched on). The values of parameters for the other calculation cases are switched off by setting the ‘G_F_CalcCase’ flag to 0 for the other calculation cases.

Table 61: Namesets Used in the AMBER Models

Nameset	Example of Items	Description
Materials	RawAsh, Sand, Shale, Limestone, Soil, LakeSed…	Several compartments may be made of the same material, but are represented as compartments for other reasons (e.g., they are in a different location). This nameset allows properties such as bulk density to be defined for specific materials, and the same value applied to several different compartments.
Elements	H, C, Cl, Fe, Co, Ni, …	Some properties are related to the element rather than the radionuclide (e.g., the same solubility applies to all isotopes of plutonium). This allows these values to be specified by element rather than contaminant.
ChemDegStage	Stage1, Stage2, Stage3	Cement degradation in the near field takes place in three characteristics stages, and this allows parameters such as distribution coefficient to take values relating to each stage.
Transition	Deg, UnDeg	This nameset allows parameters to have values that relate to a material in degraded and undegraded form and is used in the near-field model.
CalcCase	LakeRelease, ShoreRelease, HumanIntrusion…	Alternative values of parameters can be set for different calculation cases. This nameset also allows the model configuration to be altered for different calculation cases by modifying the transfers and compartment properties.
ExposureMaterial	Soil_Well, Soil_Eros, Waste, …	Different exposure groups are exposed to different exposure media. For example, soil contaminated by well water is considered separately from soil onto which waste has eroded. This nameset allows these different media, all of which can expose humans, to be managed.
ExposureGroup	Farmer, Fisherman, SiteDweller,…	The characteristics of the exposure groups considered in the assessment (e.g., ingestion rate) can be defined with separate values for each group using this nameset.
Crops	GreenVeg, RootVeg,…	Parameters that describe the uptake of contaminants by plants take different values for each crop (e.g., the amount of soil contaminating a leaf). The crops considered in the assessment

		are included as items in this nameset.
Animal	CowMeat, CowMilk,…	Parameters that describe the uptake of contaminants by animals take different values for each animal product, and animal products considered are defined in this nameset.

These parameters can then be used to change values in other parameters. For example, if the distance of the geosphere flow path is 100 m for the Well Release Calculation Case and 2000 m for the Lake Release Calculation Case, a single parameter, Length can be specified as:

Length = 100 x G_F_CalcCase[WellRelease] + 2000 x G_F_CalcCase[LakeRelease]

If G_F_CalcCase has value 1 for well release, and 0 for lake release, the value of length is 100 m.

This approach can also be used to 'switch' transfers between compartments on or off - if the transfer is multiplied by the parameter, it either takes the assigned value of 1(if G_F_CalcCase is 1) or has a transfer rate of 0 (if G_F_CalcCase has value 0).

Figure 60 shows how transfers that are only used for particular calculation cases. In this figure (for the CAGCV-T concept) the near-field submodel (blue) transports contaminants through the till, into the dolostone and to the lake for the Lake Release Calculation Case. However, additional transfers are defined that represent alternative releases of contaminants. For example, if waste is eroded (Cover Erosion Calculation Case), contaminants are transferred directly from the near-field submodel to the 'SoilCap' region of soil (Green). If the Bathtubbing Calculation Case is specified, bathtubbing can occur, and as well as transport into the till, some contaminated groundwater may be released directly to the 'SoilBath' compartment, which flows to the lake. Similarly, contaminants in the dolostone could be released to either 'SoilWell' (Well Release Calculation Case) or SedShore (shore sediments, for the Lakeshore Release Calculation Case). Each of these groups of transfers only operates when the relevant calculation case is specified.

Table 62 summarises the key changes to the model structure and data that are implemented for different calculations cases using the 'CalcCase' parameters.

G.3 IMPLEMENTATION OF THE NEAR-FIELD MODEL

G.3.1 STRUCTURE

The structure of the near-field model is shown in Figure 61, and the compartments and transfers as implemented in AMBER are shown in Figure 62. This illustrates implementation of the basic near-field model that comprises upstream and downstream compartments for engineered structures (NF_UpEng1 and NF_DwnEng1), and backfill (NF_UpBac1 and NF_DwnBac1). Three separate compartments are defined for the waste forms (NF_WF1A, NF_WF1B, NF_WF1C) so that each main type of waste (ash, compactible, and non-processible waste) can be represented with a separate compartment.

For the CAGCV concepts, the model structure illustrated in Figure 62 is repeated twice to represent each row of vaults. For the DRCV, only a single implementation is used.

The near-field compartments are assigned different media depending on the assumptions for the degree of engineering that is assumed for the concept. Two alternatives are considered for the CAGCV concepts – non-grouting and grouting. The materials assigned to the model compartments are summarised in Table 63, whilst the properties of these materials are described in Appendix F.2.

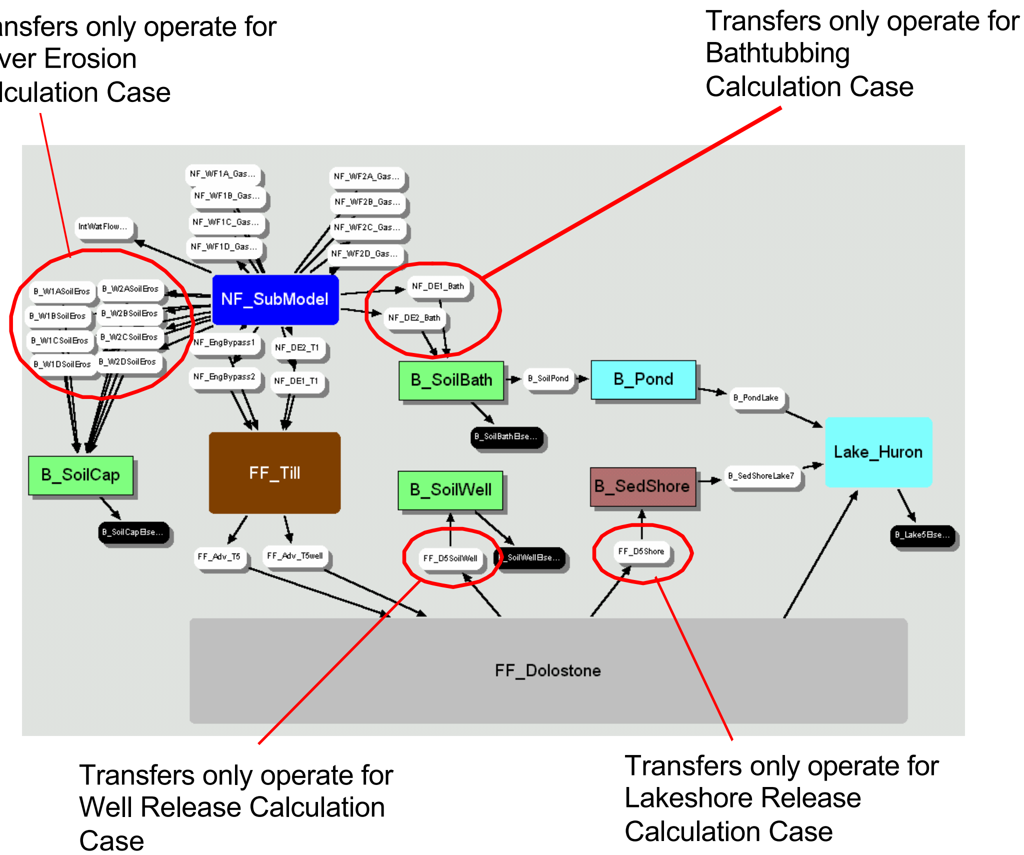

Figure 60: Illustration of Transfers that Only Operate for Particular Calculation Cases

Table 62: Key Model Structure Changes for Each Calculation Case

Calculation Case	Discharge to Biosphere	Exposure Material	Exposure Groups	Other Changes
CAGCV Concepts				
Lake Release	Dolostone to Lake	Lakeshore, Lake	Fisherman	Total pathlength to lake is considered.
Lakeshore Release	Dolostone to Lakeshore	Lakeshore, Lake	Fisherman	Dolostone pathlength reduced by 200 m
Well Release	Dolostone to Soil(Well)	Soil(Well), Well water	Farmer	Dolostone pathlength of 100 m downstream from repository
Bathtubbing	Waste leachate to Soil(Bathtub)	Soil (Bathtub)	Site Dweller	Flow through cap increased to general infiltration rate
Cover Erosion	Waste (solid) to Soil (Cap)	Soil (Cap)	Site Dweller	Erosion of repository at general erosion rate
Gas Release	Waste (gas) to House	Indoor air	Site Dweller	Radionuclides released as gas 'lost' from system
Human Intrusion	Waste (solid)	Waste, Diluted waste	Intruders, Site Dweller	Exposures calculated using activity concentration of waste
DRCV Concepts				
Lake Release	Dolostone to Lake	Lakeshore, Lake	Fisherman	Diffusion through limestone and/or shale.
Shaft Pathway	Dolostone to Lake	Lakeshore, Lake	Fisherman	Diffusion through shaft, limestone and/or shale.
Human Intrusion	Waste (solid)	Waste, diluted waste	Intruders	Exposures calculated using activity concentration of waste

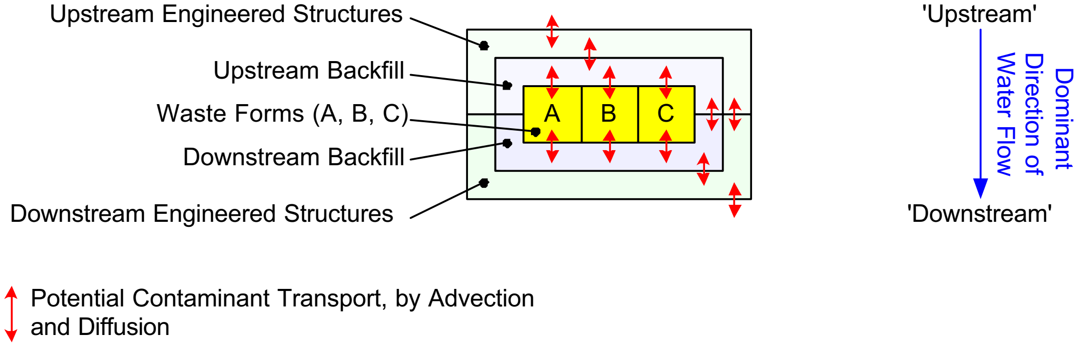

Figure 61: Near-field Model Structure

Table 63: Materials Assigned to Near-Field Model Compartments

Compartment(s)	**Material Assigned in**			
	CAGCV (Non-grouting)	**CAGCV (Grouting)**	**DRCV (Non-grouting)**	**DRCV (Grouting)**
Waste Form A (NF_WF1A)	RawAsh	GroutAsh	RawAsh	GroutAsh
Waste Form B (NF_WF1B)	RawComp	GroutComp	RawComp	GroutComp
Waste Form C (NF_WF1C)	RawNonPro	GroutNonPro	RawNonPro	GroutNonPro
Engineered structures (NF_UpEng1, NF_DwnEng1)	Eng_Conc	Eng_Conc	Water	Water
Backfill (NF_UpBac1, NF_DwnBac1)	Water	Back_Grout	Water	Back_Grout

Note:
Waste forms are either 'raw' or encapsulated in 'grout', and include Ash, Comp (compactible), or NonPro (non-processible). Other materials in the near field include grout backfill (Back_Grout) and engineering concrete (Eng_Conc). If it is a void, it is assumed to have water present.

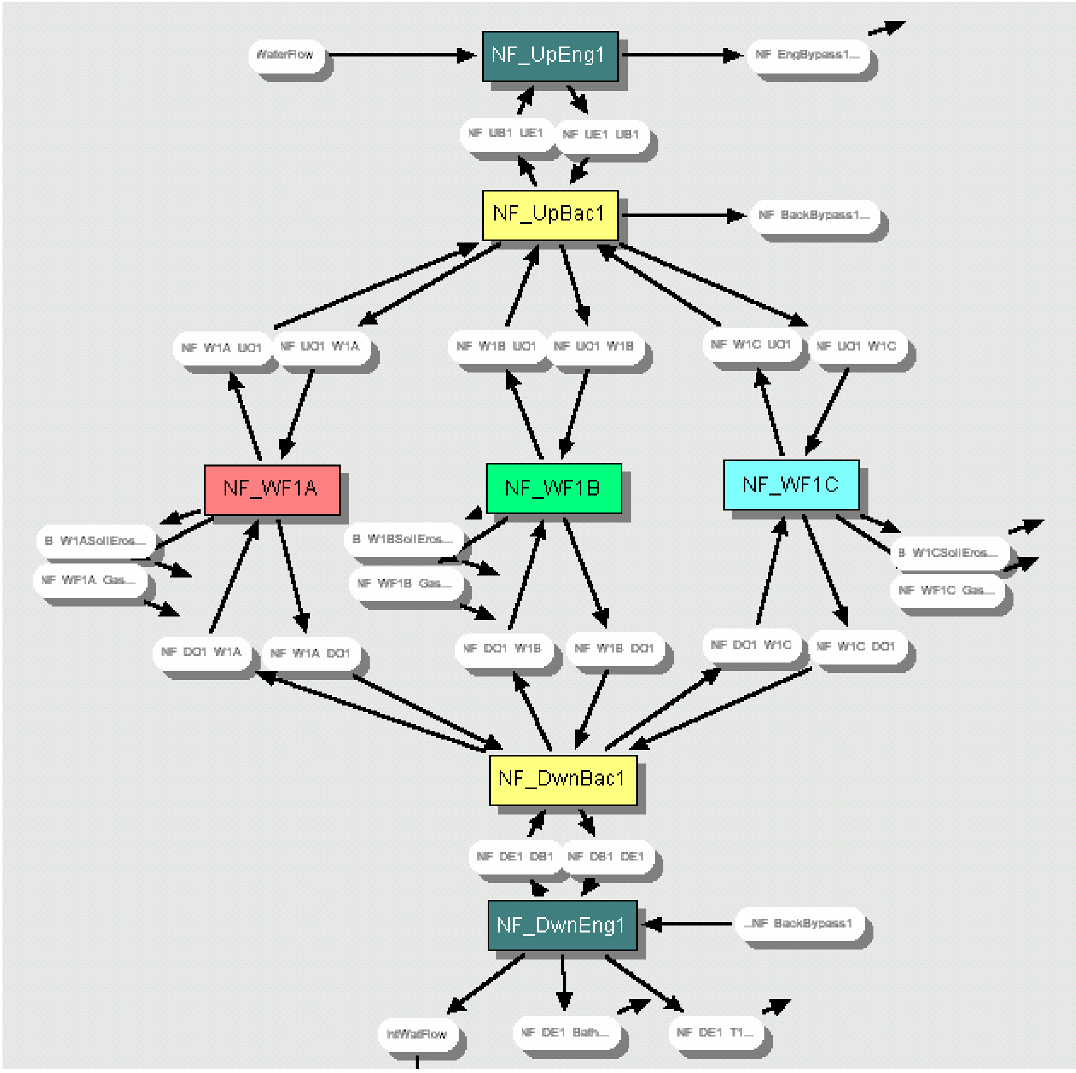

Figure 62: Near-field Compartments

Consistent with the conceptual model, advective and diffusive transfers are present between all compartments in the diagram, both in the dominant direction of flow and in the reverse direction (due to diffusion). Bypass flows can also occur via the engineered structures and backfill. Finally, radionuclides in the waste may also be transferred by erosion if the Cover Erosion Calculation Case is selected for the CAGCV.

For the DRCV, only diffusion is considered, and occurs in both directions ('upstream' and downstream' corresponding to vertically up, towards the aquifer and vertically down, away from the aquifer). Contaminants diffusing out of the near field away from the aquifer are assumed to be lost from the modelled system.

G.3.2 WATER BALANCE

General compartment modelling codes such as AMBER are primarily intended to represent contaminant transport and therefore have a limited ability to represent the governing equations for water flow. Therefore the following approach has been taken to representing the water balance in AMBER. It is aimed at providing a broadly consistent representation of the flows through successive materials, as well as taking account of the potential for bathtubbing (for the CAGCV-T case) and 'bypass' flows in permeable materials.

Because the DRCV repository is dominated by diffusion after it has resaturated, and resaturation is assumed to be instantaneous once the repository is closed, the water balance considerations discussed below do not apply to this repository.

The simple water balance model is based on the following assumptions.

- Each medium type has a characteristic hydraulic conductivity, K (m y^{-1}), which may be time-dependent. There is also a generally-applied hydraulic gradient, *Äh* (-), and an upstream Darcy velocity $q_{Upstream}$ (m y^{-1}).
- The possible flow through each compartment, q_{Poss} is the minimum of its value of *K Äh* and $q_{Upstream}$, i.e., flow can be limited by the conductivity of the compartment, and also is dependent on any limitations on the flow upstream of it. Q_{Poss} and $Q_{Upstream}$ are the associated volumetric flow rates (in m^3 y^{-1}).
- The actual flow of water through each compartment (Q_{Actual} m^3 y^{-1}) is constrained by the possible volume of water Q_{Poss} flowing through the compartment immediately upstream.
- A 'bypass' flow can occur between the upstream and downstream engineered structures or backfill. This occurs if the backfill or waste, respectively, does not have the capacity (Q_{Poss}) for the water flowing into the compartment.

One of the limitations in this approach is that it is not possible to model preferential channelled flow through one (or more) of the three waste forms present. However, the implementation is considered sufficient to ensure that the flow through the system properly reflects the properties of the media in general terms.

Firstly, for each compartment, the possible Darcy velocity (m y^{-1}) is calculated:

$$q_{Poss} = K\ \text{Ä}h \quad (1)$$

The total possible volume of flowing water for each compartment (Q_{Poss}, m^3 y^{-1}), without a change in the saturation is then computed:

$$Q_{Poss} = q_{poss}\ A\ \text{â}\ \text{å} \quad (2)$$

where A is the area (m^2) of the face through which water flows, *â* is the fraction of each compartment through which water can flow and *å* is the degree of saturation. The system under consideration is assumed to have the general geometry shown in Figure 61.

The flow through each *upstream* compartment is then limited by its value of Q_{Poss}, and the volume of water entering from upstream. So, in the example shown in Figure 63 below:

$$Q_{Actual}(B) = min[Q_{poss}(B),\ Q_{Actual}(A)] \quad (3)$$

Therefore, if any compartment limits the flow, the remainder of the flow can travel around the compartment. This is required in order to represent properly the action of backfill surrounding low-permeability concrete structures, for example. The flow rate (m^3 y^{-1}) of bypass water in the example above (Figure 63) is calculated from the balance of flows:

$$Q_{Bypass}(A) = Q_{Actual}(A) - Q_{Actual}(B) \quad (4)$$

In the geometry adopted, bypass flows travel around the inner media, emerging ‘downstream’. In Figure 63, the bypass flow, deflected by material B, travels ‘around’ it in material A.

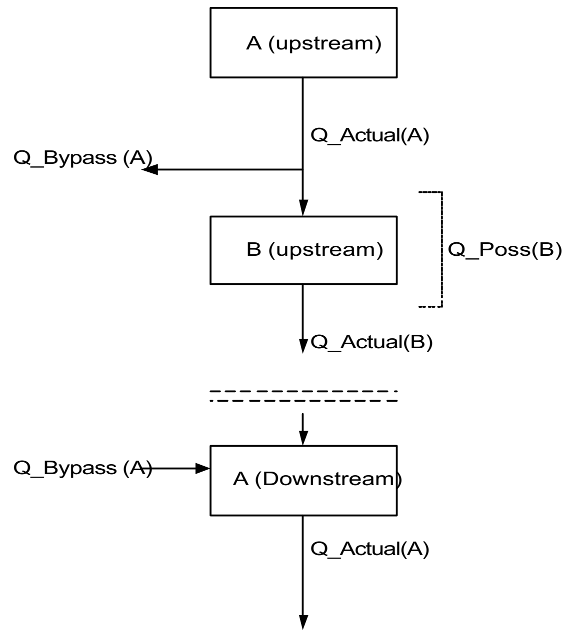

Figure 63: Computation of Water Balance in Terms of Actual and Bypass Flows

Bathtubbing can occur when the volume of flow from the base of the repository (the downstream engineered structures, NF_DwnEng1 in Figure 62) exceeds the flow capacity (Q_{Poss}) for the underlying sediments. In practice, this only occurs when the repository is constructed on till. The excess volume of water is then directed into soil surrounding the repository (the subsequent transport of contaminated water in the biosphere is discussed in further detail in Section G.5). An example of the computed water flows is presented in Table 64. This illustrates that mass is conserved, and that water is apportioned between bypass flows and bathtubbing water as a result of changes in hydraulic characteristics of the near-field materials over time.

G.4 IMPLEMENTATION OF THE FAR-FIELD MODEL

G.4.1 APPROACH

The structure of the far-field model is different for the three main AMBER case files that represent the CAGCV-T, CAGCV-S and DRCV concepts. The main features of the flow path in each case is as follows.

- CAGCV-T: Water percolates through weathered till (3 m), unweathered till (14 m) and enters the aquifer in dolostones (a further 2,000 m to the lake).
- CAGCV-S: Water percolates vertically through sand (3.5 m) and unsaturated carbonate (4 m) then enters the aquifer in dolostones (a further 725 m to the lake).
- DCRV-S: Contaminants diffuse through shales (60 m) and shaft (for the Shaft Pathway Calculation Case, also 60 m), entering an aquifer in dolostones (a further 15,000 m to the lake).

- DCRV-L: Contaminants diffuse through limestones (30 m), shales (230 m) and shaft (for the Shaft Pathway Calculation Case, 260 m), entering an aquifer in dolostones (a further 15,000 m to the lake).

Table 64: Illustration of the Computed Water Flows in the Near Field for a Case in which Bathtubbing Occurs

Time	Volume of Water Flowing (m^3 y^{-1})						
	Through Engineered Structures	Through Backfill (to waste)	Through Backfill (bypassing waste)	Through Waste	Total through Near Field	Total from Near Field to Till	Total from Near Field to Soil (bathtubbing)
0	0.5	0.5	0.0	0.4	0.5	0.5	0.0
50	0.5	0.5	0.0	0.5	0.5	0.5	0.0
100	0.8	0.8	0.0	0.8	0.8	0.8	0.0
150	1.3	1.3	0.0	1.3	1.3	1.3	0.0
200	1.5	1.5	0.0	1.5	1.5	1.5	0.0
250	1.8	1.8	0.0	1.8	1.8	1.8	0.0
300	2.0	2.0	0.0	2.0	2.0	2.0	0.0
350	2.3	2.3	0.0	2.3	2.3	2.3	0.0
400	2.5	2.5	0.0	2.5	2.5	2.5	0.0
450	2.8	2.8	0.0	2.8	2.8	2.8	0.0
500	3.0	3.0	0.0	3.0	3.0	3.0	0.0
550	154.1	154.1	0.0	154.1	154.1	144.7	9.4
600	305.1	305.1	0.0	305.1	305.1	144.7	160.4
650	456.2	456.2	0.0	456.2	456.2	144.7	311.5
700	607.2	607.2	0.0	607.2	607.2	144.7	462.5
750	758.3	758.3	0.0	758.3	758.3	144.7	613.5
800	909.3	909.3	0.0	909.3	909.3	144.7	764.6
850	1060.4	1060.4	0.0	1060.4	1060.4	144.7	915.6
900	1211.4	1211.4	0.0	1211.4	1211.4	144.7	1066.7
950	1362.5	1362.5	0.0	1362.5	1362.5	144.7	1217.7
1000	1513.5	1513.5	0.0	1513.5	1513.5	144.7	1368.8
1250	2268.8	2040.0	228.8	2040.0	2268.8	144.7	2124.0
1500	2520.0	2040.0	480.0	2040.0	2520.0	144.7	2375.3
1750	2520.0	2040.0	480.0	2040.0	2520.0	144.7	2375.3
2000	2520.0	2040.0	480.0	2040.0	2520.0	144.7	2375.3

Note:
The maximum volume of water that can penetrate the cap is the product of the infiltrating rainfall (0.2 m y^{-1}), the area of the engineered structures (21,000 m^2 for the purposes of this example only) and the cap efficiency (0.6), which is equal to 2520 m^3 y^{-1}. The maximum capacity of the till is the product of the hydraulic conductivity of weathered till (0.02 m y^{-1}), the local hydraulic gradient (0.4), the total footprint area of the repository (67 m x 360 m for the purposes of this example only) and the average saturation of the till (0.75), which is 144.7 m^3 y^{-1}.

The media identified above are represented explicitly. The flow path is then further discretised into a number of compartments in order to represent the dispersion or diffusion of contaminants in the media appropriately.

In media where advection is the dominant transport process, the flow path is generally discretised into a number of compartments equal to half the Peclet number (the total path length divided by the longitudinal dispersion length), which is assumed to be 10 for all media.

This ensures an appropriate representation of longitudinal dispersion (transverse dispersion is dealt with by increasing the width of the compartments progressively downstream from the near field). The basis for this approach is described in Penfold et al. (2002).

Where diffusion is dominant, the flow path is discretised in order to reduce the error in diffusion transport compared with the 'exact' solution. It can be found that the total error in calculated flux is equal to the square of the number of compartments into which the flow path is discretised (Penfold et al., 2002). For diffusion in shale and limestone, five compartments are considered, reducing the error to less than 1%.

These rules for discretisation have been applied to determine the compartment structure for the far field that is described in the following sub-sections.

G.4.2 CAGCV-T CONCEPT

The compartment structure is illustrated in Figure 64. The till (both weathered and unweathered) in which transport is predominantly downwards, has been discretised into 5 compartments (FF_Till1 – FF_Till5) reflecting the longitudinal dispersivity being 1/10 of the total path length in the material. The first compartment is considered to be weathered and have a height (in the vertical direction) of 3 m. The remaining pathlength is split equally between each remaining compartment, all of which are considered to be unweathered till.

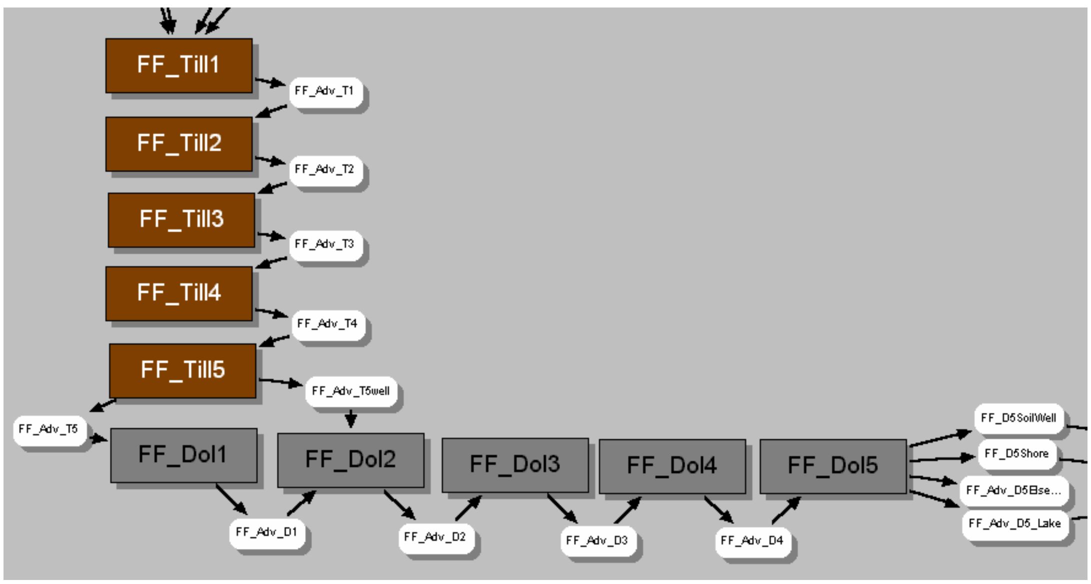

Figure 64: Compartment Structure for the Far Field of the CAGCV-T Concept

The dolostone is also discretised into five separate compartments (FF_Dol1 – FF_Dol5), reflecting its dispersivity of 1/10 the total path length. Each compartment has a length of 1/5 the total path length in the dolostone. The total path length can be varied according to the calculation case considered, and the width of each compartment is progressively increased to account for transverse dispersion in the dolostone.

The dimensions of the individual compartments, in terms of height (vertical distance), length (horizontal, in the direction of flow in the dolostone) and width (horizontal and perpendicular to the direction of flow in the dolostone) are indicated in Table 65.

The transfers throughout the far-field model are donor-controlled advective transfers, with allowance for equilibrium sorption. The characteristics of the advective transfers are dependent on the characteristics of the materials assigned to the compartment, however flows in the unsaturated region are limited to the rate of flow of water through the base of the repository (itself determined by the near-field materials). Solubility limitation is not considered (concentrations in groundwater are limited during the releases from the near field, and only become further diluted in the far field).

Table 65: Compartment Dimensions for the Far Field of the CAGCV-T AMBER Model

Compartment	Length (m)	Width (m)	Height (m)	Material
FF_Till1	67	320	3	Weathered Till
FF_Till2…5	67	320	3.5	Unweathered Till
FF_Dol1…5	L_{Dol}/5	320+	10	Saturated dolostone

Note: The length of path in the dolostone varies according to the calculation case and is indicated with the parameter L_{Dol} (m), and is taken from the upstream boundary of the repository (i.e., the total path length is 2067 m for the Lake Release Calculation Case, 1867 m for the Lakeshore Release Calculation Case and 167 m for the Well Release Calculation Case). '+' indicates that the width of compartments increases with transverse dispersion downstream, according to Equation 29 in Appendix E.2.3.

The transfer into the till is adjusted to reflect the proportion of the total flow entering the till (if bathtubbing occurs, this is less than the total volume of groundwater flowing from the repository). The transfer from the till into the dolostone occurs from FF_Till5 to FF_Dol1 for all calculation cases with the exception of the Well Release Calculation Case, in which the reduced path length in the dolostone (167 m from the upstream end of the repository) means that the Till compartment also discharge into the second dolostone compartment. An additional transfer is switched on in this case. Releases into the biosphere from the dolostone can be directed towards the lake (Lake Release Calculation Case), lakeshore (Lakeshore Release Calculation Case), or soil (Well Release Calculation Case).

G.4.3 CAGCV-S CONCEPT

The compartment structure is similar to that adopted for the CAGCV-T case owing to the similar dimensions of the modelled system, and orientation of the groundwater flows. It is presented in Figure 65. In this case, however, vertical flow in the unsaturated region takes place in sand and dolostone, before the contaminants are released to the dolostone aquifer. The characteristics of the dolostone aquifer are otherwise the same as the CAGCV-T case, with the exception that the distance to the lake is shorter.

Five unsaturated compartments are considered. Strictly, it would be appropriate to discretise the different materials (sand, dolostone) into 5 compartments each, however the physically short distance travelled by groundwater is considered to render this unnecessary. Both the sand and dolostone are also sufficiently conductive to allow the rate of flow through both media to be the same, i.e., equal to rate of infiltration of rainfall. The five unsaturated compartments are discretised into approximately equal sizes (whilst respecting the depths of the sand and unsaturated dolostone defined by Golder Associates (2003)).

The dolostone is discretised into five equal compartments in the same manner as for the CAGCV-T case. The length of these compartments varies with the calculation case assumptions, and their width is determined by the transverse dispersion in the medium.

The dimensions of the far-field compartments for the CAGCV-S AMBER model are presented in Table 66.

The transfers throughout the far-field model are organised in the same manner as those described for the CAGCV-T case, even though the characteristics of the far field are such that bathtubbing cannot occur for this case.

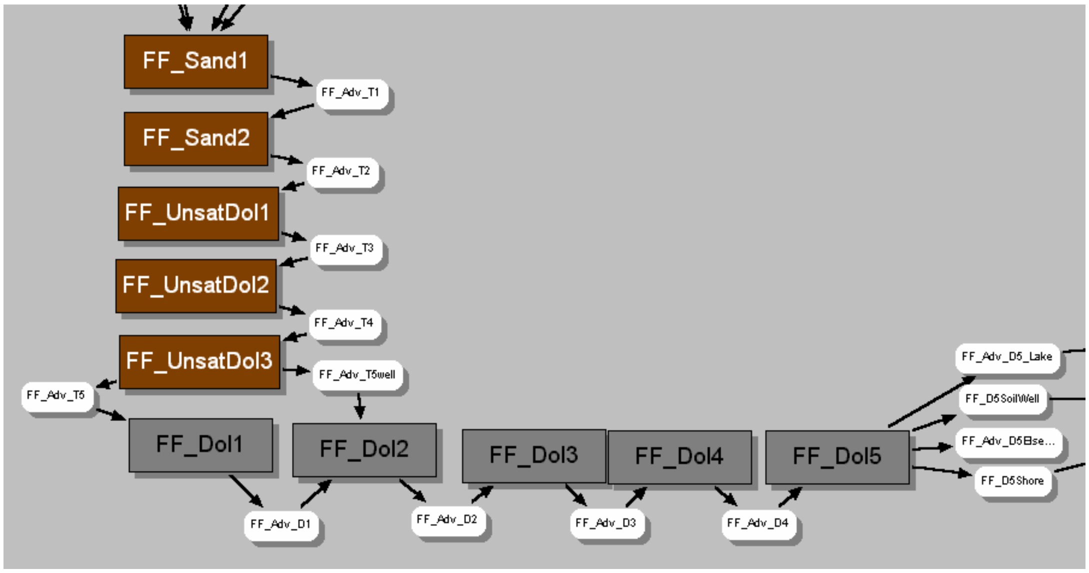

Figure 65: Compartment Structure for the Far Field of the CAGCV-S Concept

Table 66: Compartment Dimensions for the Far Field of the CAGCV-S AMBER Model

Compartment	Length (m)	Width (m)	Height (m)	Material
FF_Sand1…2	67	320	1.75	Sand
FF_UnsatDol1…3	67	320	1.33	Unsaturated dolostone
FF_Dol1…5	$L_{Dol}/5$	320+	10	Saturated dolostone

Note: The length of path in the dolostone varies according to the calculation case and is indicated with the parameter L_{Dol} (m), and is taken from the upstream boundary of the repository (i.e., the total path length is 792 m for the Lake Release Calculation Case, 592 m for the Lakeshore Release Calculation Case and 167 m for the Well Release Calculation Case). '+' indicates that the width of compartments increases with transverse dispersion downstream, according to Equation 29 in Appendix E.2.3.

G.4.4 DRCV CONCEPTS

The DRCV AMBER model differs from the CAGCV-T and CAGCV-S AMBER models in that it allows the representation of both DRCV concepts as well as all calculation cases. As noted previously, a parameter can be set by the user that directs the release of radionuclides from the near field either into shale or limestone. Both materials are represented separately in the model.

The limestone, shale and dolostone are each discretised into five separate compartments. Only diffusion occurs in the limestone and shale, and the choice of five compartments ensures that the solution to the diffusion calculations results in an error of less than 1%. Each compartment is assigned an equal length. If the DRCV-S concept is considered, the total path length in shale is assumed to be 60 m. If the DRCV-L is considered, a 30 m path in limestone is considered, with a further 230 m in shale, before reaching the overlying dolostone aquifer. The length and width of compartments is cautiously assumed to be the same as the total dimensions of the DRCV (i.e., 240 m x 160 m).

In addition a diffusive pathway via the shaft is also included, discretised into 5 compartments. In this simple representation of the shaft, contaminants migrating via the shaft are not considered to interact with those in the rest of the rock, or vice versa.

The dolostone aquifer has also been discretised into five compartments, reflecting its dispersivity of 1/10 the total path length. Each compartment has a length of 1/5 the total path length in the dolostone.

The compartments comprising the far field for the DRCV AMBER model are illustrated in Figure 66. The dimensions of these compartments are presented in Table 67.

The transfers throughout the limestone and shale compartments account for diffusion alone, whilst the transfers in the overlying aquifer are advective. The model structure is adjusted to represent the DRCV-L or DRCV-S case by switching the release of radionuclides between the FF_Lime1 or FF_Shale1 compartments. Similarly, a portion of the release can be directed via the shaft compartments for the Shaft Pathway Calculation Case.

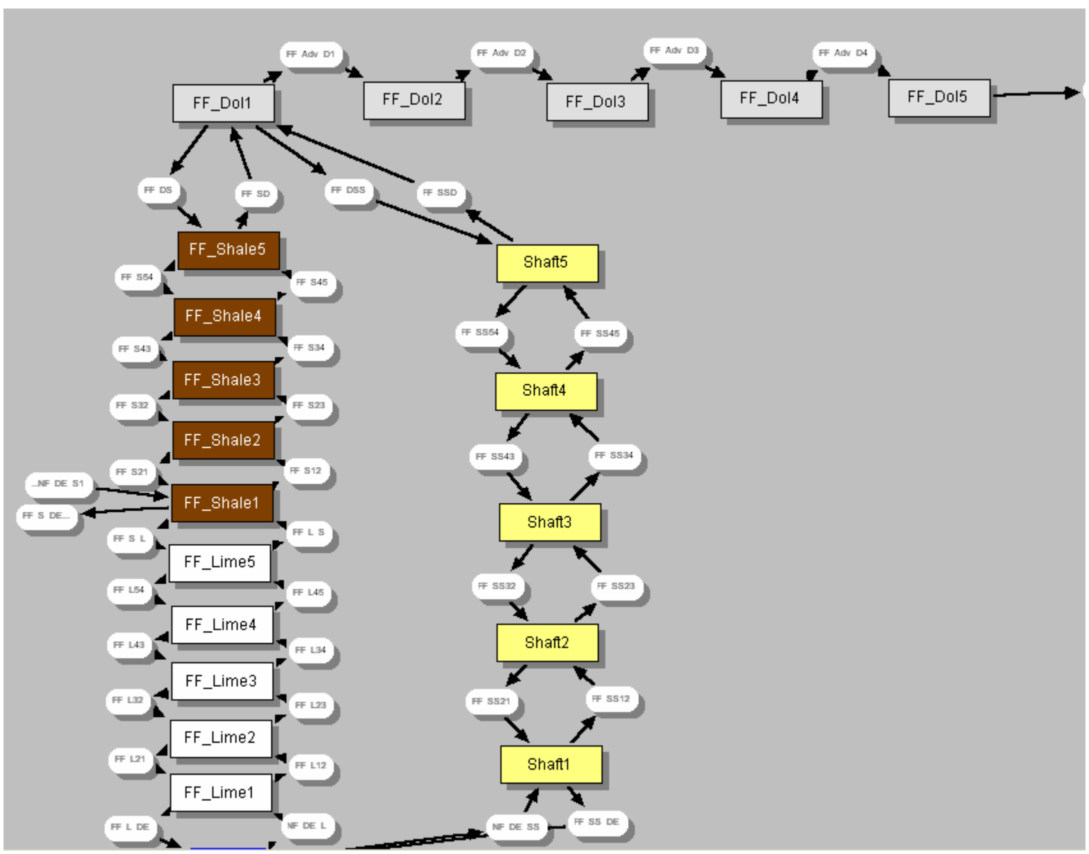

Figure 66: Compartment Structure for the Far Field of the DRCV Concept

Table 67: Compartment Dimensions for the Far Field of the DRCV AMBER Model

Compartment	Length (m)	Width (m)	Height (m)	Material
FF_Lime1…5	240	160	6	Limestone
FF_Shale1…5	240	160	12 / 46	Shale
FF_Shaft1…5	5	5	12 / 52	Sand/Gravel
FF_Dol1…5	3000	160+	100	Saturated dolostone

Note: The length of path in the shale and shaft varies according to whether the DRCV-L or DRCV-S concept is considered. In the former case, shale compartments are assumed to be 46 m in height (resulting in a total path in shale of 230 m) and shaft compartments are 52 m (total path of 260 m). If the DRCV-S concept is considered, each shale and shaft compartments are 12 m (total path 60 m in each case). '+' indicates that the width of compartments increases with transverse dispersion downstream, according to Equation 29 in Appendix E.2.3.

G.5 IMPLEMENTATION OF THE BIOSPHERE MODELS

G.5.1 LAKE MODEL

The lake model has been based on a compartment representation of Lake Huron and the AMBER implementation is illustrated in Figure 67. The lake is discretised into six main water bodies, with a seventh (B_Lake7 in Figure 67) being the region in which the release of contaminated groundwater is assumed to occur. The physical and chemical characteristics (of both water and sediment) are assumed to be the same throughout the lake, although these conditions are known to vary.

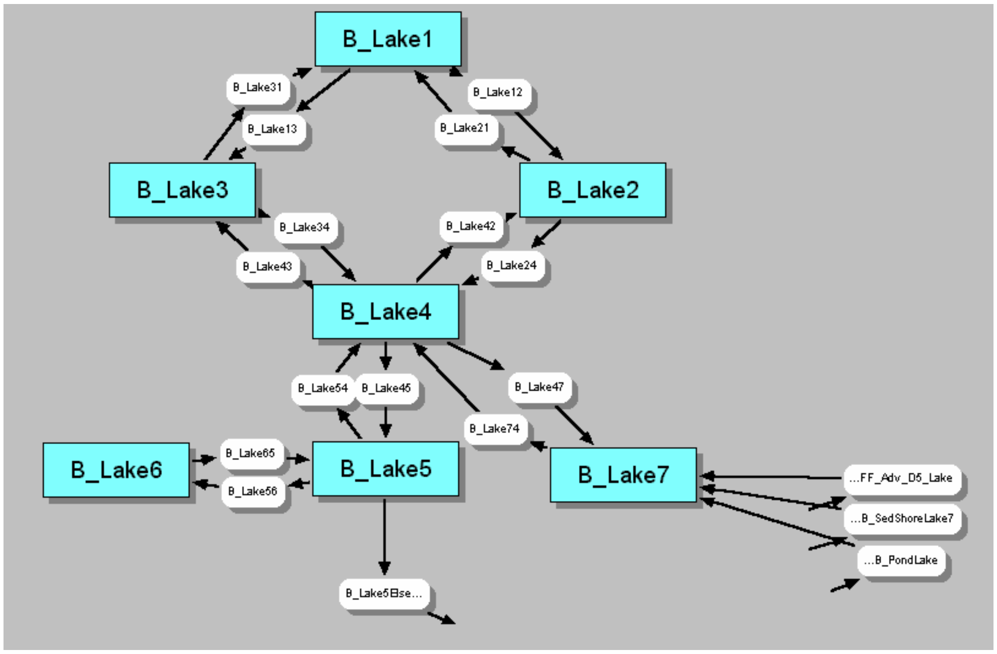

Figure 67: Lake Model Implementation in AMBER

Radionuclide releases to the lake can occur from contaminants in the geosphere or the biosphere. Direct discharge into the B_Lake7 compartment is considered for the Lake Release Calculation Case. Releases occur via shore sediments for the Lakeshore Release

Calculation Case, and contaminated soil is also discharged to the B_Lake7 compartment in the Bathtubbing Calculation Case.

Radionuclide transfers between the lake compartments are defined according to the volume exchanges described in Appendix F.4.1, and radionuclides leave the model to outside the region of interest via a loss by river from the south basin (B_Lake5). Sedimentation has not been represented dynamically in the model – sediment concentrations are inferred from the concentrations in lake water using an equilibrium sorption approach.

In dose rate calculations, radionuclide concentrations in water and fish are associated with the near-shore discharge compartment (B_Lake7) for the CAGCV case, and the central basin (B_Lake4) for the discharge of contaminated groundwater from the DRCV repositories (which is more than 10 km offshore).

G.5.2 MODELS FOR SOIL AND SHORE SEDIMENTS

The implementation of a number of calculation cases in a single AMBER model requires that various different biosphere media are represented. Whilst the lake model described above is common to all calculation cases (where it is considered), the characteristics of contaminated soil or lakeshore sediment are specific to the calculation case. Although it is possible to define a single general soil compartment, it is simpler to implement each region of potentially contaminated soil or lakeshore sediment separately.

Four calculation cases for the CAGCV require the representation of contaminated soils or sediments:

- the Lakeshore Release Calculation Case considers the discharge of contaminated groundwater through lakeshore sediments into the lake;
- the Well Release Calculation Case considers the contamination of soil by irrigation using water drawn from a contaminated well;
- the Bathtubbing Calculation Case (CAGCV-T only) considers the direct contamination of soil by groundwater from the waste; and
- the Cover Erosion Calculation Case considers the erosion of waste onto the soil surface.

Contaminated shore sediments are considered in the Lake Release Calculation Case for the CAGCV and DRCV cases. However, these do not require explicit representation in the dynamic model as the sediment concentrations are calculated using an equilibrium sorption approach.

For the Excavation Calculation Case for the Human Intrusion Scenario, soil contaminated with excavated material is assessed by simply considering the concentrations of radionuclides in waste and applying a dilution factor (which represents the proportion of waste in clean soil). This also does not require explicit representation in the dynamic model.

Therefore, the general approach has been to represent potentially contaminated soils and sediments of interest for various calculation cases in a single biosphere model, as shown in Figure 68. The transfers of radionuclides to the soil or sediment compartments are then switched on or off according to the calculation case that is assessed.

The soil and sediment compartments represented in Figure 68 include:

- B_SedShore: shore sediments considered in the Lakeshore Release Calculation Case;
- B_SoilWell: irrigated soil considered in the Well Release Calculation Case;

- B_SoilBath: soil contaminated with liquid releases from the repository in the Bathtubbing Calculation Case; and
- B_SoilCap: soil contaminated with solid releases from the repository in the Cover Erosion Calculation Case.

The implementation of models for each of the above calculation cases is discussed further in the following subsections.

G.5.2.1 Lakeshore Release

The whole volume of contaminated groundwater is assumed to discharge into an area of lakeshore sediment equal to the width of the contaminated plume in the aquifer, and a total length of 200 m perpendicular to the direction of flow in the aquifer. Contaminated groundwater then flows into the lake (B_Lake7 compartment, which represents the near-shore discharge zone).

When this calculation case is considered, the only transfer from the final dolostone compartment is advective, and directed towards the shore sediments. The transfer from the lakeshore sediments to the lake takes account of the total volume of released groundwater plus the volume of rainwater infiltrating into the sediments. In addition, the erosion of the sediments into the lake is considered.

G.5.2.2 Well Release

The volume of water abstracted from the well annually, and discharged by irrigation onto the soil, is calculated from the product of the assumed soil area and the rate of irrigation. The soil area is assumed to be the minimum to support crops and animals to feed a family or small community. This volume of irrigation water is used in an advective transfer of contaminated water from the final compartment in the near-surface aquifer, with the remainder of the flow (groundwater flow plus water abstracted for consumption by animals and humans) being directed out of the region of interest.

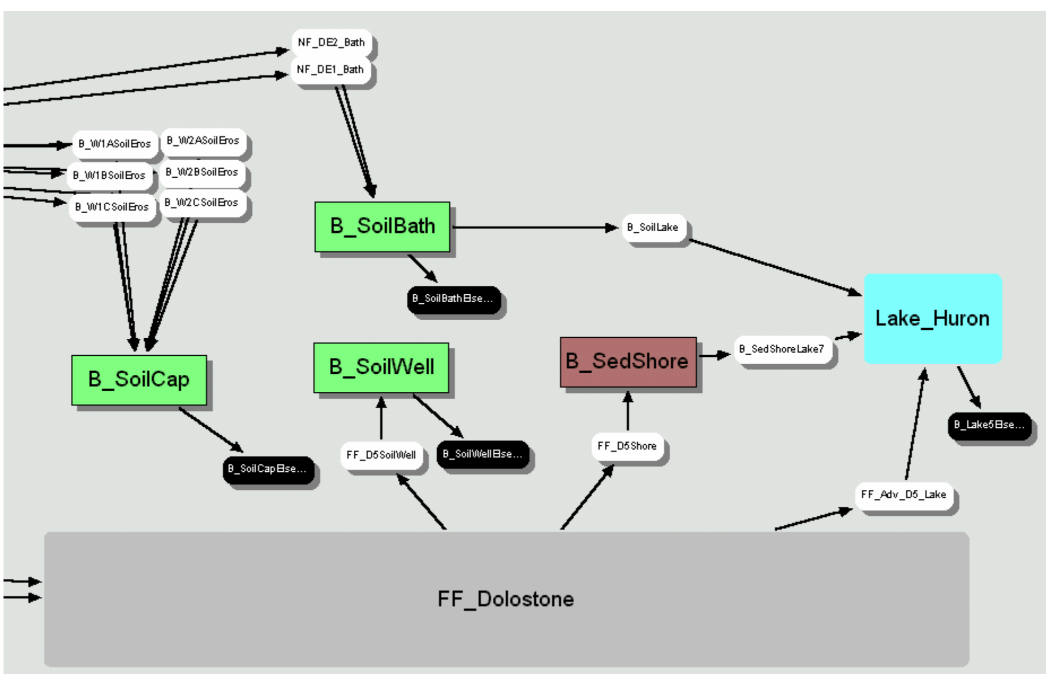

Figure 68: The Biosphere Model (CAGCV Concepts)

Radionuclides in the irrigated soil are also assumed to be lost from the modelled system when they are transported downwards, away from the top 0.3 m, by infiltrating rainfall. In practice, some radionuclides could re-enter the aquifer and be recycled into irrigation water; however, this effect is not considered in the present model.

G.5.2.3 Bathtubbing

The computation of water flows through the repository is undertaken as described in Appendix G.3.2. If this volume is greater than the flow capacity of the underlying material, the excess is assumed to be released directly to soil rather than recharge the aquifer ('bathtubbing'). The phenomenon only occurs when the hydraulic conductivity of the repository cap and repository structures is greater than that of the underlying sediments or rock, and is considered in the Bathtubbing Calculation Case (considered for the CAGCV-T concept only).

The volume of bathtubbing water is calculated automatically from the flow through the repository and the hydrological characteristics of the underlying till. The whole volume of water is assumed to flow through the sides of the repository into surrounding soil. Contaminated water is then assumed to be transported with the surface water system into the lake (the release is to compartment B_Lake7). Radionuclides in soil can also be lost from the modelled system by general surface erosion.

The implementation of the model therefore assumes that the contaminated water released to the soil from the repository moves laterally (i.e., as interflow) until it is intercepted by a surface water pathway to the lake. Given the low permeability of the till, and the additional volume of infiltrating rainfall into the soil, this is considered to be an appropriate implementation of the model, although it is possible that localised outcrops of sand may act as drainage channels that divert excess surface water to the aquifer.

G.5.2.4 Cover Erosion

General surface erosion (as a result of the action of wind and water) may ultimately result in the removal of the cap and other near-field materials, exposing the waste. The waste could subsequently be eroded onto soil.

After a period (determined by the depth of the cap and other cover materials and the rate of erosion), radionuclides in waste are eroded onto surrounding soil. Radionuclides eroded onto this soil are subsequently removed from the soil by transport with infiltrating rainfall, or the erosion of the soil itself.

G.6 COMPILATION OF AMBER COMPARTMENTS AND PARAMETERS

A full listing of AMBER compartments and parameters is included in Table 68, Table 69 and Table 70. Each table gives the AMBER name and a description.

Table 68: AMBER Model Compartment Names and Descriptions

Compartment Name	Description
NF_UpEng1…2	Upstream engineered structures in the repository (two compartments for CAGCV concepts, one for DRCV concept).
NF_UpBac1…2	Upstream backfill in the repository (two compartments for CAGCV concepts, one for DRCV concept).
NF_WF1A…C	Three compartments representing wastes in the repository. Two sets of three compartments are considered in the CAGCV concepts. One set of three compartments are considered in the DRCV concepts.
NF_DwnBac1…2	Downstream backfill in the repository (two compartments for CAGCV concepts, one for DRCV concept).
NF_DwnEng1…2	Downstream engineered structures in the repository (two compartments for CAGCV concepts, one for DRCV concept).
FF_Sand1...2	Two compartments representing the sand in overburden sediments (CAGCV-S concepts only).
FF_UnsatDol1…3	Three compartments representing the unsaturated dolostones in overburden sediments (CAGCV-S concepts only).
FF_Till1…5	Five compartments representing the tills in overburden sediments (CAGCV-T concepts only).
FF_Dol1...5	Five compartments representing the aquifer in dolostones (Shallow Bedrock Groundwater System for the CAGCV concepts, Intermediate Bedrock Groundwater System for the DRCV concepts).
FF_Shale1...5	Five compartments representing the shale in the Deep Bedrock Groundwater System (DRCV concepts only).
FF_Lime1…5	Five compartments representing the limestone in the Deep Bedrock Groundwater System (DRCV concepts only).
FF_Shaft1…5	Five compartments representing the shaft to the DRCV (DRCV concepts only).
B_Lake1	North Channel of Lake Huron.
B_Lake2	Georgian Bay of Lake Huron.
B_Lake3	Mackinac basin of Lake Huron.
B_Lake4	Central basin, Lake Huron.
B_Lake5	South Basin of Lake Huron.
B_Lake6	Saginaw Bay of Lake Huron.
B_Lake7	Discharge zone for contaminated groundwater.
B_SedShore	Shore sediments considered for the release of contaminated groundwater at the lakeshore (CAGCV concepts only).
B_SoilBath	Soil that can become contaminated with groundwater from the repository in the Bathtubbing Calculation Case (CAGCV-T concept only).
B_SoilCap	Soil that can become contaminated by erosion of solid waste in the Cover Erosion Calculation Case (CAGCV concepts only).
B_SoilWell	Agricultural soil that is contaminated by irrigation from contaminated well water (CAGCV concepts only).

Table 69: Standard Parameters Used in the AMBER Model

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
B_Q_Flow	Q_{Flow}	Appendix E.2.2, Equation 33, Table 50	$m^3\ y^{-1}$	Transfers	Volume flow rate of water in surface water compartments.
B_Q_SoilBath	Q_{Bath}	Appendix E.4.1	$m^3\ y^{-1}$	-	Volume of water flowing through soil affected by direct liquid releases from the repository (includes infiltration).
B_lambda_Flow	λ_{Flow}	Appendix E.2.2, Equation 33	y^{-1}	Transfers	Rate of flow of contaminants in surface water compartments.
B_lambda_Well	λ_{Well}	Appendix E.4.2	y^{-1}	Contaminants	Rate of transfer of contaminants from the dolostone to the soil via a well.
B_q_Irr	q_{Irr}	Appendix E.4.2	$m\ y^{-1}$	-	Rate of irrigation assumed to be applied to agricultural soil in the biosphere.
FF_D_Geo	L	Appendix E.1.2, Appendix F.3.3	m	CalcCase	Total length of the pathway in the aquifer, for each calculation case.
FF_K	K	Appendix E.2.2, Equation 26 Table 38	$m\ y^{-1}$	Materials	Hydraulic conductivity of far-field materials.
FF_alpha_T	α_T	Appendix E.2.4, Equation 28	m	-	Transverse dispersion length of far-field materials.
FF_delta_x	*Äx*	Appendix E.2.4, Appendix F.3.3 Equation 29	m	Compartments	Distance of a geosphere compartment downstream from the repository.
FF_grad	*Äh*	Appendix E.2.2, Equation 26, Table 43	-	Materials	Hydraulic gradient in far-field materials.
FF_q_poss	q_{Poss}	Appendix E.2.2, Equation 26	$m\ y^{-1}$	Compartments	Theoretical potential Darcy velocity for compartments in the geosphere.
G_A_perp	A	Appendix E.1.2, Equation 15, Table 35, Table 36	m^2	Compartments	The total area of a compartment that is perpendicular to the dominant direction of flow.

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
G_C_Coll	C_{Coll}	Appendix E.1.1 Equation 1	kg m^{-3}	Materials	The colloid concentration associated with a medium, measured as a mass concentration per unit volume of pore water.
G_CalcCase	-	-	-	-	Parameter in which the desired calculation case is set.
G_D_Cover	D_{Cover}	Appendix E.4.3	m	-	Depth of cap (including engineered structures and backfill).
G_D_Min	D_{Min}	Appendix E.1.2	m	-	Minimum dimension of any compartment.
G_D_e	D_{Eff}	Appendix E1.1, Equation 30, Table 43	m^2 y^{-1}	Materials	The effective diffusion coefficient for each medium.
G_D_llel	D_{llel}	Appendix E.1.2, Appendix F.2.1, Appendix F.3.1	m	Compartments	The effective distance travelled in each compartment in the dominant direction of flow.
G_F_CalcCase	-	-	-	CalcCase	Switch to indicate the calculation case of interest.
G_Height	Height	Appendix E.1.2, Appendix F.2.1, Appendix F.3.1	m	Compartments	Height of compartment in vertical direction.
G_Kd	*Kd*	Appendix E1.1, Equation 2, Table 41, Table 44	m^3 kg^{-1}	Elements, Materials	The equilibrium sorption coefficient for each element and each medium as a function of time.
G_Kd_Comp	*Kd*	Appendix E1.1, Equation 2	m^3 kg^{-1}	Elements, Compartments	The equilibrium sorption coefficient for each element and each compartment as a function of time (derived from G_Kd).
G_Length	Length	Appendix E1.2 Appendix F.2.1, Appendix F.3.1	m	Compartments	Length of compartment. Horizontal, in dominant direction of flow.
G_Mass	-	Appendix F.2.1	kg	Compartments	Mass of compartment, derived from other data.
G_Q_cap	-	Table 39	m^3 y^{-1}	-	Total volume flowing into the repository (calculated from other data).
G_V	*V*	Appendix E1.2, Appendix F.2.1, Table 50	m^3	Compartments	The total volume of each compartment.
G_Width	Width	Appendix E.1.2, Appendix F.2.1,	m	Compartments	Width of compartment. Horizontal, perpendicular to dominant flow direction.

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
		Appendix F.3.1			
G_beta	β	Appendix E.1.3.1 Equation 19	-	Compartments	The time-dependent fraction of a compartment through which water can flow.
G_epsilon	ε	Appendix E1.1, Appendix F.4.2, Table 37	-	Materials	The degree of saturation of a medium.
G_kappa	κ	Appendix E.1.2, Equation 4	m^3	Elements, Compartments	The total capacity of each compartment for a given element.
G_kappa_C	κ_C	Appendix E.1.2, Equation 7	m^3	Elements, Compartments	The capacity of each compartment for a given element (in terms of sorption to colloids).
G_kappa_L	κ_L	Appendix E.1.2, Equation 5	m^3	Elements, Compartments	The fluid capacity of each compartment for a given element.
G_kappa_S	κ_S	Appendix E.1.2, Equation 6	m^3	Elements, Compartments	The capacity of each compartment for a given element (in terms of sorption to fixed solids).
G_lambda_Adv	λ^{ij}_{Adv}	Appendix E.2.2, Equation 25	y^{-1}	Contaminants, Compartments	The rate of transfer of contaminants from compartments by advection.
G_lambda_Eros	λ_{Eros}	Equation 32	y^{-1}	Compartments	The rate of of transfer of contaminants by erosion.
G_q_Eros	q_{Eros}	Appendix E.2.5, Equation 32	$m\ y^{-1}$	-	Rate of erosion of surface materials.
G_q_Inf	q_{Inf}	Appendix F.4.1	$m\ y^{-1}$	-	Rate of infiltration of water through soil, without irrigation.
G_q_cap	-	Appendix F.2.4, Table 39	$m\ y^{-1}$	-	The total maximum rate of flow into the near field through the cap.
G_q_poss	q_{Poss}	Appendix E1.2, Equarion 26	$m\ y^{-1}$	Compartments	The potential flow rate through each compartment as a function of time.
G_rho	ρ	Appendix E.1.1, Appendix F.4.2, Table 37, Table 43	$kg\ m^{-3}$	Materials	The grain density of materials.
G_t_CoverGone	-	Appendix E4.3	y	-	The time at which cover has been completely eroded.
G_t_WasteGone	-	Appendix E4.3	y	-	The time at which waste and cover has been eroded.
G_theta_flow	θ_{Flow}	Appendix E.1.1, Appendix F.4.2,	-	Materials	The flowing porosity of each medium.

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
G_theta_total	θ_{Total}	Table 37, Table 43, Appendix E.1.1, Appendix F.4.2, Table 37, Table 43	-	Materials	The total porosity of each medium (equal to the flowing porosity unless a value is explicitly given).
NF_A_Bypass	-	Table 35, Table 36	m^2	Compartments	Area of the compartment that can be considered as a 'bypass' to all inner compartments.
NF_D_CoverInit	D_{Cover}	Appendix E.4.3, Appendix F.2.1.1	m	-	Initial depth of the cover (the cap and other engineered structures covering the wastes).
NF_Disposals	I	Appendix E.1.2, Equation 1, Table 4	Bq	Contaminants, Wastes	Inventory of radionuclides in various wastes.
NF_Disposals_Media	I	Appendix E.1.2, Equation 1	Bq	Contaminants, Materials	Disposals of radionuclides to different materials.
NF_Flush	-	Appendix E.1.3.1	-	-	The number of 'flushes' (total porewater exchanges) of cementitious materials in the system at a given time.
NF_K_values	K_{Undeg}, K_{Deg}	Appendix E.1.3.2 Equarion 23, Table 38	$m\ y^{-1}$	Materials, Transition	The permeabilities for each medium in either undegraded or degraded state.
NF_Kd_End	K_d	Appendix E1.3.1, Equation 14, Table 41	$m^3\ kg^{-1}$	Elements, Materials	The equilibrium sorption coefficient for each element and each medium, defined for the cement degradation stages. After Stage 3.
NF_Kd_S1	K_d	Appendix E1.3.1, Equation 14, Table 41	$m^3\ kg^{-1}$	Elements, Materials	The equilibrium sorption coefficient for each element and each medium, defined for the cement degradation stages. Stage 1.
NF_Kd_S2	K_d	Appendix E1.3.1, Equation 14, Table 41	$m^3\ kg^{-1}$	Elements, Materials	The equilibrium sorption coefficient for each element and each medium, defined for the cement degradation stages. Stage 2.
NF_Kd_S3	K_d	Appendix E1.3.1, Equation 14, Table 41	$m^3\ kg^{-1}$	Elements, Materials	The equilibrium sorption coefficient for each element and each medium, defined for the cement degradation stages. Stage 3

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
NF_Q_Bath	Q_{Bath}	Appendix E4.1	$m^3 y^{-1}$		Volume of water that is released directly to soil from the near field in the 'Bathtubbing' Calculation Case.
NF_Q_bypass	-	Appendix G3.2, Equation 4	$m^3 y^{-1}$	Compartments	Volumetric flow rate that bypasses inner compartments.
NF_Q_bypassCapacity	-	Appendix G3.2, Equation 4	$m^3 y^{-1}$	Compartments	Capacity for each near-field compartment for bypass water.
NF_Q_poss	Q_{Poss}	Appendix E.2.2, Equation 27	$m^3 y^{-1}$	Compartments	Possible volumetric flow through each compartment as a function of time.
NF_Sol	*Sol*	Appendix E1.1, Equation 14, Table 42	mol m^{-3}	Elements, Materials	The solubility limits for each element and each medium as a function of time.
NF_Sol_Comp	*Sol*	Appendix E1.3.1, Equation 14	mol m^{-3}	Elements, Compartments	The solubility limits for each element and each compartment as a function of time.
NF_Sol_End	*Sol*	Appendix E1.3.1, Equation 14, Table 42	mol m^{-3}	Elements, Materials	The solubility limits for each element and each medium, defined for the cement degradation stages. After Stage 3.
NF_Sol_S1	*Sol*	Appendix E1.3.1, Equation 14, Table 42	mol m^{-3}	Elements, Materials	The solubility limits for each element and each medium, defined for the cement degradation stages. Stage 1.
NF_Sol_S2	*Sol*	Appendix E1.3.1, Equation 14, Table 42	mol m^{-3}	Elements, Materials	The solubility limits for each element and each medium, defined for the cement degradation stages. Stage 2.
NF_Sol_S3	*Sol*	Appendix E1.3.1, Equation 14, Table 42	mol m^{-3}	Elements, Materials	The solubility limits for each element and each medium, defined for the cement degradation stages. Stage 3.
NF_b_ChemDeg	$b_{ChemDeg}$	Appendix E1.3.1, Equation 11	-	ChemDegStage	A function that indicates when a cement degradation regime is considered to be present (with a value of 1, or 0 otherwise).
NF_beta_values	β_{Undeg}, β_{Deg}	Appendix E1.3.2, Equation 19, Table 39	-	Compartments, Transition	The fraction of a medium through which water can flow, specified for undegraded and degraded Materials.
NF_delta	Δ	Appendix E2.4, Equation 31	m	Compartments	The diffusion length of the compartment.

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
NF_f_Cement	f_{Cement}	Appendix F2.2 Table 37	-	Materials	The fraction of a medium that is cement (by volume). This is used for calculating the cement degradation timescales.
NF_f_ChemDeg	$f_{ChemDeg}$	Appendix E1.3.1, Equation 11 – 13	-	ChemDegStage	A normalised linear interpolation function varying from 0 to 1 for each cement degradation stage.
NF_f_PhysDeg	$f_{PhysDeg}$	Appendix E1.3.2, Equation 20–22	-	Materials	A normalised linear interpolation function varying from 0 to 1 for the transition from undegraded to degraded status for the physical properties of each medium.
NF_f_WasteArea	-	-	-	Compartments	Fraction of flow entering the waste from the backfill (if present) or engineered structures
NF_f_beta	f_{Beta}	Appendix E1.3.2 Equations 16-18	-	Compartments	A normalised interpolation function varying from 0 to 1 for the transition from undegraded to degraded status for the 'beta' parameter.
NF_f_betaLin	f_{Beta}	Appendix E1.3.2 Equations 16-18	-	Materials	A normalised linear interpolation function for the 'beta' property.
NF_f_capil	-	-	-	Compartments	The fraction of the dominant flow that flows in the reverse direction by advection, for each compartment This is used to represent capillary rise.
NF_grad	*Äh*	Appendix E2.2, Equation 26, Table 43	-	-	Hydraulic gradient in the near field (-)
NF_k_cement	-	-	m^3	Compartments	The total fluid capacity of cement pores in each compartment.
NF_lambda_Bath	-	Appendix E4.1	y^{-1}	Contaminants	Rate of transfer of contaminants from the near field onto soil (for the 'Bathtubbing' Calculation Case).
NF_lambda_Diff	λ_{Diff}	Appendix E2.4, Equation 31	y^{-1}	Contaminants, Compartments	The rate of transfer of contaminants from compartments by diffusion.
NF_lambda_Gas	Φ_{gas}	Appendix E5.8, Equation 48	y^{-1}	Contaminants, Compartments	Rate of release of radionuclides in gas, Gas Release Calculation Case.
NF_lambda_ bypass	λ_{Bypass}	Appendix G3.2 Equation 4	y^{-1}	Contaminants, Compartments	Transfer rate of contaminants that are present in 'bypass' flow.
NF_t_ChemDeg End	$t_{ChemDegEnd}$	Appendix E1.3.1, Equation 11 – 13 Table 40	y	ChemDegStage	The time at which each cement degradation stage ends.

AMBER Parameter	Parameter in Equations in Appendix E	Value(s)	Units	Multiplicity	Description
NF_t_ChemDeg Start	$t_{ChemDegStart}$	Appendix E1.3.1, Equation 11 – 13 Table 40	y	ChemDegStage	The time at which each cement degradation stage begins.
NF_t_PhysDeg	$t_{PhysDegStart}$, $t_{PhayDegEnd}$	Appendix E1.3.2 Equations 20-22 Table 39	y	Materials, Transition	The times at which each medium can be considered to be completely undegraded, or completely degraded (in terms of its physical properties).
NF_t_beta	$t_{BetaStart}$, $t_{BetaEnd}$	Appendix E1.3.2 Equations 16-18 Table 39	y	Materials, Transition	The times at which each medium can be considered to be completely undegraded, or completely degraded (in terms of its 'beta' property).
NF_tau_Gas	τ_{gas}	Appendix E5.8, Appendix F4.5, Equation 48	y	Contaminants	Timescale for release of gas (H-3 and C-14 only) for the Gas Release Calculation Case.

Table 70: Observer Parameters Used in the AMBER Model

AMBER Parameter	Parameter in Equations in Appendix E	Units	Multiplicity	Description
O_A_h	A_h	m^2		Floor area of house considered in Gas Release Calculation Case.
O_B	B	$m^3\ hr^{-1}$	ExposureGroup	Human inhalation rate.
O_CF_Anm	CF_{Anm}	$y\ kg^{-1}$	Elements, Animal	Element-dependent concentration factor for animal products.
O_CF_Aq	CF_{Aq}	$m^3\ kg^{-1}$	Elements	Element-dependent concentration factor for freshwater fish.
O_CF_Crop	CF_{Crop}	-	Elements, Crops	Element-dependent soil to plant concentration factor (dry weight soil, fresh weight crop).
O_CM_EMDry	-	$Bq\ kg^{-1}$	Contaminants, ExposureGroup	Calculated radionuclide concentration in dry soil.
O_CM_EMWet	-	$Bq\ kg^{-1}$	Contaminants, ExposureGroup	Calculated radionuclide concentration in wet soil.
O_C_Anm	C_{anm}	$Bq\ kg^{-1}$	Contaminants, Animal	Calculated radionuclide concentration in contaminated animal products.
O_C_Aq	C_{Aq}	$Bq\ kg^{-1}$	Contaminants	Calculated concentration of radionuclides in fish.
O_C_Crop	C_{Crop}	$Bq\ kg^{-1}$	Contaminants, Crops	Calculated concentration of radionuclides in crops.
O_C_Gas	C_{gas}	$Bq\ m^{-3}$		Concentration of gaseous radionuclides indoors, for the Gas Release Calculation Case.
O_C_L	C_L	$Bq\ m^{-3}$	Contaminants, Compartments	Radionuclide concentration in the liquid phase of a compartment.
O_C_S	C_S	$Bq\ kg^{-1}$	Contaminants, Compartments	Radionuclide concentration in the solid phase of a compartment.
O_C_W	C_W	$Bq\ m^{-3}$	Contaminants, ExposureGroup	Radionuclide concentration concentration in contaminated water.
O_DC_ExtPt	DC_{ExtPt}	$Sv\ Bq^{-1}\ y^{-1}$	Contaminants	Dose factor for external irradiation by point sources.
O_DC_ExtSl	DC_{ExtSl}	$Sv\ m^3\ y^{-1}\ Bq^{-1}$	Contaminants	Dose factor for external irradiation by a semi-infinite plane of contaminated soil or sediments.
O_DC_Gas	DC_{Gas}	$Sv\ m^3\ Bq^{-1}\ hr^{-1}$	Contaminants	Dose coefficients for inhalation of radionuclides in the gaseous phase.
O_DC_Ing	DC_{Ing}	$Sv\ Bq^{-1}$	Contaminants	Radionuclide-dependent ingestion dose coefficients.

AMBER Parameter	Parameter in Equations in Appendix E	Units	Multiplicity	Description
O_DC_Inh	DC_{Inh}	Sv Bq^{-1}	Contaminants	Radionuclide-dependent inhalation dose coefficients.
O_D_d	D_d	m^2 y^{-1}		Diffusion length of radon in the cap.
O_Dil	Dil	-	ExposureGroup	Dilution factor. Only used for human intrusion scenarios.
O_E_ExtPt	E_{ExtObj}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective external dose rate from point sources.
O_E_ExtSoil	E_{ExtSed}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective external dose rate from soils and sediments.
O_E_IngAnm	E_{IngAnm}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the ingestion of animal products.
O_E_IngAq	E_{IngAq}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the ingestion of fish.
O_E_IngCrop	$E_{IngCrop}$	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the ingestion of crops.
O_E_IngSed	E_{IngSed}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the inadvertent ingestion of soil and sediment.
O_E_IngWat	E_{IngWat}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the ingestion of water.
O_E_InhDust	$E_{InhDust}$	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the inhalation of dust.
O_E_InhGas	E_{InhGas}	Sv y^{-1}	Contaminants, ExposureGroup	Calculated effective dose rate from the inhalation of gas in a house on the cap.
O_E_Tot	-	Sv y^{-1}	ExposureGroup	Total calculated effective dose rate, considering all pathways.
O_E_TotCont	-	Sv y^{-1}	Contaminants, ExposureGroup	Total calculated effective dose rate from all exposure pathways.
O_E_TotPath	-	Sv y^{-1}	ExposureGroup, ExpPath	Total calculated effective dose rate, by exposure pathway.
O_FluxNF	-	Bq y^{-1}	Contaminants	Total flux of radionuclides from the near field.
O_I_Apast	I_{APast}	kg y^{-1}	Animal	Quantity of pasture consumed per year by animals.
O_I_Ased	I_{ASed}	kg y^{-1}	Animal	Quantity of soil consumed per year by animals.
O_I_Awat	I_{AWat}	m^3 y^{-1}	Animal	Quantity of water consumed per year by animals.
O_I_Anm	I_{Anm}	kg y^{-1}	Animal, ExposureGroup	Human ingestion rate of animal products.

AMBER Parameter	Parameter in Equations in Appendix E	Units	Multiplicity	Description
O_I_Aq	I_{Aq}	kg y^{-1}	ExposureGroup	Human ingestion rate of contaminated fish from the lake.
O_I_Crop	I_{Crop}	kg y^{-1}	Crops, ExposureGroup	Rate of ingestion of contaminated crops by humans.
O_I_Sed	I_{Sed}	kg hr^{-1}	ExposureGroup	Rate of ingestion of sediment or soil by humans.
O_I_Wat	I_{Wat}	m^3 y^{-1}	ExposureGroup	Rate of ingestion of contaminated water by humans.
O_M_Obj	M_{obj}	kg	ExposureGroup	Mass of object to which an exposure group is exposed.
O_O_Anm	O_{anm}	-	Animal	Fraction of year spent on contaminated soil by animals.
O_O_Gas	O_H	hr y^{-1}	ExposureGroup	A person's occupancy indoors on the cap, where contaminated gas can be inhaled.
O_O_In		hr y^{-1}	ExposureGroup	Occupancy on (surface) contaminated soil or sediment, indoors by a person in the exposure group.
O_O_Out		hr y^{-1}	ExposureGroup	Occupancy on (surface) contaminated soil or sediment, outdoors by a person in the exposure group.
O_SF		-		Gamma shielding factor for indoors occupancy.
O_V_h	V_h	m^3		Volume of house considered in the gas release scenario.
O_Y_Crop	Y_{Crop}	kg m^{-2}	Crops	Crop yield.
O_c_Aero	c_{Aero}	kg m^{-3}	ExposureGroup	Concentration of dust in the air (respirable fraction).
O_c_Soil	c_{Soil}	-	Crops	Amount of soil on the crop surfaces.
O_epsilon_Rn	ε_{Rn}	-		Radon 222 emanting fraction.
O_f_Gas	f_{gas}	-		Fraction of the inventory assumed to be released as a gas (gas release scenario).
O_f_Prep	f_{Prep}	-	Elements, Crops	Fraction of contamination on vegetables that is lost during food preparation.
O_f_Trans	f_{Trans}	-	Elements, Crops	Radionuclide translocation factor (from plant surface to internals).
O_lambda_Rn	λ_{Rn}	y^{-1}		Decay rate of Rn-222.
O_lambda_W	$\lambda_{Weather}$	y^{-1}	Elements, Crops	Weathering rate of radionuclides from crop surfaces.
O_lambda_v	λ_v	y^{-1}		Rate of ventilation of house considered in the Gas Release Calculation Case.
O_mu_Crop	μ_{crop}	-	Crops	Fraction of irrigation water that is intercepted by crops.
O_phi	Φ_{gas}	Bq m^{-2} y^{-1}	Contaminants	Flux of contaminated gas from the cap.
O_rho_Cap	ρ_{Cov}	kg m^{-3}		Bulk density of cap.

AMBER Parameter	Parameter in Equations in Appendix E	Units	Multiplicity	Description
O_tanh	Tanh $\frac{D_C}{2\,D_d}$	-		Hyperbolic tangent of D_Cover/(2xD_d). This is used to calculate the flux of radon from capping material covering the wastes.

G.7 REFERENCES

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APPENDIX H: DETAILED RESULTS

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Page

H.1. REFERENCE SCENARIO

H.1.1 CAGCV-T NON-GROUTING OPTION

H.1.1.1 Calculated Dose Rates

The CAGCV concept could be located on fine-grained glacial till with low hydraulic conductivities, which has the ability to retard radionuclide migration. The results for this concept, without grouting, are illustrated in Figure 69, which shows the total dose rate for the calculation cases considered. This figure also indicates the average annual individual radiation dose rate from natural radiation sources in Ontario (LaMarre, 2002), equal to 2 mSv y^{-1} (0.002 Sv y^{-1}), and the constraint on dose rates recommended by ICRP (2000), 0.3 mSv y^{-1} (3 x 10^{-4} Sv y^{-1}). The Bathtubbing Calculation Case gives rise to the dominant results, exceeding the results for other calculation cases by more than two orders of magnitude.

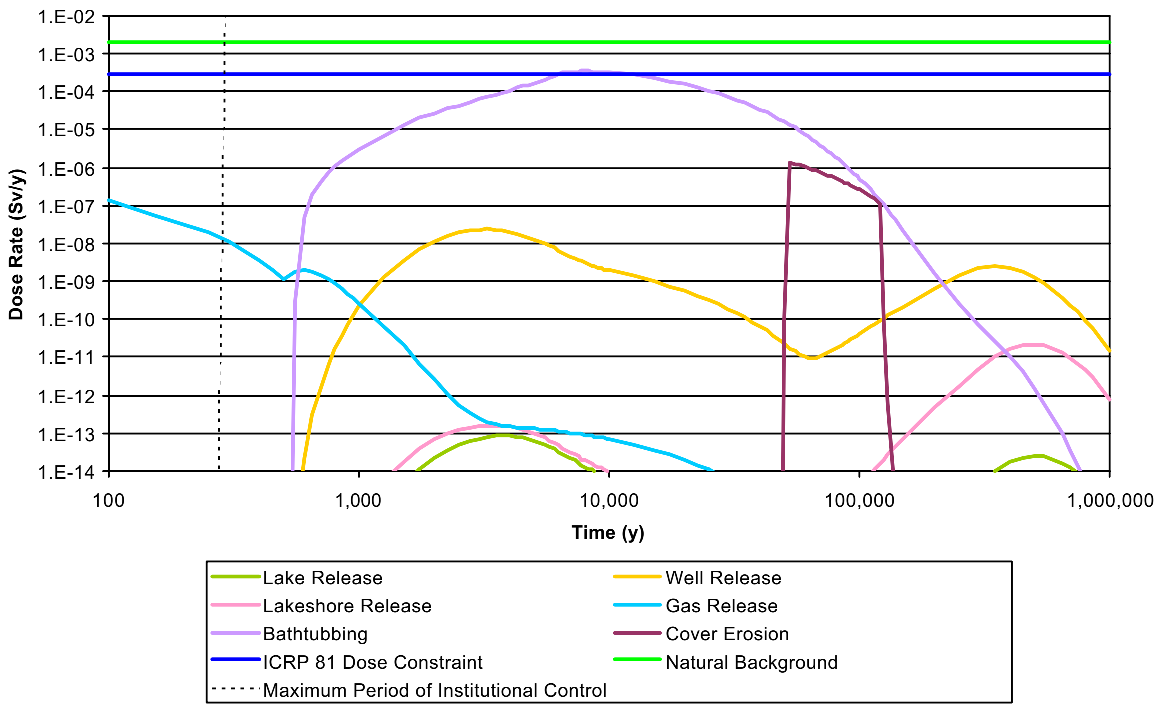

Figure 69: Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the CAGCV-T Non-grouting Option

The Bathtubbing Calculation Case considers the degradation of the repository cap to the point at which it is more permeable than the underlying tills. When the cap has degraded to this extent, a greater volume of water would flow into the facility (per unit area) than could be conducted away by the underlying till. The excess contaminated infiltrating water is assumed to be released directly into soil surrounding the facility. This provides a ‘short cut’ by which contaminants could be released to surface soils without first travelling in the sub-surface till and dolostone. Consequently, high concentrations of radionuclides could accumulate in surface soils near the repository, as there is limited dilution of contaminated porewater from the CAGCV. The use of these soils by a site-dweller could result in dose rates of 3.4 x 10^{-4} Sv y^{-1} (peaking after 8,000 years). This value is slightly in excess of the ICRP dose constraint. The key pathways, shown in Table 71, are associated with external irradiation from contaminated soil (Nb-94 is the dominant radionuclide) and the ingestion of contaminated crops (C-14 is the dominant radionuclide).

Table 71: Summary of Peak Calculated Dose Rates and Key Exposure Pathways for All Calculation Cases for the CAGCV-T Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Bathtubbing	3.4×10^{-4}	8,000	94	<	-	6	<	-	<	-
Cover Erosion	1.3×10^{-6}	55,000	100	-	<	<	<	-	<	-
Well Release	2.3×10^{-8}	3,250	<	12	-	39	<	49	<	-
Gas Release	1.1×10^{-8}	300	-	-	-	-	-	-	-	100
Lakeshore Release	2.2×10^{-11}	500,000	100	-	<	-	-	<	-	-
Lake Release	8.4×10^{-14}	3,750	<	-	92	-	-	8	-	-

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated as ‘<’. A dash (‘-‘) indicates pathways not pathways considered for the calculation case. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Anm)” is the ingestion of contaminated animal products; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Ing (Wat)” is the ingestion of contaminated water; “Inh (Dust)” is the inhalation of contaminated dust; “Inh (Gas)” is the inhalation of contaminated gas.

All other calculation cases are less significant than the Bathtubbing Calculation Case.

The Cover Erosion Calculation Case can be seen to result in doses between 50,000 and about 120,000 years, when the waste itself could be eroded. The peak dose rate of around 1 μSv y^{-1} (1×10^{-6} Sv y^{-1}) occurs shortly after erosion of the waste begins and is well below the ICRP dose constraint. However, it should be noted that the calculation case considered only exposure to the eroded wastes. Direct exposure to raw wastes exposed by the absence of the cap could be greater. The calculated dose rates for the site dweller in the Excavation Calculation Case (see Appendix H.2), indicates the potential magnitude of such exposures.

The Gas Release Calculation Case can be seen to be most significant in the first few hundred years after institutional control ceases. Institutional control is assumed to last for 300 years, during which access to the site would be controlled and the situation considered in the Gas Release Calculation Case would not occur. The peak dose rate at 300 years is 1.1×10^{-8} Sv y^{-1}, whereas if there were no institutional control (i.e. the exposure could occur immediately after closure of the facility), a dose rate of 7.5×10^{-6} Sv y^{-1} can be calculated. Therefore, the institutional control period can be seen to be of benefit in reducing the potential doses associated with gas release by more than two orders of magnitude.

The calculated dose rates from the Well Release Calculation Case reflect the low hydraulic conductivity of the till and the cap, which reduces the rate at which radionuclides could be released into the aquifer. In the aquifer, the radionuclides are also diluted and dispersed. Therefore, the resulting concentrations in irrigation water are much lower than in water affecting soil in the Bathtubbing Calculation Case, and the doses are consequently four orders of magnitude lower.

The Lakeshore and Lake Release Calculation Cases have similar dose rate profiles in the first 10,000 years, as both consider the release of contaminants to the lake. The difference is that the former considers discharge of contaminated groundwater at the lakeshore, and the latter considered discharges occurring under the lake water. Consequently, concentrations of radionuclides in lake shore sediments could become higher. This is particularly the case for well-sorbed radionuclides, which are discharged from the geosphere at times greater than 100,000 years. This explains the differences in the results at long timescales, when substantial concentrations of radionuclides have accumulated in the lakeshore sediments.

H.1.1.2 Key Radionuclides

The most significant radionuclides, in terms of contribution to the dose rate to a site dweller, are illustrated in Figure 70 for the Bathtubbing Calculation Case. The approach to plotting this figure has been to plot any radionuclide that dominates the dose rate at any time. As can be seen, Nb-94 is dominant throughout the period of calculations. This is because it is highly sorbed in soils, and so concentrations accumulate. It is far less significant in other calculation cases, because the sorption of the radionuclide in geological media means that it is transported slowly into the surface environment, and is subject to substantial dilution, and radioactive decay (over periods of tens of thousands of years). It has energetic gamma-ray emissions (700 and 870 keV), which indicates why the key exposure pathway for this calculation case is external irradiation.

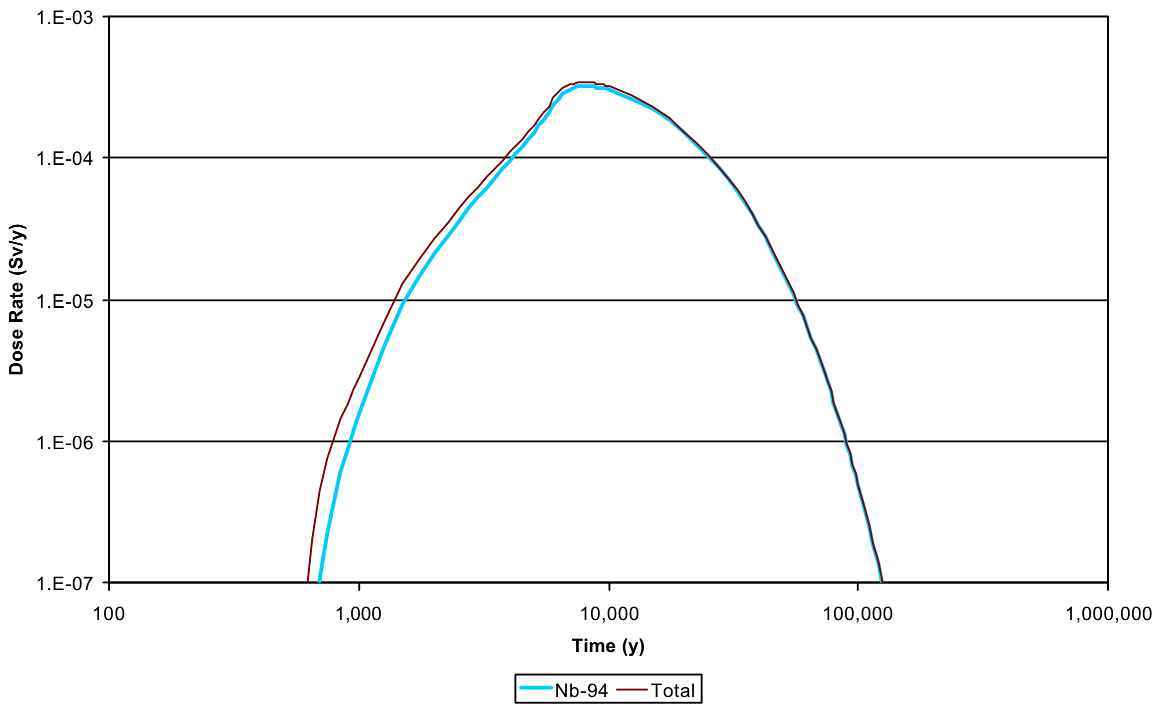

Figure 70: Radionuclides that Dominate the Dose Rate to a Site Dweller, Bathtubbing Calculation Case, CAGCV-T Non-grouting Option

H.1.1.3 Concentrations of Radionuclides in Environmental Media

The radionuclide concentrations in environmental media are illustrated in Figure 71. This shows all the radionuclides that are present with the highest concentration in wet soil at some time during the assessment calculations. As may be seen, whilst Nb-94 is dominant at long timescales, C-14 is most important in the first 30,000 years. However, it has substantially less significant radiation emissions than Nb-94, and therefore does not dominate the dose over this period.

The concentrations of key radionuclides are much greater than typical background concentrations, as can be seen from Table 72. C-14 can be seen to exceed the MAC value (a screening limit representing the maximum acceptable concentration of radionuclides in water supplies (Health Canada, 2002)), although not significantly. No MAC value has been published for Nb-94.

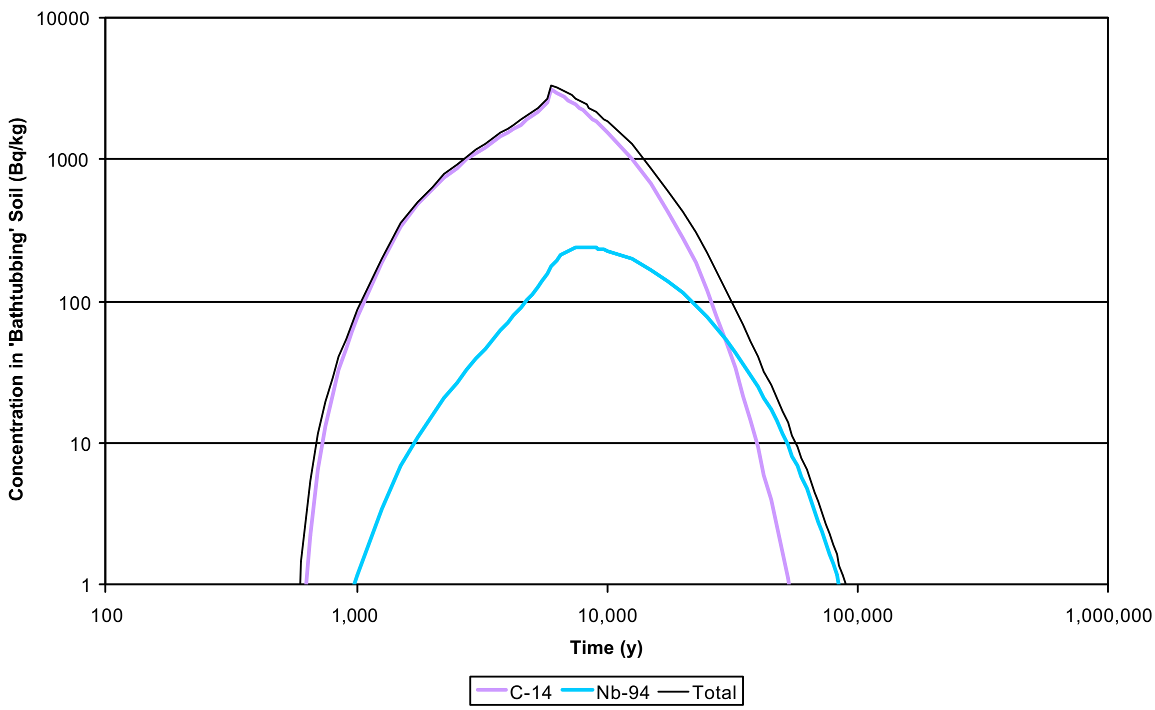

Figure 71: Concentrations of Key Radionuclides in Contaminated Soil, Bathtubbing Calculation Case, CAGCV-T Non-grouting Option

Table 72: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Bathtubbing Case, CAGCV-T Non-grouting Option

Radio-nuclide	Peak Concentration		MAC (Water, Bq m^{-3})	Background Concentration	
	(Bq kg^{-1}, Soil)	(Bq m^{-3}, Water)		(Bq kg^{-1}, Soil)	(Bq m^{-3}, Water)
C-14	3,000	300,000	200,000	200	200
Nb-94	200	700	-	4 x 10^{-7}	3 x 10^{-9}

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). ‘-‘ indicates no data available.

H.1.1.4 Total Activity Concentrations in Waste, Repository, Geosphere and Biosphere

A key design objective of a radioactive waste repository is to contain and isolate radionuclides from the environment. The variation of the maximum concentration of the key radionuclide, Nb-94, in various media (the waste, vault, till and soil) is shown to illustrate the performance of the CAGCV-T for the Bathtubbing Calculation Case (Figure 72).

Concentrations are essentially unchanged in the waste over the first few thousand years, and it is only when the chemical degradation of cement is complete (6,000 years) that Nb-94 begins to be released in more significant concentrations.

Concentrations in the vault materials increase due to diffusive release from the waste into the materials up to 500 years, whilst the cap and engineered structures are essentially undegraded. They then fall as the flow rate of water through the repository increases due to degradation of the waste, only to gradually increase again as radionuclides are released from corroded waste packages. Concentrations fall off after 6,000 years when high-pH conditions in the vaults cease.

The concentration of Nb-94 in soil reaches a peak shortly after the end of high-pH conditions in the waste due to a decrease in the sorption of Nb in the vault. The maximum concentration of Nb-94 exceeds the concentration in the vault materials due to the higher sorption of Nb in soil compared with the degraded vaults (0.6 $m^3 kg^{-1}$ for soil, compared with 0.05 $m^3 kg^{-1}$ for degraded concrete). The concentration of Nb-94 in till is almost two orders of magnitude lower, principally as a consequence of the much smaller volume of contaminated water flowing through the till compared with that released into the soil.

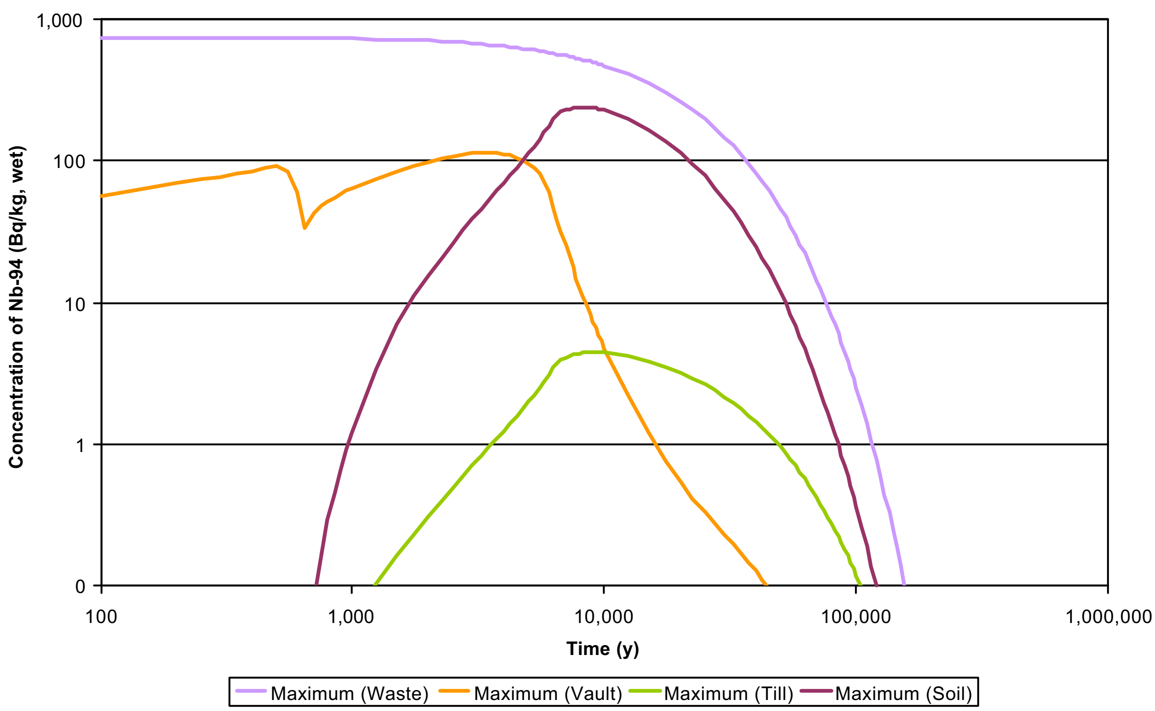

Figure 72: Maximum Concentrations of Nb-94 in Waste and Other Media (Bathtubbing Calculation Case, CAGCV-T Non-grouting Option)

H.1.2 CAGCV-T GROUTING OPTION

H.1.2.1 Calculated Dose Rates

For this set of results, the repository concept is identical to that described in the previous section, with the exception that void spaces in the waste and the repository are assumed to be filled with cementitious grout prior to the closure of the facility, which would enhance the containment of radionuclides such as C-14. As a result of grouting the CAGCV-T concept, there is a reduction of about a factor of ten in the dose rate associated with the Bathtubbing

Calculation Case, compared with the non-grouting option. The peak calculated dose rate for all calculation cases is 0.038 mSv y^{-1} (3.8 x 10^{-5} Sv y^{-1}) at 37,500 years, as is shown in Figure 73. This dose rate is almost an order of magnitude below the recommended ICRP dose constraint.

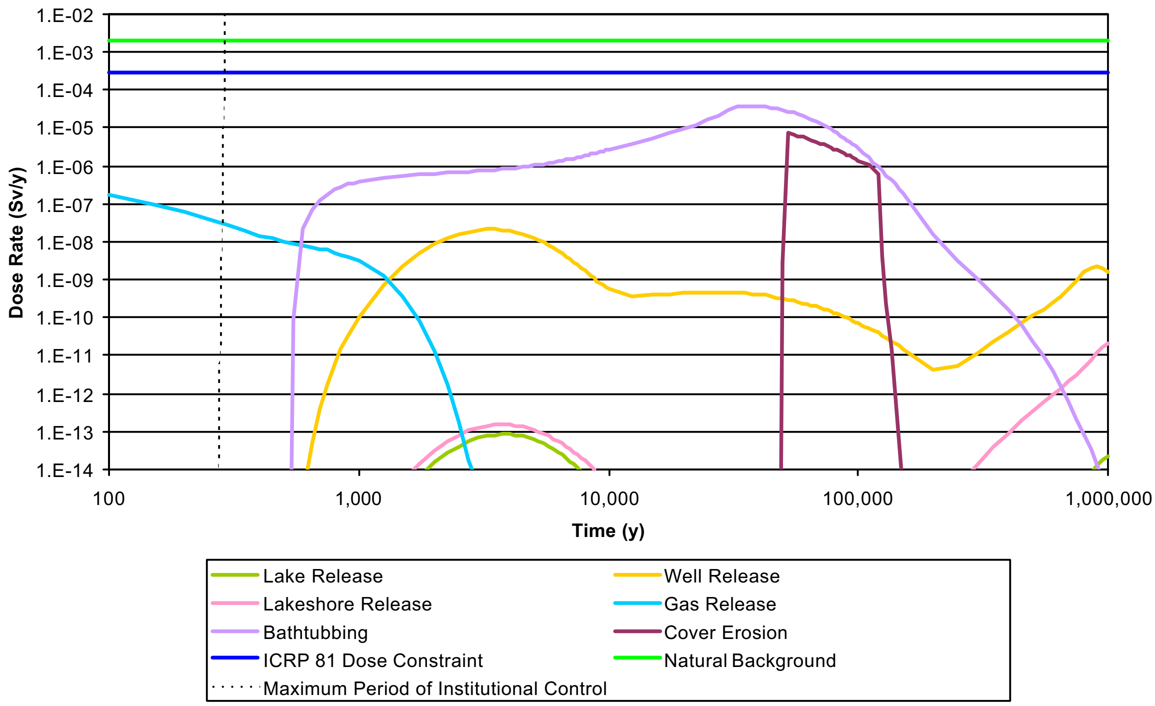

Figure 73: Total Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the CAGCV-T Grouting Option

The reduction in the dose rate results principally from the retention of key radionuclides such as Nb-94 and C-14 in the near field, compared with the non-grouting case. The improved retention is, in part, attributed to highly alkaline conditions persisting in the repository for longer time periods due to the greater amount of cement in the repository. These conditions have been calculated to persist for 28,000 years, compared with 6,000 years for the non-grouted option.

Calculated dose rates associated with the Cover Erosion Calculation Case are increased compared with the non-grouting case. This reflects the enhanced retention of key radionuclides in the repository, which results in potentially higher residual concentrations when the repository is affected by erosion. As a result, the peak dose for this calculation case is 7.1 x 10^{-6} Sv y^{-1}, compared with 1.3 x 10^{-6} Sv y^{-1} for the non-grouting option. The peak calculated dose rate for the other calculation cases remains relatively similar to the calculated dose rates for the non-grouting option; however, the enhanced retention and rate of release of radionuclides from the repository is evident by the very long timescales at which peak values occur.

Peak calculated dose rate and key exposure pathways for all calculation cases for the CAGCV-T Grouting Option are given in Table 73.

Table 73: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases for the CAGCV-T Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Bathtubbing	3.8×10^{-5}	37,500	98	-	-	2	<	-	<	-
Cover Erosion	7.1×10^{-6}	52,500	99	-	-	1	<	-	<	-
Gas Release	2.7×10^{-8}	300	-	-	-	-	-	-	-	100
Well Release	2.1×10^{-8}	3,500	<	9	<	39	-	52	-	-
Lakeshore Release	2.0×10^{-11}	1,000,000	100	-	<	-	-	<	-	-
Lake Release	8.4×10^{-14}	3750	<	-	92	-	-	8	-	-

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated as '<'. A dash ('-') indicates pathways not pathways considered for the calculation case. Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Anm)" is the ingestion of contaminated animal products; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Crop)" is the ingestion of contaminated plants and vegetables; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Ing (Wat)" is the ingestion of contaminated water; "Inh (Dust)" is the inhalation of contaminated dust; "Inh (Gas)" is the inhalation of contaminated gas.

H.1.2.2 Key Radionuclides

There is an additional radionuclide of importance (Cl-36) for the CAGCV- T grouting option compared with the non-grouting option, when considering the Bathtubbing Calculation Case. This radionuclide dominates calculated doses in the period up to 5,000 years, as shown in Figure 74. This is a result of the enhanced retention of most radionuclides (including Nb-94) over the first few thousand years due to the longer duration of the chemical degradation of cement. Chlorine, by contrast, is released relatively rapidly and remains largely unaffected by the high alkalinity in the facility in the first few thousand years. Hence, it is released into soil rapidly. Therefore, although the calculated doses for this radionuclide is almost exactly the same as calculated for the non-grouting option, it dominates doses in this case due to fact that other (more radiologically significant) radionuclides are not released until after several thousand years.

The increased cement degradation timescale results in the profile of the dose from Nb-94 changing compared with the non-grouting option. The more effective retention of radionuclides in the grouted waste is also the main reason that dose rates associated with the bathtubbing pathway are lower for the grouting case compared with the non-grouting option. For example, over the whole period of chemical degradation (0 – 28,000 years), radioactive decay reduces the amount of Nb-94 present by more than 60%. It is also released more gradually, meaning that concentrations in soil do not accumulate to the extent seen in the non-grouting CAGCV-T option.

H.1.2.3 Concentrations of Radionuclides in Environmental Media

Concentrations of C-14 and Nb-94 in both soil and water are reduced by more than an order of magnitude compared with the non-grouting options for the CAGCV-T, as may be seen in Figure 75. The more effective containment of the radionuclides in the facility means that there is an increased period during which decay could occur before the radionuclides are released into soil. As a result, poorly-sorbed radionuclides could be important, and the figure shows that Tc-99 is present in soil with the highest concentrations in the first 7,500 years. This radionuclide is less significant than Cl-36 in terms of dose, as dose coefficients are lower.

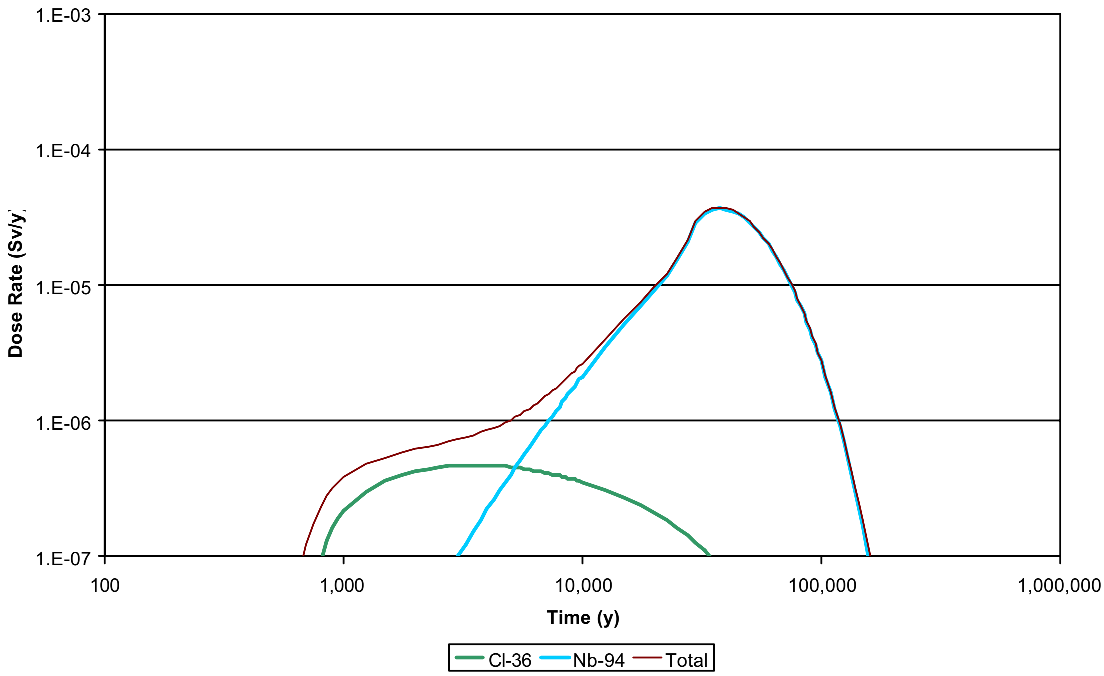

Figure 74: Radionuclides that Dominate the Dose Rate to Site Dweller, Bathtubbing Calculation Case, CAGCV-T Grouting Option

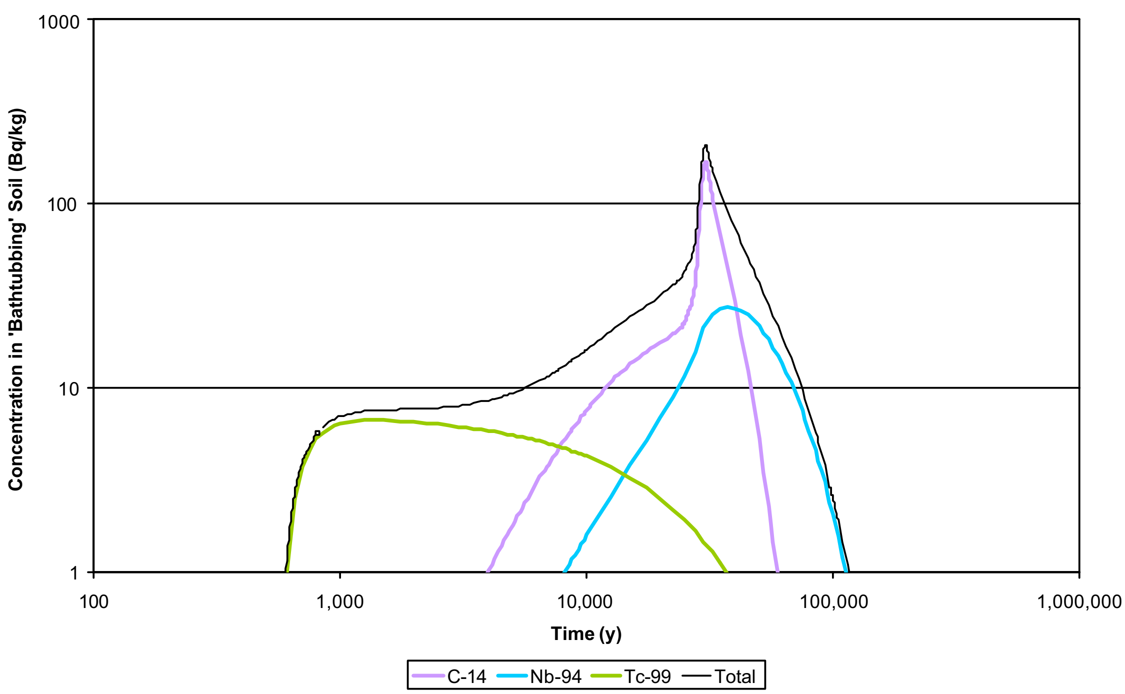

Figure 75: Concentrations of Key Radionuclides In Contaminated Soil, Bathtubbing Calculation Case, CAGCV-T Grouting Option

The peak calculated concentrations of C-14 and Nb-94 are greater than background concentrations, as can be seen from Table 74. However, the peak concentration of C-14 in water is a factor of 20 less than the MAC value. No similar value is available for Nb-94.

Table 74: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Bathtubbing Calculation Case, CAGCV-T Grouting Option

Radio-nuclide	Peak Concentration		MAC (Water, Bq m^{-3})	Background Concentration	
	(Bq kg^{-1}, Soil)	(Bq m^{-3}, Water)		(Bq kg^{-1}, Soil)	(Bq m^{-3}, Water)
C-14	200	10,000	200,000	200	200
Nb-94	30	80	-	4×10^{-7}	3×10^{-9}

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). '-' indicates no data available.

H.1.2.4 Total Activity Concentrations in Waste, Repository, Geosphere and Biosphere

Figure 76 illustrates the effect of the assumed longer duration of high-pH conditions on the concentrations of Nb-94 in various media. Compared with the non-grouting case, it can be seen that the concentration of the radionuclide in the waste is similar to the non-grouting CACGV-T option. However, the concentrations in the vault are much lower as the radionuclides are retained in the grouted waste form. This is because the rate of release of radionuclides from grouted waste is lower than non-grouted waste. Consequently, the concentrations that are accumulated in vault materials are lower.

The environmental concentrations in soils are lower in the first 10,000 years, remaining below 1 Bq kg^{-1} for 8,000 years. As the sorption coefficient for niobium gradually decreases, however, the concentrations increase to a peak at 37,500 years. Concentrations then decrease as the remaining radionuclides are gradually released over the next 100,000 years.

H.1.3 CAGCV-S NON-GROUTING OPTION

H.1.3.1 Calculated Dose Rates

The total dose rate that is calculated for the range of calculation cases considered in the assessment for the non-grouted CAGCV located on sand is presented in Figure 77. This figure shows that results for all calculation cases are comfortably below the ICRP dose criterion of 3×10^{-4} Sv y^{-1}. The contribution of various pathways, and a summary of the peak dose rate and time of occurrence are presented in Table 75.

The Bathtubbing Calculation Case is not considered for this repository concept. This is because the hydraulic conductivity of the sand on which it is assumed to be located is sufficiently high to permit the flow of infiltrating rainwater under any conditions (even if the cap offered no resistance to rainwater). Consequently, it is highly unlikely that water from the facility could be released directly to the soil.

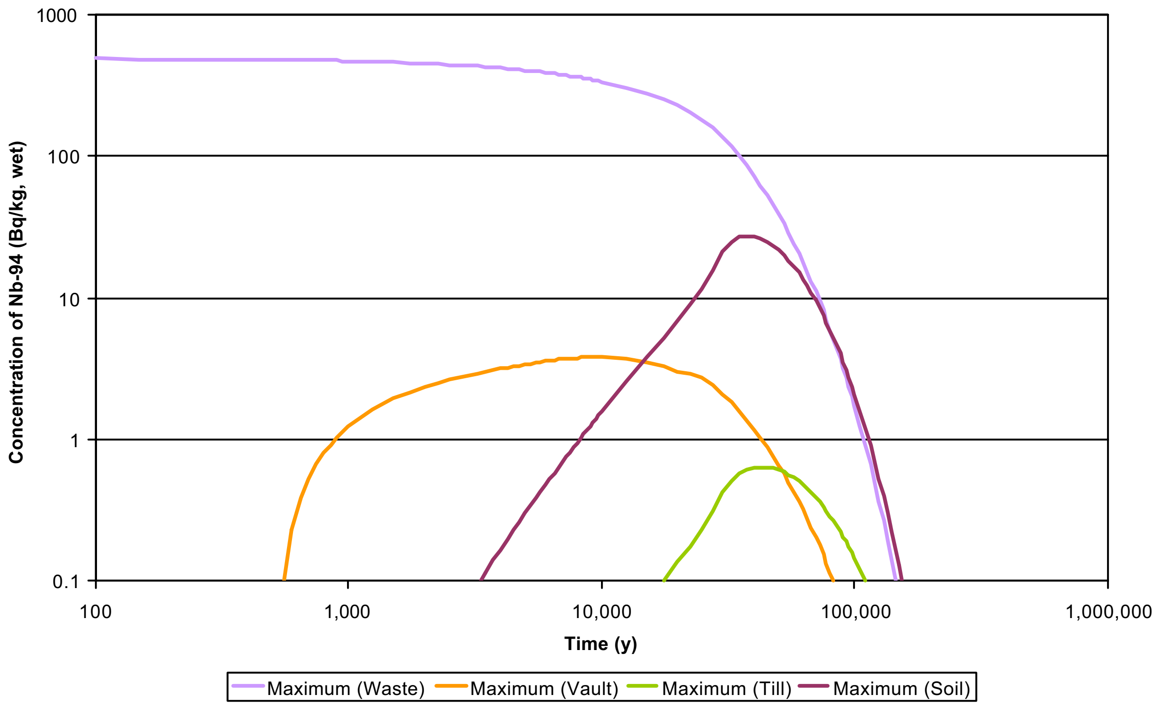

Figure 76: Maximum Concentrations of Nb-94 in Waste and Other Media (Bathtubbing Calculation Case, CAGCV-T Concept, Grouting Option)

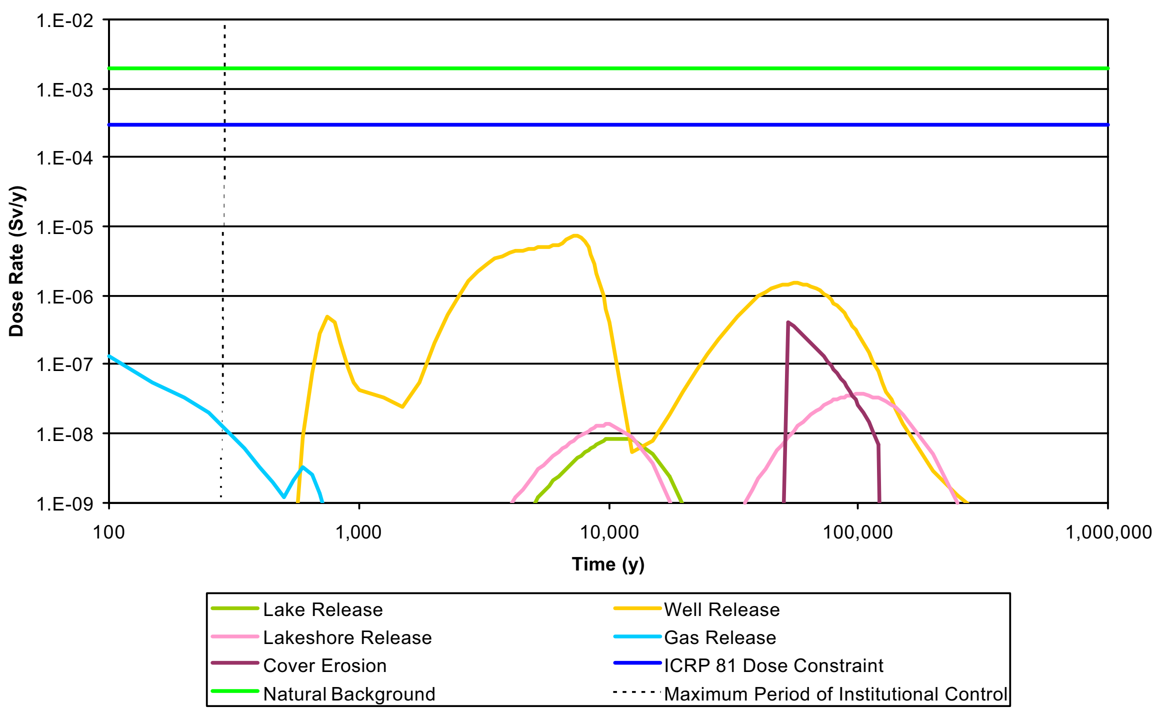

Figure 77: Total Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the CAGCV-S Non-grouting Option

Table 75: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases, CAGCV-S Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Well Release	7.3×10^{-6}	7,500	<	36	-	35	<	29	<	-
Cover Erosion	4.0×10^{-7}	52,500	100	-	-	<	<	-	<	-
Lakeshore Release	3.7×10^{-8}	100,000	100	-	<	-		<	-	-
Gas Release	1.1×10^{-8}	300	-	-	-	-	-	-	-	100
Lake Release	8.4×10^{-9}	10,000	<	-	100	-	-	<	-	-

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated as ‘<’. A dash (‘-‘) indicates pathways not pathways considered for the calculation case. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Anm)” is the ingestion of contaminated animal products; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Ing (Wat)” is the ingestion of contaminated water; “Inh (Dust)” is the inhalation of contaminated dust; “Inh (Gas)” is the inhalation of contaminated gas.

The highest dose rates are associated with the Well Release Calculation Case. The peak dose rate of 7.3×10^{-6} Sv y^{-1} occurs at 7,500 years. In this case, a farmer is assumed to abstract well water from the contaminated portion of the shallow bedrock aquifer, and use the water for drinking and to irrigate crops. The farmer is also assumed to live on the contaminated soil and raise cattle. The high dose rate associated with this calculation case, compared with others, is a result of the utilisation of contaminated groundwater close to the facility. This limits the dispersion of the plume of radionuclides in the aquifer, and the amount of time in which radioactive decay could reduce the concentrations.

The Cover Erosion Calculation Case is the next most significant in terms of peak dose rate. However, doses are only calculated when the waste itself is subject to erosion, between about 50,000 and 120,000 years. The calculated doses are about three times lower than the equivalent case for the CAGCV-T concept because releases of radionuclides from that facility are slower (with the exception of the Bathtubbing Calculation Case) even when grouting is not considered, due to the low hydraulic conductivity of the till.

The calculated dose rates for the Gas Release Calculation Case are the same as the CAGCV-T non-grouting option. However, the results for the Lake and Lakeshore Release Calculation Cases are notably higher, reflecting the more rapid release of radionuclides into groundwater, which is assumed to transport them towards the lake. Nevertheless, the calculated dose rates remain much lower than the ICRP dose criterion.

H.1.3.2 Key Radionuclides

The radionuclides of importance in the Well Release Calculation Case are presented in Figure 78, which shows all radionuclides that dominate dose rates at a given time in the assessment calculations. A greater variety of radionuclides prove to be significant compared with the CAGCV-T options. This is largely because radionuclides can be released more rapidly for this option, and consequently are more likely to reach the surface environment before there has been substantial radioactive decay.

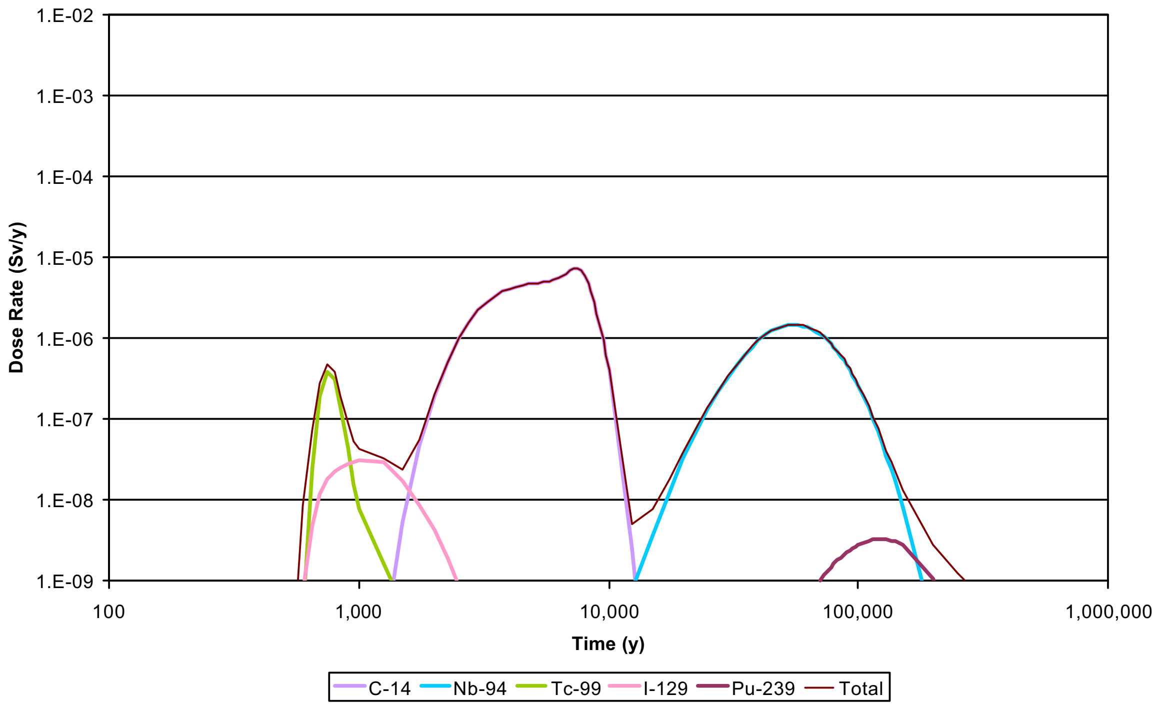

Figure 78: Radionuclides that Dominate the Dose Rate to Farmer, Well Release Calculation Case, CAGCV-S Concept Non-grouting Option

Initially, relatively mobile radionuclides such as Tc-99 and I-129 are released. The mobility of these radionuclides also means that the peak in dose rate is sharp (particularly for Tc-99, which peaks at a dose rate of 4.0×10^{-7} Sv y^{-1} after 800 years). Thereafter, C-14 is dominant between 1,500 and 15,000 years. The profile of the dose rate from C-14 is determined by the timescales for cement degradation, which is complete after 6,000 years for the non-grouting option of the CAGCV-S.

In the period of 15,000 to about 200,000 years after closure of the repository doses are dominated by Nb-94. The peak dose for this radionuclide occurs much later than observed for the Bathtubbing Calculation Cases for the CAGCV-T options because the contaminated groundwater from the facility is released into the geosphere before being discharged to soil via the well, rather than being released directly into soil. At very long timescales, long-lived alpha emitters with radiologically significant progeny become important (specifically Pu-239).

H.1.3.3 Concentrations of Radionuclides in Environmental Media

The concentrations in the environmental media to which a farmer is assumed to be exposed in the Well Release Calculation Case are shown in Figure 79 (well water) and Figure 80 (soil irrigated with contaminated well water). In each figure, radionuclides that are dominant at some period in the calculations are shown, and can be seen to be similar to those that are the main contributors to dose rate, although there are differences in their relative significance.

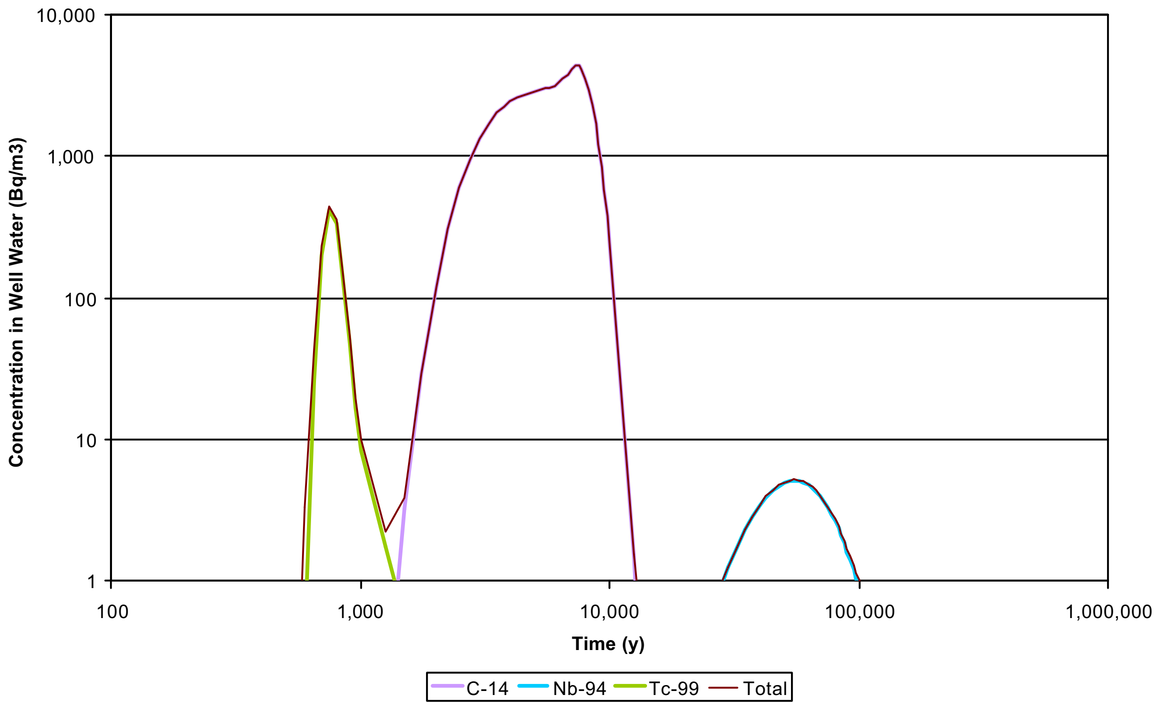

Figure 79: Concentrations of Key Radionuclides in Well Water, Well Release Calculation Case, CAGCV-S Concept Non-grouting Option

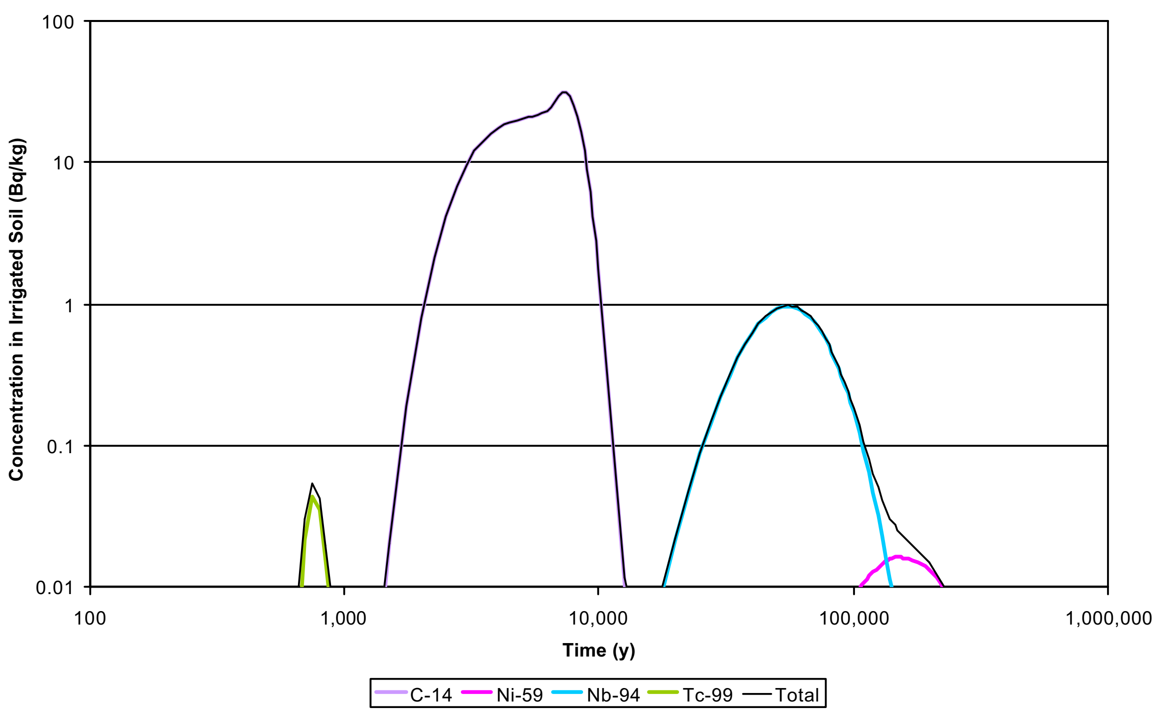

Figure 80: Concentrations of Key Radionuclides in Irrigated Soil, Well Release Calculation Case, CAGCV-S Concept Non-grouting Option

The peak concentrations are compared with Maximum Acceptable Concentrations (MACs) for typical background concentrations in Table 76. This table shows that, for the radionuclides for which MAC values are available, the only MAC value that is exceeded is for Tc-99. This radionuclide is very mobile, in the environmental media considered, and the concentrations are reached relatively early, but also decrease quickly (concentrations greater than 1 Bq m^{-3} in well water are only calculated between 650 and 1,500 years). Concentrations in soil are generally greater than background concentrations in soil (with the exception of Pu-239, for which background concentrations, as a result of atmospheric nuclear weapons tests, are greater).

Table 76: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Well Release Calculation Case, CAGCV-S Non-grouting Option

Radio-nuclide	Peak Concentration		MAC	Background Concentration	
	(Bq kg^{-1}, Soil)	(Bq m^{-3}, Water)	(Water, Bq m^{-3})	(Bq kg^{-1}, Soil)	(Bq m^{-3}, Water)
C-14	30	4,000	200,000	200	200
Nb-94	1	5	-	4×10^{-7}	3×10^{-9}
Tc-99	0.04	400	200	6×10^{-3}	2×10^{-5}
I-129	3×10^{-4}	0.2	1	3×10^{-5}	3×10^{-5}
Pu-239	3×10^{-3}	0.01	200	2	0.01

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). '-' indicates no data available.

H.1.3.4 Total Activity Concentrations in Waste, Repository, Geosphere and Biosphere

A key design objective of a radioactive waste repository is to contain and isolate radionuclides from the environment. Figure 81 illustrates the performance of the facility by showing the maximum calculated concentrations of C-14 (Bq kg^{-1}, wet) for the Well Release Calculation Case in several key media – the waste, the vault materials, the sand sediments, the dolostone aquifer and the irrigated soil.

The radionuclides can be seen to be contained in the wastes and vault for around 600 years before concentrations in the geosphere begin to increase. C-14 is retained in the highly alkaline conditions of the enclosing cementitious materials for the first thousand years; however, the pH reduces to neutral conditions over the period of 1000 – 6000 years, during which time C-14 is released from the facility more readily. This illustrates the importance of the cementitious materials in the overall performance of the repository. The shape of the curve for the vault simply reflects the increase in concentrations over the first few hundred years whilst the engineered structures are relatively intact, and their sorption is greater than that of the waste. After 500 years, the structures degrade and the concentrations of C-14 decrease as it is 'flushed' from the near field. At this point, the concentrations in the vault materials are higher than the waste because of the much greater sorption of the radionuclide in the alkaline cement.

The C-14 released into the environment is relatively mobile and migrates through the geosphere (sand and dolostone) into the irrigated soil. The sharp peak concentration in sand at 6,000 years reflects the rapid release of C-14 as chemical degradation of the cementitious materials is completed. Concentrations in all media decrease at around 10,000 years, when there ceases to be a source of radionuclides in the repository. This decrease reflects the limited sorption and retention of C-14 in environmental media.

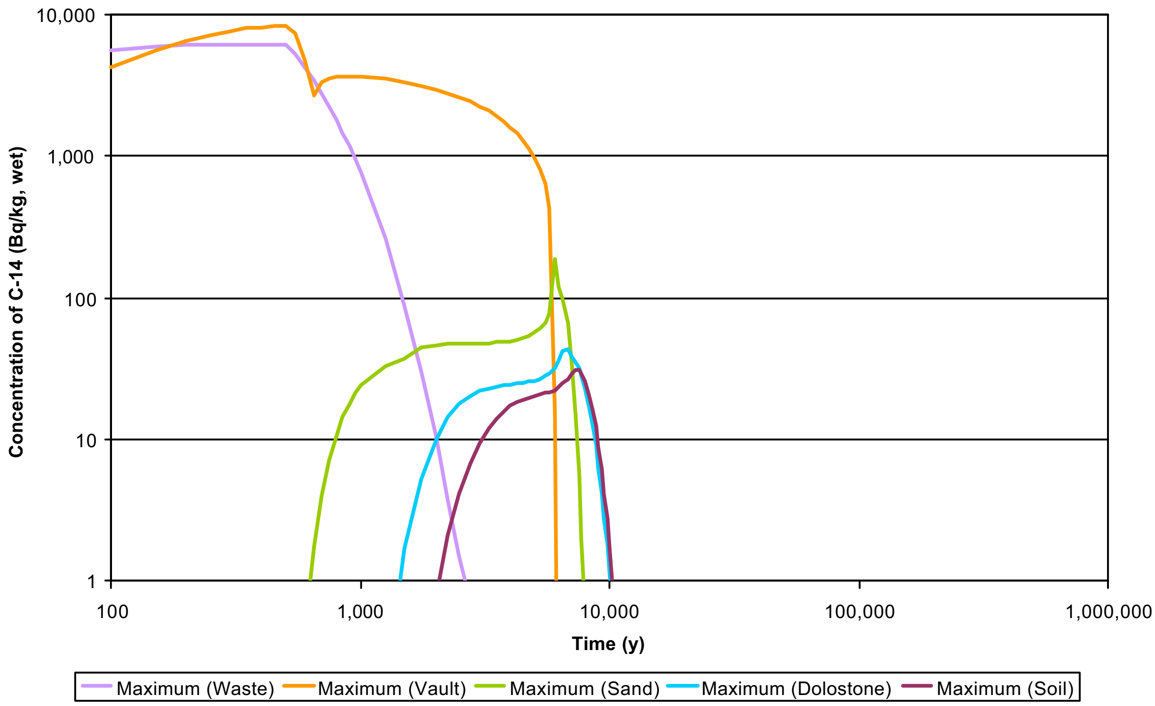

Figure 81: Maximum Concentrations of C-14 in Waste and Other Media (Well Release Calculation Case, CAGCV-S Concept Non-grouting Option)

Figure 81 also illustrates that the slow release of C-14 from the repository, and its subsequent dilution, dispersion and decay, results in peak soil concentrations that are a thousand times smaller than in the waste.

H.1.4 CAGCV-S GROUTING OPTION

H.1.4.1 Calculated Dose Rates

The calculated radiation dose rates for the CAGCV-S concept with grouting option are presented in Figure 82. This concept is identical to that described in the previous section, with the exception that void spaces in the waste and the repository are assumed to be filled with cementitious grout prior to the closure of the facility, which would enhance the containment of radionuclides such as C-14. These additional measures serve to chemically condition the facility for a longer period, and reduce the rate of physical degradation of key structures. As can be seen from the figure, for most calculation cases this results in lower calculated dose rates.

However, the increased retention of radionuclides means that the most significant dose rates are calculated for the Cover Erosion Calculation Case (although the results are well below the ICRP dose criterion of 3×10^{-4} Sv y^{-1}). The doses for this pathway are more than two orders of magnitude greater than those for the other calculation case, although they do not occur until far into the future, and the assumption is made that the cover materials over the facility could be completely removed.

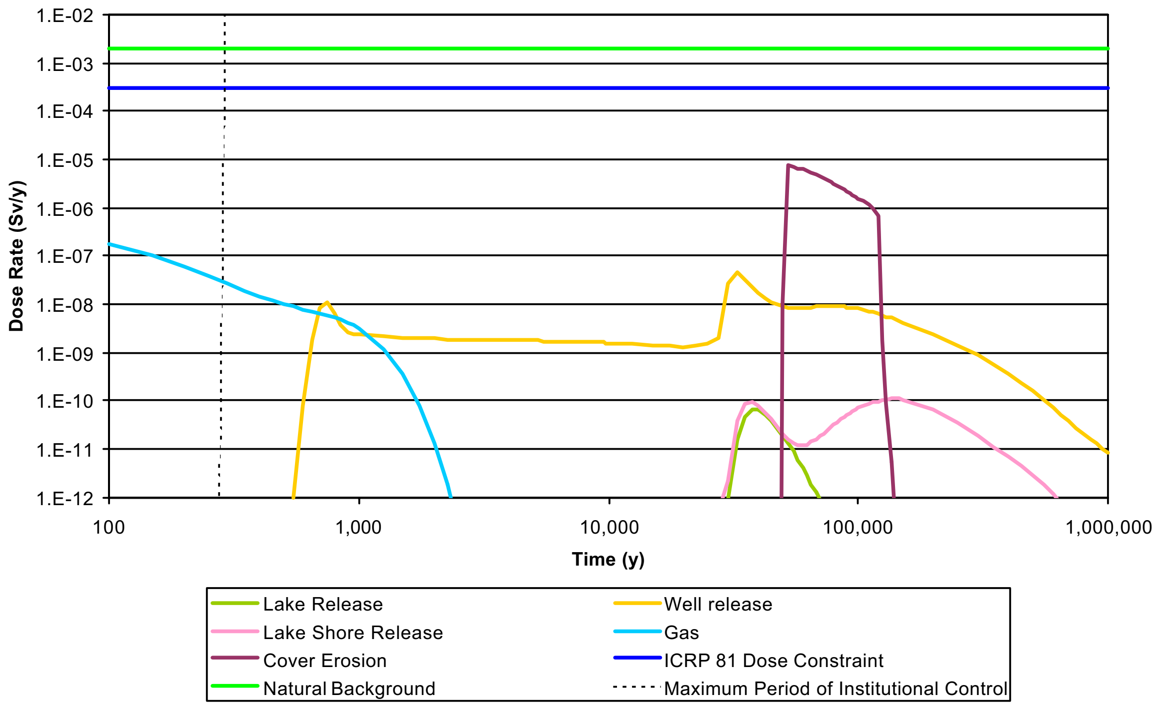

Figure 82: Total Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the CAGCV-S Grouting Option

The calculated dose rate for the Gas Release Calculation Case is similar to that calculated for the non-grouting case (as the performance of the engineering is similar for both cases, over the first few hundred years). However, for other calculation cases, the grouting has resulted in reducing the peak dose rate by more than a factor of 10, due to the increased retention of radionuclides within the repository over timescales of tens of thousands of years. Radionuclides such as C-14 are retained as a result of the longer period of alkaline conditions.

Peak calculated dose rate and key exposure pathways for all calculation cases for the CAGCV-S, Grouting Option are given in Table 77.

H.1.4.2 Key Radionuclides that Contribute to Dose Rate

The key radionuclides are presented in Figure 83 for the Cover Erosion Calculation Case, which gives rise to the highest doses. The doses are dominated by Nb-94, because its energetic gamma ray emissions give rise to external irradiation doses when it is in unshielded soil. This radionuclide is effectively retained in the wastes whilst the pH is high, and only migrates slowly from the near field even after the chemical degradation of the cement structures is complete.

H.1.4.3 Concentrations of Radionuclides in Environmental Media

The concentration of Nb-94 in the soil that has become contaminated with eroded waste is presented in Figure 84, which also shows the total. This indicates that Nb-94 dominates the environmental concentrations as well as the dose rates. The radionuclide has a peak concentration of 5 Bq kg^{-1} that occurs after 55,000 years. This can be compared with background concentration for the radionuclide (as a result of atmospheric weapons testing) of less than 10^{-6} Bq kg^{-1}. For this radionuclide, no MAC value has been published by Health Canada [2002].

Table 77: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases for the CAGCV-S Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)							
			Ext (Soil)	Ing (Anm)	Ing (Fish)	Ing (Crop)	Ing (Soil)	Ing (Wat)	Inh (Dust)	Inh (Gas)
Cover Erosion	7.7×10^{-6}	52,500	100	-	-	<	<	-	<	-
Well Release	4.5×10^{-8}	32,500	<	35	-	35	<	30	<	-
Gas Release	2.7×10^{-8}	300	-	-	-	-	-	-	-	100
Lakeshore Release	1.1×10^{-10}	135,000	100	-	<	-	<	<	<	-
Lake Release	6.6×10^{-11}	37,500	<	-	100	-	<	<	<	-

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated as ‘<’. A dash (‘-‘) indicates pathways not pathways considered for the calculation case. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Anm)” is the ingestion of contaminated animal products; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Ing (Wat)” is the ingestion of contaminated water; “Inh (Dust)” is the inhalation of contaminated dust; “Inh (Gas)” is the inhalation of contaminated gas.

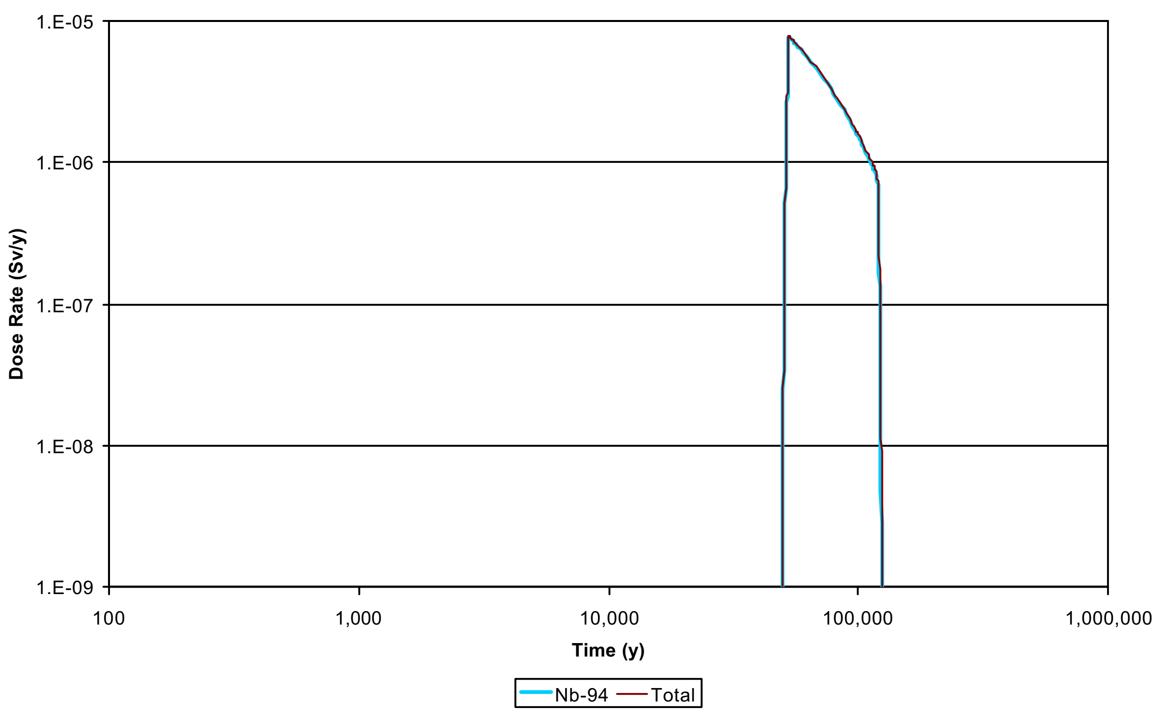

Figure 83: Radionuclides that Dominate the Dose Rate to Site Dweller, Cover Erosion Calculation Case, CAGCV-S Grouting Option

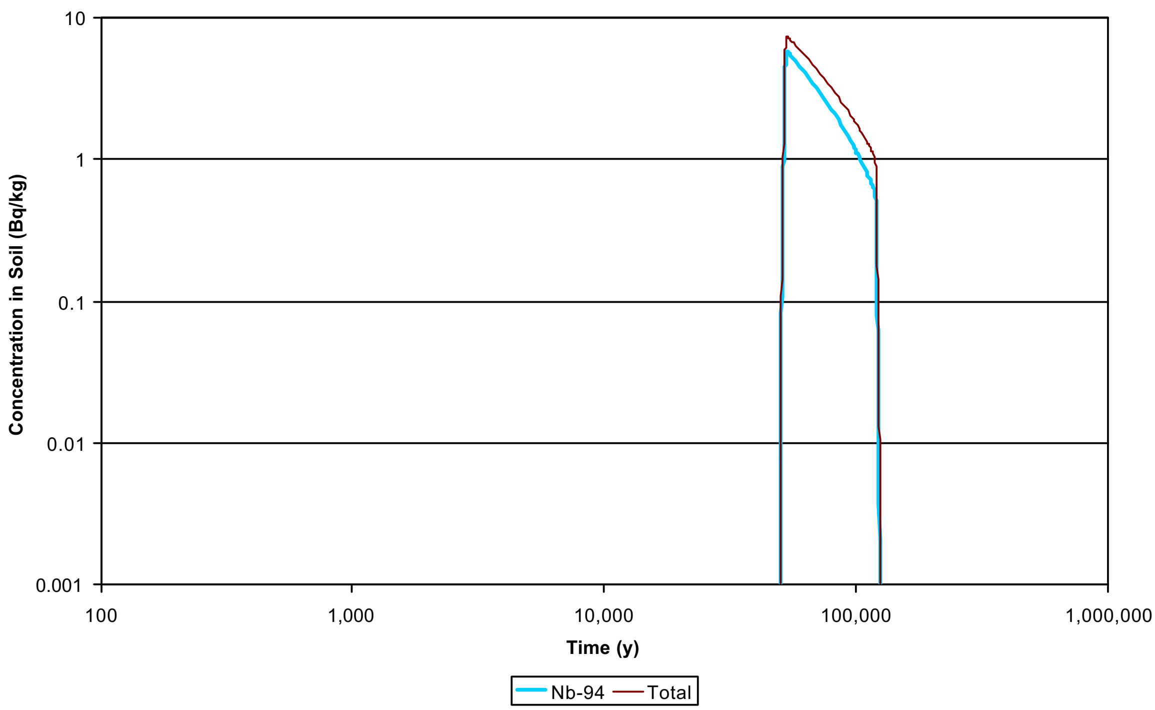

Figure 84: Concentrations of Key Radionuclides in Soil, Cover Erosion Calculation Case, CAGCV-S Concept Grouting Option

H.1.4.4 Total Activity Concentrations in Waste, Repository, Geosphere and Biosphere

Figure 85 shows the maximum concentrations of Nb-94 in several key media – the waste, the vault materials, the sand sediments, the dolostone aquifer and the soil that has become contaminated with the eroded waste.

This clearly demonstrates the enhanced retention of this radionuclide within the waste (and the repository generally) compared with the non-grouting option. In the non-grouting option, C-14 was released from the ungrouted waste following waste containers failure. In the grouting case, grouted waste can be seen to retain radionuclides over much greater timescales; the vault materials have much lower concentrations. It is only on the timescale of tens of thousands of years calculated concentration of Nb-94 in the geosphere are noticeable, even then the concentrations are a few hundredths of a Bq kg^{-1}.

Once erosion of the waste begins, the concentrations in soil increase to about one tenth that in the waste, as waste eroded into soil is subsequently eroded elsewhere, and is also subject to leaching from the soil by infiltrating rainfall.

H.1.5 DRCV-S NON-GROUTING OPTION

H.1.5.1 Calculated Dose Rates

In the safety assessment, two potential locations have been considered for the DRCV repository: in shale or limestone formations in the deep bedrock groundwater system, about

400 to 700 m below the surface. The results calculated for a non-grouted facility located in the shales are presented in this section, and are summarised in Figure 86.

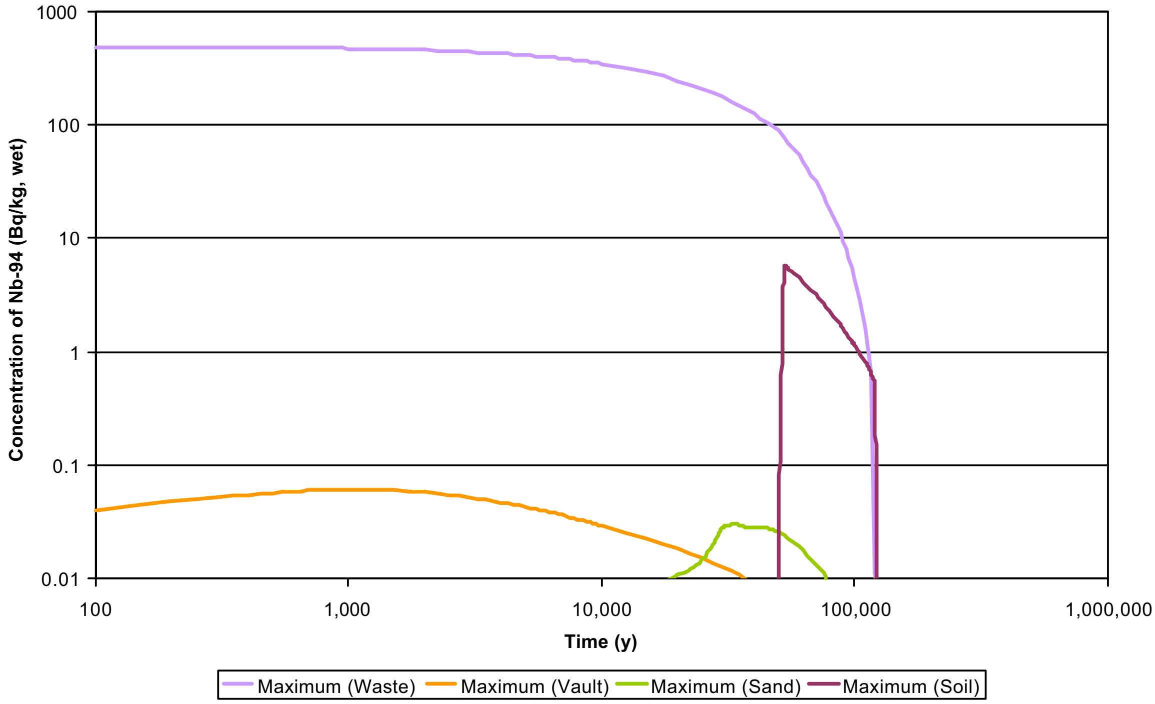

Figure 85: Maximum Concentrations of Nb-94 in Waste and Other Media (Cover Erosion Calculation Case, CAGCV-S Concept Grouting Option)

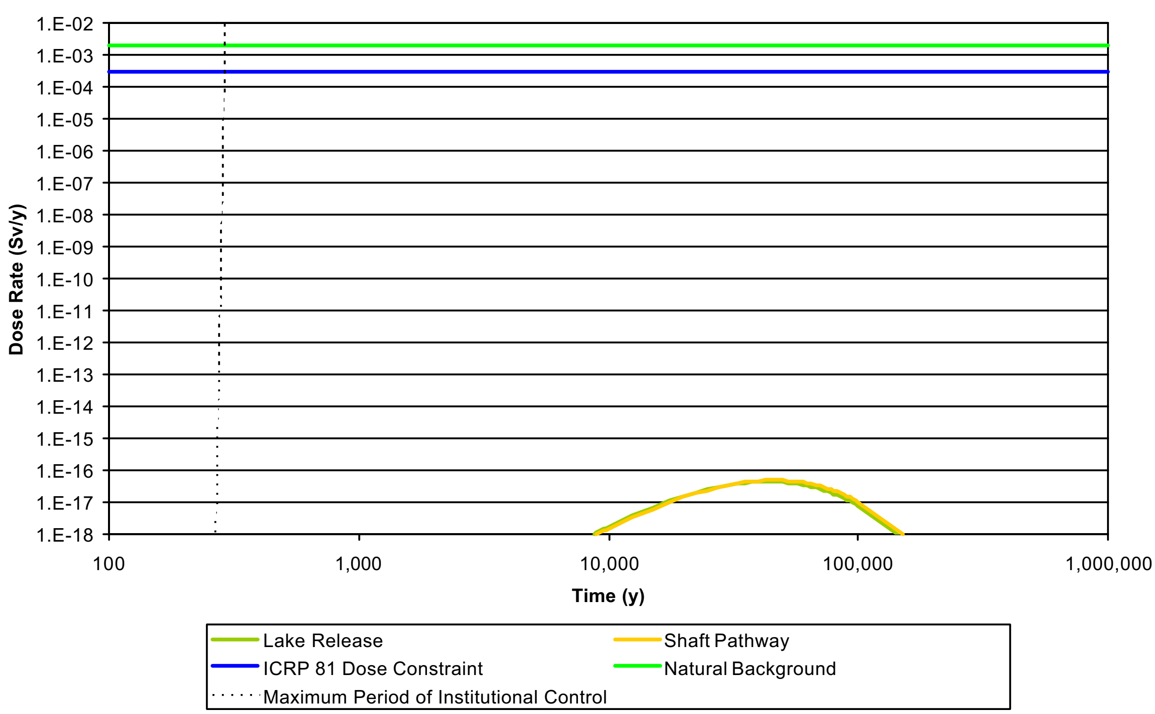

Figure 86: Total Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the DRCV-S, Non-grouting Option

This shows the results for two groundwater release calculation cases considered for the DRCV concepts, and it is immediately obvious that the calculated dose rates are extremely low, many orders of magnitude below natural background and ICRP dose constraints. This is due to the extremely effective confinement of the radionuclides by the host rock. In the shales, there is no advective circulation of groundwater, and so radionuclide migration can only occur via diffusion. Even if a more rapid diffusion pathway is present, as assumed in the shaft pathway calculation case, the results are only affected marginally. This occurs, in part, as the aquifer into which the diffusive shale pathway releases radionuclides is expected to discharge into Lake Huron at a distance of 15 km where it sub-crops in the lake.

The only point of release that is considered likely is into the lake water, where radionuclides are further diluted. The main pathways by which the potentially exposed group receives a dose are indicated in Table 78, which shows that fish and lake water ingestion pathways dominate the dose rate. The dose rate from the Shaft Pathway is slightly greater, but also occurs slightly later.

Table 78: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases for the DRCV-S Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext (Soil)	Ing (Fish)	Ing (Wat)
Shaft Pathway	4.6×10^{-17}	47,500	<	91	9
Lake Release	4.2×10^{-17}	42,500	<	91	9

Note: Contributions of less than 0.5 % have been indicated ‘<’. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Wat)” is the ingestion of contaminated water.

H.1.5.2 Key Radionuclides that Contribute to Dose Rate

The very effective containment of radionuclides in the DRCV case means that only highly mobile and long-lived radionuclides are released within the timeframe of the calculations. Figure 87 shows that the calculated dose rate is dominated by I-129. The next most significant radionuclide is Tc-99.

Although these radionuclides are highly mobile in groundwater, the slow rate of transport by diffusion through the shales means that the peak dose rate is not reached until 47,500 years after facility closure. Other radionuclides that are more highly sorbed are transported more slowly, and consequently they are not released in the period of calculations. This gives the opportunity for most of these radionuclides to decay before reaching the lake.

H.1.5.3 Concentrations of Radionuclides in Environmental Media

The radionuclide concentration in lake water is very low, both because of the long period over which radionuclides are released and the large volumes into which groundwater is diluted. Figure 88 shows that the peak concentration of any radionuclide in lake water is only 1×10^{-9} Bq m^{-3} for Cl-36. It also illustrates that concentrations of Cl-36 exceed those of I-129; however, I-129 dominates the dose due to a greater ingestion dose coefficient (1.7×10^{-7} Sv Bq^{-1} compared with 9.3×10^{-10} Sv Bq^{-1} for Cl-36). Tc-99 dominates the second peak.

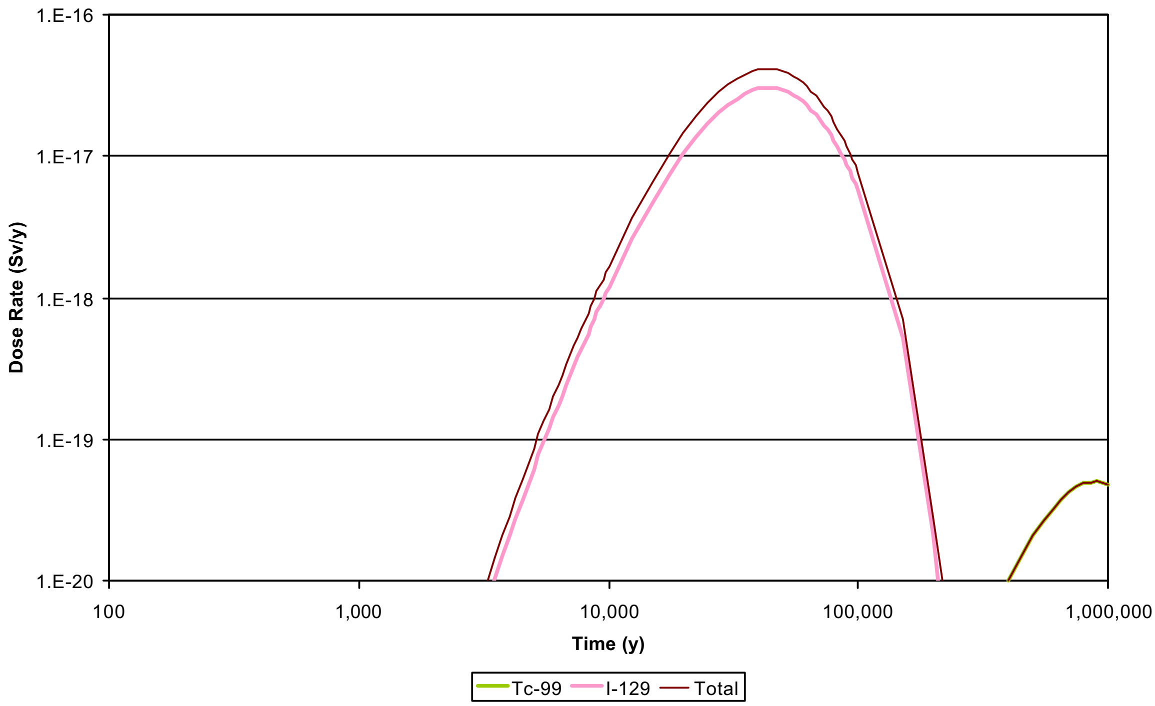

Figure 87: Radionuclides that Dominate the Dose Rate to Fisherman, Shaft Pathway Calculation Case, DRCV-S Non-grouting Option

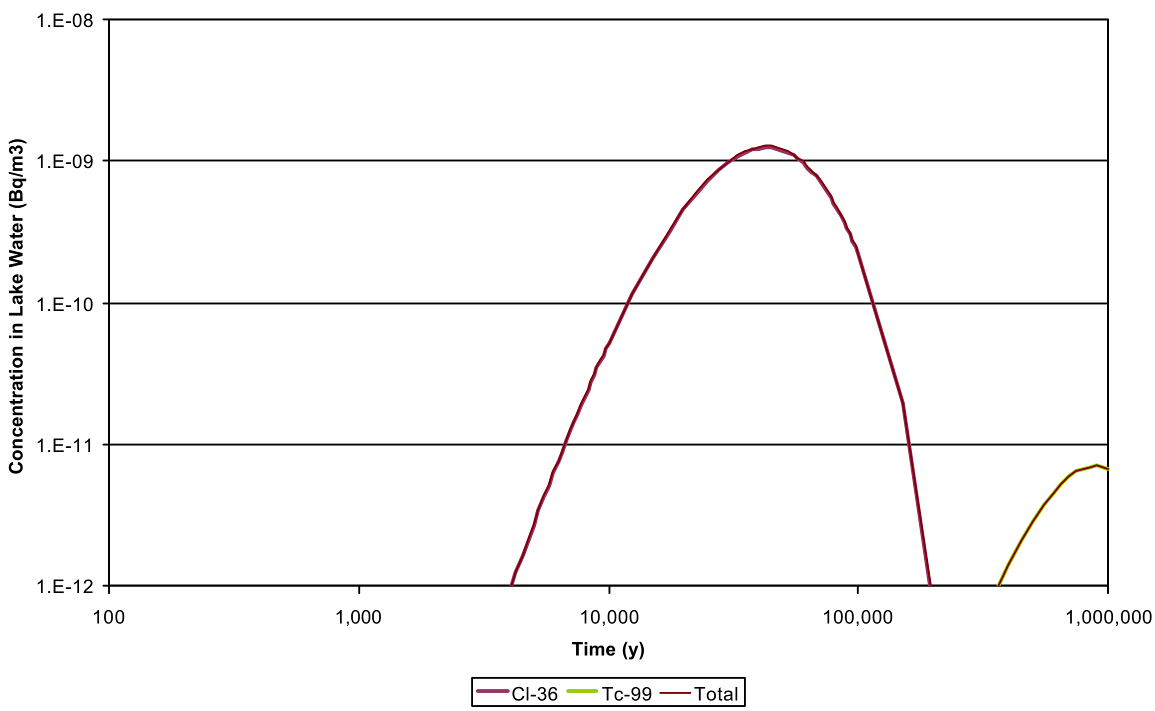

Figure 88: Concentrations of Key Radionuclides In Lake Water, Shaft Pathway Calculation Case, DRCV-S Non-grouting Option

No values are available on the maximum acceptable concentration for Cl-36, but calculated concentrations are well below the lowest MAC value for any radionuclide (100 Bq m^{-3} for Pb-210 and Th-232 (Health Canada, 2002)). Data are available for Tc-99. Calculated concentrations are well below the MAC limit (see Table 79), and are much lower than background concentrations resulting from fallout from atmospheric nuclear weapons testing.

H.1.5.4 Total Activity Concentrations in Waste, Repository, Geosphere and Biosphere

The effectiveness of the natural barriers to radionuclide migration is further demonstrated in Figure 89. This shows that the maximum concentration of I-129 (which is initially quite low in wastes) is more than five orders of magnitude lower in the dolostone than the wastes, due to the very slow release and the relatively rapid dispersion of the released radionuclides in the dolostone aquifer.

Table 79: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Shaft Pathway Calculation Case, DRCV-S Non-grouting Option

Radionuclide	Peak Concentration (Bq m^{-3}, Lake Water)	MAC (Water, Bq m^{-3})	Background Concentration (Bq m^{-3}, Lake Water)
Cl-36	1×10^{-9}	-	4.8×10^{-3}
Tc-99	7×10^{-12}	200,000	$1.5\ 10^{-5}$

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). Cl-36 background concentration in Lake Huron water is given from Bird and Schwartz (1997).

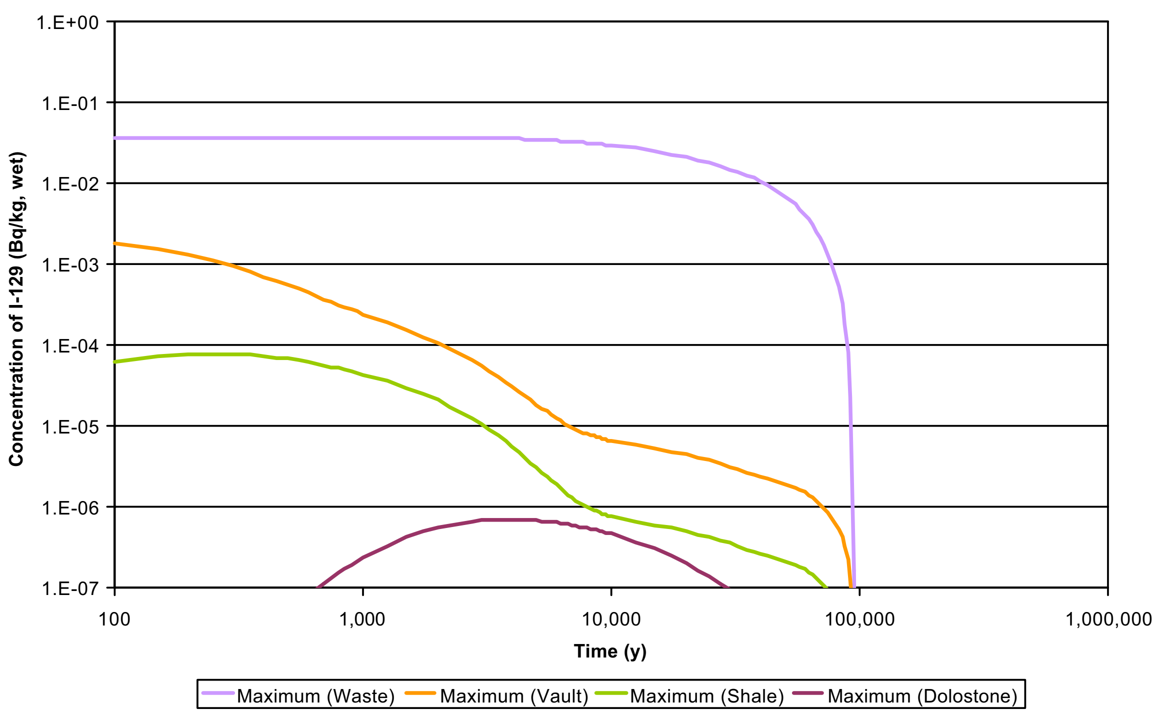

Figure 89: Maximum Concentrations of I-129 in Waste and Other Media (Shaft Pathway Calculation Case, DRCV-S Non-grouting Option)

H.1.6 DRCV-S GROUTING OPTION

H.1.6.1 Calculated Dose Rates

As with the CAGCV repository concepts, it is possible to include cementitious grout in the repository. This would increase the sorption of key radionuclides. The results that are calculated for such an option are shown in Figure 90. The figure shows that the calculated dose rates are reduced by a factor of four, and remain extremely low. The profile of the curve is also changed, indicating that the different radionuclides contribute to the dose. It can also be seen that the peak dose is substantially later.

The peak dose rates, time of peak and relative contribution of the radionuclides at the peak are shown in Table 80.

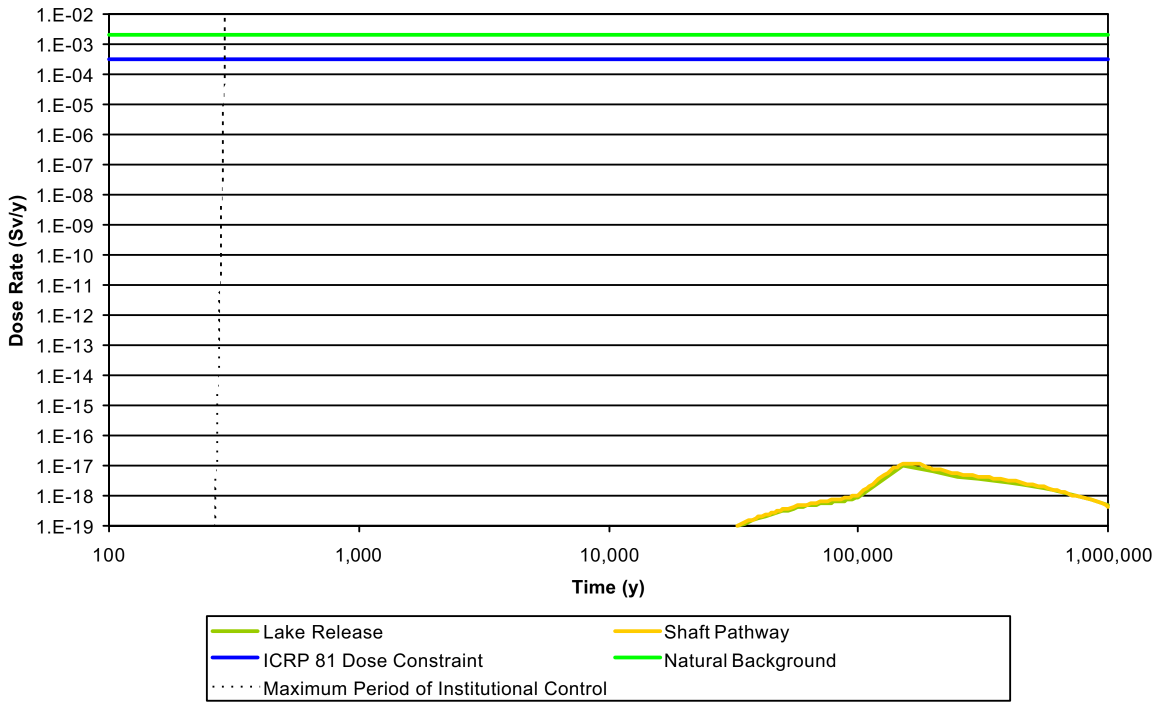

Figure 90: Total Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the DRCV-S Grouting Option

Table 80: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases for the DRCV-S Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext (Soil)	Ing (Fish)	Ing (Wat)
Shaft Pathway	1.1×10^{-17}	150,000	<	91	9
Lake Release	9.1×10^{-18}	150,000	<	91	9

Note: Contributions of less than 0.5 % have been indicated ‘<’. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Wat)” is the ingestion of contaminated water.

H.1.6.2 Key Radionuclides that Contribute to Dose Rate

Although the radionuclides are contained very effectively by the geology surrounding the DRCV, the additional engineering of the grout option can be seen to increase the retention of radionuclides further. Figure 91 shows that the profile of I-129 is significantly changed compared with that for the non-grouted option (whilst Tc-99 remains the same, as its sorption is unaffected by the presence of the cementitious materials). The result is that Cl-36, dominated by I-129 in the non-grouting option, is the most significant radionuclide, overall, for this option.

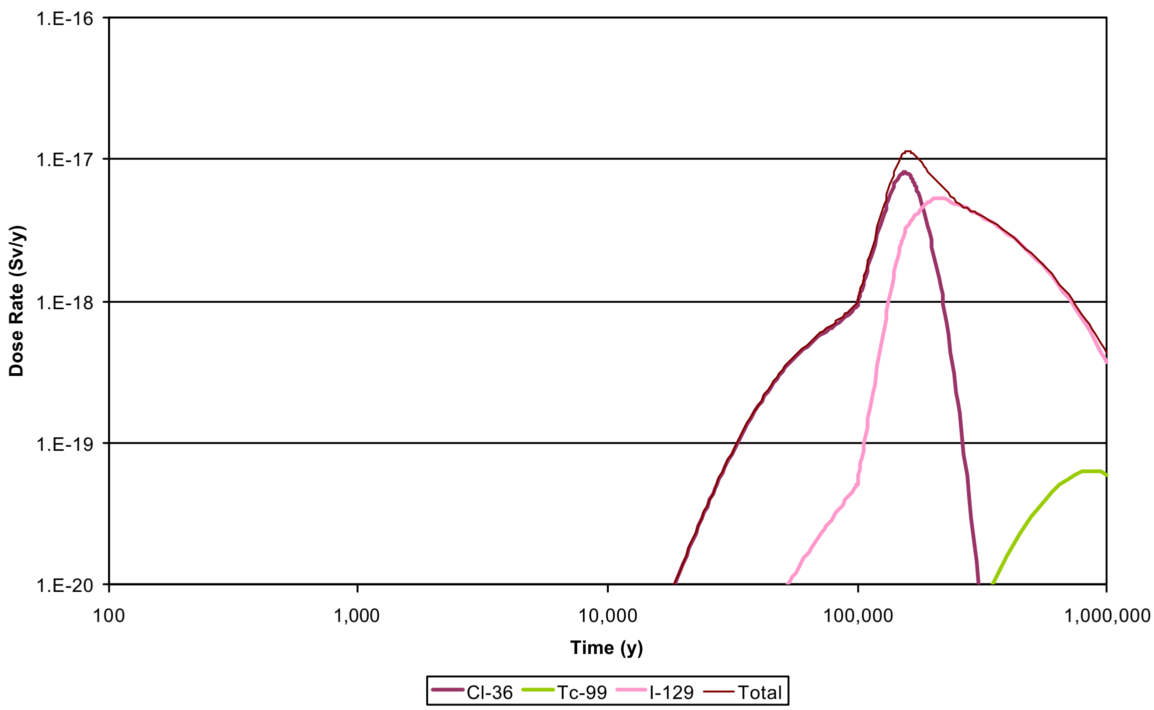

Figure 91: Radionuclides that Dominate the Dose Rate to Fisherman, Shaft Pathway Calculation Case, DRCV-S Grouting Option

H.1.6.3 Concentrations of Radionuclides in Environmental Media

The calculated concentrations in lake water, shown in Table 81, are similar to those for the non-grouting case. This is because the radionuclides of interest, Cl-36 and Tc-99, are not significantly affected by the differences in conditions in the grouted or non-grouted waste. There are also limited differences in the porewater concentrations of various media of interest (e.g. the waste, vault, shale and dolostone) for the radionuclides of interest.

H.1.7 DRCV-L NON-GROUTING OPTION

H.1.7.1 Calculated Dose Rates

An alternative location for the DCRV facility is 200 m below the shales in a limestone formation. Radionuclides released from a facility in this location would diffuse through the limestone and overlying shales before being released into the dolostone aquifer in the intermediate bedrock groundwater system.

Table 81: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Shaft Pathway Calculation Case, DRCV-S Grouting Option

Radionuclide	Peak Concentration ($Bq\ m^{-3}$, Lake Water)	MAC (Water, $Bq\ m^{-3}$)	Background Concentration ($Bq\ m^{-3}$, Lake Water)
Cl-36	9×10^{-10}	-	4.8×10^{-3}
Tc-99	9×10^{-12}	200,000	$1.5\ 10^{-5}$

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). Cl-36 background concentration in Lake Huron water is given from Bird and Schwartz (1997).

The increased length of the diffusive pathway to the overlying aquifer results in an increased time before radionuclides are released into the aquifer, and consequently slightly lower calculated dose rates when compared with the non-grouting option for the DRCV-S. The total calculated dose rates for this case are shown in Figure 92. The results are also summarised in Table 82.

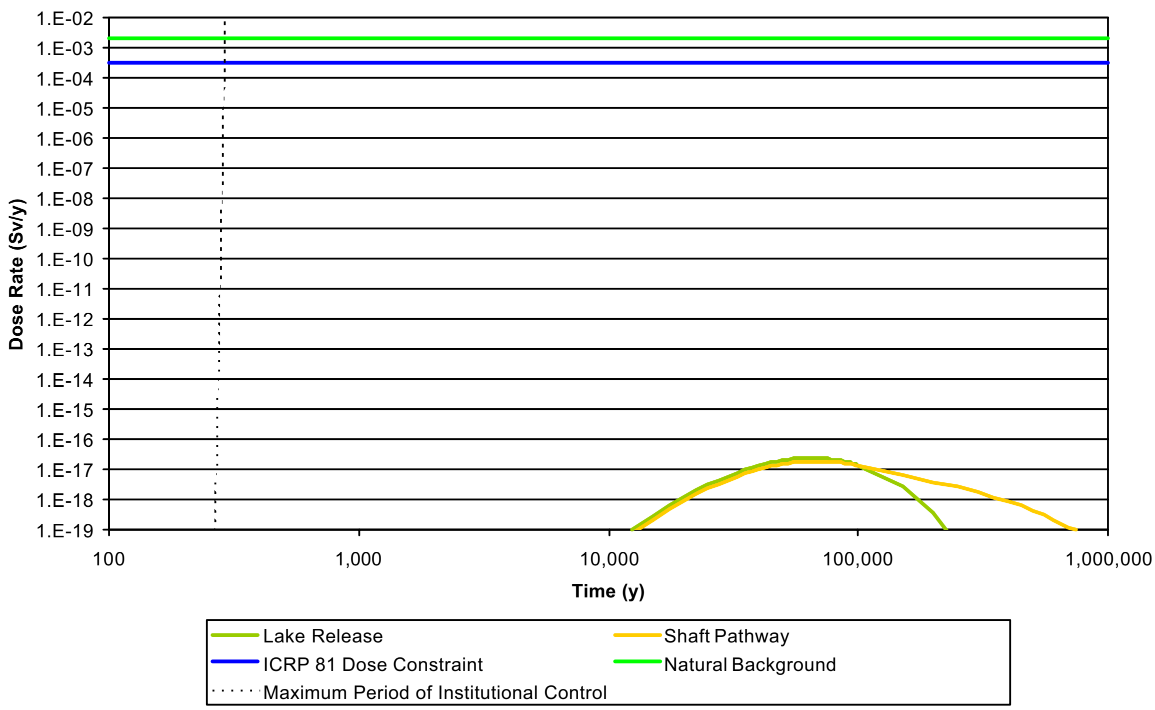

Figure 92: Total Calculated Dose rates to Potentially Exposed Groups, from All Calculation Cases for the DRCV-L Non-grouting Option

H.1.7.2 Key Radionuclides that Contribute to the Dose Rate

The calculated dose rate for the DCRV in limestone is dominated by I-129, as was observed for the DRCV concept in shale. Figure 93 shows that, for the shaft release pathway the dose rate is distributed over a longer timescale compared with the DRCV in shale. As with the DRCV in shale, radionuclides that exhibit any significant sorption, and do not have a half life of greater than a few tens of thousands of years, would not be released into the environment with any notable concentration, owing to the very long timescales for diffusion and transport to the lake.

Table 82: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases for the DRCV-L Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext (Soil)	Ing (Fish)	Ing (Wat)
Lake Release	2.3×10^{-17}	65,000	<	91	9
Shaft Pathway	1.8×10^{-17}	67,500	<	91	9

Note: Contributions of less than 0.5 % have been indicated '<'. Pathways are indicated as follows: "Ext (Soil)" is the abbreviation for external irradiation from soil; "Ing (Fish)" is the ingestion of contaminated fish; "Ing (Wat)" is the ingestion of contaminated water.

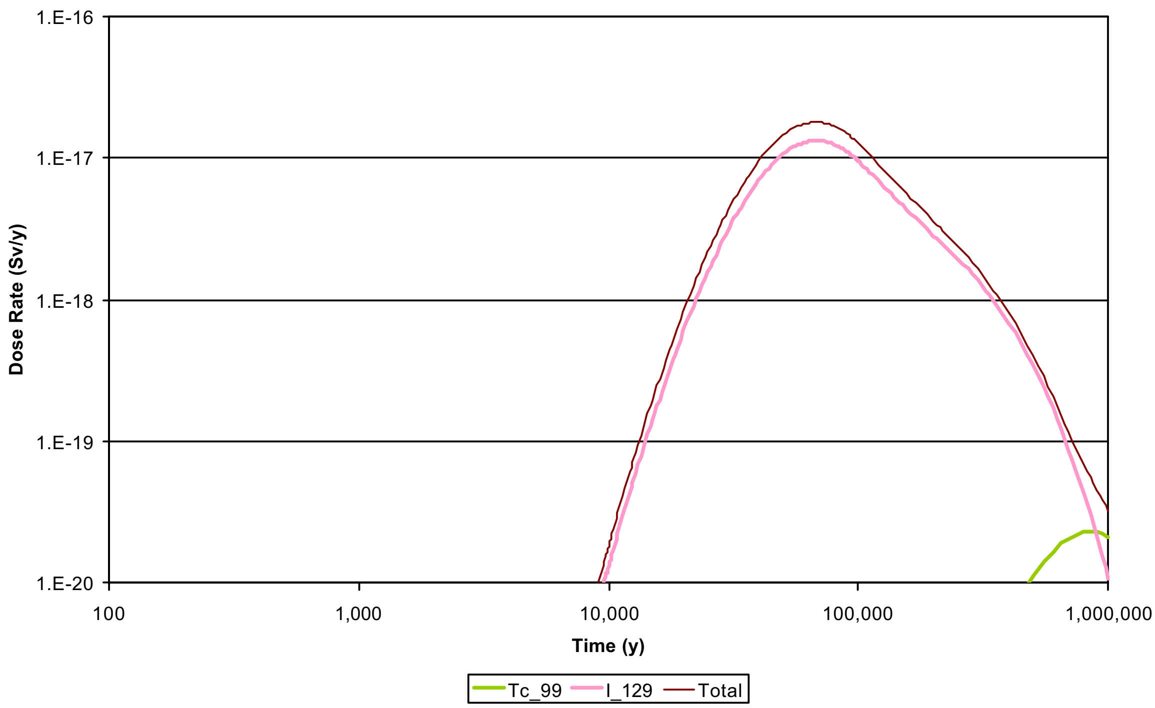

Figure 93: Radionuclides that Dominate the Dose Rate to Fisherman, Shaft Pathway Calculation Case, DRCV-L Concept, Non-grouting Option

As the key radionuclides for the DRCV options are long-lived mobile radionuclides such as Cl-36, Tc-99 and I-129, the change in the performance of the DRCV in limestone, compared with that in shale, is minor. As noted for the DRCV in shale concept, the calculated dose rates are extremely low.

H.1.7.3 Concentrations of Radionuclides in Environmental Media

The Cl-36 concentration in lake water is very low, being less than 5×10^{-10} Bq m^{-3}, or about half the concentration calculated for the DRCV-S concept (non-grouted). However, the peak concentrations and associated doses again differ, by being distributed over a longer timescale than for the DRCV-S concept (Figure 94). The peak concentration is again associated with Cl-36, rather than I-129. This demonstrates that the I-129 is more significant due to its substantially greater dose coefficient, compared with radionuclides such as Cl-36 and Tc-99. The concentrations, MAC values and background concentrations are summarised in Table 83.

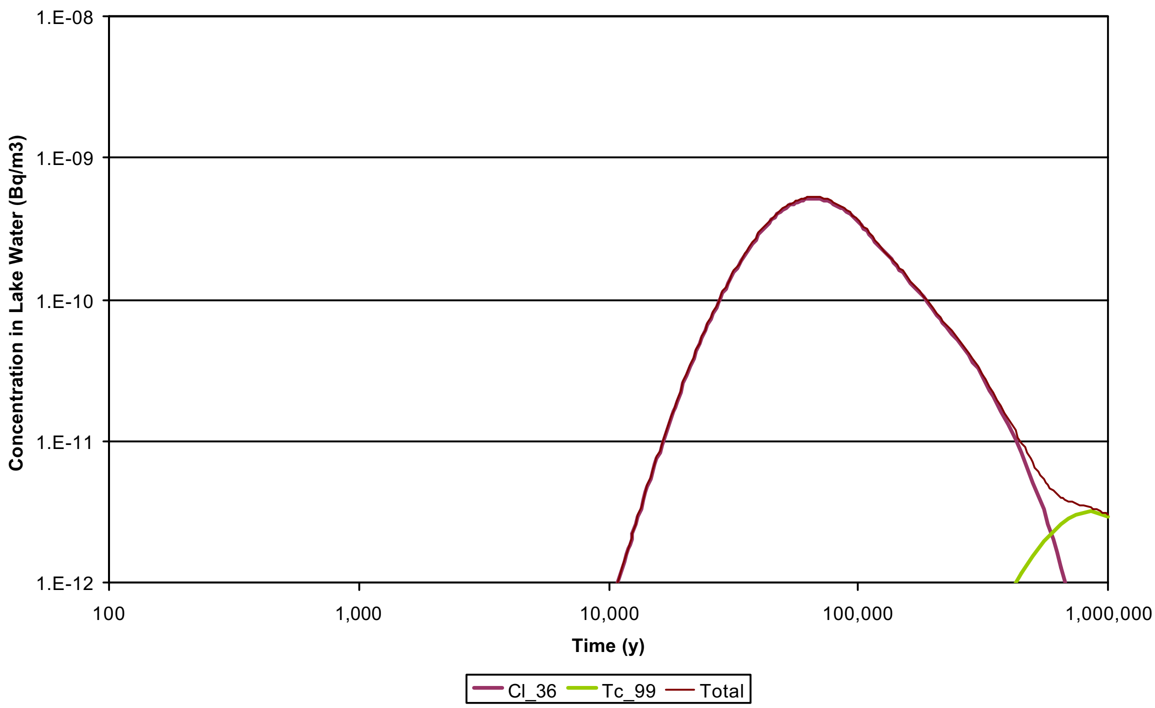

Figure 94: Concentrations of Key Radionuclides In Lake Water, Shaft Pathway Calculation Case, DRCV-L Non-grouting Option

Table 83: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Shaft Pathway Calculation Case, DRCV-L Non-grouting Option

Radionuclide	Peak Concentration ($Bq\ m^{-3}$, Lake Water)	MAC (Water, $Bq\ m^{-3}$)	Background Concentration ($Bq\ m^{-3}$, Lake Water)
Cl-36	5×10^{-10}	-	4.8×10^{-3}
Tc-99	3×10^{-12}	200,000	1.5×10^{-5}

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). Cl-36 background concentration in Lake Huron water is from Bird and Schwartz (1997).

H.1.7.4 Total Activity Concentrations in Waste, Repository, Geosphere and Biosphere

As with the DRCV-S non-grouting case, the concentrations of radionuclides in environmental media are substantially lower than the concentrations in the waste. Figure 95 shows how concentrations change with successive media. It is notable that the maximum concentration in the shale increases more slowly than those in the limestone, reflecting the fact that, for any given kg of wet rock, there is a greater pore space in the shale, and hence a greater amount of radionuclides at the same concentration dissolved in the water. The profile of concentrations in the dolostone can also be seen to reach a peak much later than for the

DRCV-S, illustrating the effects of the extra confinement offered if the facility were to be located in limestone.

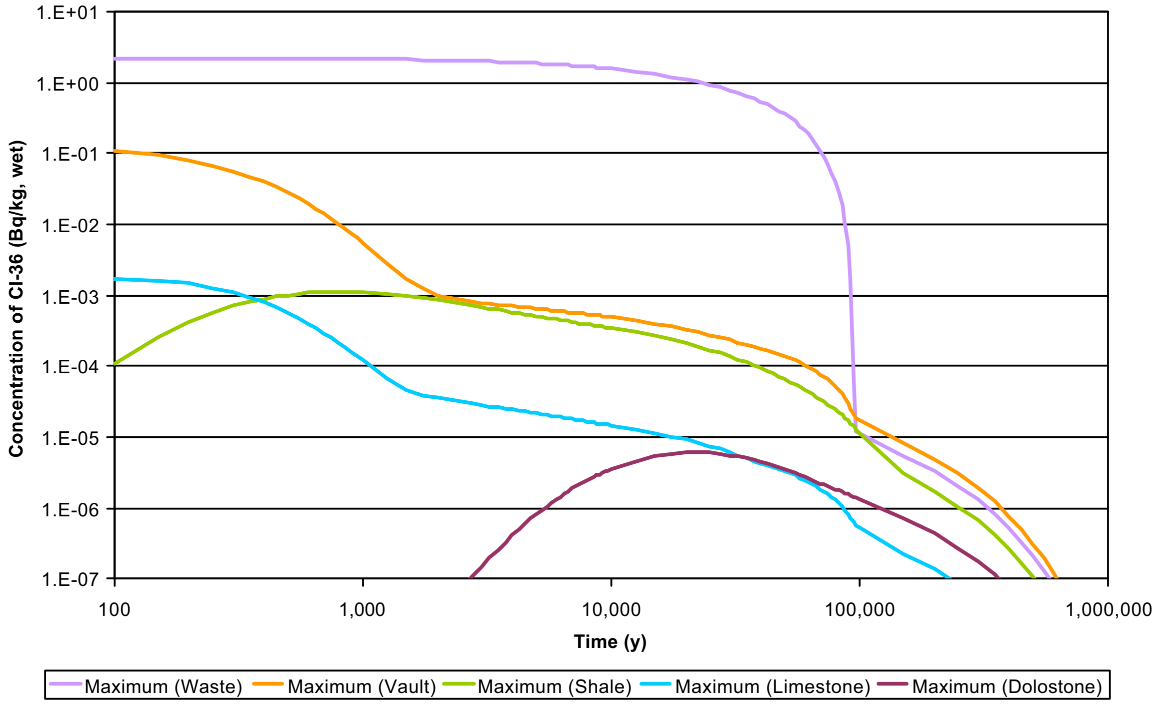

Figure 95: Maximum Concentrations of Cl-36 in Waste and Other Media (Shaft Pathway Calculation Case, DRCV-L Non-grouting Option)

H.1.8 DRCV-L GROUTING OPTION

H.1.8.1 Calculated Dose Rates

The DRCV-L concept with the addition of grout to the wastes, and as a backfill, has also been considered. The additional cementitious material would increase the sorption of many radionuclides, although it is unlikely to affect the long-lived mobile radionuclides that can be seen to dominate the results for the DRCV concepts.

The results are shown in Figure 96. The figure shows that the calculated dose rates are reduced by more than a factor of five. The profile of the curve is also changed, as was seen with the grouting option for the DRCV-S concept. The peak dose rates, time of peak and relative contribution of the radionuclides at the peak are shown in Table 84. This indicates that the pathways remain the same, but the peak dose is reached later.

H.1.8.2 Key Radionuclides that Contribute to Dose Rate

The key radionuclides, and their profile in time can be seen to be more similar to the DRCV-S grouting option (Figure 97). All peaks are later, being affected by presence of the cementitious materials. Once again, it is notable that Cl-36 is a significant radionuclide for this option, where it is not in the non-grouting option.

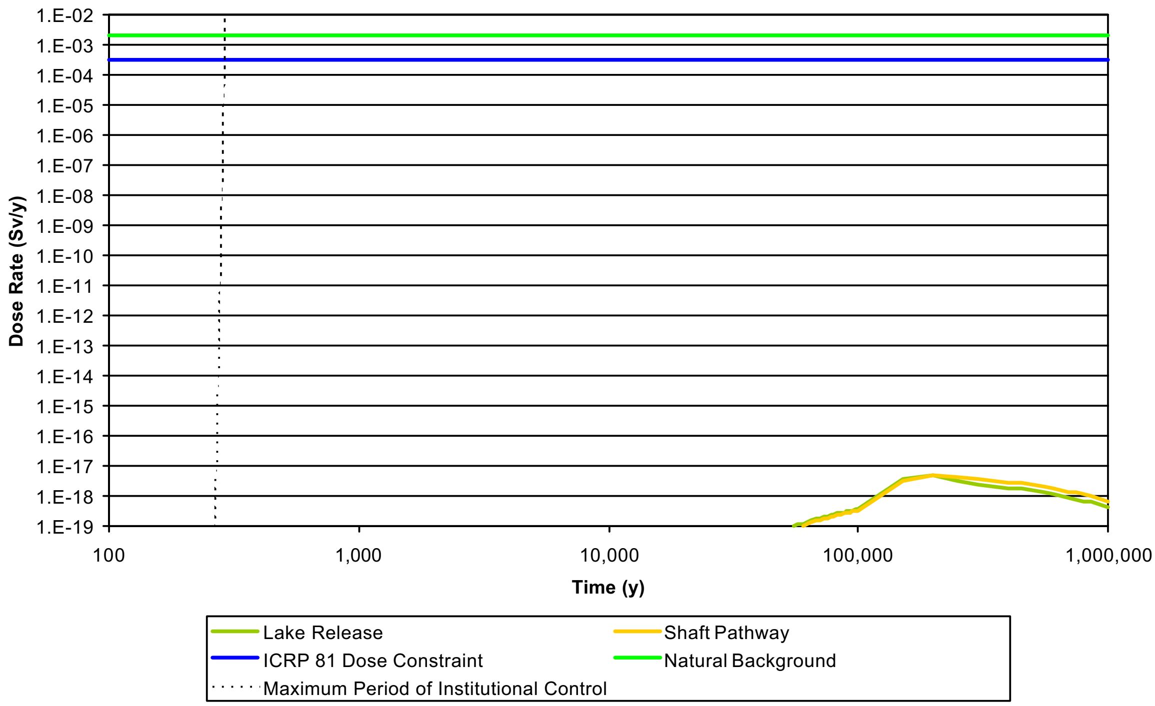

Figure 96: Total Calculated Dose Rates to Potentially Exposed Groups, from All Calculation Cases for the DRCV-L Grouting Option

Table 84: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for All Calculation Cases, DRCV-L Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext (Soil)	Ing (Fish)	Ing (Wat)
Lake Release	4.9 x 10^{-18}	200,000	<	91	9
Shaft Pathway	4.6 x 10^{-18}	200,000	<	91	9

Note: Contributions of less than 0.5 % have been indicated as ‘<’. Pathways are indicated as follows: “Ext (Soil)” is the abbreviation for external irradiation from soil; “Ing (Fish)” is the ingestion of contaminated fish; “Ing (Wat)” is the ingestion of contaminated water.

H.1.8.3 Concentrations of Radionuclides in Environmental Media

The calculated concentrations in lake water are very similar to those calculated for other DRCV options, although they are approximately a factor of 3 lower than calculated for the DRCV-S option with grout (see Table 85). The same radionuclides are of interest (Cl-36 and Tc-99), which are not significantly affected by the grouted of waste. There are also limited differences in the porewater concentrations of various media of interest (e.g., the waste, vault, shale and dolostone) for the radionuclides of interest.

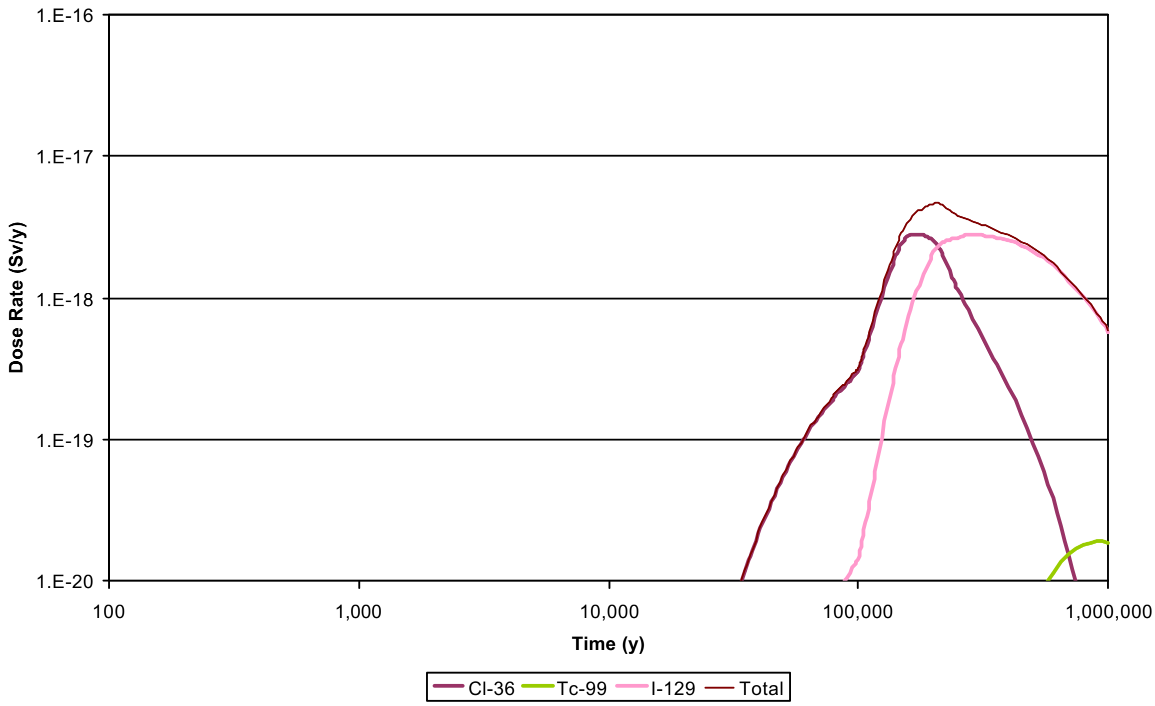

Figure 97: Radionuclides that Dominate the Dose rate to Fisherman, Shaft Pathway Calculation Case, DRCV-L Grouting Option

Table 85: Comparison of Calculated Peak Concentrations with Maximum Acceptable Concentrations and Background Concentrations, Shaft Pathway Calculation Case, DRCV-L Grouting Option

Radionuclide	Peak Concentration ($Bq\ m^{-3}$, Lake Water)	MAC (Water, $Bq\ m^{-3}$)	Background Concentration ($Bq\ m^{-3}$, Lake Water)
Cl-36	3×10^{-10}	-	4.8×10^{-3}
Tc-99	3×10^{-12}	200,000	$1.5\ 10^{-5}$

Notes: Maximum Acceptable Concentrations are defined in Health Canada (2002). Data on background concentrations of radionuclides in soil and water have been obtained from Amiro (1992). Cl-36 background concentration in Lake Huron water is given from Bird and Schwartz (1997).

H.2 HUMAN INTRUSION SCENARIO

Human intrusion calculation cases are reported separately from natural release processes, consistent with recent guidance from ICRP (2000) on the consideration of such scenarios. Dose rates are calculated with reference to the residual concentrations in wastes – for the borehole and excavation (CAGCV only) calculation cases, exposure is assumed to be directly to undiluted waste. For the site resident, following excavation (CAGCV only), excavated waste is assumed to have become mixed with soil that is lived upon and is used for growing vegetables.

The calculated dose rate is the dose rate that occurs to an individual member of the relevant exposure group assuming that the intrusion event occurs in the specified year. For example, the calculated dose rate at 1000 years is the dose rate that would be received assuming the intrusion event occurred at 1000 years.

H.2.1 CAGCV NON-GROUTING OPTION

The results are reported for the CAGCV case without grouting in Figure 98 and Table 86. No distinction is made between the facility location on sand and till as the residual concentrations in the facilities will be similar.

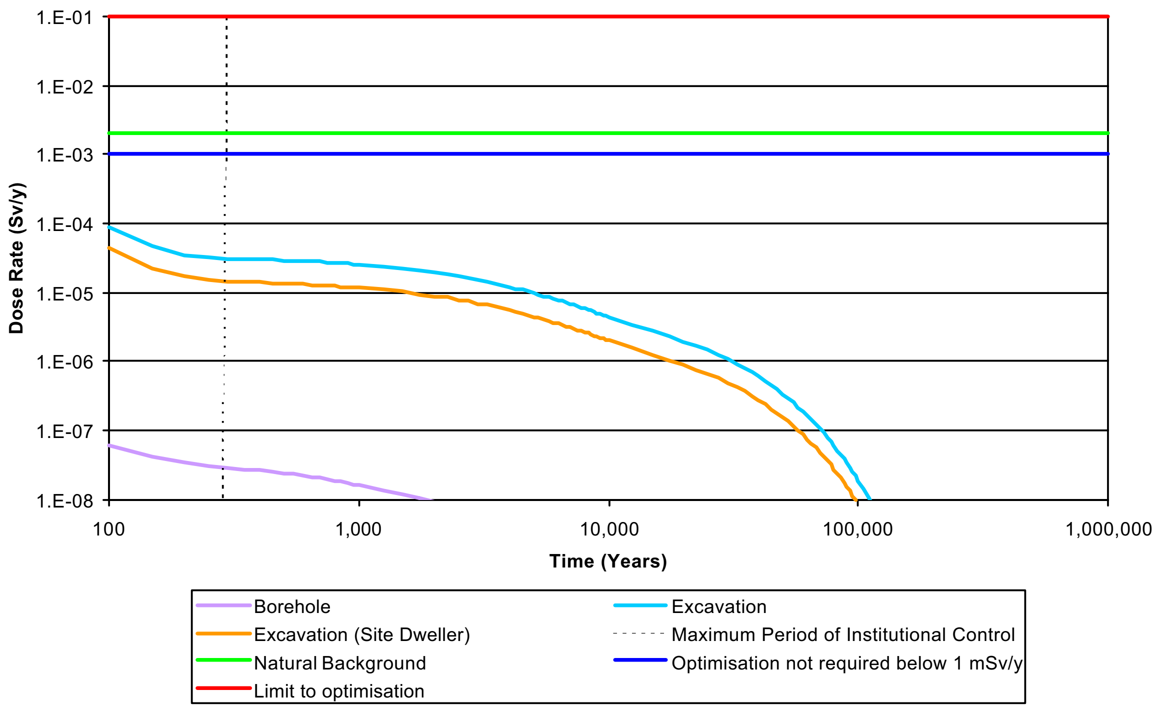

Figure 98: Total Calculated Dose Rates for Human Intrusion, for the CAGCV Non-grouting Option

The results for the CAGCV without grouting show that the peak dose rates for all calculation cases are well below the criterion below which optimisation of the waste repository design is not required, in the context of human intrusion hazards. The results are also well below typical natural background dose rates.

The most significant calculation case is the Excavation Calculation Case, in which a person is assumed to be involved in excavation works that inadvertently affect the repository. In this case, a long duration of exposure to waste is considered, with relatively little dilution. This exposure group is calculated to receive substantially greater dose rates than the other groups. Table 86 shows that the key pathway is external irradiation, when working close to uncovered undiluted waste.

The dose rate only decreases reasonably slowly (about an order of magnitude over 10,000 years). The figure also demonstrates that, if intrusion were to occur earlier than 300 years, the dose rate would still be below the criterion below which optimisation is not considered to be necessary. This result could be used to argue that a shorter institutional control period could be considered.

Table 86: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the CAGCV Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)			
			Ext	Ing (Crop)	Ing (Soil)	Inh (Dust)
Excavation	3.1×10^{-5}	300	98	-	<	2
Excavation (Site Dweller)	1.4×10^{-5}	300	96	4	<	<
Borehole	2.9×10^{-8}	300	29	-	20	51

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated '<'. '-' indicates pathways not considered for the calculation case. Pathways are indicated as follows: "Ext" is the abbreviation for external irradiation from soil or waste; "Ing (Crop)" is the ingestion of contaminated plants and vegetables; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Inh (Dust)" is the inhalation of contaminated dust.

In Figure 99, the dose rate to the exposure group in the Excavation Calculation Case can be seen to be dominated initially by Cs-137; however, this has decayed substantially by the end of the assumed institutional control period of 300 years. Thereafter, Nb-94 is the dominant radionuclide. It can be seen to be present with the highest activity concentration in the waste after about 1000 years (see Figure 100). Both radionuclides have high external irradiation dose coefficients.

Figure 100 indicates the high concentrations of C-14 in the waste over the first 1000 years, however this radionuclide has much lower dose coefficients than Cs-137 and Nb-94 radionuclides, and does not have significant gamma emissions that can contribute to external irradiation. Its rapid decrease in concentration in the waste reflects its rapid release into the vault materials for the non-grouting CAGCV option.

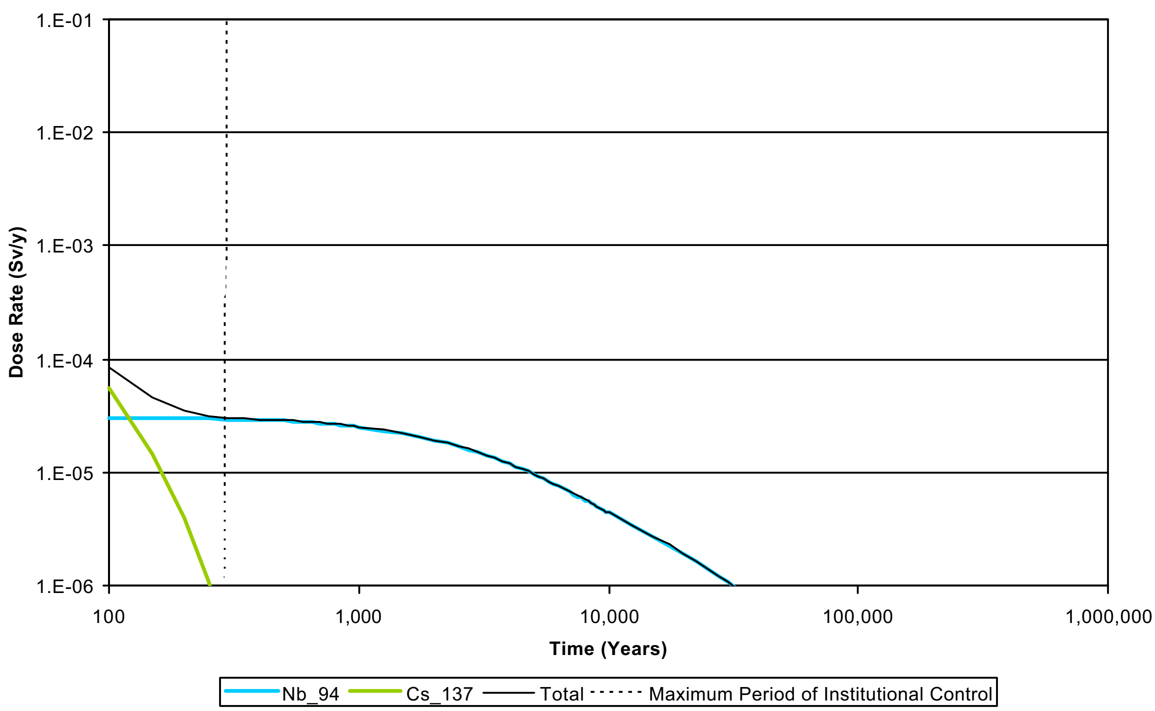

Figure 99: Contribution of Key Radionuclides to Calculated Dose Rates from Excavation for the CAGCV Non-grouting Option

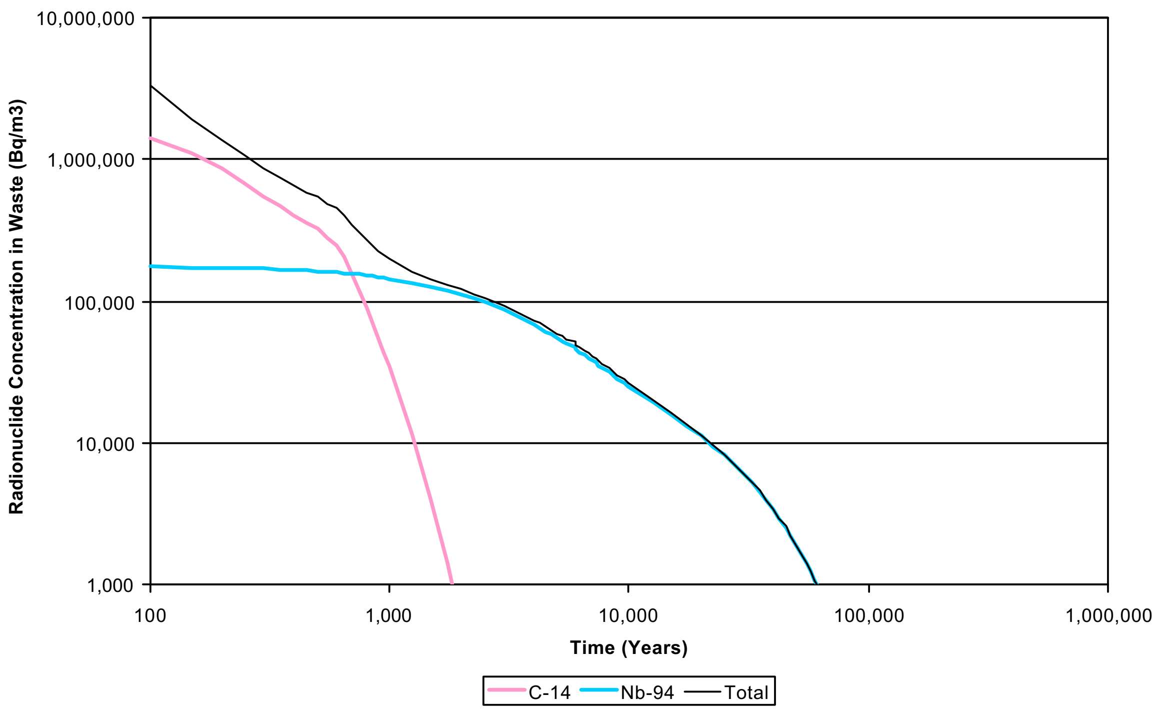

Figure 100: Concentration of Key Radionuclides in the Waste, CAGCV Non-grouting Option

H.2.2 CAGCV GROUTING OPTION

The increased retention of key radionuclides such as Nb-94 isotopes by the grouting option for the CAGCV concept result in calculated dose rates for the excavation calculation case that are sustained for a longer period of time compared with the non-grouting option, as demonstrated by Figure 101. The difference is particularly noticeable in the period of 10,000 – 100,000 years.

Once again, the highest dose rates are associated with the excavation exposure group, and the dose rates remain well below the 1 mSv y^{-1} criterion (below which optimisation is not considered to be necessary). The actual dose rates are very similar to the non-grouting case. The results for the Borehole Calculation Case are slightly lower, because the addition of grout to the waste reduces the radionuclide concentrations in the waste. The results for the Excavation and Site Dweller Calculation Cases are slightly higher because the key radionuclides are retained in the waste more effectively.

The most significant calculation case is again the Excavation Calculation Case, for the same reasons noted previously (i.e., the same exposure pathways and radionuclides are dominant). The peak dose rates and key pathways for all calculation cases considered are presented in Table 87.

The radionuclides that dominate the dose are shown in Figure 102, and the radionuclides present in the waste at the highest concentrations are shown in Figure 103. These are the same as found for the non-grouting option, and the only difference is the profile of Nb-94 at times greater than 10,000 years. This reflects the influence of the long lasting high-pH conditions in the wastes for this option, which means that most radionuclides are retained in the wastes over longer timescales than the CAGCV non-grouting option.

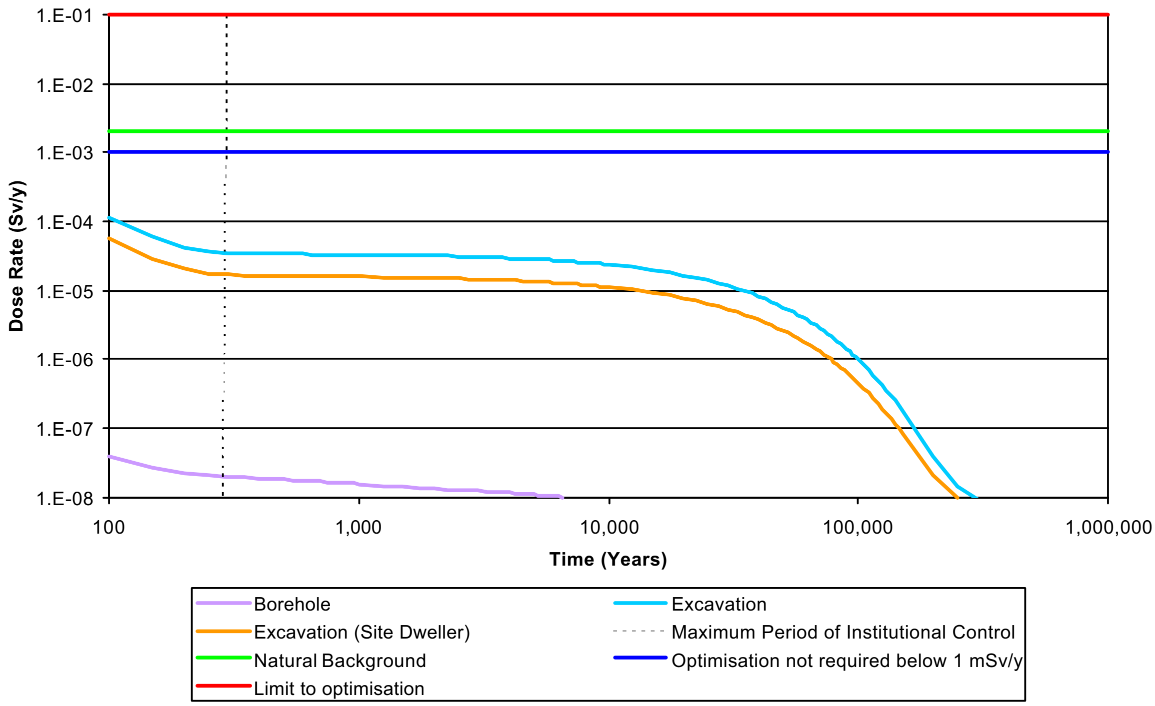

Figure 101: Total Calculated Dose rates for Human Intrusion, for the CAGCV Grouting Option

Table 87: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the CAGCV Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)			
			Ext	Ing (Crop)	Ing (Soil)	Inh (Dust)
Excavation	3.5×10^{-5}	300	99	-	<	1
Excavation (Site Dweller)	1.7×10^{-5}	300	93	7	<	<
Borehole	2.0×10^{-8}	300	22	-	22	56

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated ‘<’. ‘-‘ indicates pathways not considered for the calculation case. Pathways are indicated as follows: “Ext” is the abbreviation for external irradiation from soil or waste; “Ing (Crop)” is the ingestion of contaminated plants and vegetables; “Ing (Soil)” is the ingestion of contaminated soil or sediments; “Inh (Dust)” is the inhalation of contaminated dust.

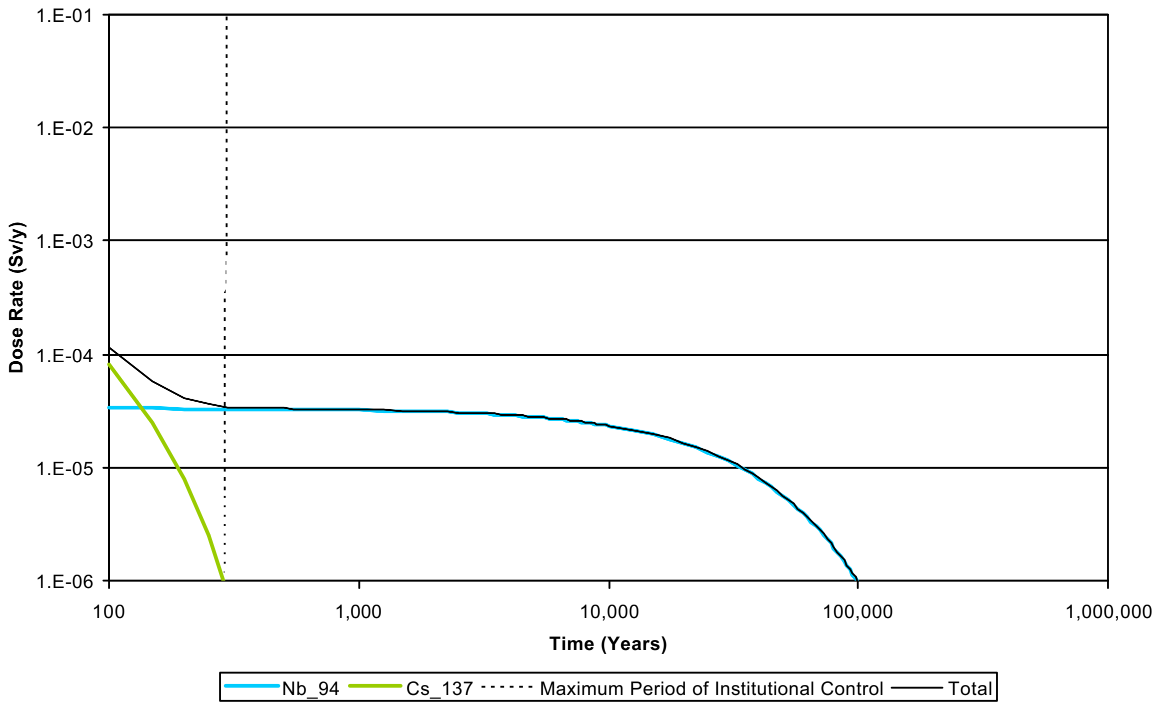

Figure 102: Contribution of Key Radionuclides to Calculated Dose rates from Excavation for the CAGCV Grouting Option

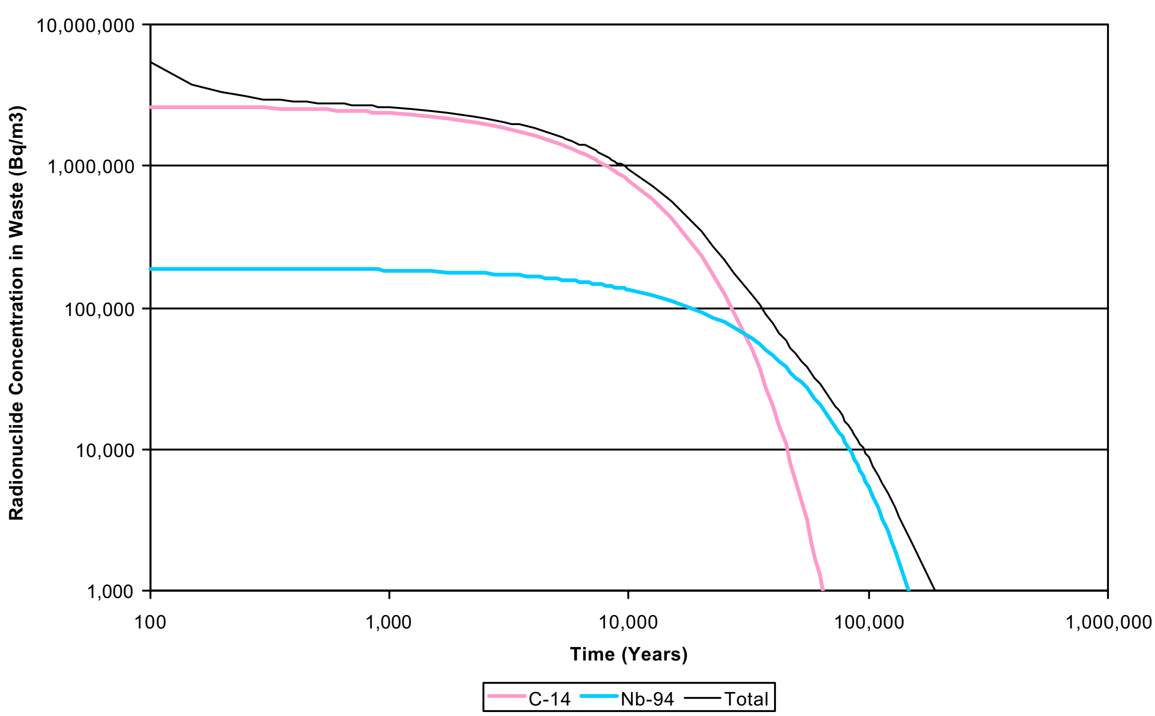

Figure 103: Concentration of Key Radionuclides in the Waste, CAGCV Grouting Option

H.2.3 DRCV NON-GROUTING OPTION

The increased isolation of the waste from the surface reduces the range of intrusion events that could affect the wastes for the DRCV concepts. For the DRCV, located several hundred metres below the surface, it is only possible to envisage the incidental extraction of borehole samples that contain waste. Larger excavations are not credible, given the low mineral value of the formations under consideration.

Human intrusion results for the DRCV concept therefore only consider the Borehole Calculation Case. In this case, even though the radionuclides are effectively retained in the facility over very long periods of time, the limited amounts of waste retrieved means that calculated dose rates very low, as shown in Figure 104. The dose rates are well below the 1 mSv y^{-1} threshold (below which detailed optimisation of the facility design is not required in respect of human intrusion hazards). Table 88 shows that doses are dominated by the inhalation of dust. External irradiation is less significant that has been seen for other human intrusion results, because the source of irradiation, a borehole sample, is much smaller than an expanse of uncovered waste considered previously in the Excavation Calculation Case for CAGCV concepts.

The key radionuclides for the human intrusion scenario for the DRCV concepts differ from those identified as being important for the CAGCV concepts. This is because of the exposure conditions, which mean that external irradiation is less significant. Consequently, the radionuclides that dominate doses are those with high inhalation dose coefficients – long-lived alpha emitters such as Pu-239, Pu-240 and Am-241, as shown in Figure 105.

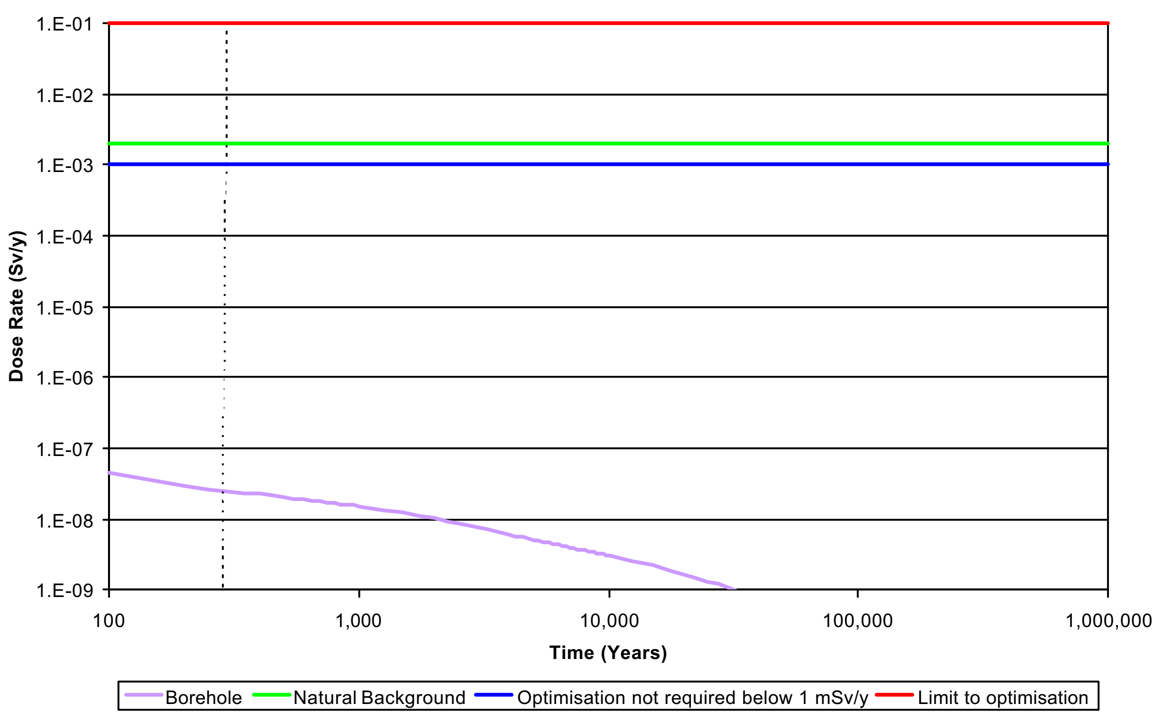

Figure 104: Total Calculated Dose rates for Human Intrusion, for the DRCV Non-grouting Option

Table 88: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the DRCV Non-grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext	Ing (Soil)	Inh (Dust)
Borehole	2.5×10^{-8}	300	7	26	67

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have not been indicated. Pathways are indicated as follows: "Ext" is the abbreviation for external irradiation from soil or waste; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Inh (Dust)" is the inhalation of contaminated dust.

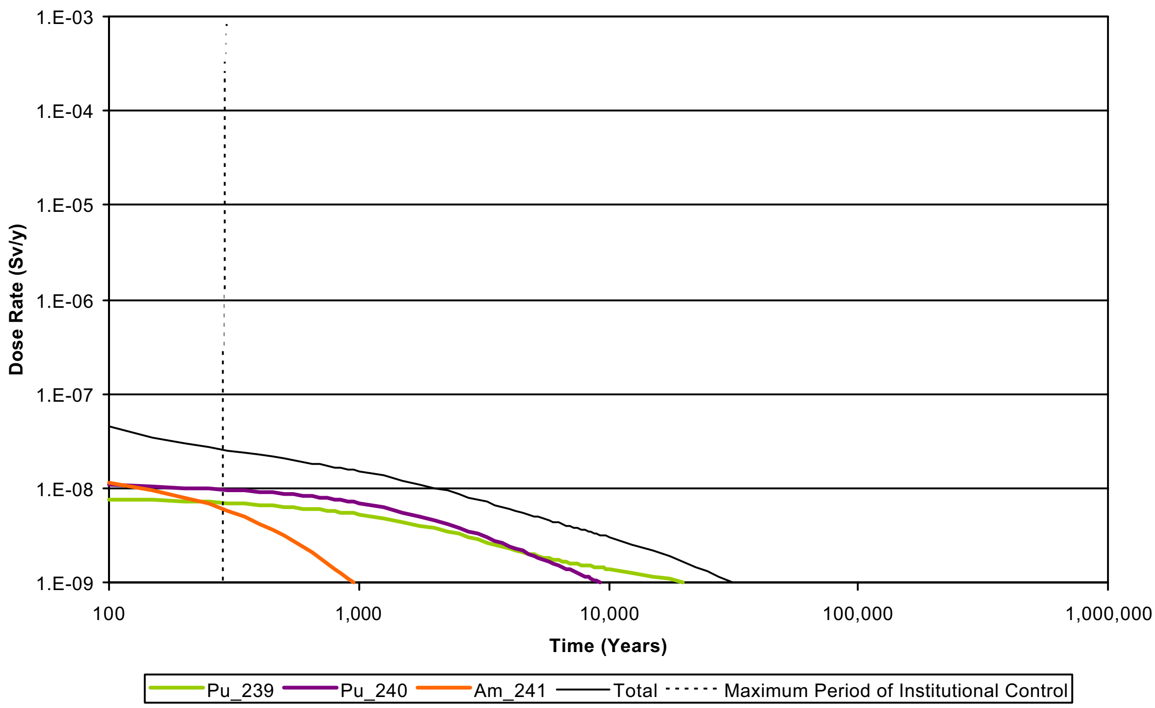

Figure 105: Contribution of Key Radionuclides to Calculated Dose rates from Borehole Inspection, DRCV Non-grouting Option

These radionuclides that dominate doses differ from those that are present with the highest concentrations in the waste (see Figure 106). These are similar the same as noted for the CAGCV concepts (C-14 and Nb-94); however, their profile of concentration with time differs, due to the different transport mechanism that is relevant to the DRCV concepts (diffusive transport, whereas in the CAGCV concepts advection is most significant).

H.2.4 DRCV GROUTING OPTION

The results calculated for the human intrusion scenario for the non-grouting DRCV concepts show that dose rates are likely to be well below the relevant criteria. Nevertheless, it was considered to be of interest to consider the potential performance of the concept if wastes were grouted and a grout backfill were added.

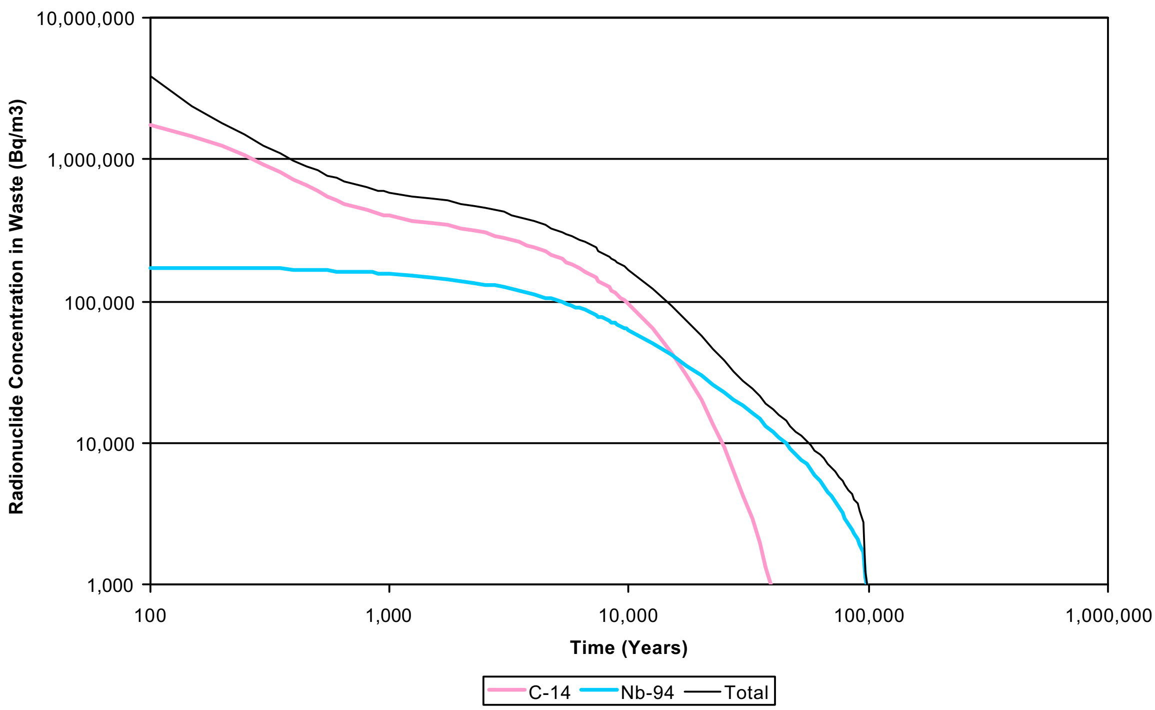

Figure 106: Concentration of Key Radionuclides in the Waste, DRCV Non-grouting Option

The calculated dose rates for such an option remain very low, as shown in Figure 107 and summarised in Table 89, and are slightly lower than those calculated for the non-grouting option. This reflects the additional mass of grout, which reduces the overall activity concentration of radionuclides in the wastes.

A slight difference in the calculated dose rates can be observed at long timescales (in excess of 10,000 years) as a result of the more effective retention of radionuclides in the grouted wastes. This is principally because the pore water in the waste is conditioned by the cement to be highly alkaline.

The key radionuclides for the grouted DRCV options are the same as the non-grouting options, and are shown in Figure 108 (radionuclides that dominate dose) and Figure 109 (radionuclides that with the highest concentrations in the waste). The most notable feature of these figures is the difference in C-14 concentrations for this option, reflecting its enhanced retention in the grouted waste. However, C-14 does not dominate doses for the human intrusion scenario and therefore the profile of doses is not significantly altered.

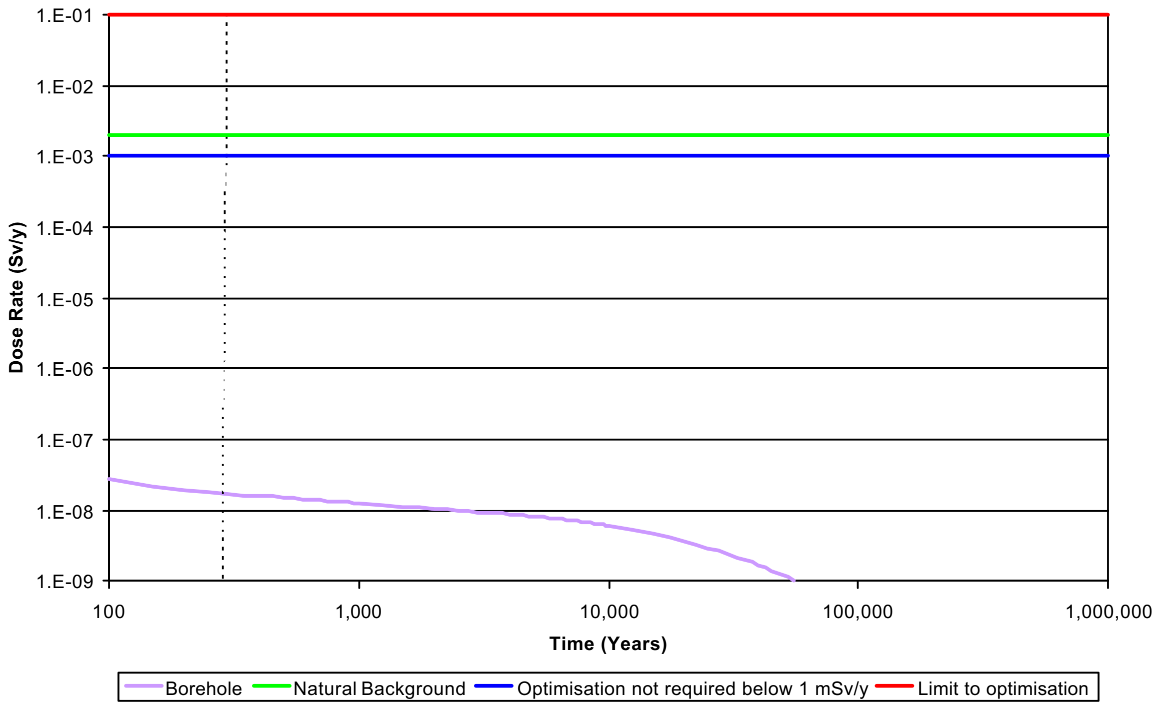

Figure 107: Total Calculated Dose rates for Human Intrusion, for the DRCV Concepts, Grouting Option

Table 89: Summary of Peak Calculated Dose Rate and Key Exposure Pathways for Human Intrusion for the DRCV Grouting Option

Calculation Case	Peak Dose Rate, Sv y^{-1}	Time of Peak, y	Contribution of Pathway to Peak Dose Rate (%)		
			Ext	Ing (Soil)	Inh (Dust)
Borehole	1.7 x 10^{-8}	300	5	27	67

Note: An institutional control period of 300 years is assumed for the purposes of this table. Contributions of less than 0.5 % have been indicated '<'. Pathways are indicated as follows: "Ext" is the abbreviation for external irradiation from soil or waste; "Ing (Soil)" is the ingestion of contaminated soil or sediments; "Inh (Dust)" is the inhalation of contaminated dust.

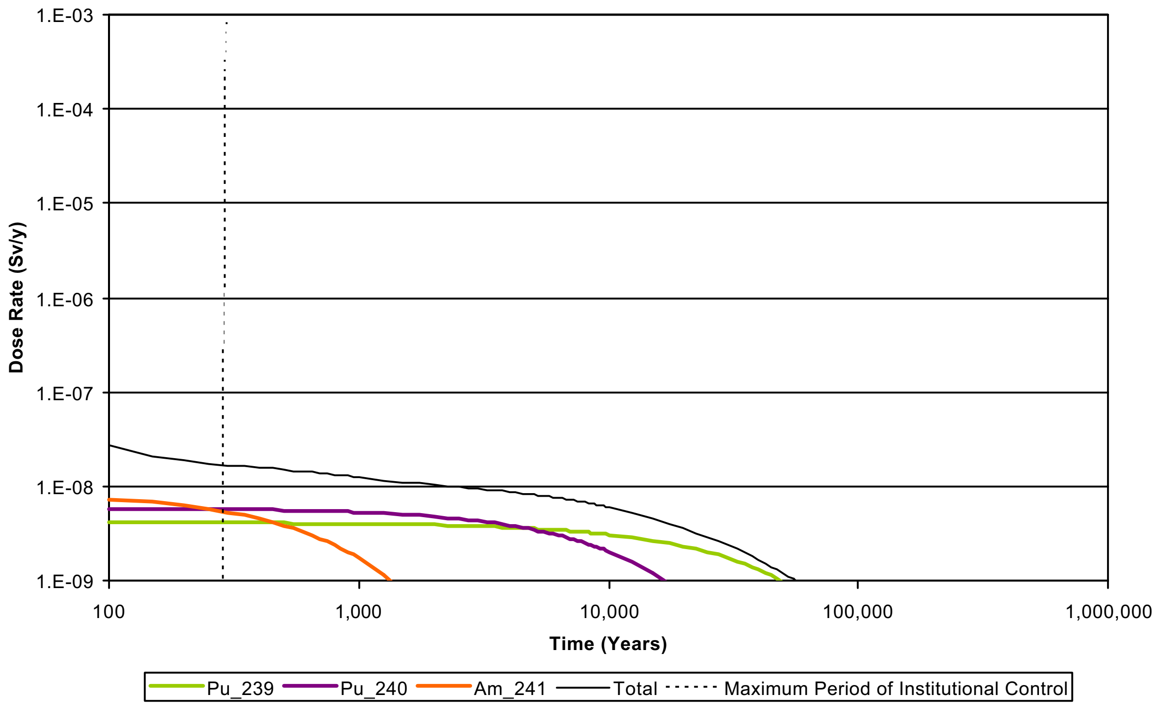

Figure 108: Contribution of Key Radionuclides to Calculated Dose rates from Borehole Inspection, DRCV Grouting Option

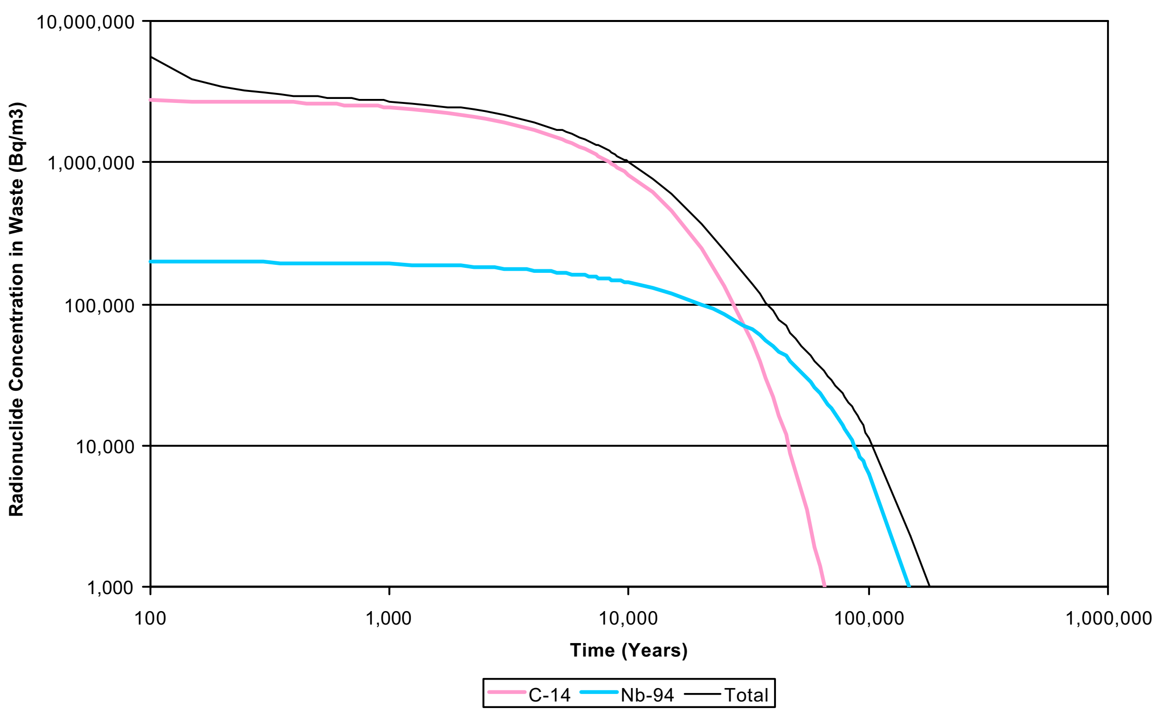

Figure 109: Concentration of Key Radionuclides in the Waste, DRCV Grouting Option

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PRELIMINARY SAFETY ASSESSMENT OF CONCEPTS FOR A PERMANENT WASTE REPOSITORY AT THE WESTERN WASTE MANAGEMENT FACILITY BRUCE SITE: SUMMARY REPORT

Submitted to:

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1. INTRODUCTION

In April 2002, a Memorandum of Understanding (MOU) was signed between Ontario Power Generation Inc. (OPG) and the Municipality of Kincardine, Ontario. This MOU sets out the terms under which OPG, in consultation with the Municipality of Kincardine, will develop a long-term plan to manage low level radioactive waste (LLW) and intermediate level radioactive waste (ILW) at the Western Waste Management Facility (WWMF) on the Bruce Site (Figure 1). The plan also includes a review of permanent repository concepts at the Bruce Site. As part of this review, OPG has commissioned two studies.

The first is a geotechnical feasibility study of the Bruce Site, which has identified four geotechnically feasible repository concepts (Golder Associates, 2003). The second study is a preliminary assessment of the long-term radiological safety of these repository concepts (Penfold et al., 2003). This second study is summarised in this report.

Although the safety assessment is preliminary, it uses an approach that is consistent with best international practice as developed under a research programme (Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM)) of the International Atomic Energy Agency (IAEA, 2002a) (Figure 2). The approach is designed to provide a reasoned and comprehensive analysis of *postclosure*[1] radiological impacts of the repository concepts. It consists of the following steps:

- specification of the assessment context (what is being assessed and why it is being assessed);
- description of the repository system (the *near field*, *geosphere* and *biosphere*);
- development and justification of the *scenarios* to be assessed;
- formulation and implementation of models and associated data; and
- presentation and analysis of the results.

Safety issues during the operational period of the repository, non-radiological safety and impacts on the environment (other than humans) associated with the development of the permanent repository are not considered in this study.

2. SPECIFICATION OF THE ASSESSMENT CONTEXT

The assessment context provides information concerning what is being assessed and why it is being assessed. OPG is at the early stage of investigating the suitability of permanent repository concepts at the Bruce Site, and the assessment context reflects the preliminary nature of the work. The specific purposes of the current safety assessment, in order of importance, are:

a) to assess the postclosure radiological safety from a permanent waste repository at the Bruce Site;

b) to help identify potentially acceptable permanent repository concept(s) at the Bruce Site;

c) to provide insight with respect to the level of engineering barrier systems required for the identified concept(s); and

d) to identify where further data or information would be most useful.

[1] All terms in italics in this report are defined in the glossary of terms section.

For the purposes of this study, a permanent repository concept is considered potentially acceptable if the concept is geotechnically feasible and the postclosure radiological safety assessment results for the concept are acceptable, when compared against relevant radiological protection criteria. The radiological protection criteria (Box 1) are the same as the recommendations given in Publication 81 of the International Commission on Radiological Protection (ICRP) (ICRP, 2000), with the exception that the criteria for *human intrusion* are more restrictive. In addition to annual *dose* rate, radionuclide concentrations in various environmental media are used as indicators of safety.

BOX 1: RADIOLOGICAL PROTECTION CRITERIA USED IN THIS STUDY

For all events other than human intrusion: the calculated dose[1] rate constraint is 0.3 mSv y^{-1} ($3x10^{-4}$ *Sv* y^{-1})

For inadvertent human intrusion:

a) if the calculated dose rate is below 1 mSv y^{-1}, optimisation of the repository system is not required;

b) if the calculated dose rate is above a level of 1 mSv y^{-1}, reasonable efforts should be made to reduce the likelihood of human intrusion or to limit its consequences;

c) if the calculated dose rate is above a level of 100 mSv y^{-1} efforts must be made to reduce the consequences of human intrusion below this level.

[1] Annual individual effective dose rate to an average adult member of a hypothetical potential exposure group which is expected to receive the highest annual dose rate (i.e., the critical group)

3. DESCRIPTION OF THE REPOSITORY SYSTEM

3.1 THE NEAR FIELD

3.1.1 Inventory and Waste Characteristics

The most recent estimates of OPG's inventory of LLW are provided in Leung and Krochmalnek (2000). Data are available for operational and decommissioning wastes. However, the focus of the current study is the development of emplacement capacity for operational wastes alone. It is assumed that:

- the inventory results from all nuclear generating plants operating for a 40 year lifetime (resulting in a total inventory of around 12 TBq ($1.2x10^{13}$ *Bq*) at repository closure);
- waste is incinerated where possible; and
- compactible waste is compacted using low force compaction.

It is estimated that there will be a total of 89,000 m^3 of packaged LLW in 20,000 containers.

The waste containers (drums and boxes) are constructed of mild steel. Currently, the operational wastes are not grouted into the waste containers. However, the addition of a cement grout is a waste conditioning option and is considered in the current study.

3.1.2 Facility Designs

Four generic permanent repository concepts have been considered for the emplacement of LLW:

- Covered Above Grade Concrete Vault (CAGCV);
- Shallow Concrete Vault (SCV);
- Deep Concrete Vault (DCV); and
- Rock Cavern Vault (RCV or Deep Rock Cavern Vault, DRCV).

These permanent repository concepts were developed for generic sites (Golder Associates, 1998). They have been subsequently screened, assessed and adapted to the Bruce Site setting (Golder Associates, 2003) and four geotechnically feasible repository concepts were identified:

- Covered Above Grade Concrete Vault on sand (CAGCV-S) (Figure 3);
- Covered Above Grade Concrete Vault on till (CAGCV-T) (Figure 3);
- Deep Rock Cavern Vault in shale (DRCV-S) at a depth of 460 m (Figure 4); and
- Deep Rock Cavern Vault in limestone (DRCV-L) at a depth of 660 m (Figure 4).

Two engineering options have been considered in the current study.

a) **Non-grouting**: vaults with ungrouted waste packages with no additional material to fill voids in the vaults ('backfill')
b) **Grouting**: vaults with cement grouted waste. Backfilling with cement grout would result in the void space between the waste packages in each vault being filled, as well as the central access aisle/tunnel and the primary drainage system.

3.2 THE GEOSPHERE

3.2.1 Geology

The Bruce Site lies on the eastern edge of the Michigan Basin. The *Palaeozoic* bedrock sequence overlying *Precambrian* granitic basement has been estimated by extrapolation from regional gas exploration drilling results to be about 800 m thick (Golder Associates, 2003). It comprises (from top to bottom) (Figure 5):

- approximately 375 m of *Devonian* and *Silurian* dolostones (dolomitic limestones);
- approximately 230 m of Lower Silurian – Upper *Ordovician* shale; and
- 185 - 190 m of Middle Ordovician fine grained, argillaceous to shaly limestone.

Unconsolidated ('overburden') sediments overlie this bedrock sequence. These sediments are comprised of a comparatively complex sequence of surface sands and gravels from former beach deposits overlying clayey-silt to sandy silt till of glacial origin with interbedded lenses and layers of sand of variable thickness and lateral extent. The total thickness of this overburden varies from less than 1 m along the shore of Lake Huron to a maximum of about 20 m on the eastern margin of the Bruce Site.

3.2.2 Hydrogeological and Geochemical Characterisation

Information concerning the hydrogeological and transport properties of the glacial sediments and bedrock at the Bruce Site is provided in Golder Associates (2003) and summarised in Table 1 Four groundwater systems are identified in Golder Associates (2003) (Figure 6).

- **The Surficial Deposits (Overburden) Groundwater System** – includes overburden sediments in which groundwater flows westward to discharge into Lake Huron. Layers of sand and gravel constitute local aquifers while the till layers comprise aquitards (i.e., they restrict groundwater flow).

- **The Shallow Bedrock Groundwater System** – includes the dolostone sequence of the Amherstburg, Bois Blanc and Bass Island Formations and the top of the Salina Formation. The upper portions of this sequence contain fresh water (often abstracted shallow wells) while at greater depths, sulphur water occurs. The direction of groundwater flow is westward towards the lake where it is discharged.

- **The Intermediate Bedrock Groundwater System** – includes the dolostone sequence of the Salina, Guelph, Lockport and Reynales Formations. The upper portion of the Salina Formation is typically freshwater or sulphur water, whilst the lower dolostone strata can contain either sulphur or saline water. The shales in the Salina Formation act as aquitards between the upper and lower portions of the Intermediate Bedrock Groundwater System. Lake Huron is considered to be the ultimate receptor of groundwater within this system since the strata outcrop on the lake bed 10 to 20 kilometres off-shore.

- **The Deep Bedrock Groundwater System** – is associated with the low permeability Ordovician shales and limestones. The groundwater is saline and the movement of pore water is very slow measured in the context of millions of years (i.e., mass transport is diffusion dominated).

3.3 THE BIOSPHERE

A summary of the present-day biosphere at the Bruce Site and in its vicinity is given in Box 2.

4. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

The aim of a scenario development and justification is to develop illustrative descriptions of the possible future evolution of the repository and its surrounding environment. The emphasis is on identifying general themes, rather than undertaking detailed simulations of projected change. In this way, the wide range of potential future conditions can be condensed to an inclusive, yet manageable, set of scenarios. This approach should allow the importance of key influences and uncertainties in possible future changes to the repository system to be explored. The safety assessment of these scenarios using calculation cases then helps provide a meaningful input to decision making.

BOX 2: SUMMARY OF PRESENT-DAY BIOSPHERE IN THE VICINITY OF THE BRUCE SITE

Climate	• Annual average temperature is 7°C; average daily temperatures vary from -5°C to 20°C. • Winds are moderate and predominantly from the south and southwest. • Total annual precipitation is about 0.86 m y^{-1}.
Topography	• Bruce Site is about 190 m above sea level, and large areas have been cleared and graded. • Abrupt ridge of 1 – 3 m in height, running roughly north-south, divides the Bruce Site, and similar features are found further inland corresponding to historic lake shorelines.
Surface water bodies	• The dominant surface water feature is Lake Huron with a total surface area of 59,600 km^2 and mean depth of 59 m. • No major rivers in the vicinity of the Bruce Site, although there are several small streams that eventually discharge into Lake Huron.
Soils	• In the vicinity of the WWMF, there is generally a shallow layer of topsoil, typically about 30 cm, overlying silt till with occasional regions of peat-like material. • Moisture varies, but it is generally moist and often wet/saturated.
Land use	• Land uses on the Bruce Site are presently restricted to those associated with the nuclear operations and support activities. • The region around the Bruce Site is mainly used for agriculture, recreation and some residential development. Farmland accounts for around 60% of the land use in Bruce County, with many cattle farmers, as well as farmers of pigs and sheep, and crops such as oats, barley, canola and hay. • Farms and rural populations obtain water from wells. The lake provides water for larger communities, and is used for fishing.
Flora and fauna	• The WWMF site is vegetated with balsam fir, sugar maple and American beech. There is also a meadow and wetland area. • There is a wide variety of wildlife in the area, all common for the region.
Natural resources	• Some sand and gravel extraction in the region. • Both municipal and domestic users of groundwater exist in the vicinity of the Bruce Site. Water is drawn from the Shallow Bedrock Groundwater System at depths of between 30 and 100 m.

Based largely on expert judgement and use of the ISAM list of features, events and processes associated with a LLW repository, two scenarios have been considered in the preliminary assessment. Neither considers future long-term environmental change (e.g., global warning and glaciation), as there is no need to develop such detailed scenarios due to the preliminary nature of the assessment. The **Reference Scenario** considers the gradual release of radionuclides from the repository in liquid form, gaseous form and solid form (e.g., contaminated material) due to natural processes such as leaching, gas generation and erosion. The subsequent migration and accumulation of radionuclides in the environment and the resulting potential exposure of humans to the radionuclides is considered. The **Human Intrusion Scenario** considers the possible inadvertent disruption of the wastes in the future. There are two main categories of disruption: small and large. The former is representative of the type of disturbance that might be caused by the drilling of boreholes during site investigation resulting in the potential direct exposure of individuals to essentially undiluted waste materials. The latter is representative of large-scale excavations resulting in the potential exposure of both the intruder and individuals with no direct connection to the intrusion event, but who may nevertheless encounter waste materials incorporated into local surface environmental media.

5. FORMULATION AND IMPLEMENTATION OF MODELS AND DATA

A total of ten calculation cases have been identified associated with these two scenarios (Table 2). Each has a specific conceptual model that provides a description of the release, migration and fate of radionuclides from the repository and the associated features, events and processes considered in the model. The features, events and processes associated with each conceptual model have been represented using algebraic expressions within a mathematical model. Site-specific data from the Bruce Site and its vicinity has been obtained and supplemented with other information, e.g. from compilations of data from other sources. The mathematical models and associated data have then been implemented in a software tool (AMBER[2]) to simulate the migration of radionuclides from the near field into the environment, and calculate the resulting dose and environmental consequences for each calculation case.

6. PRESENTATION AND ANALYSIS OF RESULTS

Detailed results from all calculation cases for permanent waste repository concepts can be found in the detailed preliminary safety assessment report (Penfold et al. 2003). The key results for potentially acceptable repository concepts (DRCV-S, DRCV-L and CAGCV-S) are summarised in Table 3, Figure 7 and Figure 8[3]. The main findings are as follows.

- For the deep repository concepts (DRCV-S and DRCV-L), the calculated dose rates are below the ICRP 81 dose criteria by many orders of magnitude for all of the calculation cases. Grouting the wastes and the repository voids reduces the calculated dose rates from liquid releases by less than an order of magnitude because the release is already significantly restricted by the low permeability host rocks at depth.

- For the surface repository concept on sand (CAGCV-S), the calculated dose rates are below the ICRP 81 dose criteria for all of the calculation cases by about an order of magnitude or more. Grouting the wastes and the repository voids limits the flow of

[2] AMBER was developed under Quintessa's quality management system, which is compliant with the international standard ISO 9001:2000. It has been used in the assessment of a range of proposed and operating LLW repositories (see for example BNFL (2002), Chapman et al. (2002), IAEA (2002b and c) and Penfold et al. (2002)). For the current study AMBER version 4.4 has been used (Enviros QuantiSci and Quintessa, 2002).

[3] The calculated dose rate in Figure 8 is the dose rate that occurs to an individual member of the relevant exposure group assuming that the intrusion event occurs in the specified year. Thus the calculated dose rate at 1000 years on the graph is the dose rate that would be received assuming the intrusion event occurred at 1000 years.

water through the repository and increases the retention time of radionuclides in the near field, thus reducing the calculated dose rates from liquid releases.

- Varying the institutional control period between 100 years and 300 years has no significant impact on the dose rates for the Reference Scenario. This is because the calculated dose rates for the most significant calculation case in the period between 100 and 300 years (i.e., the Gas Release Calculation Case) are more than three orders of magnitude below the ICRP dose criterion of 0.3 mSv y^{-1}. For the Human Intrusion Scenario, calculated dose rates are higher in the period between 100 years and 300 years because there is less time for radioactive decay and leaching to reduce the inventory in the repository. Nevertheless, calculated dose rates for the most restrictive calculation case are still more than an order of magnitude below the level above which reasonable efforts should be made to reduce the likelihood of human intrusion or to limit its consequences.

7. CONCLUSIONS AND RECOMMENDATIONS

A preliminary assessment has been undertaken to assess the radiological safety of four geotechnically feasible repository concepts for the long-term management of LLW at the Bruce Site. The assessment has used an approach consistent with best international practice.

It has demonstrated that, from a postclosure radiological safety assessment perspective, the deep repository concepts in shale (DRCV-S) and limestone (DRCV-L), and the surface repository concept on sand (CAGCV-S) should meet the radiological protection criteria adopted for this study, even without grouting of the waste and repository voids. Whilst grouting has benefits for the surface repository concepts such as reducing and/or delaying dose rates, its benefits for the deep repository concepts are minimal. Although extending the institutional control period from 100 to 300 years has no significant impact on the dose rates for the limiting calculation cases for the Reference Scenario, it does reduce calculated dose rates but only by about a factor of three for Human Intrusion Scenario calculation cases. Furthermore, the calculated dose rates at 100 years for the most restrictive calculation case are still more than an order of magnitude below the level above which reasonable efforts should be made to reduce the likelihood of human intrusion or to limit its consequences.

The ability of the repository designs to accept OPG's ILW has been assessed qualitatively. Due to the very low permeability of the host rocks, the deep repository concepts in shale (DRCV-S) and limestone (DRCV-L) are likely to meet the radiological protection criteria adopted for this study for a wide range of ILW, although quantitative analyses would be required to confirm this. The surface repository concept on sand (CAGCV-S) would require additional analyses to ascertain the degree to which the concept could accept ILW.

The calculations associated with this preliminary postclosure radiological safety assessment have been undertaken at a scoping level. This preliminary safety assessment would need to be updated in both its breadth and depth based on future site-specific geotechnical investigations and/or design updates, should it be decided to proceed with a repository at the Bruce Site.

In terms of increasing the breadth of the evaluation of the repository concepts, it could be extended to consider operational issues. Operational issues could include not only radiological safety but also non-radiological safety and impacts associated with the development of the repository.

In terms of increasing the depth of the evaluation of repository concepts, the more detailed consideration could be given to certain aspects of the safety assessment. Issues of particular interest could include the following.

- The relatively simple groundwater flow and transport calculations, which have been undertaken for the current assessment, could be supported with more detailed two and three dimensional calculations especially for the Surficial Deposits and Shallow Bedrock Groundwater Systems. This in turn would require more detailed characterisation of the physical and chemical characteristics of these systems at the Bruce Site.

- The results presented in Section 6 show that the timescales of potential interest extend well beyond 10,000 years. Over such timescales, environmental change, caused by factors such as major climate change, can be significant and could be addressed in future safety assessments.

- Although site-specific data from the Bruce Site and its environs have been used where available in the current assessment, much of the data used in the assessment comes from non-Bruce specific sources. Whilst this is appropriate for certain parameters (for example, dose coefficients), for certain other parameters (for example, sorption coefficients) the use of site-specific data would be preferable.

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Table 1: Estimated Hydrogeological and Geosphere Transport Properties for the Bruce Site (Golder Associates, 2003)

Stratigraphic Sequence	Effective Hydraulic Conductivity (m/s)[1]			Groundwater Chemistry				Matrix Porosity	Effective Transport Porosity[3]	Dry Density	Chloride-Matrix Effective Diffusion Coefficient	Distribution Coefficient[4] (K_d)	Dispersivity (α)	Matrix Tortuosity Factor (τ)[5]
	min	max	Geometric Mean	TDS (mg/L)[2]	Chloride (mg / L)	pH	Redox Condition (mV)	%	%	(t/m3)	m^2/s @23°C	(mL/g)	(m)	Estimate
SURFICIAL SEDIMENTS GROUNDWATER SYSTEM						Neutral to slightly alkaline								
Sand and Gravel	4×10^{-8}	3×10^{-5}	(1×10^{-5})	Fresh	1-45	7.0 - 8.3	>100	30%	30%	1.8	7×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.7
TILL	1×10^{-10}	6×10^{-10}	2×10^{-10}								6×10^{-10}	C=20 Cl=0 I=0 Nb=160 Pu=1200 Tc=0.1		0.6
SHALLOW BEDROCK GROUNDWATER SYSTEM				Fresh to Brackish		Slightly Alkaline								
Bedrock Surface (Upper 15 m)	3×10^{-7}	6×10^{-5}	(1×10^{-5})	1,000 - 2,500	1-100		> 100	5 - 15	0.5 - 1.5	2.7	1.5×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.15
Devonian/Silurian/Limestone/ Dolostone Amherstburg, Bois Blanc and Bass Island Formations	7×10^{-10}	2×10^{-4}	(1×10^{-5})	Fresh to Brackish, sulphurous 1,000 - 2,500	10-100	7.2 - 7.7				2.6 - 2.7	1.5×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.15
INTERMEDIATE BEDROCK GROUNDWATER SYSTEM				Saline to Brine Sulphurous		Slightly Acidic								
Silurian Dolostones Salina, Guelph and Lockport & Reynales Formations	n.a.	n.a.	(1×10^{-7})	100,000 - 300,000	50,000 - 200,000	6.3 - 6.7	<0	4.8 - 11.0	0.5 - 1.1%	2.5 - 2.7	0.65×10^{-10} to 1.2×10^{-10}	C=5Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.04 - 0.08
Silurian Shales Salina C and F members,	n.a.	n.a.	(1×10^{-10})					1.9 - 3.1	0.2 - 0.3	2.6 - 2.7	0.5×10^{-10} to 1×10^{-10}	C=20 Cl=0 I=0 Nb=160 Pu=1200 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.03 - 0.07
DEEP BEDROCK GROUNDWATER SYSTEM				Saline to Brine Sulphurous		Slightly Acidic								
Silurian Dolostones/Shales Cabot Head Formation	n.a	n.a.	(1×10^{-10})	100,000 - 300,000	50,000 - 200,000	n.a.	<0	1.9 - 3.1	0.2 - 0.3	2.6 - 2.7	0.5×10^{-10} to 1×10^{-10}	C=20 Cl=0 I=0 Nb=160 Pu=1200 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.03 - 0.07
Manitoulin Formation			(1×10^{-8})											
Ordovician Shales Queenston Formation	n.a.	n.a.	1×10^{-12}	Brine, Sulphurous 150,000 - 300,000	25,000 - 150,000	Slightly Acidic n.a.	<0	10.2- 11.4	1.0	2.6	1.4×10^{-10} to 1.6×10^{-10}	C=1 Cl=0 I=0 Nb=900 Pu=5100 Tc=1		0.095 to 0.108
Georgian Bay, Blue Mountain and Whitby Formations	9×10^{-14}	7×10^{-11}	1×10^{-12}											
Ordovician Limestones Lindsay Formation	3×10^{-14}	7×10^{-11}	7×10^{-13}	Brine, Sulphurous		Slightly Acidic		0.5 - 3	0.05 - 0.3	2.6	1×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.1
Verulam Formation	5×10^{-14}	7×10^{-9}	3×10^{-12}			6.2 - 6.3								
Bobcaygeon and Gull River Formations	2×10^{-15}	6×10^{-9}	4×10^{-12}	40,000-300,000	25,000-200,000		<0							
Shadow Lake Formation Cambrian Sandstone Precambrian Granitic Gneiss	4×10^{-4}	1×10^{-8}	8×10^{-12}			Slightly Acidic 5.1 - 6.2		<0.5	0.05	2.8	0.1×10^{-10}	C=5 Cl=0 I=0 Nb=160 Pu=550 Tc=0.1	Longitudinal=10% of travel path length (m) transverse=1% of travel path length (m)	0.01

1 (1×10^{-5}) Bracketed values indicate "*Best Estimate*"
2 For TDS (total dissolved solids) classification:
Classification:
TDS mg/L
Fresh 100 - 1,000
Brackish 1,000 - 10,000
Saline 10,000 - 100,000
Brine >100,000

3 Effective Transport Porosity is assumed to be 10 percent of the Matrix Porosity
4 Distribution Coefficients for radionuclides (excluding iodine) are taken from Sheppard and Thibault 1990, Default Soil Solid/ Liquid Partition Coefficients, K_ds, for Four Major Soil Types: A Compendium, Health Phyries Vol. 59, No. 4 (October) pp 471-482,1990.
5 Matrix Tortuosity Factor x Free Water Diffusion Coefficient = Effective Diffusion Coefficient
n.a. indicates data not available.

Table 2: Calculation Cases Assessed

Scenario	Release Mechanism	Calculation Case Name	Permanent Repository Concept(s)	Potential Exposure Group(s)	Features
Reference Scenario	Liquid	Lake Release	CAGCV-S, CAGCV-T	Fisherman	Contaminated groundwater released to overburden sediments and transported to lake via Shallow Bedrock Groundwater System.
		Lakeshore Release	CAGCV-S, CAGCV-T	Fisherman	Contaminated groundwater released to overburden sediments and transported to lakeshore via Shallow Bedrock Groundwater System.
		Well Release	CAGCV-S, CAGCV-T	Farmer	Contaminated groundwater released to overburden sediments and transported to well via Shallow Bedrock Groundwater System.
		Bathtubbing	CAGCV-T	Site dweller	Contaminated groundwater released directly into surface water after degradation of near field barriers.
	Gas	Gas Release	CAGCV-S, CAGCV-T	Site dweller	Contaminated gas released into a house on the cap after failure of containers or loss of institutional control (whichever is later).
	Solid	Cover Erosion	CAGCV-S, CAGCV-T	Site dweller	Waste exposed at the surface after degradation of near field barriers and its erosion by wind and surface water.
	Liquid	Lake Release	DRCV-S, DRCV-L	Fisherman	Contaminated groundwater release by diffusion to Intermediate Bedrock Groundwater System, then transport to off-shore lake sediments.
	Liquid	Shaft Pathway	DRCV-S, DRCV-L	Fisherman	Contaminated groundwater released via shaft and transported via more diffusive pathway to Intermediate Bedrock Groundwater System, then transport to off-shore lake sediments.
Human Intrusion Scenario	Solid	Exploration Borehole	CAGCV-S, CAGCV-T, DRCV-S, DRCV-L	Intruder	Waste retrieved to the surface via shallow (CAGCV) or deep (DRCV) borehole.
		Excavation	CAGCV-S, CAGCV-T	Intruder, Site dweller	Large excavation disrupts waste and spoil from large excavation contaminates surface soils, which are then used to grow crop.

Note: All calculation cases for the CAGCV and DRCV concepts are considered for both non-grouting (no grouting of waste or voids) and grouting cases (cement grouting of waste and voids).

Table 3: Summary of Key Results for the Potentially Acceptable Repository Concepts

Scenario	Repository Concept	Waste Conditioning	Time of Peak Dose (y)	Peak Dose Rate (mSv y^{-1})	Most Significant Calculation Case
Reference	DRCV-S	Non-grouting	47,500	$5x10^{-14}$	Shaft Pathway
Reference	DRCV-L	Non-grouting	65,000	$2x10^{-14}$	Shaft Pathway
Reference	CAGCV-S	Non-grouting	7,500	0.007	Well Release
Human Intrusion	DRCV-S	Non-grouting	300	$3x10^{-5}$	Borehole
Human Intrusion	DRCV-L	Non-grouting	300	$3x10^{-5}$	Borehole
Human Intrusion	CAGCV-S	Non-grouting	300	0.03	Excavation

Note:

An institutional control period of 300 years is assumed for the purposes of this table. The effect of reducing this period to 100 years is minimal (see Figure 8)

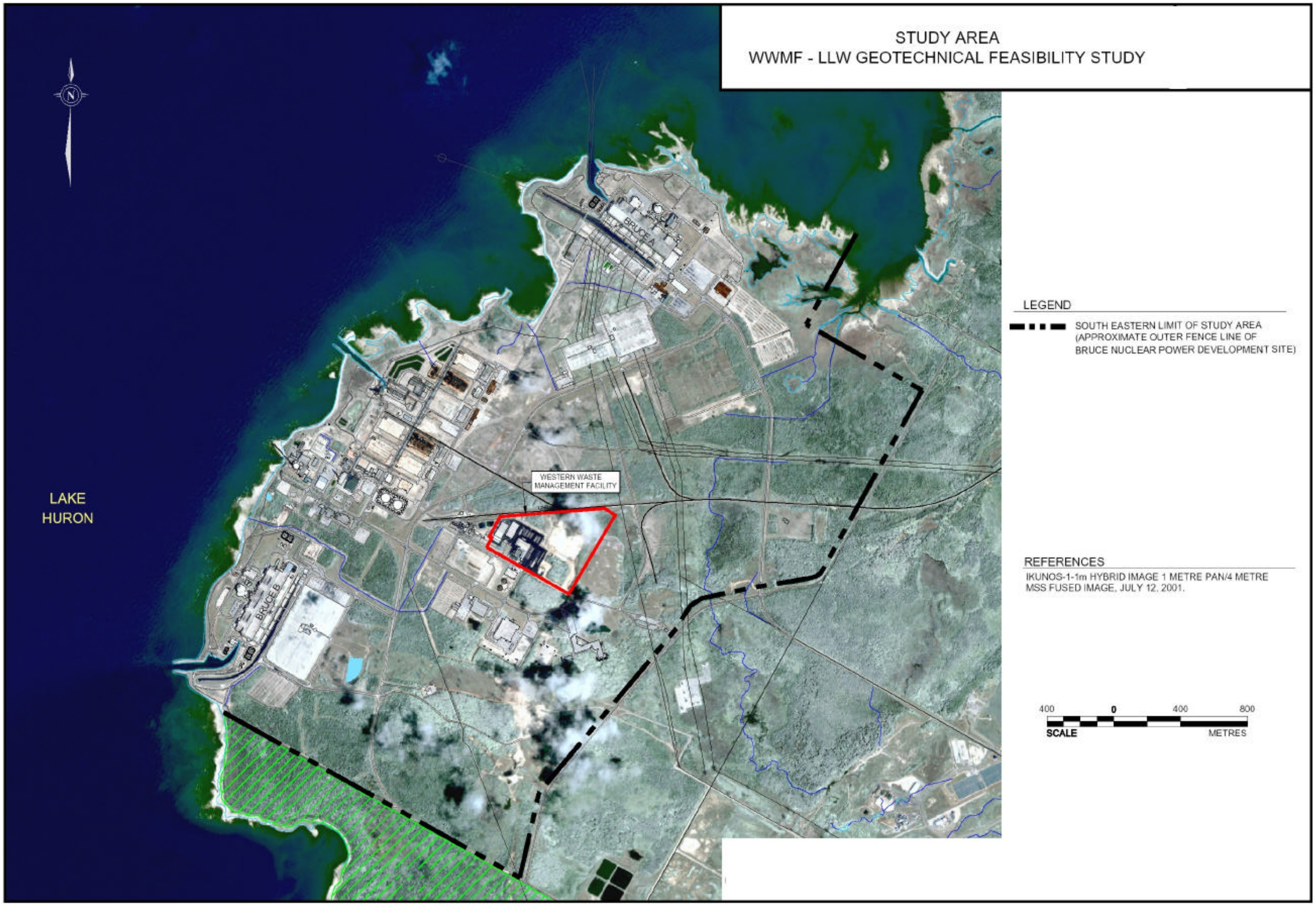

Figure 1: Location of the WWMF within the Bruce Site (Golder Associates, 2003)

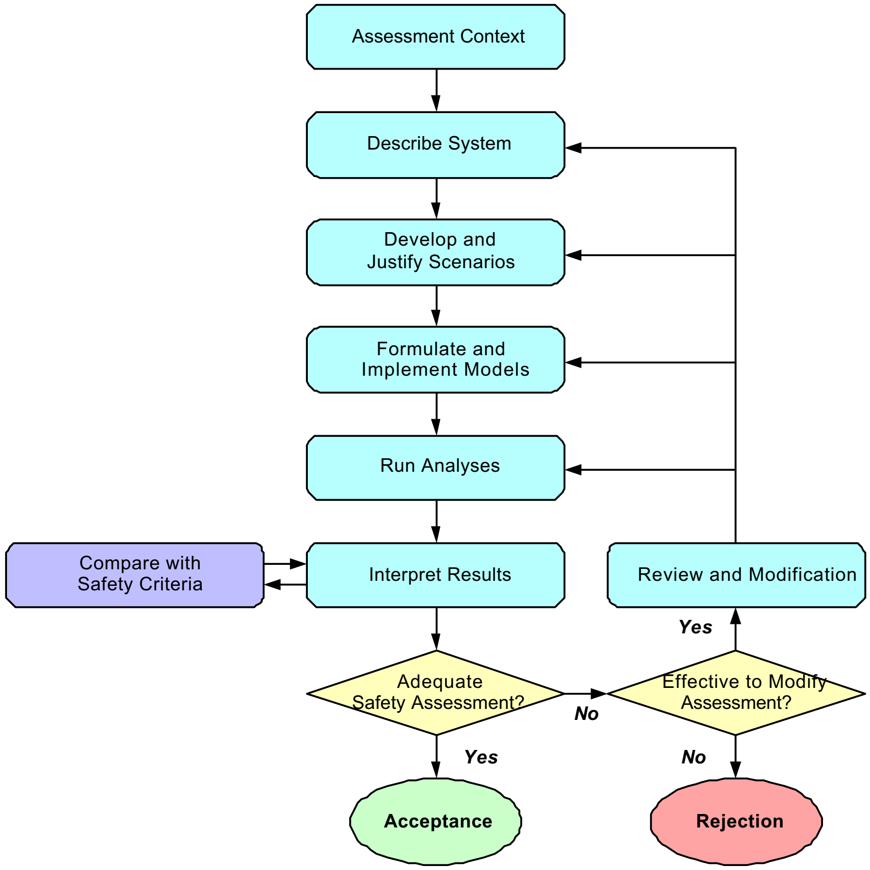

Figure 2: The ISAM Safety Assessment Methodology, the Basis of the Approach Applied in this Study

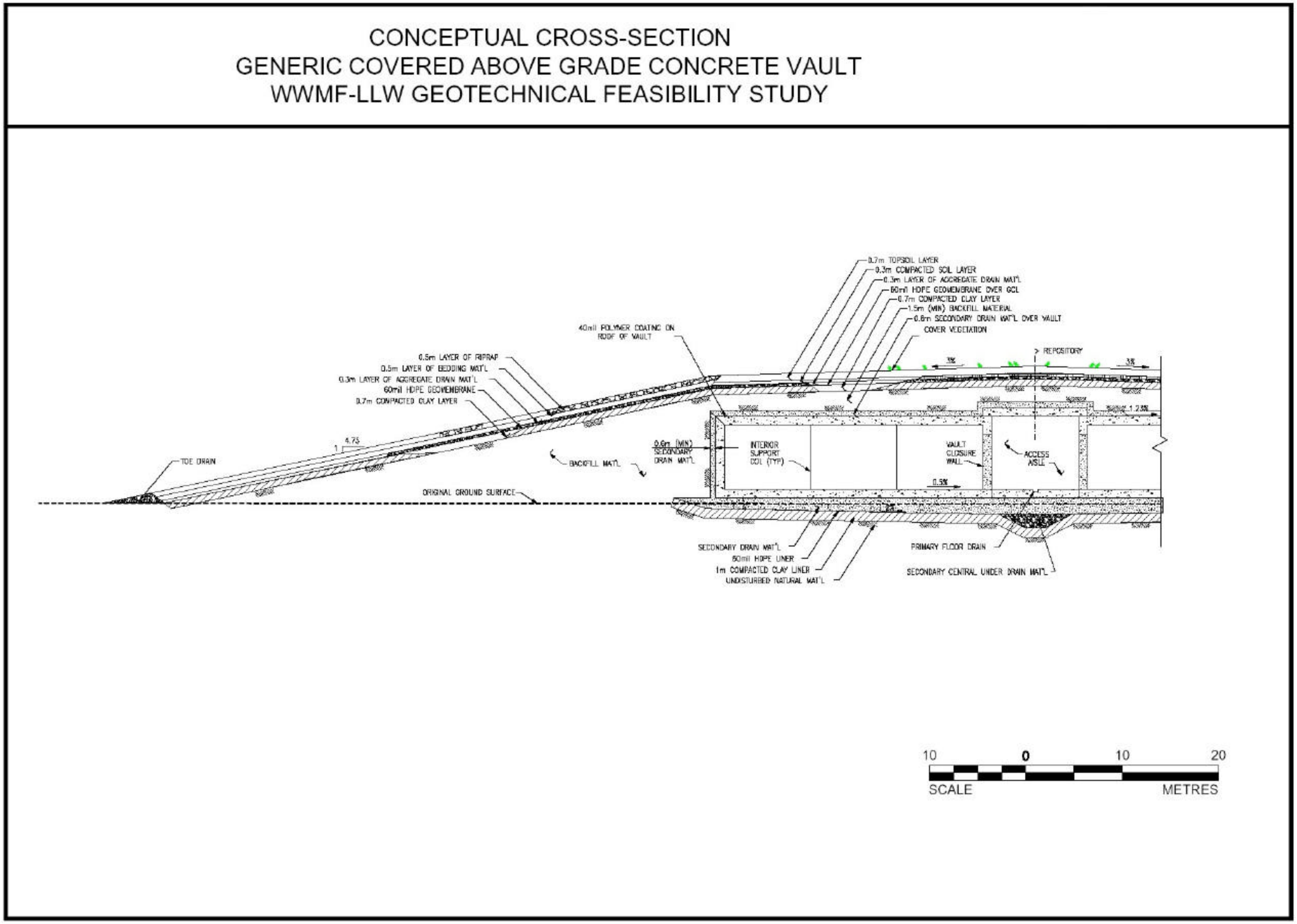

Figure 3: Conceptual Cross-Section through the CAGCV (Golder Associates, 2003)

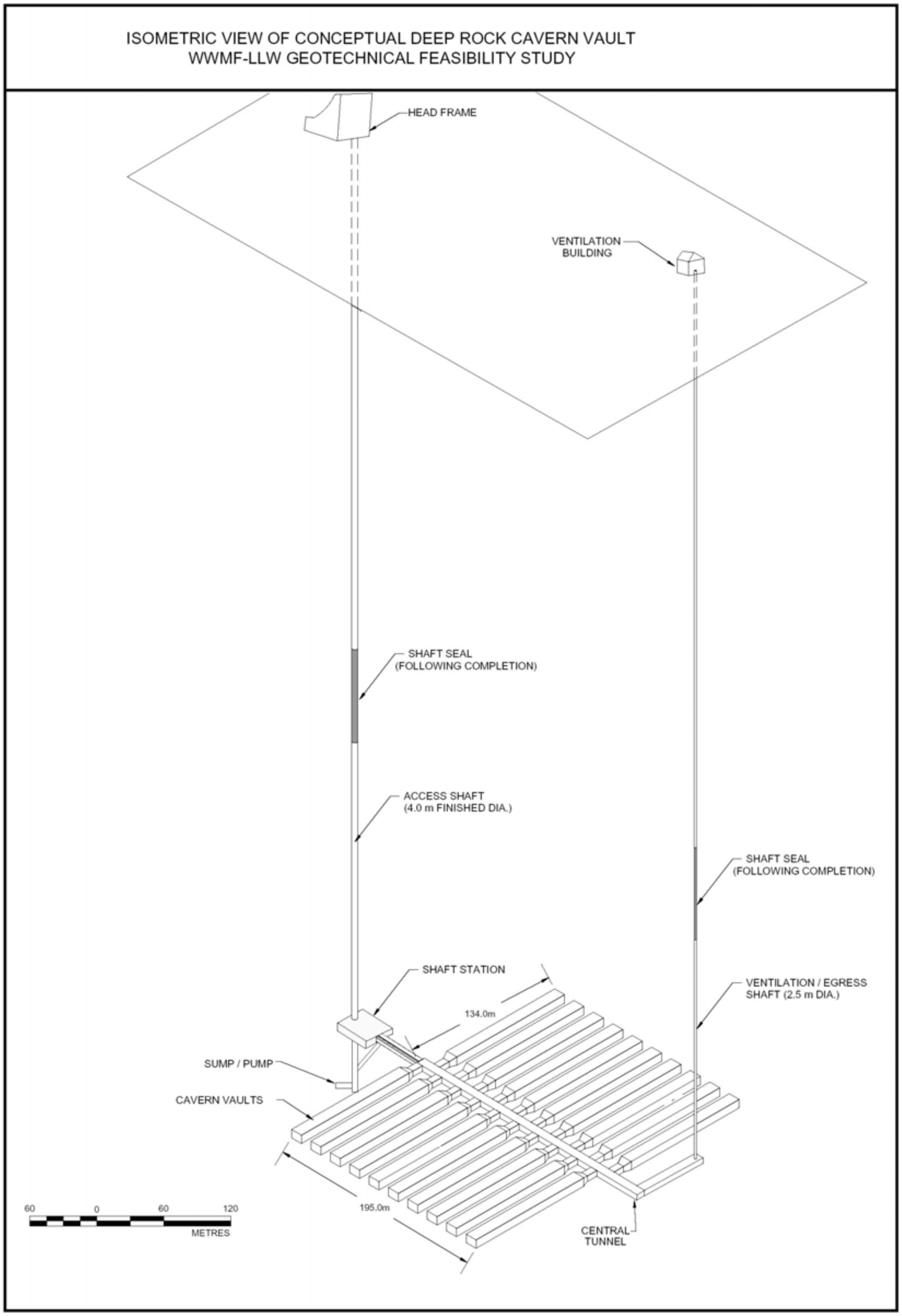

Figure 4: Conceptual Cross-Section through the DRCV (Golder Associates, 2003)

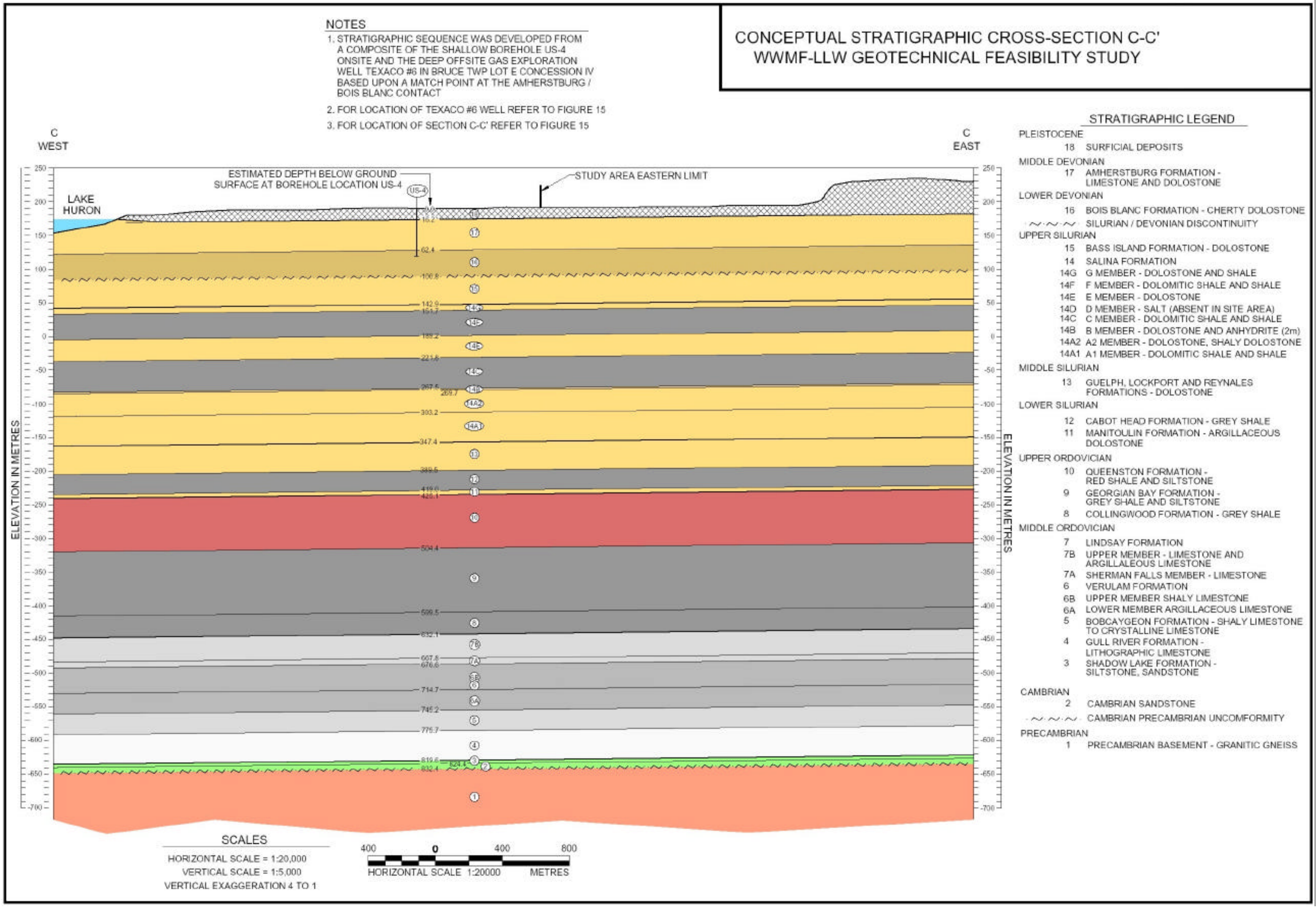

Figure 5: Cross-Section of the Stratigraphy below the Bruce Site (Golder Associates, 2003)

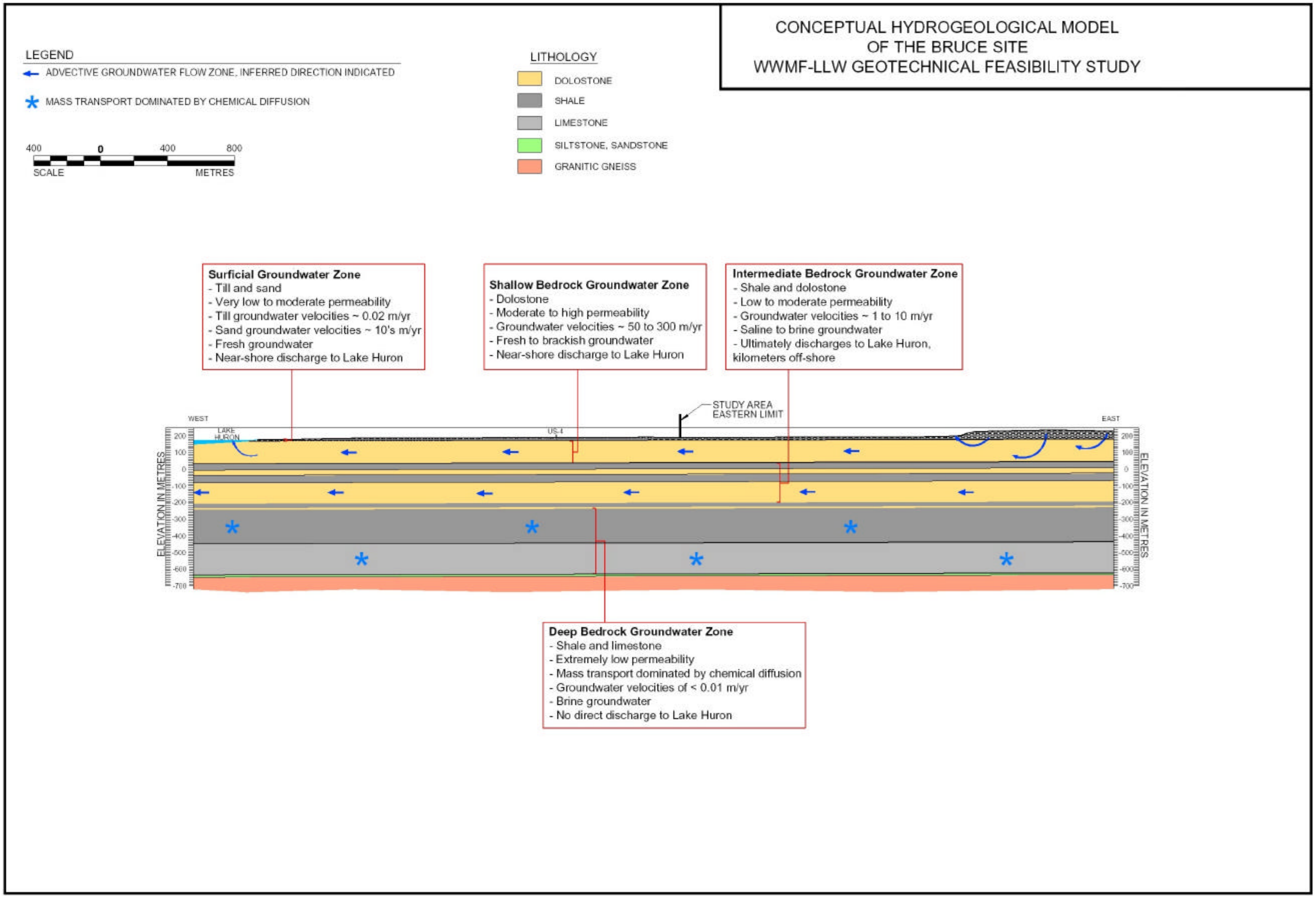

Figure 6: Conceptual Hydrogeological Model of the Bruce Site (Golder Associates, 2003)

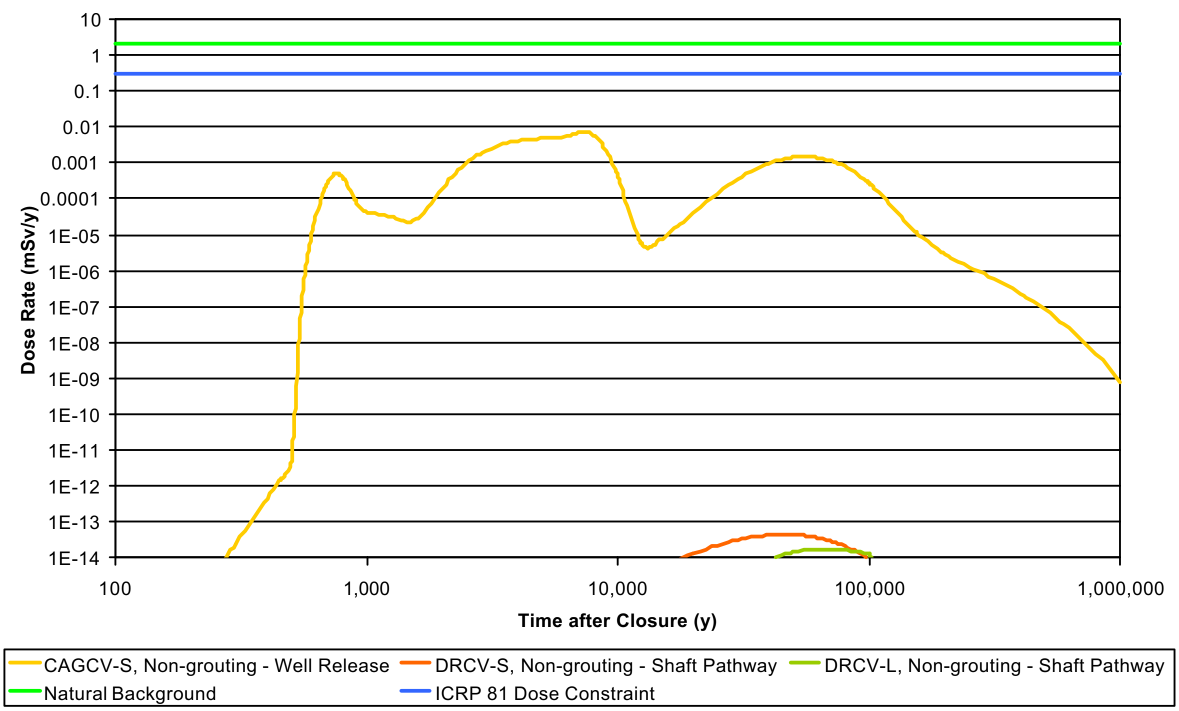

Figure 7: Calculated Dose Rates for the Most Significant Calculation Cases for the CAGCV and DRCV Concepts, Reference Scenario

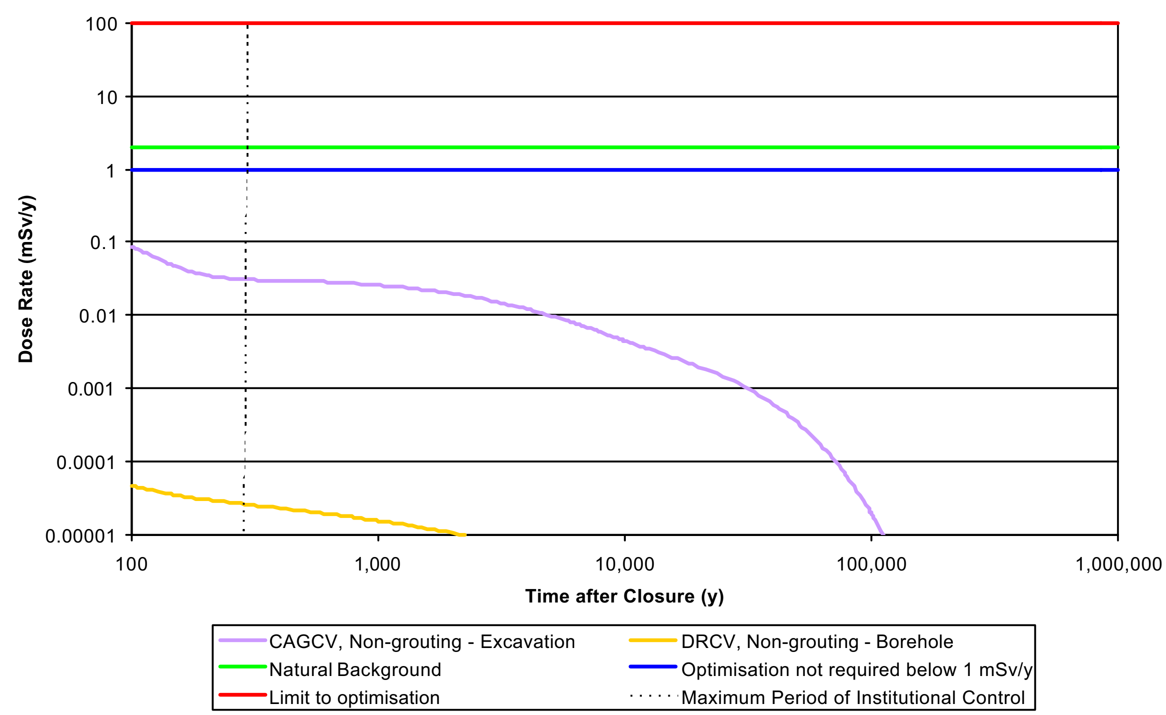

Figure 8: Calculated Dose Rates for the Most Significant Calculation Cases for the CAGCV and DRCV Concepts, Human Intrusion Scenario

GLOSSARY OF TERMS

Bathtubbing: The process by which a proportion of the water infiltrating vertically into a surface repository flows horizontally out of the repository through its sides and/or base. This results from the rate of infiltration into the repository being greater than the rate at which the water can flow vertically out from the base of the repository into the underlying geosphere.

Biosphere: Physical media (atmosphere, soils, surface sediments and surface waters) and the living organisms (including humans) that interact with them.

Becquerel (Bq): Name for the SI unit of radioactivity (the amount of a radionuclide in a given energy state at a given time).

Devonian: The geological period extending from 395 to 345 million years before present.

Dose: A measure of the radiation received or absorbed by a target.

Geosphere: The rock and unconsolidated material that lie between the near field and the biosphere. The geosphere can consist of both the unsaturated zone (which is above the groundwater table) and the saturated zone (which is below the groundwater table).

Human intrusion: Human actions that adversely affect the safety of the permanent repository by modifying the performance of engineered and/or natural barriers leading to the creation of a route by which humans (potentially both the intruder(s) and members of the public) are exposed to radionuclides derived from the waste repository.

Near field: The waste, the emplacement area, the engineered barriers of the permanent repository plus the disturbed zone of the natural barriers that surround the repository.

Ordovician: The geological period extending from 500 to 435 million years before present.

Palaeozoic: The geological era extending from 600 to 225 million years before present.

Postclosure: The time following the final sealing of a permanent repository.

Precambrian: The period of time from the consolidation of the Earth's crust (4,500 million years before present) to the start of the Cambrian period (600 million years before present).

Scenario: A hypothetical sequence of processes and events, forming one of a set devised for the purpose of illustrating the range of future behaviours and states of a repository system.

Sievert (Sv): Name for the SI unit of effective dose equal to 1 Joule per kilogram.

Silurian: The geological period extending from 435 to 395 million years before present.