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Scenario Analysis for the Postclosure Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal

Analyse de scénarios pour l'évaluation de la phase de post-fermeture du concept canadien de stockage permanent des déchets de combustible nucléaire

B.W. Goodwin, M.E. Stephens, C.C. Davison, L.H. Johnson, R. Zach

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SCENARIO ANALYSIS FOR THE POSTCLOSURE ASSESSMENT OF THE CANADIAN CONCEPT FOR NUCLEAR FUEL WASTE DISPOSAL

by

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1994

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ANALYSE DE SCÉNARIOS POUR L'ÉVALUATION DE LA PHASE DE POST-FERMETURE DU CONCEPT CANADIEN DE STOCKAGE PERMANENT DES DÉCHETS DE COMBUSTIBLE NUCLÉAIRE

par

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L.H. Johnson et R. Zach

RÉSUMÉ

EACL Recherche a mis au point et évalué un concept pour le stockage permanent des déchets de combustible nucléaire du Canada qui consiste à enfouir les déchets à grande profondeur dans la formation de roche ignée intrusive du Bouclier canadien. L'évaluation de post-fermeture de ce concept porte surtout sur les effets sur la santé et sur le milieu naturel que pourraient avoir les contaminants éventuellement rejetés dans la biosphère après la fermeture de l'enceinte de stockage. Les contaminants radiotoxiques et chimiquement toxiques y sont étudiés.

L'une des étapes du processus d'évaluation de la phase de post-fermeture est l'analyse de scénarios. Cette analyse de scénarios détermine les facteurs qui pourraient influer sur l'efficacité du système de stockage permanent et regroupe ces facteurs dans des scénarios qui doivent faire l'objet d'une évaluation quantitative détaillée.

Le présent rapport documente un mode d'analyse systématique des scénarios qui a été mis au point en vue de l'évaluation de post-fermeture et appliqué par la suite à l'étude d'un système de stockage hypothétique. La mise en application donne une liste exhaustive de facteurs et un jeu de scénarios qui nécessitent une évaluation quantitative plus poussée. Cette mise en application permet aussi de déterminer un certain nombre d'autres facteurs et de scénarios éventuels pour lesquels le système de stockage hypothétique n'aurait pas d'incidences importantes sur la sûreté et sur le milieu naturel.

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ABSTRACT

AECL Research has developed and evaluated a concept for disposal of Canada's nuclear fuel waste involving deep underground disposal of the waste in intrusive igneous rock of the Canadian Shield. The postclosure assessment of this concept focusses on the effects on human health and the environment due to potential contaminant releases into the biosphere after the disposal vault is closed. Both radiotoxic and chemically toxic contaminants are considered.

One of the steps in the postclosure assessment process is scenario analysis. Scenario analysis identifies factors that could affect the performance of the disposal system and groups these factors into scenarios that require detailed quantitative evaluation.

This report documents a systematic procedure for scenario analysis that was developed for the postclosure assessment and then applied to the study of a hypothetical disposal system. The application leads to a comprehensive list of factors and a set of scenarios that require further quantitative study. The application also identifies a number of other factors and potential scenarios that would not contribute significantly to environmental and safety impacts for the hypothetical disposal system.

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1. INTRODUCTION

In 1978 AECL Research and Ontario Hydro were assigned responsibility for the Canadian Nuclear Fuel Waste Management Program (CNFWMP), a program set up to evaluate the concept for deep underground disposal of nuclear fuel waste in intrusive igneous rock of the Canadian Shield (Joint Statement 1978, 1981). Nuclear fuel waste from CANDU™ nuclear power reactors would be immobilized within durable containers and isolated in a vault located at a depth of 500 to 1000 m in plutonic rock of the Shield (Boulton 1978; Dormuth and Nuttall 1987; AECL 1994a,b).

One element of the Program is the assessment of potential impacts on the environment and humans that may arise from a disposal system (AECL 1994a, 1994b). The assessment has been separated into two distinct phases.

- The preclosure assessment phase (Grondin et al. 1994) deals with environmental and safety issues that may arise during the facility construction, operation, decommissioning and extended monitoring stages, prior to and including closure of the disposal facility.

- The postclosure assessment phase (Goodwin et al. 1994) deals with long-term environmental and safety issues. The time frame of concern for the postclosure assessment begins after the disposal facility has been closed and all shafts, tunnels and boreholes have been sealed, such that the facility is placed in a passively safe state. Regulatory criteria from the Atomic Energy Control Board (AECB) require quantitative estimates of radiological risk for times up to 10^4 a following closure of the disposal facility and reasoned arguments for times beyond 10^4 a (AECB 1987a).

An important step in the postclosure assessment is the identification of factors and scenarios that require detailed study. A factor is a distinguishing characteristic of the disposal system and its surroundings, or a characteristic of perturbing external or internal events. A scenario is "a sketch, outline or description of an imagined situation or sequence of events" (NEA 1992). For the postclosure assessment study, a scenario defines a possible future of the waste disposal system and includes a set of factors that define pathways and processes that could lead to an effect on the natural environment, including a hypothetical group of individuals, called the critical group, who are expected to be most at risk from the disposal system.

Several earlier studies have been conducted on scenario analysis for the CNFWMP.

- Merrett and Gillespie (1983) described events that may be initiated by disruptive actions of man, by vault-related processes and by natural phenomena. They also defined two categories of events: events that are likely to be unimportant (such as volcanic eruption and meteorite impact), and events that require further consideration (glaciation, seismic activity and changes in the biosphere).

- Heinrich (1984) documented results of a workshop dealing with long-term stability of the geosphere. One major conclusion was that the effect of potential perturbations should be examined in terms of their influence on groundwater flow near the vault and their influence on the mechanical and thermal stability of the vault.

- Davis (1986a, 1986b) described time-dependent processes that could affect the biosphere. His analysis includes a recommended approach to modelling those processes that are expected to be most important. Further work by Elson and Webber (1991) has focussed on pathways and parameter values required to evaluate the effects of glaciation.

This report is a consolidation and extension of the above studies. An interim description of the current study has been given by Stephens and Goodwin (1989). In the following discussion, we first describe a systematic procedure that was developed to identify the scenarios for the postclosure assessment of the concept for disposal of Canada's nuclear fuel waste. We then document its application for a particular hypothetical disposal system.

This report also draws from similar studies recently performed and in progress in other countries, notably those described by Cranwell et al. (1982, 1987), Bonano et al. (1988), the NEA (1980, 1988b, 1992), NAGRA (1985), SKB (1989a, 1989b), SKI (1991) and the IAEA (1985).

2. THE NEED FOR SCENARIO ANALYSIS

Scenario analysis is a procedure aimed at identifying and describing all the factors that must be considered in the assessment. It is an integral part of the postclosure assessment process (Figure 1) and has two main objectives.

> *Prepare a comprehensive list of factors that could affect the performance of the disposal system.* Scenario analysis provides a systematic procedure for listing factors that are potentially important and gives confidence that all such factors have been identified on the basis of current knowledge and understanding.
>
> *Provide a logical structure within which the importance of each factor can be evaluated.* Scenario analysis also produces a framework for collecting factors into scenarios and identifying those scenarios that could contribute significantly to potential impacts.

The postclosure assessment is to provide quantitative estimates of radiological risk for times up to 10^4 a following closure of the disposal facility and, if the estimated risk does not peak within this time, reasoned arguments on potential impacts for times beyond 10^4 a (AECB 1987a). Thus a systematic approach is required for scenario analysis because over these long time scales the disposal system may be influenced by a large number of diverse and interacting factors. These factors (or features, events and processes) include the following examples:

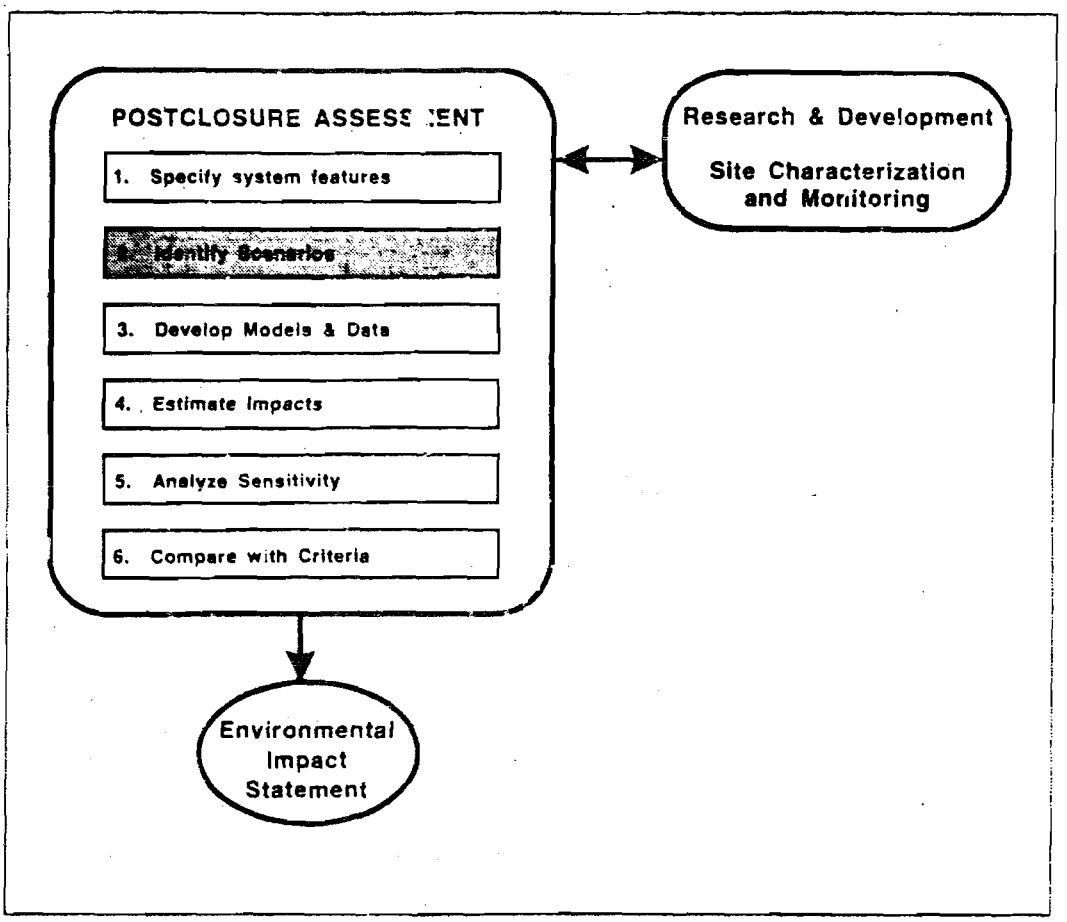

FIGURE 1: The Scenario Analysis Step in the Assessment Approach.
The postclosure assessment approach is described in terms of six steps (Goodwin et al. 1994). The second step is scenario analysis, a systematic and comprehensive procedure aimed at identifying all factors that require further detailed evaluation and determining how these factors should be combined and treated in scenarios. A factor is a distinguishing characteristic of any affected part of the disposal system, such as radioactive decay and contaminant transport through fractures. A scenario defines a possible future of the waste disposal system that includes potential impacts on the critical group or the natural environment.
The specifications of the disposal system (from step 1) define the breadth of scenario analysis. Once scenarios are defined, we proceed through the remaining steps to document the results in an environmental impact statement. There is considerable feedback between each of the steps in the postclosure assessment approach. In particular, the discussion in the text points out that the probabilistic method used to estimate impacts (step 4), together with the capabilities of the system model (step 3), greatly influence the characteristics of the scenarios that are defined. There are also close links in all steps of the assessment with research related elements of the CNFWMP.

Features that vary in importance or are conditionally important. Features expected to be important are the diet of the critical group and the presence of fractures that conduct groundwater from the vault to the biosphere. A conditionally important feature would be the potential for enhanced contaminant transport if an open borehole existed near the vault.

Events that vary in frequency of occurrence. The assessment should consider commonly occurring events that would frequently affect members of the critical group, such as forest or agricultural fires. The assessment should also consider events with a smaller probability of occurrence, such as glaciation, meteorite impact and human intrusion.

Processes that vary in time. Some processes would be complete or reach steady state within 10^4 a, the time limit for quantitative estimates of radiological risk specified by the AECB (1987a). Other processes might not have proceeded to any significant degree over this period of time. Relatively fast processes include the resaturation of rock near the vault following closure and uptake of contaminants by plants once contaminants reach the biosphere. Processes such as hydrothermal alteration of rocks and minerals and surface erosion of the exposed geosphere are much slower.

Scenario analysis meets its first objective by providing evidence that a comprehensive collection of such factors has been examined.

To meet the second objective, it would suffice to identify a single, all-inclusive scenario that included every important factor. It must be recognized, however, that the postclosure assessment relies on mathematical models to simulate the long-term performance of the disposal system and to infer potential effects. These mathematical models and related data must represent all important factors, but it may not be practical or efficient to include all features, events and processes within a single system model. As well, different factors may not warrant the same type of treatment, as will be seen in the application described in Section 4.

To simplify the subsequent modelling and analysis of the hypothetical disposal system, we define in Section 4 three types of scenarios, called the central scenarios, the open-borehole scenarios and the inadvertent human intrusion scenarios. We have found a separate assessment of these scenarios is more effective for several reasons.

- Their evaluations have slightly different objectives. We conclude that the central and inadvertent human intrusion scenarios should be examined in detail to provide a quantitative estimate of their contributions to radiological risk. In contrast, we conclude that studies of the open-borehole scenarios should be focussed on the examination of quality assurance measures that would decrease the probability of occurrence of open boreholes. (We expect that effective measures could be achieved such that the open-borehole scenarios would make a negligible contribution to radiological risk.)

- The scenarios require models and data that are substantially different, even though they have a large number of common factors and differ only in the presence or absence of factors pertaining to open boreholes and inadvertent human intrusion. For example, a system model for the open-borehole scenarios would require a much finer resolution of the rock and the disposal vault, especially near the open borehole, than does a system model for the central scenarios. Similarly, the system models for the inadvertent human intrusion scenarios and for the central scenarios require the definition of different critical groups to ensure that impacts are estimated for the individuals who are exposed to the greatest risk.

The above discussion suggests that it is desirable to maintain a strong link between the application of scenario analysis and the development of models. Our first intent was to decouple the two activities to the extent possible, and this is certainly feasible (and desirable) during the identification of important factors. However, we have observed that scenario analysis and model development are very interdependent and they tend to mature in parallel. Examples of their interactions are discussed in the application of the scenario analysis procedure.

3. A SYSTEMATIC PROCEDURE FOR SCENARIO ANALYSIS

It is important that a scenario analysis procedure be systematic, to provide confidence that a comprehensive set of factors and scenarios has been examined. Our procedure is described below in general terms; it could potentially be adapted for other scenario analyses. In Section 4, we describe the particular application in which we were interested, the post-closure assessment of the concept for disposal of Canada's nuclear fuel waste.

Our procedure evolved from one developed at Sandia National Laboratories (Cranwell et al. 1982, 1987; Bonano et al. 1988). We also drew on the studies by the Working Group on the Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal (NEA 1980, 1988b, 1992), sponsored by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development.

Our procedure consists of the six steps shown in Figure 2. There is considerable feedback between steps, particularly between steps 3 and 5. Steps one through three generate a comprehensive list of factors that could influence the performance of the system to be assessed. These steps should be carried out by a large multidisciplinary group whose members have a wide range of relevant experience and expertise. Steps four through six identify important scenarios that should be evaluated quantitatively in the assessment. They may be carried out by a smaller group of experts, but the results and conclusions should be subjected to a broad review.

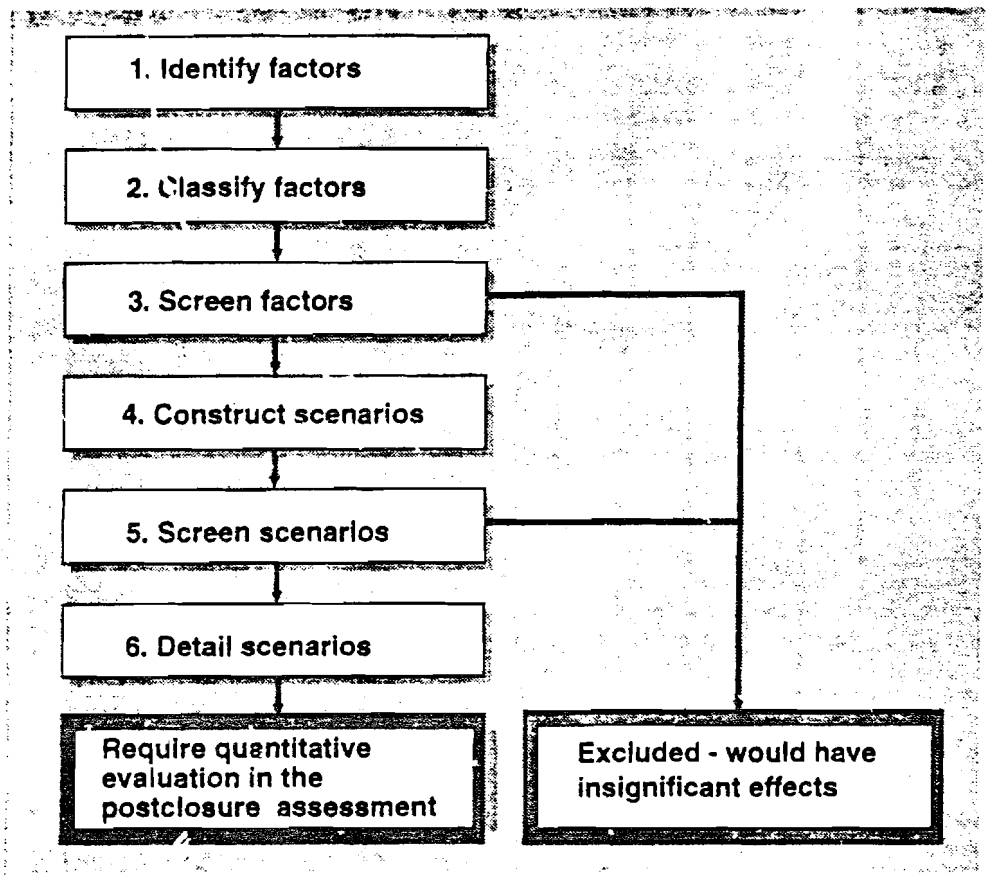

FIGURE 2: The Six-Step Procedure Used to Identify and Select Scenarios.
A large list of factors are first identified and classified. Some factors are excluded in the first screening step; they need not appear in any scenarios because they would not have significant effects. The other factors are used to construct scenarios. Some scenarios may be eliminated during the screening of scenarios (step 5) because they would not contribute significantly to the estimate of risk. The remaining scenarios (and their associated factors) require quantitative evaluation in the postclosure assessment; they are described in more detail in the last step.

3.1 STEP 1: LIST FACTORS

The objective in this step is to prepare a comprehensive list of factors, with no consideration as to whether they might be improbable or unimportant. For this application, a factor is defined as any feature, event or process that could influence the performance of any component of the disposal system. We include factors that are expected to occur as well as low-probability features, events and processes that could disrupt the system.

Features in an underground disposal system might include preferred pathways for water flow in the geosphere, both known and conjectured, and chemical conditions in the vault that promote or impede contaminant movement. Events might include earthquakes that change hydraulic connections in pathways, and dam failures that change hydraulic heads and land uses. Processes might include transport of contaminants by diffusion and convection in groundwater, sorption of contaminants onto minerals, corrosion of waste containers, and human consumption of edible plants grown on contaminated soil.

Factors identified in related studies are worth considering when preparing an initial list of factors.

3.2 STEP 2: CLASSIFY FACTORS

Confidence in the comprehensiveness of the list of factors is developed by organizing and ordering the information in many different ways. The objective is to identify factors missed in the first step (and not to devise an all-purpose classification), and thus it is desirable to explore many different classification schemes.

Some schemes may be used to classify all factors in the list; for example, each factor might be classified as a feature, event or process. Other schemes may deal only with a subset of factors, such as those factors that can affect only one component of the system.

3.3 STEP 3: SCREEN FACTORS

All the factors are subjected to a critical detailed review. Decisions are taken on how each factor should be treated in the remaining steps of the scenario analysis. The objective is to identify factors that are sufficiently important to require quantitative evaluation and that should be passed on to the next step. These important factors will be included in one or more scenarios for analysis in the postclosure assessment.

Some factors may be eliminated at this step; that is, they are excluded from any of the scenarios that are evaluated further in the postclosure assessment. For all such factors, formal documentation of the arguments for exclusion is required. It is preferable that these arguments be based on quantitative reasons; for example, an event may be excluded because it has an extremely small probability of occurrence or it could not have a significant effect on the consequences of the system. Quantitative reasons are not always feasible, however. In some instances, a decision may have

to be made on the basis of expert opinion and judgement, or a decision might be qualified and depend on further research studies. Often it may be concluded that exclusion of a factor would lead to overestimates of impact.

3.4 STEP 4: CONSTRUCT SCENARIOS

All factors requiring quantitative evaluation are combined to yield a comprehensive set of potential scenarios. A secondary objective is to minimize the number of scenarios that require separate quantitative evaluation using distinct system models. Ideally, only one scenario is required: it would contain all factors from step 3, describe all possibilities in the future behaviour of the disposal system, and be represented by a single, comprehensive system model. In practice, however, it may be difficult to combine the many diverse factors within a single mathematical model.

This is the most problematic step in scenario analysis because there is no rigorous and prescribed formula that leads to the definition of a unique set of scenarios (and their associated system models). In fact, the types and number of scenarios that are selected are strongly affected by the methodology and by the evolving models and data employed for the postclosure assessment.

- In our studies for the postclosure assessment, we use a probabilistic systems assessment methodology implemented in the the SYstems Variability Analysis Code, Generation 3 (SYVAC3) (Goodwin et al. 1994). We show, in Section 4.4, that this methodology and the use of SYVAC3 permit the evaluation of a large number of factors, including many mutually exclusive factors, within one system model. (This system model is associated with the central scenarios discussed below and in Section 4.4.)

- Moreover, our experience has shown that interim identification of a set of scenarios prompted changes to models and data such that some members of the set of scenarios could be combined. Thus evolution of the models and data leads to a smaller number of scenarios.

To make this step more tractable, we first construct the central or base case scenarios. (We use the plural for scenarios because, as described in Section 4.4, the central scenarios may be regarded as a compound collection of many simpler scenarios.) The central scenarios contain as many important factors as possible. As a general rule, these factors are expected to be always important, to occur frequently or to proceed to a significant degree over the time scale of the assessment. A factor may be excluded from the central scenarios for several reasons, such as it would be important only rarely or under unusual conditions, or its presence is incompatible with the presence of another factor. Another reason for excluding a factor from the central scenarios is that it cannot be readily included in the associated system model, and it would be more efficient to evaluate the factor in a different scenario using a different system model. This last reason is predicated, in part, on a good understanding of available analytical modelling and assessment capabilities.

Residual factors are those not included in the central scenarios; they are used to construct a complete set of alternative scenarios by grouping them together in all possible combinations. If there are "r" residual factors, then there are a total of (2^r-1) possible combinations of one or more residual factors. Each of these combinations may then be added to the factors in the central scenarios to define a total of (2^r-1) alternative scenarios. Following this approach, each alternative scenario contains a unique combination of one or more of the residual factors, plus all factors from the central scenarios (if required, any incompatible or unimportant factors from the central scenarios are removed). We generally choose a descriptive name for each alternative scenario that is based on its unique residual factor(s).

Other systematic approaches for the construction of scenarios are described in a report by the NEA Working Group for the Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal (NEA 1992).

3.5 STEP 5: SCREEN SCENARIOS

Each scenario from step 4 is reviewed and the ones that must be considered quantitatively in the assessment are identified and passed to step 6. The central scenarios almost certainly require quantitative evaluation. Some alternative scenarios may also require quantitative evaluation; other alternative scenarios may be eliminated.

For each instance where a scenario is eliminated, formal documentation of the reasoning for elimination must be provided. As in the screening of factors (step 2), quantitative arguments are preferable, but may not always be possible.

3.6 STEP 6: DEFINE SCENARIOS

Each scenario passing from step 5 must be described in detail, listing its component factors and stating the concerns that led to the selection of its factors. Finally, a value is assigned to the probability of occurrence of the scenarios.

It may not be possible to provide a quantitative estimate of the probability of occurrence for all scenarios, and it may also not be realistic to assign a conservatively large value. This is the case for the open-borehole scenarios described in Section 4.6.2, and in this instance we provide a recommended treatment so that an appropriate assessment can be performed.

4. APPLICATION OF THE PROCEDURE

We applied the scenario analysis procedure specifically to the concept for disposal of Canada's nuclear fuel waste. We further restricted the application to a particular hypothetical disposal system, called the "reference disposal system", that is studied in the postclosure assessment (AECL

1994a,b; Davis et al. 1993; Davison et al. 1994a; Goodwin et al. 1994; and Johnson et al. 1994a). For example, the reference disposal system considers the use of a metallic titanium container (Johnson et al. 1994a), a hydraulic setting that is consistent with research information from the Whiteshell Research Area (Davison et al. 1994a), and a biosphere that is compatible with environments on the Canadian Shield (Davis et al. 1993).

Although several interim reports were produced, the final application and documentation of the procedure is based on more than a decade of studies, to accommodate feedback from other elements of the CNFWMP and new information generated in related scenario analyses. For example, one group of potentially important factors relate to the production and transport of gases. These factors required further research to determine their likelihood of occurrence and their subsequent effects. We also periodically updated the list of factors, including conclusions from similar scenario analysis studies carried out by the Swedish Nuclear Fuel and Waste Management Company and the Swedish Nuclear Power Inspectorate for a Swedish disposal concept (SKB 1989a, 1989b; SKI 1991). The discussion in Sections 4.1 to 4.6 summarizes the conclusions reached at the end of the application of the procedure.

The first three steps of the scenario analysis procedure were performed by a core group of scientists and engineers consisting of more than 15 members with wide-ranging experience, and representing all major research disciplines within the CNFWMP (Appendix A lists members of the group). Other personnel within AECL Research also participated through reviews of interim reports prepared by the group. The following discussion and Figure 3 summarize the work completed by the group in each of the steps in the procedure.

4.1 LISTING FACTORS

This step identifies any factor that could influence the performance of any component of the reference disposal system. It involved a series of brainstorming sessions to develop lists of factors, drawing on previous studies, including Merrett and Gillespie (1983), the NEA (1980, 1988a, 1988b, 1992), NAGRA (1985) and the IAEA (1985). Three draft lists concentrated on factors that mostly affected the disposal vault, the geosphere and the biosphere.

There were no restrictions on the types of factors identified throughout the initial free-ranging meetings. More than 1000 factors were identified during this step. For convenience, many were collected into about 300 more broadly defined general factors, most of which are listed in Appendix B. For example, the biosphere list in Appendix B contains the general factor "human diet" that includes many different types of food that may be consumed by man.

Only a few other factors were subsequently added, either as a consequence of the classification step (Section 4.2) or as a consequence of reviews of related studies such as those reported by the Swedish Nuclear Fuel and Waste Management Company and Swedish Nuclear Power Inspectorate (SKB 1989a, 1989b; SKI 1991).

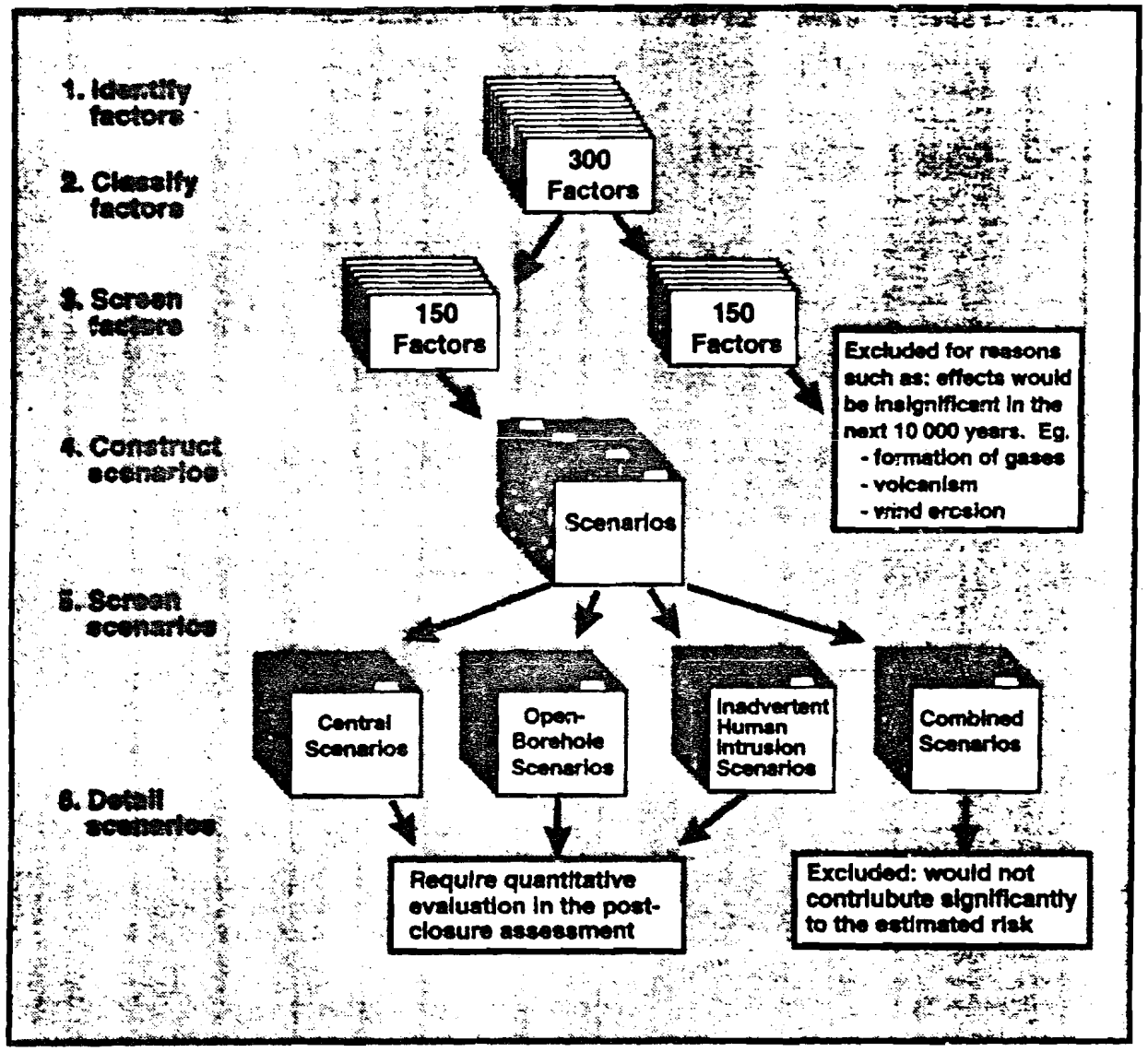

FIGURE 3: Results from Scenario Analysis of the Hypothetical Reference Disposal System. Approximately 300 factors are identified in steps 1 and 2, and about half that number pass the screening in step 3. Four scenarios are constructed in step 4 but one (the combined scenario) is eliminated in step 5 because it could not contribute significantly to the estimated radiological risk. Only three scenarios require quantitative evaluation in the postclosure assessment: the central, open-borehole and inadvertent human intrusion scenarios.

4.2 CLASSIFYING THE FACTORS

This step increases confidence that a comprehensive list of factors has been identified, by systematically searching for missing classes or members of a class of factors.

Several classification schemes were used:

- type of factor: feature, event or process;
- component of the disposal system mostly affected: disposal vault, geosphere or biosphere.
- origin of the factor: naturally occurring, induced by the presence of the vault, or caused by human intrusion into the vault;
- major mode of action of the factor: biological, chemical, or physical;
- sub-components affected: for example, in the disposal vault the sub-components considered were the waste matrices, container, buffer, backfill, and seals and grouts; and
- pathway by which the critical group is directly affected: ingestion, inhalation or external exposure.

These classification schemes were discussed by the expert group and helped to identify a few additional factors. Some of these classification schemes are included in the tables of factors in Appendix B.

4.3 SCREENING THE FACTORS

This step resolves how the factors should be treated in the remaining steps of scenario analysis.

We critically examined each of the factors produced from steps 1 and 2 to identify those factors that required detailed quantitative consideration in one or more scenarios for the postclosure assessment of the reference disposal system. Initially, individual experts separately examined factors that they were most familiar with in the vault, geosphere or biosphere classifications. Their recommendations were then reviewed by other members of the group. The tables in Appendix B summarize the results of the screening step in the "Treatment" columns, using the flags "C", "I", "O" and "X".

The "C", "I" and "O" flags identify factors requiring quantitative treatment in the central or one of two alternative scenarios for the postclosure assessment of the reference disposal system (see Section 4.4 below). Approximately half of the factors listed in the tables in Appendix B were so identified and were therefore passed on to the next step (construction of scenarios).

The "X" flag identifies factors that are eXcluded from these scenarios because we have concluded they would not contribute significantly to estimates of impact, notably radiological risk, within 10^4 a after closure of the reference disposal system. Some of these excluded factors may, however, require consideration for times beyond 10^4 a.

Often these excluded factors can be examined on an individual basis without taking into account interactions (or coupling) with other unrelated factors of the disposal system. In other cases, more quantitative arguments are used. For each such factor, we outline in Appendix B the reasons for its exclusion. More details are provided in research documents that provide underlying support for the models used in the postclosure assessment (Davis et al. 1993, Davison et al. 1994a, Goodwin et al. 1994, Johnson et al. 1994a) and in related documents describing other facets of the concept for the disposal of Canada's nuclear fuel waste (AECL 1994a,b; Davison et al. 1994b; Greber et al. 1994; Grondin et al. 1994; Johnson et al. 1994b; Simmons and Baumgartner 1994). Types and examples of the arguments used to exclude factors from the central and alternative scenarios are as follows.

- A factor is outside the mandate of this application of scenario analysis, which is focussed on the postclosure assessment of the reference disposal system. The reference disposal system represents a hypothetical implementation of the concept for disposal of Canada's nuclear fuel waste, but some specific design and siting choices have been assumed. Thus the group excluded factors that do <u>not</u> apply to nuclear fuel waste from CANDU™ nuclear power reactors, disposal sites in crystalline rock of the Canadian Shield, or titanium containers. Similarly, the group excluded the factor for incomplete closure of the vault, because the scope of the postclosure assessment assumes all shafts, tunnels and rooms have been sealed according to design specifications.

  Still another factor was excluded through a modification to the design of the titanium containers assumed for the reference disposal system. This factor, relating to formation and transport of gases and gas-induced transport is not yet well understood. However, studies by Johnson et al. (1994a) have shown that a gas phase could not occur for at least 2×10^4 a in the vault, provided the container design precludes the use of internal iron supports that could corrode to produce hydrogen gas. This design change has since been adopted as part of the design of the container in the reference disposal system (Johnson et al. 1994a, Goodwin et al. 1994). Thus formation and transport of gases is of no concern for times up to 10^4 a after closure of the reference disposal system, although there is a need to consider possible effects for times beyond 10^4 a.

- A factor is inconsistent with the need to estimate impacts on members of the critical group.

  The critical group is "the group of people that is assumed to be located at a time and place where the risks are likely to be the

greatest, irrespective of national boundaries" (AECB 1987a). We believe the critical group should have the characteristics of a succession of rural communities that live in the vicinity of potential discharges from the reference disposal vault (Zach and Sheppard, 1992, Davis et al. 1993). Thus we exclude properties pertaining to an urban group, and instead we consider the properties that would pertain to a rural community, including their sources of food, diet, house location and leisure activities.

We also consider impacts on individuals of the critical group and not collective impacts to a population. This last consideration follows from the Canadian regulatory requirements (AECB 1987a) and is in concord with international opinion: "Individual dose or risk limits were generally regarded as more appropriate for determination of the long-term acceptability of high-level waste disposal practices than collective dose or risk limits, which should be used mainly as a comparison tool for discussion of vault design alternatives" (NEA 1991).

- A factor would make an insignificant contribution to estimates of impact when compared with Canadian regulatory standards, criteria and guidelines, notably those from the AECB (AECB 1985, 1987a, 1987b). One important criterion for the postclosure assessment is that "the predicted radiological risk to individuals from a waste disposal facility shall not exceed 10^{-6} fatal cancers and serious genetic effects in a year, calculated without taking advantage of long-term institutional controls as a safety feature. . . . risk is defined as the probability that a fatal cancer or serious genetic effect will occur to an individual or his or her descendants. . . . a risk of 10^{-6} in a year is the risk associated with a dose of 0.05 mSv in a year. Individual doses of 0.05 mSv in a year are a small fraction . . . of the annual dose received by the general population in Canada from natural background radiation. . ." (AECB 1987a).

Thus a factor was excluded if scenarios involving that factor would have a very small probability of occurrence, or a very small health impact, or both. The group assumed that a factor could be excluded if its maximum contribution to radiological risk could never exceed 10^{-8} fatal cancers and serious genetic effects in any estimates of impact involving that factor. Since the maximum health impact is unity (that is, an individual in the critical group does sustain a fatal cancer or serious genetic effect), a factor has been excluded if its probability of occurrence is less than 10^{-8}, or if its annual probability of occurrence is less than 10^{-8} per year. Similarly, since the maximum probability of occurrence is unity, a factor has been excluded if its estimated impact is less than 10^{-8} fatal cancers and serious genetic effects per year.

Two examples of factors excluded for the above reason are meteorite impact and the formation of faults due to earthquakes.

Impacts from meteorites large enough to cause significant damage to the reference disposal system have a very small probability of occurrence, of the order of 10^{-11} events per year (Merrett and Gillespie 1983, Goodwin et al. 1994). For the reference disposal system, we believe the probabilities of formation of new faults, of extension of existing faults, and of damage to the vault and its contents, are less than 10^{-8}/a for at least the next 10^4 a (Davison et al. 1994a, Goodwin et al. 1994).

- A factor would not have occurred to any appreciable extent over the period of time required for quantitative estimates of impact, the first 10^4 a following closure of a disposal vault (AECB 1987a).

  Thus we have excluded factors such as metamorphic activity and very slow geochemical reactions because they would not occur to any appreciable extent within 10^4 a. We have also excluded glaciation, because the next onset of a major glacial episode is expected about 2×10^4 a or more from the present (Eronen and Olander 1990, Davis et al. 1993). Note, however, that the effects of glaciation should be included in the qualitative assessment of impacts for times beyond 10^4 a.

- A factor need not be considered quantitatively because it would not significantly affect the performance of the disposal system, or its omission would lead to overestimates of impact.

  Examples of two factors that have been excluded for these reasons are erosion of the land surface and reflooding of the disposal vault. Erosion of exposed rock on the Canadian Shield (from the action of wind and water) is expected to be small and to have insignificant effects on the performance of the geosphere, because the rock is generally strong and cohesive and because the topography has low relief and poor drainage (Davison et al. 1994a). The time for reflooding of the vault and saturation of its contents might vary from several years to 1000 years (Johnson et al. 1994a). However, this time is not taken into consideration, and thus it is effectively assumed that the containers contact groundwater, and begin corroding, at the time of vault closure. This leads to earlier container failures and earlier release of nuclear fuel waste.

4.4 CONSTRUCTING SCENARIOS

This step builds up a complete set of scenarios from combinations of factors that have passed the screening step.

We first constructed the "central scenarios". We concluded that all but two of the important factors passed from step 3 could be incorporated into the central scenarios. This was made possible because the postclosure assessment uses a probabilistic systems assessment methodology to analyze the central scenarios. These scenarios are contained within the Canadian Concept generation 3 (CC3) system model used with SYVAC3, and the CC3 model

has evolved and grown to accommodate more and more factors. (The central scenarios are referred to in the postclosure assessment (Goodwin et al. 1994) as the SYVAC scenarios because they are evaluated using SYVAC3.)

Probabilistic systems assessment involves the analysis of results from thousands of simulations in which parameter values are randomly sampled from their specified probability density functions, and was developed to take into account the effects of parameter uncertainty (including parameter variability). In many instances, we can define "switch" parameters for the CC3 system model that effectively describe uncertainty in the future behaviour of a disposal system. For example, the postclosure assessment uses a well-usage parameter that determines, for each simulation, whether a well or a lake serves as the source of drinking water for the critical group. We assume that these two options are the only choices and that they are mutually exclusive. Thus if the probability of use of well water is p_w, then the probability of use of lake water is $(1-p_w)$, and we use this information to define a probability density function for the well-usage parameter (Davis et al. 1993). We then use SYVAC3 to perform a large number of simulations using random sampling of parameter values. In 1000 such simulations, the well would be selected as the source of drinking water about $p_w \times 1000$ times and the lake would be selected in all other simulations. This mix of simulations is analyzed to evaluate impacts, such as the annual dose and radiological risk to individuals in the critical group (Goodwin et al. 1994).

Other examples of switch parameters describe the possibility that lake sediments are used as soil for the garden of the critical group, the possibility that the garden is irrigated (and whether the water is from the well or the lake), the possibility that the forage field used by domestic and wild animals is irrigated, the possibility that the critical group uses wood or peat as a source of household heat and the possibility that the rate of water withdrawal from a well affects groundwater flow pathways and hydraulic heads at depth in the rock of the geosphere (Goodwin et al. 1994).

Each mutually exclusive option selected by a switch parameter may be regarded as a scenario. For example, a large number of randomly sampled simulations using the CC3 system model will contain cases where the critical group uses the well as their source of domestic water and cases where the group uses the lake; these cases may be regarded as "well" and "lake" scenarios. Sensitivity analyses described in the postclosure assessment can determine whether either or both of these scenarios are important, either separately or in combination with other switch parameters (Goodwin et al. 1994).

The CC3 system model has also evolved to embrace other potential scenarios. For example, an interim study suggested that there was a need to consider two situations involving the well: one in which there would be modest rates of water withdrawal and a second in which the rates of water withdrawal would be large enough to perturb substantially existing groundwater flow patterns. Modest rates of water withdrawal were described within an interim version of the CC3 system model, and it was envisioned that another model would be required for the "high-demand well" scenarios. Subsequent

research studies of the reference disposal system indicated that significant perturbations would occur for well demands of the order of 10^4 m^3/a (Reid and Chan 1988, Reid et al. 1989, Davison et al. 1994a). An additional study then examined the hydrogeological effects of drawing these larger volumes of groundwater from a water supply well in the Whiteshell Research Area (Chan et al. 1991) and concluded that the hydrogeological effects of pumping a water supply well at rates exceeding 10^4 m^3/a could be simulated by incorporating some relatively minor changes into the interim CC3 system model (Chan and Nakka 1992). That is, a single system model could be used to encompass the high-demand well scenarios within the central scenarios (this conclusion pertains specifically to the reference disposal system). Consequently, the central scenarios and the associated CC3 system model were expanded to include the factor describing a high-demand well.

The central scenarios describe the expected behaviour of the reference disposal system and contain all but two of the factors passed from step 3. The two residual factors, open boreholes and human intrusion, describe unlikely possibilities for the reference disposal system. Human intrusion can also be associated with a more general class of "disruptive" factors that could significantly disrupt the expected performance and integrity of the reference disposal system. Other disruptive factors include meteorite impacts and earthquakes, but only human intrusion remained after the screening step.

The two residual factors are used to construct the three (2^r-1) alternative scenarios.

- The open borehole factor (Appendix B, Table B-2) accounts for an unlikely situation in which a borehole remains open after closure of the reference disposal system. It is assumed the open borehole passes near the disposal vault from the surface environment. The <u>open-borehole scenarios</u> contain all factors in the central scenarios plus the presence of one or more open boreholes that could affect groundwater flow fields and contaminant transport in the geosphere and vault.

- The human intrusion factor is complex, with many different aspects (see, for example, "Intrusion (human)" and "Sabotage and improper operation" in Table B-1; "Intrusion (mines)", "Wells" and "Wells (high-demand)" in Table B-2; and "Intrusion (deliberate)" and "Intrusion (inadvertent)" in Table B-3 of Appendix B). Some aspects are included in the central scenarios, such as the possible use by the critical group of a water-supply well that is drilled into the geosphere near the reference disposal vault (Davison et al. 1994a, Davis et al. 1993, Goodwin et al. 1994). Other aspects are considered to be outside the scope of the postclosure assessment; for example, we exclude deliberate intrusion to recover the materials in the vault, assuming that a society desiring these materials would be aware of and capable of dealing with the hazards involved. It was concluded, however, that there was a need to consider an unlikely situation, called the <u>inadvertent human intrusion scenarios</u>. They involve actions that are unintentional, or inadvertent, in the sense that they

are carried out without knowledge of the presence of a disposal vault and its potential hazards.

- The combined scenarios have the characteristics of both the open-borehole and inadvertent human intrusion scenarios.

4.5 SCREENING SCENARIOS

This activity identifies which of the constructed scenarios should be quantitatively evaluated in the postclosure assessment. It is desirable to have a small number of such scenarios. This screening step played an important role in interim scenario analyses and led, for example, to the inclusion of the high-demand well within the central scenarios.

The four scenarios constructed in Section 4.4 are the central, open-borehole, inadvertent human intrusion and combined scenarios. We concluded that only the combined scenarios do not require further consideration in the postclosure assessment, because it deals with two independent events, each of which has a small probability of occurrence. The joint probability of occurrence of two or more independent events is given by the product of their individual probabilities and is even smaller; we believe the probability of occurrence of the combined scenario would be much smaller than 10^{-8} and thus its estimated impact would be less than 10^{-8} fatal cancers and serious genetic effects per year for times up to and beyond 10^4 a.

4.6 SCENARIO DEFINITION

This final step provides information to the assessment analysts; it defines the concerns that led to identification of each scenario, details of the processes to be modelled, the timing of events, and other important conditions. The information includes an estimate of a probability of occurrence for each scenario that must be evaluated in detail or an acceptable strategy for dealing with all scenarios.

The broad characteristics of the central, open-borehole and inadvertent human intrusion scenarios are described below. Appendix B contains a brief description of the factors pertaining to these scenarios. More detailed discussions of these factors are contained in the documentation of the vault model (Johnson et al. 1994a), the geosphere model (Davison et al. 1994a), the biosphere model (Davis et al. 1993) and the postclosure assessment (Goodwin et al. 1994). Wuschke (1991, 1992) provides further discussion on inadvertent human intrusion.

4.6.1 The Central Scenarios

The central scenarios contain most of the factors listed in Tables B-1 to B-3 of Appendix B and are focussed on groundwater-mediated processes affecting the performance of the reference disposal system. We assume that groundwater in the rock surrounding the disposal vault saturates the buffer and contributes to the corrosion of the titanium containers. Upon failure of the containers, contaminants are released into the groundwater. The

contaminants are then transported by diffusion and advection in groundwater through the engineered and natural barriers to the surface environment. Specific pathways to the surface include fracture zones and a water-supply well that could intercept the contaminated groundwater, including a high-demand well that might substantially alter existing groundwater flow patterns. Potential discharge points on the surface environment are low-lying areas such as bogs and lakes. Once in the surface environment, the contaminants could potentially cause radiological or chemical toxicity effects if they were to come in contact with people or other organisms at sufficiently high concentrations. Exposure pathways include ingestion and inhalation. Other important factors involve the properties of the critical group.

More details of the CC3 system model, used to represent the central scenarios, are provided in documentation for the vault model (Johnson et al. 1994a), the geosphere model (Davison et al. 1994a), the biosphere model (Davis et al. 1993) and the postclosure assessment (Goodwin et al. 1994).

Since the central scenarios contain most of the important factors (and exclude only two unlikely factors), we assume their collective probability of occurrence is unity in the calculation of risk.

4.6.2 The Open-Borehole Scenarios

The open-borehole scenarios have the same factors as the central scenarios with the addition of a factor accounting for the possibility that an open borehole may remain near the reference disposal vault after closure of the vault.

Open boreholes could affect the performance of the disposal concept by changing groundwater flow fields and by providing additional or altered pathways along which contaminants could flow. Chan and Stanchell (1992) used a detailed hydrogeological model of the reference disposal system to simulate the effect of open boreholes on the groundwater flow fields. Their results showed that the transport of contaminants from the vault can be significantly changed if an open borehole passes close to a vault room containing nuclear waste, and that the effects are greater when a nearby water-supply well is being pumped.

One important characteristic of these scenarios, therefore, is the location of the borehole relative to the reference disposal vault. We assume that the borehole extends downwards from the surface and reaches the depth of the reference disposal vault and that it remains open at the time of vault closure. We further assume that the location of the borehole at the surface is not known, and hence it is not used as a water-supply well, although it may affect and be affected by nearby water-supply wells. Finally, we assume that the borehole was drilled before closure of the vault; boreholes drilled after closure are considered to be part of the inadvertent human intrusion scenarios.

We were unable to identify suitable precedents in the literature that would permit a quantitative estimate of the probability of occurrence of the open-borehole scenarios. We expect the probability is very small because

decommissioning plans for the disposal facility include the permanent sealing of all boreholes. Thus the probability of occurrence of an open borehole would be strongly dependent on quality assurance measures followed during implementation of a disposal facility. Moreover, any potential impacts would be dependent on factors such as the properties of the geosphere that would affect the distance between an open borehole and the disposal vault where impacts would be significant.

The recommended treatment of the open-borehole scenarios in the postclosure assessment of the reference disposal system involves an evaluation of the expected effectiveness of three quality assurance measures that we believe would result in a very small probability that any borehole would remain open after closure of the vault. These measures would involve procedures to

- ensure that all boreholes are properly sealed,
- locate the vault such that rooms containing nuclear waste are isolated by some minimum acceptable distance from all deep boreholes, and
- confirm that there are no open boreholes near any vault rooms containing nuclear fuel waste.

We believe that these three redundant quality assurance procedures would provide a high degree of confidence that no boreholes would remain open at the time of vault closure that could have a significant effect on the performance or safety of the reference disposal system.

4.6.3 The Inadvertent Human Intrusion Scenarios

The inadvertent human intrusion scenarios describe activities involving drilling, mining and related actions that might be carried out in the vicinity of the reference disposal vault and that occur after closure of the disposal facility. It is assumed that the intruder is not aware of the presence of the disposal vault and its potential hazards.

There are a wide range of possibilities for these scenarios; the tables in Appendix B describe variants such as "Sabotage and improper operation" and "Intrusion (deliberate)". For the postclosure assessment of the reference disposal system, we recommend that the human intrusion scenarios should be similar to those studied by Wuschke (1991, 1992) and that are

> . . . considered likely to present the highest risk to the intruder, i.e., those likely to have the highest product of probability and consequence. Each scenario selected is generally representative of a set of similar scenarios with lower probability or consequence. All of the scenarios analyzed would be initiated by a drilling operation that penetrates the waste and brings it to the surface. (Wuschke 1991).

Wuschke (1991, 1992) has classified inadvertent human intrusion into five categories:

- exposure to undispersed waste,
- exposure to waste dispersed by previous intrusions,
- human-induced alteration of the expected evolution of the disposal system,
- contact with a contaminated groundwater plume, and
- contact with materials contaminated by the groundwater plume.

The first two categories are of concern for the inadvertent human intrusion scenarios, whereas the last three categories are considered to be part of the central scenarios.

Wuschke (1991, 1992) evaluated four inadvertent human intrusion scenarios that begin with the same initiating event: it is assumed a drilling operation, started after closure of a nuclear waste disposal facility, leads to the direct removal of waste from a disposal vault and dispersion of this waste in the biosphere. The main differences between the four scenarios pertain to the characteristics of the humans most at risk. Two scenarios involve exposure to undispersed waste and evaluate the radiation dose that would be received by a member of the drilling crew and by a laboratory technician who prepares and examines the drill core. The other two scenarios assume the extracted waste from a drilling operation is dispersed and left on the drilling site, and evaluate the radiation dose to a construction worker who works at the site and to a resident who lives in a house built on the drilling waste.

These four human intrusion scenarios should be examined in the postclosure assessment of the reference disposal system. Wuschke (1991, 1992) provides more details on the characteristics of these scenarios.

The probabilities of occurrence of the inadvertent human intrusion scenarios are also based on the studies reported by Wuschke (1991, 1992). These probabilities were estimated using an event-tree methodology, and are zero at the time of closure of the vault and slowly increase thereafter. For times up to 10^4 a, the maximum probabilities are less than 5×10^{-6} (Wuschke 1991, 1992).

5. SUMMARY

A scenario analysis procedure has been developed to guide the postclosure assessment of the concept for disposal of Canada's nuclear fuel waste. It was then applied to a hypothetical disposal system that conforms to the reference disposal system evaluated in the postclosure assessment. The objectives of the application are

- to identify all factors that could affect the performance of the hypothetical reference disposal system; and

- to provide a framework to evaluate the importance of each factor.

The procedure identified approximately 150 broadly defined factors that could have important effects on the performance of the disposal system. These factors appear in three scenarios requiring quantitative evaluation in the postclosure assessment.

- The central scenarios contain most of the factors and have been assigned a probability of occurrence of unity. These scenarios describe the expected behaviour of the reference disposal system, and their potential impacts and contributions to radiological risk should be evaluated in the postclosure assessment.

- The open-borehole scenarios are similar to the central scenarios, except they include an unlikely factor in which an open borehole passes near the vault from the surface environment. These scenarios should also be considered in the postclosure assessment, to evaluate the effectiveness of quality assurance measures.

- The inadvertent human intrusion scenarios describe an unlikely situation involving the direct removal of waste from the reference disposal vault. It is assumed these scenarios are initiated by a drilling operation that occurs after closure of the reference disposal facility. Their probabilities of occurrence are small, less than 5×10^{-6} for all times up to 10^4 a, but their potential impacts and contributions to radiological risk should be evaluated in the postclosure assessment. The individuals most at risk are somewhat different for the inadvertent human intrusion and central scenarios.

Many other factors and possible scenarios do not require quantitative evaluation in the postclosure assessment of the hypothetical reference disposal system because they would lead to small or insignificant impacts and small or insignificant contributions to radiological risk.

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* Internal report available from SDDO, AECL Research, Chalk River Laboratories, Chalk River, ON, K0J 1J0.

APPENDIX A

COMPOSITION OF THE EXPERT GROUP FOR SCENARIO ANALYSIS

A large number of people contributed to the identification of factors for the postclosure assessment, including technical experts from within AECL and other research organizations and less technical persons from the general public. The following list identifies the AECL experts who attended one or more of the meetings organized to identify, critically review and screen the factors, describes their academic disciplines and indicates some of their research expertise for the Canadian Nuclear Fuel Waste Management Program.

Member	Academic Discipline	Research Expertise
B.D. Amiro	physics	atmosphere modelling
G. Bird	biology, limnology	surface water modelling
A. Brown	geology	regional geological studies
P.A. Davis	physics	atmosphere modelling
C.C. Davison	hydrogeology	geoscience, WRA characterization
N.C. Garisto	theoretical chemistry	vault chemistry
M. Gascoyne	geochemistry	groundwater chemistry
B.W. Goodwin	physical science	environmental assessment
M.N. Gray	civil engineering	buffer and seals performance
L.H. Johnson	physical chemistry	used fuel dissolution
D.M. LeNeveu	physical science	environmental assessment
T.W. Melnyk	physical science	environmental assessment
M.I. Sheppard	soil chemistry	soil modelling
S.C. Sheppard	soil science	food chain modelling
M.E. Stephens	chemistry and physics	environmental assessment
M. Stephenson	zoology	limnology
J.C. Tait	physical science	contaminant inventory
S.H. Whitaker	geoscience	long-term reasoned arguments
R. Zach	animal ecology	food chain modelling

APPENDIX B

RESULTS OF AN APPLICATION OF THE SCENARIO ANALYSIS PROCEDURE

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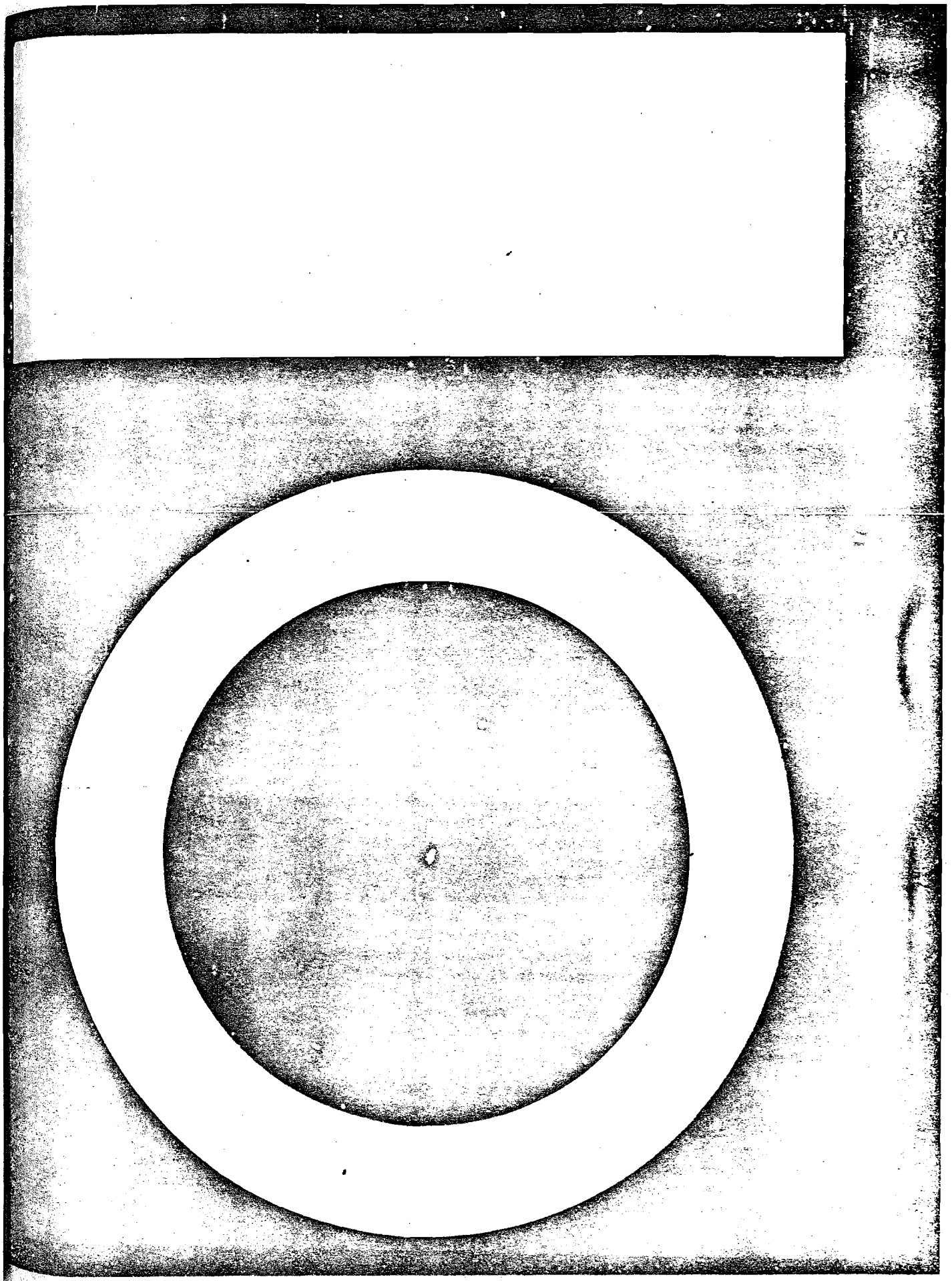

APPENDIX B

RESULTS OF AN APPLICATI[illegible]N OF THE SCENARIO ANALYSIS PROCEDURE

The following tables summarize the results of a scenario analysis applied to the hypothetical reference disposal system for disposal of Canada's nuclear fuel waste.

More than 1000 factors were identified during steps 1 and 2 of the scenario analysis procedure. The number of such factors has been reduced by combining some under more general factor headings. For example, the "human diet" factor includes many different types of food that may be consumed by members of the critical group. We have also eliminated some spurious and redundant factors, and factors that are not credible or relevant to the application.

The factors are sorted into three lists, depending on whether they affect mostly elements of the vault (Table B-1), the geosphere (Table B-2) or the biosphere (Table B-3) of the reference disposal system. A brief statement is provided with each factor, outlining its characteristics and properties that are of concern. Some factors (such as glaciation and climate change) appear in more than one of the tables if they could have different types or degrees of effect on the vault, geosphere and biosphere.

The three tables provide other classification schemes:

- **F/E/P** denotes whether the factor is best described as a **F**eature, an **E**vent or a **P**rocess.

- **Comp**(onent) describes which components of the vault, geosphere or biosphere are affected by the factor. For the vault, the components are **B**ackfill and buffer, **C**ontainer, **S**eals and grouts, and **W**aste matrix. For the geosphere, they are **F**low, **T**ransport and **W**aste. For the biosphere, the components are route to man (**C**ontact, **I**ngestion and **R**espiration) and cause or source of the factor (**A**nthropogenic, **F**acility and **N**atural).

- **Mech**(anism) gives other details on the nature of the factors. For the vault and biosphere, the mechanisms considered are **C**hemical, **P**hysical and **B**iological. For the geosphere, they are **A**nthropogenic, **E**xpected (natural), **U**nexpected (natural) and induced by the presence of the disposal **V**ault.

The second last column, entitled "**Treat**(ment)", indicates how the factor should be treated in the postclosure assessment of the reference disposal system. A factor may be

- quantitatively evaluated in the **C**entral scenarios and/or in one of the alternative scenarios - the **O**pen-borehole scenarios or the **I**nadvertent human intrusion scenarios; or

- e**X**cluded from further evaluation in these scenarios. For these factors, a statement (in square brackets) outlines the rationale for exclusion.

In many instances, some aspects of a factor may require evaluation in the central and/or alternative scenarios, whereas other aspects may be excluded. In general, a factor that is included in the central scenarios also appears in the alternative scenarios. The central scenarios are so named because they describe the expected behaviour of the disposal system and exclude only two unlikely factors. The names of the two alternative scenarios are chosen to describe its distinguishing factor(s).

The last column indicates references where more detail on each factor may be found.

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TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

term physical stability and Seal evolution. Related discussion is provided under Groundwater composition and Groundwater - evolution in the list of geosphere factors.]

Biological activity	P	BCSW	B	CX	V

Biological activity (microorganisms, bacteria) could change the physical and chemical environment in the vault, affecting the corrosion of containers, mineralogy of the clay in the buffer and backfill, generation or stability of colloids, mobility of contaminants, selective release of specific contaminants, and the porosity and conductivity of the buffer, backfill, seals and rock. Bacteria and microbes may also chemically transform contaminants and thereby change their mobility in the environment (Loewen and Flett 1984).

[Microbial activity is likely to be present, although it would be limited by the low nutrient supply, elevated temperatures and presence of radiation fields (Stroes-Gascoyne and West 1994). It is anticipated that the effects of such biological processes could be adequately addressed through the use of conservative assumptions used to define the various submodels and parameter distributions in the vault. This is the case, for example, in the calculations of solubility limits (Johnson et al. 1994) and for the case of crevice corrosion of titanium, which is assumed to occur on all containers and may occur under a biofilm or any other crevice former. We have therefore assumed that no further evaluation is warranted for the postclosure assessment, although additional research effort may be indicated. See also Complexation by organics, Methylation and Mutation. Further discussion is provided under Complexation by organics, Methane and Microbes in the list of geosphere factors (Table B-2), and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table B-3).]

Boundary conditions	P	BCSW	P	C	V

Processes occurring at the boundaries or interfaces between the waste matrices, container, buffer, backfill and rock may be important. The boundary conditions should account for complex geometries, microstructures, and time-dependent changes.

Buffer additives	F	BCSW	BCP	CX	V

Additives may be put in the vault to enhance performance; for example stable iodine may be added to the used fuel waste matrix and ferrous iron may be placed in the buffer.

[It is clear that any such additives must be considered in the postclosure assessment, particularly where such additives would

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

affect the performance of the disposal vault or the overall disposal system. Magnetite, a redox additive, is assumed to be added to the glass bead particulate in the container in small quantities in order to consume residual oxygen upon container failure. No other additives are currently included in the reference disposal system. See also Backfill characteristics, Buffer characteristics, and Sabotage and improper operation.]

Buffer characteristics P SB CP C V

The movement of water and contaminants would be affected by properties of the buffer, such as porosity, tortuosity, hydraulic conductivity, temperature gradients, swelling pressure and sorption.

Buffer evolution P B CP X V

The properties of the buffer could evolve with time in the high-temperature environment of the vault as a result of processes such as silica cementation and alteration of bentonite to kaolinite or illite. These changes would then affect the movement of water and contaminants in the buffer.

[Evolution of the buffer would be enhanced by several processes, such as elevated temperatures, and by high concentrations of the potassium cation, K^+, relative to other cations. The vault design is such that the maximum temperature would be less than 100°C (Baumgartner et al. 1993,1994). Also the ratio of K^+ to other cations is relatively small in deep groundwaters of the Canadian Shield (Gascoyne 1988; Gascoyne and Kamineni 1992). Under these conditions, chemical and physical changes are expected to be extremely slow; for example, there would be no appreciable conversion of bentonite clay (a smectite) to illite within 10^4 a. We have therefore excluded evolution of the buffer from any scenarios requiring quantitative evaluation in the postclosure assessment, although there may be a need to consider the possible effects over longer time scales. See also Backfill evolution, Buffer characteristics, Hydrothermal alteration, Long-term physical stability and Seal evolution. Related discussion is provided under Groundwater composition and Groundwater - evolution in the list of geosphere factors (Table B-2).]

Cave-ins E BCW P X EV

Cave-ins and stress-induced fracturing of rock may occur, changing the characteristics of the buffer and backfill. These events could affect the movement of groundwater and contaminants in the vault, and damage the containers and seals.

[The design of the vault takes such events into consideration (Baumgartner et al. 1993, 1994; Simmons and Baumgartner 1994). It

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

is expected that the chemical and physical properties of the buffer and backfill would remain unchanged for long periods of time. For example, the buffer and backfill materials would exert pressure against the rock and limit rock movement. This pressure would continue even after the vault resaturated, because of the swelling capacity of bentonite clay used in the buffer and backfill; thus, the rate of movement of groundwater and contaminants would be unaffected and it is expected that there would be no significant rock movement and no damage to the containers and seals. We have therefore assumed that no further quantitative evaluation is required for the postclosure assessment, although there may be a need to consider the possible effects over longer time scales. See also Backfill characteristics, Backfill evolution, Buffer characteristics, Buffer evolution, Hydrothermal alteration, Long-term physical stability and Seal evolution. Related discussion is provided under Damaged zone in the list of geosphere factors.]

Chemical gradients	P	BCSW	C	CX	V

Migration of salts and dissolved contaminants may be enhanced near the container, due to the formation of chemical concentration gradients. Such gradients could arise from temperature changes, radiolysis (changing local redox conditions) and ingress of saline groundwater. Possible effects include altered dissolution rates of the waste matrices and dissolution and precipitation of chemical compounds, with subsequent opening or plugging of pores.

[It is expected that only dissolution of the waste matrices and radiolysis have the potential to cause significant changes; these processes are discussed further under Precipitation and dissolution, Source terms (expected) and Radiolysis. Other processes forming chemical gradients are expected to be unimportant because they would not occur to any appreciable extent or because they would not have any substantial effects. Thermal gradients are expected to be relatively small; for example, after 100 a the maximum temperature change would be less than 10°C over a distance of 10 m (Johnson et al. 1994). This gradient is not large, and is not expected to lead to substantial concentration gradients. It is also expected that saline groundwaters may be pervasive in and near the vault, but that no chemical reactions would occur that would lead to significant concentration gradients. Although the effects of groundwater composition and temperature should be accounted for in the modelling of the vault, we do not expect that these factors will lead to concentration gradients that would significantly alter dissolution of the waste matrices or dissolution and precipitation of chemical compounds. We have therefore assumed that further consideration is not warranted in the postclosure assessment. See also Backfill evolution, Buffer evolution, Chemical interactions, Chemical kinetics, Complexation by

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

organics, Container corrosion products, Coupled processes, Galvanic coupling, Hydrothermal alteration, Long-term physical stability, Precipitation and dissolution, Radiolysis, Seal evolution, and Speciation. Related discussion is provided under Groundwater - evolution, Precipitation and dissolution and Speciation in the list of geosphere factors (Table B-2).]

Chemical interactions P BCSW C CX V

Chemical interactions at high temperature and pressure may affect corrosion of the container, dissolution of the waste matrices, sorption of contaminants, alteration of the buffer, backfill and seals, and formation of gases.

[All important chemical interactions must be quantitatively evaluated in the postclosure assessment. There are, however, many chemical interactions that are known to be insignificant, and that do not warrant further evaluation. For example, the pressures in the vault would be relatively low, temperatures would be limited to 100°C (Baumgartner et al. 1993, 1994) and no high concentrations of reactive chemical species are found in the surrounding groundwater (Gascoyne and Kamineni 1992). Under these conditions, the chemical alteration of bentonite clay would not occur to any appreciable extent for more than 10^4 a. See also Backfill evolution, Buffer evolution, Chemical gradients, Chemical kinetics, Complexation by organics, Container corrosion products, Coupled processes, Galvanic coupling, Hydrothermal alteration, Long-term physical stability, Precipitation and dissolution, Radiolysis, Seal evolution, and Speciation. Related discussion is provided under Groundwater composition, Groundwater - evolution and Speciation in the list of geosphere factors (Table B-2).]

Chemical kinetics P BCSW C CX V

Chemical kinetics could be important and could cause effects such as poorly poised Eh due to the slow alterations between magnetite and hematite, or concentrations of uranium and zirconium that are less than their solubility limits.

[Evidence exists that redox equilibration can occur at depth in the Canadian Shield, even at temperatures of 15 to 20°C for the redox couples of interest (Gascoyne and Kamineni 1992). For example, conditions in the Cigar Lake ore body are strongly reducing because of the presence of ferrous and sulphide minerals, consistent with the observed oxidation state of the uraninite ore (Sunder et al. 1988). We have assumed that effects attributable to chemical kinetics are either not important or can be implicitly included in the models, and that further quantitative evaluation for the postclosure assessment is not warranted. See also

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Backfill evolution, Buffer evolution, Chemical interactions, Chemical kinetics, Hydrothermal alteration, and Seal evolution.]					
Climate change	E	BCSW	BCP	X	-
Changes to the current climate may affect the performance of the vault. For example, increased or decreased rates of meteoric precipitation may affect the volume and rate of groundwater flow past the disposal vault.					
[This factor is considered with the discussion on Global effects. Further discussion is provided under Climate change in the lists of geosphere and biosphere factors (Tables B.2 and B.3).]					
Colloids	P	BCSW	BCP	X	V
The expected vault environment, or changes to the vault environment caused by biological activity, chemical processes and physical agitation could promote the generation of colloids or pseudo-colloids, affecting contaminant transport.					
[Colloids are particles of contaminants, whereas psuedo-colloids are naturally occurring particulates (such as clay) that contain sorbed contaminants. It is possible that true colloids may be generated within the container once groundwater enters the failed container. However, studies demonstrate that such colloids cannot migrate through the high-density buffer, which would be very effective in filtering out colloidal particles. We have therefore assumed that there is no need for the further evaluation of the effect of colloids in the vault, but note that further experimental support is desirable. Further discussion on colloids is provided in the lists of geosphere and biosphere factors (Tables B.2 and B.3).].					
Complexation by organics	P	B	C	X	V
The formation of stable complexes with organics found in natural groundwaters, including humates and fulvates, could affect the transport of contaminants.					
[Concentrations of organic material in the vault are expected to be relatively small, and would not affect contaminant transport (Oscarson et al. 1986). Organic material may have an effect on the dissolution of used fuel, and is included with another factor, Stability of UO_2. It is assumed that no further evaluation is warranted for the postclosure assessment. See also Biological activity and Methylation. Related discussion is provided under Complexation by organics, Humic acid, Fulvic acid, Methane and Microbes in the list of geosphere factors (Table B-2), and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table B-3).					

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Concrete	F	BCSW	C	X	V

Large amounts of concrete present in the vault may lead to an altered chemical environment, or an environment that changes with time.

[The major concern with respect to concretes is the creation of an alkaline environment that may affect the stability of clays. This concern can be minimized by using concretes that have very low $Ca(OH)_2$ content, and that would not bring about large or lasting changes to the local chemistry. For example, such concretes would have very limited effects on other sealing materials, such as the bentonite clay in the backfill. Moreover, the concretes and grouts in the vault would not be used in the vicinity of the emplacement boreholes, and thus would have smaller potential effects on the chemical environment near the waste containers. Further research on this factor may be warranted, and may lead to a design specification governing the characteristics of the concrete used in the vault. We have assumed that no further evaluation is required for the postclosure assessment of the reference disposal system.]

Container corrosion products	P	BCSW	CP	X	V

Container corrosion products could affect the vault environment, causing significant changes to sorption, transport, dissolution and long-term stability.

[For the reference disposal system, the corrosion products of concern are titanium oxide from the titanium containers, and zirconium oxide from the Zircaloy fuel sheaths. Both titanium and zirconium oxides are highly insoluble and thus would not effectively compete with most contaminants for sorption sites on the buffer. These corrosion products would also not enhance waste matrix dissolution or long-term stability of the vault buffer, nor would they increase contaminant transport. Conversely, precipitated compounds of titanium and zirconium could reduce buffer porosity (by filling pore spaces), or serve as sorption sites for contaminants, and thereby decrease and delay the transport of contaminants. It is assumed that further evaluation for the postclosure assessment is not warranted.]

Container failure (early)	P	C	CP	C	V

Containers could fail before the expiration of their design lifetime, as a result of welding or material defects, of mishandling and breakage during transport. See also Container failure (long-term), Container failure (mechanical processes), Container healing and Containers - partial corrosion.

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Container failure (long-term)	P	C	CP	C	V

Long-term container failure could be affected by factors that include elemental solubilities, thermal transients (duration and temperature rise) and the presence and concentration of reactants, such as chloride, sulphide, acids and oxidants. Possible failure mechanisms include delayed hydride cracking, uniform corrosion, pitting and crevice corrosion. For the reference disposal system, it is assumed that the container is fabricated from titanium. See also Container failure (early), Container failure (mechanical processes), Container healing, Containers - partial corrosion and Swelling pressure.

Container failure (mechanical processes)	P	C	CP	X	EV

Other long-term container failure processes could be important, such as damage due to hydrostatic pressures or bentonite swelling.

[The design and properties of the titanium container are such that the containers could withstand handling stresses and hydrostatic and buffer swelling loads. These factors are not expected to lead to failure prior to failures caused by corrosion. Therefore, it is assumed that no further evaluation for the postclosure assessment is required. See also Container failure (early), Container failure (long-term), Container healing, Containers - partial corrosion and Swelling pressure.]

Container healing	P	C	C	X	-

Corrosion holes or pits could heal or be plugged by subsequent chemical reactions (with the buffer for example).

[These processes are very difficult to quantify, but the omission of these processes would lead to overestimates of impact. It has been concluded that no further evaluation for the postclosure assessment is required. See also Container failure (early), Container failure (long-term), Container failure (mechanical processes) and Containers - partial corrosion.]

Containers - partial corrosion	P	C	CP	X	V

Containers that have been partially breached may still significantly impede mass transport.

[It is difficult to predict the effects of such processes. However, it is prudent to assume that a container loses all of its effectiveness at the instant it is breached, because omission of these processes would lead to overestimates of impact. We have therefore assumed that partial corrosion can be ignored in the postclosure assessment. See also Container failure (early),

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Container failure (long-term), Container failure (mechanical processes) and Container healing.]					
Convection	P	B	P	C	V
Contaminant transport may occur within the buffer and backfill by convection, that is by transport within flowing water. Convection in the surrounding rock would influence convection within the buffer and backfill, through the effect of boundary conditions. See also Boundary conditions, Diffusion and Dispersion.					
Correlation	P	B	CP	C	V
Model parameters are not always independent; that is, given a value for one parameter, the value for another may be restrained or fixed. For example, different chemical elements would show some degree of correlation in their interactions with the buffer and for their solubility limits, depending on their chemical environment. Some elements of this factor are treated quantitatively in the postclosure assessment, such as the solubility of uranium, thorium, technetium, neptunium and plutonium. Other correlations are included where there is supporting experimental evidence.					
Corrosion	P	C	CP	C	V
Corrosion mechanisms would affect the performance of the containers and lead to their eventual failure. Corrosion may be affected in groundwaters that are highly saline, and in the presence of radiation fields. This factor is discussed elsewhere; see Container failure (long-term), Container corrosion products, Radiation damage, Radiolysis and Recharge groundwater.					
Coupled processes	P	BCW	CP	X	V
Many coupled processes and irreversible thermodynamics may affect contaminant transport in the backfill and buffer. Examples of these processes include density effects due to saline groundwaters, charge gradients, temperature gradients, electrochemical or chemical gradients, electrophoresis, osmosis and the Soret effect (thermal diffusion in liquids).					
[Analysis of the impact of coupled processes on contaminant transport suggests that most are relatively unimportant compared with Fickian diffusion. Processes requiring quantitative treatment are listed separately, such as Chemical interactions and Diffusion. We have assumed that evaluation of other coupled processes is not required for the postclosure assessment. See also Backfill evolution, Biological activity, Boundary conditions, Buffer evolution, Chemical interactions, Chemical kinetics, Complexation by					

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

organics, Container corrosion products, Diffusion, Formation of gases, Galvanic coupling, Hydrothermal alteration, Long-term physical stability, Precipitation and dissolution, Radiolysis, Seal evolution, Speciation and Temperature effects.]

Criticality	E	W	P	X	V

Critical masses of uranium-235 or plutonium-239 or both could be accumulated in the vault, resulting in fission reactions.

[Scoping analyses have suggested that this process is very unlikely to occur (McCamis 1992, Johnson et al. 1994). It requires a series of unlikely steps, starting with selective segregation and accumulation of a fissile radioisotope from the used fuel. Relatively high concentrations and purities are required, as is the presence of an efficient moderator. Any possible fission reaction would be readily poisoned by the presence of impurities, which include non-fissile isotopes. For example, criticality involving the fissile isotope plutonium-239 would require separation of plutonium from all other elements in used fuel, and from other plutonium isotopes such as plutonium-240. No possible mechanisms are expected in the vault environment that would support these separation, accumulation and purification processes.]

Diffusion	P	B	P	C	V

Contaminant movement would occur as a result of diffusion through the water and sealing materials in the vault. Diffusion is temperature dependent. Surface effects may be very important in clays. See also Convection and Coupled processes.

Dispersion	P	B	P	C	V

Dispersion may be important within the buffer and backfill. It would certainly be important in the rock that immediately surrounds the vault, because this rock could strongly influence the mass transfer boundary between the vault and geosphere. See also Boundary conditions and Convection.

Earthquakes	E	BCSW	P	X	EGP

Large earthquakes, vibration from many smaller earthquakes, or related events such as movement of the crust or plate could affect all components of the vault.

[The vibratory effects of earthquakes are expected to have insignificant impacts on the vault and surrounding plutonic rock (Atkinson and McGuire 1993). Moreover, the growth of faults or formation of new faults is expected to have a very low probability of occurrence in stable portions of the Canadian Shield. For

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

example, Merrett and Gillespie (1983) estimate that the frequency of new fault formation at a vault is 1.5×10^{-9}/a. In addition, the siting process would avoid regions where seismic activity is known to be a problem (Davison et al. 1994b). It is therefore assumed that the effect of earthquakes on the vault can be excluded from any scenarios requiring quantitative evaluation in the postclosure assessment. See also Cave-ins, Formation of cracks and Long-term physical stability. Further discussion may also be found under Earthquakes in the lists of factors for the geosphere and biosphere (Tables B.2 and B.3).]

Electrochemical gradients	P	CW	C	X	V

Electrochemical gradients may be set up between distant ore bodies and material in the vault, or between different materials in the vault. These gradients may affect the rate of corrosion of the containers and the rate of dissolution of the waste matrices.

[This factor is discussed under Chemical gradients, Container failure (long-term), Galvanic coupling and Stability of UO_2. See also Radiolysis.]

Excessive hydrostatic pressures	P	BCS	P	X	-

Excessive hydrostatic pressures might arise from the plugging of inlets to or outlets from the vault system, coupled with temperature increases.

[The design of the disposal vault is such that the maximum temperatures would be less than 100°C (Baumgartner et al. 1993, 1994). These temperatures are insufficient to cause pressure increases significantly greater than those normally expected at the 500-m depth. It is also expected that the plugging of inlets or outlets would not substantially affect hydrostatic pressures in the vault. It is assumed that no further evaluation for the postclosure assessment is warranted.]

Explosions	E	BCSW	BCP	X	-

Explosions within the vault, and bomb blasts at the surface, could affect the performance of the vault.

[This factor is discussed under Sabotage and improper operation. Related discussion is provided under Blasting and vibration, Bomb blast, Meteorite and Sabotage in the list of geosphere factors.]

Faulty buffer emplacement	P	F	P	X	EV

Voids or spaces might be created in the buffer during its emplacement in the borehole. These voids would reduce the effectiveness

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

of the buffer. The container might not be located in the centre of the borehole.

[The buffer emplacement method involves in situ compaction, which is designed to achieve very high densities of buffer, and would preclude the creation of significant voids or gaps. We have assumed that adequate quality assurance measures would ensure the correct emplacement of the buffer and container, and therefore that no further quantitative evaluation is required for the post-closure assessment.]

Formation of cracks F BS P CX V

Cracks and faults could form or exist within or near the vault, affecting the performance of seals, grouts and the buffer. Cracks may form as a result of failed seals, damage to the nearby rock (the "damaged" zone), cave-ins, faulty buffer materials, and voids in the buffer and backfill (including voids along the top of a drift and voids resulting from human error in emplacement).

[This group of related factors was examined in detail by the Vault Model Working Group. It was concluded that some elements must be treated quantitatively, whereas other may be treated qualitatively. For example,

- cracks near the vault (such as the damaged zone) should be treated quantitatively in modelling the geosphere and geosphere-vault boundary; whereas
- cracks in the sealing materials do not require quantitative evaluation because they would not persist for any significant period of time. The swelling bentonite clay would close any open voids when vault resaturation occurred.

Other elements of this feature are discussed elsewhere. See Backfill characteristics, Boundary conditions, Buffer characteristics, Earthquakes, Faulty buffer emplacement, Long-term physical stability, Percolation in shafts and Seal failure.]

Formation of gases P BCS CP X V

Chemical reactions such as radiolysis and corrosion of iron may lead to the formation of gases, such as hydrogen, oxygen and hydrogen sulphide. Gas pressure could act as a driving force to expel contaminated water from the vault or to prevent the ingress of water.

[We assume that carbon steel, which could be a significant source of hydrogen gas upon corrosion, is not used in the reference disposal vault. Under these conditions, scoping calculations have shown that the hydrogen produced by radiolysis of water and the general (uniform) corrosion of Zircaloy and titanium would not lead to gas phase formation in the disposal vault until after

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

approximately 2 x 10^4 a. The effects of such gas phase formation on contaminant migration in the vault are therefore not included quantitatively in the postclosure assessment, although there may be a need to consider effects over longer time scales. Another concern is the production of methane due to microbial degradation of organic matter in the backfill. We have assumed that no further evaluation is warranted for the postclosure assessment, although additional research studies are indicated. See also Methylation and Microbes. Related information is provided under Complexation by organics, Methane and Microbes in the list of geosphere factors (Table B-2).]

Galvanic coupling	P	CW	C	X	V

Electrical or electrochemical gradients could result in galvanic coupling with a far ore body, and enhanced movement of contaminants or other material.

[It is expected that other sources of electrical currents would be much more significant. For example, the corrosion current arising from crevice corrosion of containers would far exceed any current produced by weak gradients that might arise from ore bodies. We also expect that any such ore bodies would be located at a great distance from the disposal facility, because site selection criteria would avoid sites that were near ores of possible economic value (Davison et al. 1994b). It is therefore assumed that further evaluation for the postclosure assessment is not warranted. See also Chemical gradients and Container failure (long-term).]

Geochemical pump	P	BCSW	C	X	V

A sequence of geochemical reactions might be established that would act to move material from one place to another. For example, uranium might be dissolved at the surface of the UO_2, moved to the interior of the vault and precipitated.

[This factor is discussed elsewhere, under Chemical gradients, Chemical interactions, Galvanic coupling and Radiolysis.]

Glaciation	E	BCSW	BCP	X	-

Glaciation would change stress fields, flow regimes and temperatures. It could have many complex effects on processes occurring in the vault.

[The next glacial episode will not occur until about 2 x 10^4 a from now (Eronen and Olander 1990, Davis et al. 1993, Davis 1986), beyond the 10^4 a time period required for quantitative evaluation of potential impacts (AECB 1987a). Moreover, it is expected that glaciation will not affect the performance of the vault; see, for

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
example, Heinrich (1984). It is therefore assumed that the effects of glaciation on the vault can be excluded from further quantitative evaluation in the postclosure assessment, although there is a need to consider the possible effects over longer time scales. See also Global effects, and the discussion of Glaciation in the list of factors for the geosphere and biosphere (Tables B.2 and B.3)].					
Global effects	E	BCSW	BCP	X	-
The vault behaviour might be modified by global effects, such as movement of molten material, climate change, greenhouse warming, drought and flooding.					
[It is expected that such events are very unlikely or would not affect the performance of the reference disposal vault located at a depth of 500 m in the Canadian Shield; see, for example, Heinrich (1984). It is therefore assumed that further quantitative evaluation for the postclosure assessment is not warranted, although it may be necessary to consider possible effects over longer time scales. See also Glaciation. Further discussion is provided under Climate change in the lists of geosphere and biosphere factors (Tables B.2 and B.3).]					
Hydraulic conductivity	P	SB	P	C	V
Variations in hydraulic conductivity within the buffer, backfill and seals may lead to unforseen flow pathways, such as along the top of a drift.					
Hydraulic head	P	BS	P	C	V
Variations in hydraulic head may produce local flows and stresses that affect the performance of the vault.					
Hydride cracking	P	C	CP	C	V
A potential failure mechanism for containers involves the uptake of hydrogen gas and the formation of metal hydrides, which may mechanically weaken the container and promote corrosion processes. (This factor is included with the discussion under Container failure (long-term).)					
Hydrothermal alteration	P	BCS	C	X	V
Hydrothermal reactions may result in alteration of the minerals in the buffer, backfill and seals.					
[This process is described in more detail under Backfill evolution, Buffer evolution, Long-term physical stability and Seal evolution. Related discussion is provided under Groundwater					

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
composition and Groundwater - evolution in the list of geosphere factors. It is assumed that further quantitative evaluation for the postclosure assessment is not warranted.]					
Improper operation	E	BCSW	BCP	X	E
The long-term performance of the disposal vault might be seriously affected by unplanned or improper activities that take place during the construction, operation and closure of the disposal vault. [This factor is discussed elsewhere, under Incomplete closure and Sabotage.]					
Incomplete closure	E	BCSW	P	X	-
Disintegration of society could result in incomplete construction and or premature abandonment of the disposal facility (incomplete closure). [The starting time for the postclosure assessment is after the closure, sealing and decommissioning of the disposal vault. Thus this factor is considered to be outside the scope of the post-closure assessment. See also Sabotage and Improper operation.]					
Incomplete filling of containers	E	CW	CP	X	-
Some containers may be incompletely filled with glass bead particulate, leading to structural instability. [In the postclosure assessment of the reference disposal system, it is assumed that the container void space is infilled with glass beads (to provide mechanical support). Container quality control and inspection techniques would detect incomplete filling of the container and remedial action would be taken. Thus, it is assumed that no further evaluation for the postclosure assessment is warranted.]					
Interfaces (boundary conditions)	P	BCSW	P	C	V
Important physical and chemical effects may occur at the interfaces between materials in the vault, such as the interfaces between the container and buffer, and backfill and rock. (This factor is also considered elsewhere. Physical effects are discussed under Boundary conditions, while chemical effects are included in a number of factors, such as Chemical gradients, Chemical interactions, Container corrosion (long-term) and Radiolysis.)					

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Intrusion (animal)	P	-	B	X	-

Animals might intrude into the vault, promoting the release and spread of contamination.

[No animals are known that could survive in the disposal vault after closure. No further evaluation for the postclosure assessment is warranted.]

Intrusion (human)	E	BCSW	BCP	CIX	-

Human intrusion could occur during the postclosure phase as a result of various activities: attempts to retrieve useful material (used fuel, Zircaloy, containers, buffer and tools); borehole drilling, and construction and operation of a mine for valuable ores near the disposal site; borehole drilling for development of a well; use of explosives in seismic studies; and use of warm waters as a health spa.

[Different aspects of this factor should be considered in the central and inadvertent human intrusion scenarios; other aspects can be excluded.

- Intrusion to retrieve most of the materials in the vault is thought to be unlikely because of the magnitude and cost in time and money of the operation that would be required. One possible exception is the retrieval of potentially valuable isotopes, such as fissile plutonium-239. In this case, however, it is reasonable to assume that any society wishing to recover such materials would have the technology to understand and avoid the hazards, and further consideration in the postclosure assessment is not warranted.
- Nearby activities, such as the use of explosives, are unlikely to affect the performance of the vault and should be excluded (compare with Earthquakes).
- The quantities of heat generated by the vault are unlikely to be of interest for use as a health spa. Site selection criteria would avoid the siting of a vault where there was a likely potential for exploitation of geothermal energy (Davison et al. 1994b).
- Drilling and mining for valuable ores would be unlikely because site selection criteria would avoid a host rock that was of any economic interest (Davison et al. 1994b). This is generally the case for the plutons of interest in the Canadian Shield (Eedy and Hart 1988). Although unlikely, this aspect should be examined in the inadvertent human intrusion scenarios, similar to those studied by Wuschke (1991, 1992).
- One aspect that should be considered in the central scenarios is the possible drilling of boreholes into the geosphere for use as a water-supply well; see Wells in the list of geosphere factors (Table B-2).

See also Earthquakes, Sabotage and improper operation. Further discussion is provided for intrusion in the lists of geosphere and biosphere factors (Tables B.2 and B.3).]

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Inventory	F	BCSW	BCP	C	V

The description of the vault should include identification of all potential sources of radiotoxicity and chemical toxicity, including used UO_2 fuel, Zircaloy, containers, buffer, backfill and seals. See also Other waste (other than used fuel), Source terms (expected) and Source terms (other).

Long-term physical stability	P	BCSW	PC	X	EV

Long-term physical stability of the containers, waste matrices, buffer and backfill could be affected by processes such as silica cementation, geothermal reactions, alteration of buffer and seals, plugging or opening of pores or fractures, inflow of saline groundwaters, radiolysis and formation of reactive organic material (including microbes).

[It is expected that these processes would not result in changes to physical properties that would affect the overall performance of the components of the vault. For example, no fundamental changes to the physical properties of the bentonite clay of the buffer are expected for times up to 10^4 a. Other sealing materials would be subjected to lower temperatures, with less likelihood of physical alteration. We have therefore assumed that further quantitative evaluation for the postclosure assessment is not required, although further consideration may be required for time scales in excess of 10^4 a. For further discussion on changes to the components of the vault, see Backfill evolution, Biological activity, Buffer Evolution, Cave-ins, Earthquakes, Formation of cracks, Hydrothermal alteration, and Seal evolution. Related discussion is provided under Groundwater composition and Groundwater - evolution in the list of geosphere factors.]

Long-term transients	E	BCSW	CP	CX	V

Long-term transient events, singly or coupled together, may affect contaminant transport. These effects include the thermal pulse of decaying fuel, formation of steam, reflooding, excavation stress relief and altered flows due to grouting.

[Some long-term transients should be considered quantitatively. For example, significant effects should be evaluated from temperature rises in the vault due to radioactive decay of used fuel, excavation stress relief, and groundwater flow fields affected by grouting (see Temperature rises, Formation of cracks and Convection). Other long-term transients do not require quantitative evaluation; for example, the formation of steam is of no concern because the vault design precludes temperatures greater than 100°C (Baumgartner et al. 1993, 1994). It is very difficult to quantify all effects that may occur for some transients. However, it is generally expected that such transients would not be important, or

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

that overestimates of impacts would be obtained if the transient was ignored or included in a simplified manner. For example, corrosion of the containers is promoted by the presence of water. If the delay in vault reflooding was ignored, then corrosion would begin at the instant of closure, leading to earlier failure of the containers and larger impacts. See also Reflooding and Unsaturated transport. Related discussion is provided under Dewatering and Unsaturated Rock in the list of geosphere factors (Table B-2).]

Methylation	P	BCW	C	X	V

Methane or other organic compounds in the vault may lead to the formation of methylated species that would change the properties of the buffer, container and waste matrices, and affect the movement of contaminants.

[This factor is discussed elsewhere; see Biological activity, Complexation by organics, Methylation and Mutation. Further discussion is provided under Complexation by organics, Methane and Microbes in the list of geosphere factors (Table B-2).]

Microbes	P	BCSW	B	X	V

Microbial action could have specific effects, especially on compounds and minerals containing redox-sensitive elements such as sulphur and iron. Microbial activity could affect the physical and chemical environment of the vault, or it could directly affect some of the materials in the vault, such as the buffer and containers.

[This factor is considered in detail elsewhere, under Biological activity, Complexation by organics, Methylation and Mutation. Further discussion is provided under Complexation by organics, Methane and Microbes in the list of geosphere factors (Table B-2), and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table B-3).]

Microorganisms	P	BCSW	B	X	V

Microscopic organisms, including bacteria, protozoans, yeast, viruses and algae, may affect the expected performance of the disposal vault.

[This factor is discussed in detail elsewhere, under Biological activity, Complexation by organics, Methylation and Mutation. Further discussion is provided under Complexation by organics, Methane and Microbes in the list of geosphere factors (Table B-2), and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table B-3).]

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Monitoring and remedial activities	E	BCSW	P	X	E

Boreholes used to monitor performance could provide pathways for contaminant transport. Similarly some activities to remedy problems could lead to enhanced transport.

[In the concept for disposal of Canada's nuclear fuel waste, one underlying premise is that monitoring and remedial activities are not a fundamental technical requirement. Nevertheless, these activities would take place during the operational stages of the disposal system. It is reasonable to assume that these activities would be constrained such that the performance of the vault would not be compromised. For example, we expect that all monitoring boreholes would be completely sealed, so that no new contaminant flow pathways would result.]

Mutation	E	BCSW	B	X	-

Radiation fields could cause mutation of microorganisms, leading to unexpected chemical reactions and impacts.

[Mutation of biota is unpredictable, and cannot be considered quantitatively. Nevertheless, because microorganisms have evolved that can survive in many different environments, utilizing a diverse range of redox reactions for energy sources, it is reasonable to assume that any new organisms that evolved would not be capable of producing unique impacts that are not already observed with present-day microorganisms. We have therefore assumed that no further evaluation for the postclosure assessment is warranted, although further research may be warranted. See also Biological activity. Further discussion is provided under Biological evolution in the list of biosphere factors (Table B-3).]

Other waste (other than used fuel)	F	W	CP	X	-

The vault could be used for the disposal of other types of waste, such as low- and intermediate-level radioactive waste, reactor remains and toxic chemicals, or other types of waste forms, such as borosilicate or aluminosilicate glasses containing fuel reprocessing wastes.

[The scope of the postclosure assessment of the reference disposal system is limited to nuclear fuel waste from CANDU™ nuclear power reactors. Both radiotoxic and chemically toxic impacts are evaluated for this waste. It is considered that other types of waste are outside the scope of the assessment, and therefore no further quantitative evaluation is warranted. See also Inventory, Source terms (expected) and Source terms (other).]

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Percolation in shafts	P	BCSW	P	X	EGV

Localized percolation driven by temperature gradients could lead to early failure of seals and grouts and the formation of new significant flow pathways within both the vault and shafts leading to the vault.

[The design of the vault includes a combination of bulkheads, seals and backfill within the vault drifts and shafts. The purpose of each of these elements is to control and limit groundwater movement, such that contaminant transport would be dominated by diffusion and not convection. The properties of these elements would remain relatively unchanged for long periods of time (see Backfill evolution, Buffer evolution, Long-term physical stability and Seal evolution). Thus the expected behaviour of these elements is such that localized percolation would not be important during the time required for quantitative evaluation. It is also expected that no significant flow pathways would occur even if some seals and grouts did not function as expected, because of the redundancy of barriers (Chan and Stanchell 1990, Johnson et al. 1994). For example, the vault design calls for a number of distinct seals along the shafts. The possible dysfunction of one seal would have very localized effects, and would not seriously affect the overall performance of the disposal vault. Moreover, the shafts would be located over 100 m from any vault rooms containing nuclear fuel waste. Over longer periods of time, possible effects would become less likely because temperature gradients in the vault would be greatly reduced. We have therefore assumed that localized percolation driven by temperature gradients need not be considered quantitatively in the postclosure assessment. Related discussion is provided under Damaged zone and Shaft seal failure in the list of geosphere factors (Table B-2).]

Pitting	P	C	CP	C	V

Pitting, or the selective localized formation of cavities in a metal surface due to nonuniform corrosion, is a potential container corrosion mechanism. (Discussion of this factor is included under Container failure (long-term).)

Preclosure events	E	BCSW	BCP	X	EV

Unplanned events occurring during the preclosure phase could have serious consequences on the postclosure phase; for example, flooding of the vault could alter local groundwater characteristics, unwanted organic materials could be introduced, containers could be broken during installation, and seals could fail early due to vibrations from underground traffic.

[It is reasonable to assume that these effects would be addressed during the operation of the disposal facility, and corrective actions taken so that performance was not impaired.]

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Precipitation and dissolution	P	BCW	C	CX	V

Solubility constraints may be important in controlling transport in the buffer, backfill and container. For example, the dissolution rate of the waste matrices could be affected by local dissolution and precipitation, and precipitation could change porosity of the buffer and backfill. Solubility constraints are affected by temperature.

[All important components of this factor should be included in the postclosure assessment. Important components include the dissolution of the UO_2 and Zircaloy waste matrices and the dissolution and precipitation of key chemical elements. On the other hand, it would be acceptable to ignore some other components. For example, precipitation of chemical compounds in the buffer is expected to result in a decrease in the buffer porosity. It is difficult to predict in detail the extent of the porosity decrease, but it is known that the effect would be a reduction in contaminant transport. Thus if changes to buffer porosity are ignored in the postclosure assessment, the result would be to overestimate impacts. Related discussion is provided under Groundwater - evolution and Precipitation and dissolution in the list of geosphere factors (Table B-2).]

Psuedo-colloids	P	BCSW	BCP	X	V

The formation of psuedo-colloids, whereby contaminants are sorbed onto naturally occurring particulates (such as clay), may affect the movement of contaminants in the disposal vault.

[This factor is discussed further under Colloids. Further discussion on colloids is provided in the lists of geosphere and biosphere factors (Tables B.2 and B.3).]

Radiation damage	P	BCSW	P	X	V

Strong radiation fields could lead to radiation damage to the waste matrices, containers, buffer, backfill, seals and surrounding rock.

[Apart from chemical effects due to radiolysis products, it is expected that radiation damage to all components of the vault would be negligible. For example, experimental evidence shows that g-irradiation would have little or no effect on the crystal structure of clay minerals (Oscarson and Cheung 1983). Except for radiolysis (which is discussed separately), it is assumed that no further evaluation is required for the postclosure assessment. See also Radiolysis.]

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Radioactive decay	P	W	P	C	V

Radioactive decay, including the ingrowth of progeny in decay chains, would affect concentrations of radionuclides and stable isotopes in the waste matrices, and in other parts of the vault.

Radiolysis	P	BCW	C	CX	V

Radiolysis may change the chemical environment in the vault, locally affecting the electrochemical potential (Eh), acidity (pH) and concentration of reactive radicals, with consequent impacts on the buffer, backfill, waste matrices and surrounding rock.

[Radiolysis is the dissociation of molecules caused by the absorption of high-energy radiation. For example, radiolysis of water produces (an equal number of) oxidizing and reducing radicals and new molecular compounds, although concentrations are typically very small. Effects due to radiolysis would diminish with time, following the decrease with time of the radiation fields of used fuel (particularly a-radiacion). Experimental evidence suggests that the most significant affect of radiolysis in the vault would be an increase in the electrochemical potential of groundwater, which may lead to chemical reactions with redox-sensitive compounds. In particular, radiolysis may affect the rate of dissolution of the used fuel (UO_2) matrix. We have assumed that other effects of radiolysis can be excluded from any scenarios requiring quantitative evaluation in the postclosure assessment of the reference disposal system, although further research may be indicated. See also Chemical gradients, Coupled processes, Formation of gases, Long-term physical stability, Precipitation and dissolution, and Radiation damage. Further discussion is provided under Radiation effects in the list of geosphere factors (Table B-2).]

Recharge groundwater	P	BCSW	C	C	V

Different sources of recharge water or intrusion of saline water could affect the chemistry of the groundwaters passing through the vault. A broad range of feasible concentrations of ionic species should be evaluated.

Reflooding	E	BCSW	CP	X	V

The reflooding transient may be important, leading to high localized temperatures and pressures that affect all components of the vault. Limited ingress of water may lead to unsaturated conditions in the buffer/backfill for long periods of time; unsaturated transport may be important. Reflooding may require the use of alternative boundary conditions to describe transport between the container and buffer, buffer and backfill, and backfill and rock.

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
[The transient phase prior to complete resaturation is not expected to be detrimental to container or sealing material performance. Contaminant transport is not expected to occur under unsaturated conditions because, for example, vault temperatures would be less than 100°C (Baumgartner et al. 1993, 1994), which precludes the formation of steam. Lower (not higher) temperatures would be predicted if the vault were completely saturated. Although it is very difficult to quantify all effects of reflooding, it is expected that overestimates of impacts will be obtained if this transient is ignored. That is, if it is assumed the vault is completely saturated at the instant of closure, container corrosion would begin at that time, leading to earlier failure of the containers and larger impacts. We have therefore assumed that no further evaluation is required for the postclosure assessment. See also Long-term transients and Unsaturated transport. Related discussion is provided under Dewatering and Unsaturated rock in the list of geosphere factors (Table B-2).]					
Retrievability	–	F	BCSW	BCP	X	EV
There may be a requirement to retrieve all or part of the waste stored in the vault; for example, to recover valuable fissile materials or to replace defective containers.						
[The design of the vault for the reference disposal system does not specifically include retrieval of nuclear fuel waste. Thus we have assumed that this factor is beyond the scope of the postclosure assessment, and that no further evaluation is required. See also Monitoring and remedial activities, Intrusion (human), and Unmodelled design features.]						
Sabotage and improper operation		E	BCSW	BCP	X	E
Sabotage and/or improper operation could compromise the long-term performance of the vault. Examples include sabotage of vault containers, seals, backfill and buffer; undesirable or unexpected material left in the vault (timbers, organics, tools, equipment and concrete); explosions changing rock integrity; improper placement of containers by automated waste-handling procedures; design and construction faults and failure of quality assurance of engineering and construction; flooding and pumping of contaminants to the accessible environment; incompletely backfilled boreholes or drifts; unfilled or improperly sealed shafts and boreholes; fires during construction that mobilize airborne contaminates; swelling of buffer in the boreholes before the drift is backfilled; terrorist activity related to the strategic value of fissionable material; and terrorist activities that prevent the use or closure of the facility.						

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
[We have assumed that each of these items are more appropriately considered in the preclosure assessment, and that corrective actions would be taken such that the performance of the vault would not be significantly affected. It is therefore assumed that further evaluation for the postclosure assessment is not warranted.]					
Seal evolution	P	S	PC	X	V
The properties of the seals and grouts could evolve with time, as a result of processes such as silica cementation, and alteration or dissolution of seal and grout materials.					
[The alteration of clay and cement-based seals at low temperatures is a very slow process. No changes are expected within 10^4 a that would have a significant effect on the flow of groundwater or contaminants in the vault. It is therefore assumed that further evaluation for the postclosure assessment is not warranted, although some consideration may be required for time scales in excess of 10^4 a. See also Backfill evolution, Buffer evolution, Cave-ins, Chemical interactions, Concrete, Formation of cracks, Hydrothermal alteration, Long-term physical stability and Seal failure. Related discussion is provided under Damaged zone, Groundwater composition, Groundwater - evolution, and Shaft seal failure in the list of geosphere factors (Table B-2).].					
Seal failure	P	BCSW	CP	CX	V
Chemical or physical processes may cause early or accelerated failure of the seals and grouts (including all seals and grouts in boreholes, air vents, drifts and shafts). This would lead to changed water flow patterns and transport pathways to and from the vault.					
[This factor could affect the performance of the vault and geosphere. Following detailed investigation by the Vault Model Working Group, it was concluded that seal failures should be included in the central scenarios through variability in parameter values (see Uncertainties). Significant changes in water flow are not expected to occur because of seal degradation. The use of composite seals incorporating highly compacted bentonite blocks and high-performance concrete bulkheads, along with durable cement-based grouts for fractures and a clay-granite mixture for backfill, would limit water movement to diffusion control within the sealing materials. For development of the geosphere model, only backfill materials are assumed to be present in shafts and drifts, and (for the geosphere model) any degradation in performance could be adequately described in the central scenarios through variability in parameter values. Neglecting to incorporate the superior sealing properties of highly compacted bentonite					

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

and cement-based materials would result in significant overestimate of the impacts. The Vault Model Working Group concluded that the complete failure of all seals or absence of all seals (including shaft seals) should be excluded from any scenario. Chan and Stanchell (1990) have indicated that there would be no effect on contaminant transport in the geosphere unless the shafts and backfilled rooms were left open or were filled with a highly permeable material. This possibility is considered to be outside the scope of the postclosure assessment. See also Cave-ins, Chemical interactions, Concrete, Formation of cracks, Hydrothermal alteration, Long-term physical stability, Percolation in shafts and Seal evolution. Further discussion is provided under Damaged zone and Shaft seal failure in the list of geosphere factors (Table B-2).]

Sorption P B C C V

Sorption is a collective term used to describe the partitioning of contaminants in groundwater onto surrounding substrates. It is known to be an important process in the buffer and backfill, and may result in substantial delays in contaminant transport. For most elements at very small concentrations, sorption is linear in the sense that the mass of sorbed element is proportional to its concentration in solution. See also Sorption - nonlinear. Related discussion is provided under Sorption in the list of geosphere factors (Table B-2).

Sorption - nonlinear P B C X V

Some chemical elements may display non-linear sorption characteristics for reasons such as chemical kinetic effects, concentration effects and the formation of precipitates. The saturation of available ion exchange sites could also give rise to non-linear sorption.

[Parts of this factor may require a quantitative treatment, such as the formation of precipitates of sparingly soluble elements like technetium and uranium. For some elements, it may be possible to make simplifying assumptions; for example many non-linear sorption isotherms can be replaced with a linear isotherm such that impacts would be overestimated (Walker and LeNeveu 1987). We have assumed that these two issues are implicitly included within the factors Precipitation and dissolution, and Sorption. We have also assumed that further quantitative evaluation is not warranted for the postclosure assessment. Related discussion is provided under Sorption in the list of geosphere factors (Table B-2).]

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Source terms (expected)	P	CW	CP	C	V

Source term refers to the mode(s) of release of a contaminant from its waste matrices. There are two waste matrices of interest for the postclosure assessment of the reference disposal facility: UO_2 and Zircaloy. The expected source terms from these waste matrices are known as congruent dissolution and instant release. See also Inventory, Other waste (other than used fuel), Source terms (other) and Stability of UO_2.

Source terms (other)	P	CW	CP	X	V

The modes of release of a contaminant from the UO_2 and Zircaloy waste matrices could occur by unexpected mechanisms, such as mechanical breakdown, phase changes (UO_2 transforming to UO_3), selective leaching and other fast reactions induced by the effects of temperature or radiolysis.

[A number of experimental investigations support the contention that the release of a contaminant from used CANDU™ fuel is adequately described by two expected source terms: congruent dissolution and instant release (Johnson and Shoesmith 1988, Sunder and Shoesmith 1991). The properties of Zircaloy suggest that its only feasible source term is congruent dissolution. We have therefore assumed that no further evaluation is required for the postclosure assessment. See also Source terms (expected) and Stability of UO_2.]

Speciation	P	BCW	C	C	V

Chemical speciation would affect dissolution and precipitation, and would change with time following the thermal pulse. Speciation is dependent on pressure. See also Chemical interactions.

Stability	EFP	BCSW	BCP	X	-

The stability of the vault and its contents may undergo substantial changes over 10^4 a.

[See other specific factors such as Earthquakes, Long-term transients, Reflooding, Seal failure, Stability of UO_2 and Time dependence.]

Stability of UO_2	P	W	C	C	V

The thermodynamic stability and solubility of UO_2 could be affected by a number of variables, such as electrochemical potential (Eh), pH, solutions containing significant concentrations of calcium or sodium ions, and availability of organic complexing materials. See also Inventory and Source terms (expected).

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Swelling pressure	P	BC	P	X	EV

Swelling of wetted bentonite could damage containers; increased pressures could affect pressure-dependent solubilities.

[The swelling pressure generated by buffer material would be limited to a maximum of 2.5 MPa through control of density during emplacement. The design and properties of the titanium container are such that the containers could withstand buffer swelling loads, and would not lead to failures prior to failures caused by corrosion. Pressures at vault depth, even including swelling pressures, have an insignificant impact on solubilities. It is therefore assumed that further evaluation for the postclosure assessment is not warranted. See also Container failure (early), Container failure (long-term), Container healing, Containers - partial corrosion, and Precipitation and dissolution.]

Temperature effects	P	BCSW	BCP	C	-

The heat released by the containers would increase the temperature in the vault. These higher temperatures would affect chemical reactions in the vault, such as container corrosion, and transport of contaminants by diffusion. See also Backfill evolution, Buffer evolution, Container failure (long-term), Chemical interactions, Diffusion, Hydrothermal alteration, Long-term physical stability, Seal evolution and Temperature rises (unexpected). Further discussion is provided under Vault heating effects in the lists of geosphere and biosphere factors (Tables B.2 and B.3).

Temperature rises (unexpected effects)	P	BCSW	BCP	X	V

Local temperature rises could be high, and could produce unexpected effects, such as formation of molten materials, very high stresses, percolation of groundwaters, formation of an ore body, and fire or explosion.

[It is considered that these processes are improbable or would have an insignificant effect on the performance of the vault. For example, the vault design is such that the maximum temperature would be less than 100°C (Baumgartner et al. 1993, 1994; Johnson et al. 1994); hence the formation of molten materials would not occur, and the contents of the vault would consist of material that could not burn or explode. It is assumed that no further evaluation for the postclosure assessment is warranted.]

Time dependence	P	BCSW	BCP	CX	V

Time-dependent effects would exist because of factors such as the thermal pulse and reflooding; these effects should be reflected in

TABLE B-1: VAULT FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
parameters such as flow fields and diffusion coefficients and in the models in which they are used. Other time-dependent effects include the variable flow rate of contaminants out of the containers and buffer.					
[A few time-dependent processes need not be evaluated in detail. For example, it is possible to simplify the treatment of transient processes, such as reflooding, in such a way as to overestimate impacts. Other time-dependent processes are discussed separately elsewhere. See, for example, Backfill evolution, Chemical kinetics, Container failure (long-term), Diffusion, Long-term transients, Reflooding and others.]					
Transport in gases or of gases	P	BW	P	X	V
Volatile material may be transported as gases or in gases; gas bubbles may affect flow paths through the buffer; and two-phase flow may be important.					
[This factor is expected to be unimportant, since any contaminant gases (see Formation of gases) are likely to be dissolved in water under the conditions expected in the vault. Dissolved gases could be released if these conditions (particularly pressure) changed, but no such changes are expected in the vicinity of the vault. It is therefore assumed that further evaluation for the postclosure assessment is not warranted although some consideration may be required for periods in excess of 10^4 a.]					
Uncertainties	EFP	BCSW	BCP	C	BGVP
The vault system consists of many important components that could have complex physical and chemical interactions. Considerable uncertainties will exist in modelling its behaviour over 10^4 a. The effect of these uncertainties should be included in the postclosure assessment, using techniques such as sensitivity analysis and probabilistic systems assessment. Virtually all of the factors in this list have associated uncertainties that should be addressed in a quantitative fashion.					
Uniform corrosion	P	C	CP	C	V
Uniform corrosion, where the surface of the container is uniformly worn away by chemical or physical attack, is a potential mechanism leading to container failures. (This factor is discussed under Container failure (long-term).)					
Unmodelled design features	F	BCSW	BCP	X	EV
Some design features of the vault may be important and might require explicit modelling. For example, there may be significant					

TABLE B-1

VAULT FACTORS (concluded)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
the rooms containing nuclear fuel waste and the rock immediately surrounding these rooms. Many other features are expected to have little or no significance, because they are relatively remote from any waste. For example, in the design of the reference vault, the nuclear fuel waste is more than 100 m from the shafts leading to the vault and from the rooms used for storage of material and equipment. All of these features would be fully backfilled and sealed, in the same manner as all rooms containing nuclear waste. We have therefore assumed that no further consideration is required for the postclosure assessment, but caution that other vault designs may require further evaluation. See also Unmodelled design features.]					

TABLE B-2

GEOSPHERE FACTORS FOR THE REFERENCE DISPOSAL SYSTEM

The headings **F/E/P**, **Comp.**, **Mech.**, **Treat.**, and **Ref.** use the following abbreviations:

- **F/E/P** - classified as **F**eature, **E**vent or **P**rocess.
- **Comp**(onent) - component of the geosphere affected: groundwater **F**low, **R**ock properties, contaminant **T**ransport and **W**aste.
- **Mech**(anism) - classified as **A**nthropogenic, **E**xpected natural factors, **U**nexpected natural factors and **V**ault-induced.
- **Treat**(ment) - recommended treatment for the postclosure assessment. Some factors should appear in the **C**entral scenarios and/or in one of the **O**pen-borehole or **I**nadvertent human intrusion alternative scenarios. Others may be e**X**cluded from scenarios because they would not contribute significantly to estimated impacts.
- **Ref**(erence) - reports on the **B**iosphere model (Davis et al. 1993), **E**ngineering description (Simmons and Baumgartner 1994), **G**eosphere model (Davison et al. 1994a), **P**ostclosure assessment (Goodwin et al. 1994), **S**ite characterization studies (Davison et al. 1994b) and **V**ault model (Johnson et al. 1994a).

Factor	F/E/P*	Comp.	Mech.	Treat.	Ref.
Blasting and vibration	P	FR	A	C	GS

Blasting and vibration during construction of the vault (or afterwards) could substantially alter rock properties and water flow fields. See also Bomb blast, Meteorite impact and Sabotage. Related discussion is provided under Sabotage and improper operation in the list of vault factors (Table B-1).

Bomb blast	E	FR	A	X	E

Nuclear or conventional bombs exploded over the vault may alter rock properties and flow regimes.

[Events of this type can be eliminated from quantitative evaluation. No known explosive device exists that would breach the vault, and none would seriously affect structural integrity (except, perhaps, during the preclosure phase). Further, the direct impacts to the critical group, over both short and long time frames, from the effects of a nuclear bomb exploded over a disposal vault location, would likely outweigh any additional impacts arising from the disposal system. It is therefore assumed that further evaluation for the postclosure assessment is not warranted. See also Merrett and Gillespie (1983), Blasting and vibration, Meteorite impact and Sabotage. Related discussion is provided under Sabotage and improper operation in the list of vault factors (Table B-1), and under Collisions, explosions and impacts in the list of biosphere factors (Table B-2).]

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

decrease in the groundwater levels in the rocks of the Canadian Shield. Any such decrease in groundwater level would tend to reduce the rate of groundwater movement through the geosphere, which would in turn reduce the transport of any contaminants migrating from the vault. We believe that, by assuming the water table in the geosphere conforms to the present day topography, we would describe a situation that would include the possible subsurface effects of a wetter climate and that would tend to overestimate impacts of a drier climate. We also expect that warmer or cooler conditions and permafrost would not significantly affect the performance of the geosphere. These comments generally apply to all climate shaping forces, such as the greenhouse effect and destruction of the ozone layer (the effects of glaciation are discussed separately below). We have therefore assumed that further evaluation of the effects of climate change on the geosphere is not required in the postclosure assessment of the reference disposal system. See also Glaciation, Topography (current) and Topography (future). Related discussion is provided under Global effects in the list of vault factors (Table B-1) and under Climate change in the list of biosphere factors (Table B-3).]

Colloid formation	P	T	E	X	GV

The formation of colloids or pseudo-colloids could affect the transport of contaminants.

[Colloids are particles of contaminants; pseudo-colloids are naturally occurring particles, such as clay, that contain sorbed contaminants. Most contaminants will not form long-lasting colloids in the geosphere. Since the concentrations of naturally occurring colloid-sized particles in groundwaters from granite are small (0 to 5 mg/L), less than 0.01% of any contaminant leaving the vault could form pseudo-colloids in the geosphere, and provided contaminant sorption on groundwater particles is reversible, the impact of colloids on contaminant transport would be negligible (Vilks et al. 1991a, 1991b). If stable pseudo-colloid formation occurred by irreversible contaminant sorption onto particles, colloid transport could be important, provided colloid-sized particles can migrate for significant distances in granite rock. Since colloid transport is probably limited by filtration in fractures, colloid-induced migration is not included in the postclosure assessment of the reference disposal system, but could be considered if colloid migration studies show the possibility of particle transport. The movement of colloids and dissolved contaminants in the geosphere are controlled by the same processes: for example, both are transported by slowly moving groundwater and by diffusion, and both are delayed by sorption. Thus the models describing the movement of dissolved contaminants could also be used to describe the movement of colloids, with appropriate selection of data. In practice, experiments used to determine such

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

data do not differentiate between dissolved and colloidal contaminants. That is, the experimental data provide an overall description of contaminant movement, implicitly including the effects of colloids. Based on these considerations, we have assumed that there is no need for the further evaluation of the effect of colloids in the geosphere for the postclosure assessment of the reference disposal system, but note that further experimental investigations are desirable. Further discussion is provided under Colloids in the lists of vault and biosphere factors (Tables B.1 and B.3).]

Complexation by organics P T E X G

The formation of stable complexes with organics could affect the transport of organics. Stable organics include humic and fulvic acids.

[The concentrations of naturally occurring organic carbon in groundwaters from the granitic Lac du Bonnet batholith range from 0 to about 5 mg/L, which could correspond to very small concentrations of organic ligands, in the range of 10^{-7} to 10^{-5} mol/L. (Geochemical and hydrogeological data for the postclosure assessment of the reference disposal system are chosen to be consistent with information from the Whiteshell Research Area, which includes the granite of the Lac du Bonnet batholith.) To have a significant effect on contaminant complexation, organic ligands must compete effectively with inorganic ligands, such as carbonate and fluoride. With their small concentrations in groundwater, only organic ligands with stability constants higher than about 10^6 to 10^8 could have a significant impact on contaminant migration. Based on our observations at the Lac du Bonnet batholith, we have concluded that no further evaluation is necessary for the postclosure assessment of the reference disposal system. Note that this conclusion applies only to the reference disposal system; if it is shown that groundwaters associated with another disposal site contain significant quantities of organic ligands (humics for example), the postclosure assessment could require modification to account for complexation with organics. See also Microbes and Speciation. Further discussion is provided under Biological activity, Complexation by organics and Long-term physical stability in the list of vault factors (Table 1), and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table 3).]

Conceptual model - hydrology F FT U X GS

The conceptual model of the geosphere may be incorrect, due to invalid assumptions about porous versus fracture flow, and the presence or absence of fractures. Other conceptual models might be equally likely.

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

[For the postclosure assessment, it is assumed that the conceptual model of the hydrology is correct for the reference disposal system. The model has incorporated the effects of fracture flow by treating known fracture zones as explicit features. Although flow within these zones is described by a porous media equivalent model, the transport properties reflect the fracture effects of channelling and heterogeneity and are derived from analyzing hydraulic test data and groundwater tracer tests. For a different, site-specific assessment, it may be reasonable to assume that sufficient data would have been generated to develop an acceptable conceptual model. For an actual disposal site, several decades of study would be performed, extending over the selection, construction, operation, extended monitoring and decommissioning stages of the disposal facility. We expect that, over this long time frame, a thoroughly calibrated and rigorously tested conceptual model could be developed. Note also that sensitivity analysis studies are used to evaluate alternative conceptual models. We have therefore assumed that further evaluation is not warranted for the postclosure assessment of the reference disposal system. See also Damaged zone, Hydraulic properties - evolution, Rock properties, Rock properties - undetected features, Shaft seal failure, Topography (current) and Topography (future).]

Convection	P	T	E	C	G

Convecting groundwaters would affect the transport and spread of dissolved contaminants.

Correlation	P	T	E	C	G

Some parameters used to define the geosphere model should be correlated to each other. For example, parameters that describe the behaviour of similar chemical elements are often similar, such as the solubilities of uranium and thorium; two segments of adjacent rock would have a similar suite of minerals and subsequently similar sorption properties and conductivities unless there was a major structural change. (Correlations known to be important are accounted for in the postclosure assessment, such as the solubilities and retardation coefficient for elements with similar chemical properties, and the hydrogeological and mineral contents of adjacent rock.)

Damaged zone	F	FRT	AV	X	G

Enhanced groundwater flow and contaminant transport could occur within the zone of rock surrounding the shafts and vault that was damaged during blasting or excavation.

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

[The possible extent of the damaged zone would be very dependent on the quality, strength and stress conditions of the host rock and the methods used to excavate the vault rooms and shafts, and could range over centimetres to metres. The principal effect of concern is the influence of the damage zone on groundwater flow and contaminant transport.

- There would be little effect on flow and transport away from the vault, since we expect that the damaged zone would be surrounded by a much larger zone of relatively low-permeability rock.
- For the reference disposal system, sensitivity analyses using the MOTIF groundwater flow model have shown that significant alterations in the hydrogeological properties of the rock immediately surrounding the excavations (the excavation damage zone) had only a minor effect on the overall groundwater transit time from the vault to the surface (Chan and Stanchell 1990).

From these considerations, we have assumed that no further consideration of the damaged zone is warranted for the postclosure assessment of the reference disposal system. However, we note that characterization studies would be required at an actual disposal vault site to establish the extent of the damaged zone at that site and to confirm that its effects were not (or were) important. A related issue requiring study at an actual disposal site would be the effectiveness of the grouts and bulkheads used to seal off the vault rooms from the potential damaged zone. See also Blasting and vibration, Borehole seal failure, Conceptual model - hydrology, Hydraulic properties - evolution, Open boreholes, Rock properties, Rock properties - undetected features and Shaft seal failure.]

Dams	E	F	A	X	GS

Construction or destruction of dams (hydroelectric dams, water reservoirs, beaver dams) would affect hydraulic heads.

[The possible long-term effects of such major projects would be examined in the site selection process and appropriate corrective action taken (Davison et al. 1994b). In addition, because preferred disposal sites would occur in areas of relatively low topographic relief, any dams in the area would be low hydraulic head structures (typically less than 20 m) and these would have no effect on groundwater flows at disposal vault depths in the geosphere. We have assumed that further evaluation for the postclosure assessment of the reference disposal system is not warranted. See also Climate Change, Discharge zones, Earthmoving, Topography (current) and Topography (future). Related discussion is provided under Earthmoving projects, Flooding and Water management projects in the list of biosphere factors (Table B-3).]

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Dewatering	E	F	A	CX	GS

Severe dewatering may occur near the vault, caused either by wells used for drinking water or for geothermal heating, or by the construction of the vault.

[The factors Wells and Wells (high-demand) include discussion of cases where existing flow fields could be perturbed by a well used for drinking water. Use of a well for geothermal heating is not probable because the temperature difference between the surface and the vault would be too small to be worth exploiting, and the total heat generated would not be of commercial interest. Also, any areas of unusually high heat flow would be avoided during site selection (Davison et al. 1994b). Finally, it is expected that any dewatering during construction of the vault would be of relatively short duration and would actually be a favourable situation since groundwater flows would be toward the disposal vault until reflooding had completed, and since temperature rises in the vault would be lower if the rock were completely saturated. We have therefore assumed that the effects of dewatering (except for wells used for drinking water) can be excluded from any scenarios requiring quantitative evaluation in the postclosure assessment. See also Unsaturated rock, Wells and Wells - high-demand. Related discussion is provided under Reflooding and Unsaturated transport in the list of Vault factors (Table B-1).]

Diffusion	P	T	E	C	G

Molecular diffusion would affect the transport and spread of contaminants; diffusion acts parallel to and transverse to the direction of convection.

Discharge zones	P	F	E	C	GS

Groundwater discharge may occur to surface water bodies (rivers, lakes), to a domestic or commercial well, to unsaturated terrestrial soils, and to wetlands (bogs). These discharge zones could be local or regional, with regional discharges likely resulting in greater dispersion and longer travel times. See also Critical group - house location, Urbanization on the discharge site and Wetlands in the list of biosphere factors (Table B-3).

Dispersion	P	T	E	C	G

Dispersion caused by variations in velocity and/or pathways would affect the transport and spread of contaminants; dispersion acts parallel to and transverse to the direction of convection.

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Drought	E	F	E	X	G

The current levels of meteoric precipitation could change substantially, leading to much less flow of water through the geosphere, with accompanying changes to the biosphere.

[This factor is considered with the discussion under Climate change. See also Climate change, Dust storms and desertification and Precipitation (meteoric) in the list of biosphere factors (Table B-3).]

Earthmoving	E	F	A	X	GS

Topography could undergo significant alteration due to massive earthmoving schemes, affecting generic or site-specific hydraulic head and flow regimes.

[The possible long-term effects of such major projects would be examined in the site selection process (Davison et al. 1994b) and appropriate corrective action taken. The most problematical schemes are those involving rock excavation for quarries, mines or hydroelectric projects. Potential disposal sites would not be in areas of likely economic interest for mining minerals, including open pit mining (Davison et al. 1994b). We believe that the distances involved would be such that the effects of any mines in adjacent areas would be negligible. Quarrying and the development of hydroelectric projects affect only the shallow parts of the rock (see also Dams and Climate Change) and would have no effect on groundwater flows at vault depths in the geosphere. We have therefore assumed that no further evaluation for the postclosure assessment is required. See also Dams, Erosion, Topography (current) and Topography (future). Related discussion is provided under Earthmoving projects, Flooding and Water management projects in the list of biosphere factors (Table B.3).]

Earthquakes	E	FR	E	X	EGPS

Earthquakes could produce jointed rock motion, rapid fault growth, slow fault growth or new fault formation, resulting in changes in hydraulic heads, changes in groundwater recharge or discharge zones, changes in rock stresses and severe disruption of the integrity of the vault (including shearing one or more containers).

[The Canadian Shield is the least seismically active portion of the North American continent and one of the least seismically active regions on Earth. Moreover, almost all earthquakes on the Shield of magnitudes greater than four occur near the Shield margin or near large regional geologic structures, such as ancient rifts. Locations near such features would be avoided when siting

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

a disposal vault (Davison et al. 1994b). The potential effects from earthquakes would need to be evaluated for the specific conditions at any proposed disposal site. Data for the postclosure assessment of the reference disposal system are chosen to be consistent with information from the Whiteshell Research Area. At this Area, studies of existing faults and fracture zones indicate that they formed during the cooling of the Lac du Bonnet batholith more than two billion years ago. Therefore, we do not consider it to be credible that earthquakes would lead to the formation of comparable new faults and fracture zones within the next tens of thousands of years. Atkinson and McGuire (1993) developed estimates for the probability of damage to a disposal vault caused by an earthquake on a nearby active fault. On the basis of their work, we concluded that the probability of effects from earthquakes at the Whiteshell Research Area was sufficiently small that such effects did not need to be included in the modelling of the geosphere for the postclosure assessment of the reference disposal system. Thus further quantitative evaluation of earthquakes for the postclosure assessment is not warranted. See also Blasting and vibration, Groundwater - evolution, Hydraulic properties - evolution, Metamorphic activity, Topography (current), Topography (future) and Volcanism. Further discussion may be found under Earthquakes in the lists of factors for the vault and biosphere (Tables B.1 and B.3).]

Erosion	E	FR	U	X	GS

Massive erosion of rock (by glaciation or water) could result in significant changes to hydraulic heads and a shorter transport path for contaminants.

[Merrett and Gillespie (1983) discuss denudation of land surfaces and fluvial erosion, and note that rates of erosion of the Canadian Shield are estimated to be only about 2×10^{-5} m/a. These rates are of no concern for a vault located 500 to 1000 m below the surface. Studies of glacial erosion in eastern Canada (Kaszycki and Shilts 1980) show that the depth of erosion ranges from 2 to 10 m per glacial event. Moreover, glaciation of the Canadian Shield is not likely to occur until about 2×10^4 a from now (Eronen and Olander 1990, Davis et al. 1993, Davis 1986). We have therefore assumed that further evaluation for the postclosure assessment is not required. See also Earthmoving, Topography (current) and Topography (future). Related discussion may be found under Erosion - lateral transport in the list of factors for the biosphere (Table B-3).]

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Explosion	E	FR	A	X	E

Explosions near the disposal system, or in the disposal system during its operation, may affect the performance of the geosphere.

[This factor is discussed elsewhere, under Bomb blast, Blasting and vibration, Meteorite impact and Sabotage. Related discussion is provided under Explosions, and Sabotage and improper operation in the list of vault factors (Table B-1), and under Collisions, explosions and impacts in the list of biosphere factors (Table B-2).]

Faulting	E	FR	E	X	EGS

Movement between adjacent rock masses, along a fracture, could result in changed hydraulic heads, groundwater flow and rock stresses.

[This factor is discussed elsewhere, under Earthquakes, Hydraulic properties - evolution, and Topography (future) and Volcanism. Further discussion may be found under Earthquakes in the lists of factors for the vault and biosphere (Tables B.1 and B.3).]

Flood	E	F	E	X	G

The current levels of meteoric precipitation could change substantially, leading to much greater flows of water through the geosphere, with accompanying changes to the biosphere.

[This factor is discussed under Climate change. See also Climate change, Flooding and Precipitation (meteoric) in the list of biosphere factors (Table B-3), and Sabotage and improper operation in the list of vault factors (Table B-1).]

Fulvic acid	P	T	E	X	G

Fulvic acids and fulvates may affect the movement of contaminants, by forming complexes.

[Fulvates are weather-resistant organic polymers with a molecular weight of about 1000 g. They are somewhat soluble in water, and generally found in soils. Concentrations of all organic material found in the granitic Lac du Bonnet batholith in the Whiteshell Research Area are very small, and no significant effects of complexation by fulvates are expected. (Geochemical and hydrogeological data for the postclosure assessment of the reference disposal system are chosen to be consistent with information from the Whiteshell Research Area, which includes the granite of the Lac du Bonnet batholith.) This factor is discussed further under Complexation by organics. See also Humic acid and Microbes. Related discussion is provided under Biological activity, Complex-

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
ation by organics and Long-term physical stability in the list of vault factors (Table 1), and under Bacteria and microbes in soil in the list of biosphere factors (Table 3).]					
Gases and gas transport	P	FT	V	X	GV
Contaminants that are volatile or that form gases, or other gases, such as hydrogen from corrosion of steel, may be transported as gases or in two-phase flow. Degassing could therefore affect flow and transport of these contaminants. It also could affect other contaminants if water flow is driven by large gas bubbles forming in the vault.					
[It is expected that no gases will form in sufficient quantity within the vault to result in a gas phase: see Formation of gases in the list of factors for the vault (Table B-1). For example, the design of the container for the reference disposal system excludes the use of metallic iron, and thus corrosion of the container would not produce significant quantities of hydrogen gas. Some degassing may occur as groundwater approaches the water table; however effects are expected to be small and limited to areas very close to the surface environment. We have therefore assumed that no further evaluation is warranted for the post-closure assessment.]					
Geothermal gradient effects	P	F	EV	C	G
Groundwater flow would be influenced by existing geothermal gradients: groundwater may tend to form convection cells.					
Geochemical interactions	P	FRTW	EV	CX	G
Geochemical interactions may lead to dissolution and precipitation of minerals along the groundwater flow path, affecting groundwater flow, rock properties and sorption of contaminants.					
[This general factor is discussed in more detail under separate factors: some require quantitative evaluation and others may be excluded. See Colloid formation, Complexation by organics, Groundwater composition, Groundwater - evolution, Microbes, Precipitation and dissolution, Recharge groundwater, Salinity effects on flow, Saturation, Sorption, Speciation and Vault heating effects. Related discussion is provided under Chemical gradients, Chemical interactions and Chemical kinetics in the list of vault factors (Table B-1).]					
Glaciation	E	FR	E	X	G
Glaciation may cause activation and creation of faults, changes in topography, changes in hydraulic heads, changes in groundwater					

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

recharge and discharge zones and isostatic depression. These effects may significantly change rock and flow characteristics. During interglacial periods, isostatic rebound and permafrost could affect rock and flow characteristics.

[Glaciation of the Canadian Shield is not likely to be a concern within the next 2 x 10^4 a (Eronen and Olander 1990, Davis et al. 1993, Davis 1986), beyond the period of time for which quantitative evaluation is necessary. We have therefore assumed that no further quantitative evaluation is required for the postclosure assessment. When glaciation does occur, some effects are expected to be unimportant; for example, studies of glacial erosion by Kaszycki and Shilts (1980) have shown that the depth of erosion ranges from 2 to 10 m per glacial event. Other effects on the geosphere are very difficult to quantify, although it is expected that no significant changes will occur at the 500 m depth of the reference disposal vault (Heinrich 1984, Davison et al. 1994a). See also Climate change, Topography (current) and Topography (future). Related discussion is provided under Glaciation in the lists of factors for the vault and biosphere (Tables B.1 and B.3).]

Greenhouse effect	E	F	E	X	G

The greenhouse effect could increase concentrations of carbon dioxide and other gases in the atmosphere, and lead to changes in the climate at the disposal site.

[This factor is considered under Climate change. Further information is provided under Climate change and Greenhouse effect in the list of biosphere factors.]

Groundwater composition	E	FRT	AV	CX	G

Groundwater compositions, including changes due to activities such as the construction of dams and pollution, could affect groundwater flow regimes; complexing agents could affect transport and dissolution of minerals and contaminants.

[Because of the very slow groundwater flow rates at disposal vault depths, groundwater compositions are controlled by the rock water interactions that occur at those depths. Activities such as dam construction could change the chemical composition of near-surface groundwaters, but are not expected to have significant effects at the 500-m depth of the reference disposal vault. The effects of expected groundwater composition should be considered in the scenarios requiring quantitative evaluation for the postclosure assessment of the reference disposal system. However, changes to expected composition due to events occurring on the surface can be excluded. See also Colloid formation, Groundwater - evolution,

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

Precipitation and dissolution, Recharge groundwater, Salinity effects on flow, Speciation and Vault heating effects. Related discussion is provided under Backfill evolution, Buffer evolution, Chemical gradients, Chemical interactions, Chemical kinetics and Seal evolution in the list of vault factors (Table B-1).]

Groundwater - evolution	P	FRT	EV	X	GS

Groundwater compositions would evolve, because of the presence of the vault as a heat source.

[Heat conduction studies by Chan et al. (1986) indicate that the temperature could rise by about 35°C in the geosphere within about 50 m of the reference disposal vault. The maximum temperature rise would occur within approximately 1000 a after emplacement of the waste in the vault and would return to ambient levels after about 10^5 a. The heating of groundwater (to a maximum of 35°C above ambient) close to the vault region would not induce chemical changes that would appreciably increase the transport of contaminants from the vault or affect groundwater chemistry in the geosphere surrounding the vault. This is because the two principal hydrogeochemical conditions that affect contaminant transport in the geosphere model, salinity and redox conditions of the groundwater, would not change significantly:

- Groundwater salinity should increase only slightly during passage through the vault due to the effects of greater dissolution of silicates (mainly the more reactive clay buffer in the vault) and increased reaction kinetics of salt dissolution and ion exchange at the elevated temperatures. Groundwaters flowing from the vault would therefore tend to be near saturation with respect to calcite, gypsum and silica minerals. Under the lower temperatures and different buffering capability of the surrounding rock, precipitation of such minerals would likely be the dominant process rather than dissolution. Any precipitation would result in a reduction in permeability rather than an increase in permeability. Finally, it is also expected that the solids that might precipitate would be similar to those already found within the geosphere.
- Redox conditions downstream of the vault are likely to remain reducing and similar to the redox conditions of the groundwater entering the vault because of the highly reducing conditions imposed by reactions within the vault. Groundwaters passing through the vault are likely to be more reducing and rich in ferrous iron than ambient groundwaters in the geosphere. This would lead to precipitation of iron oxyhydroxides, and hence would also tend to reduce the permeability of flow paths beyond the vault.

Given these considerations, we believe that groundwater evolution due to the vault heat would not be an important factor, and that

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

potential impacts would be overestimated if this factor were ignored. We have therefore assumed that no further consideration is required for the postclosure assessment. See also Colloid formation, Groundwater composition, Hydraulic properties - evolution, Precipitation and dissolution, Recharge groundwater, Salinity effects on flow, Speciation and Vault heating effects. Related discussion is provided under Backfill evolution, Buffer evolution, Chemical gradients, Chemical interactions, Chemical kinetics and Seal evolution in the list of vault factors (Table B-1).]

Humic acid P T E X G

Humic acids and humates may affect the movement of contaminants by forming compexes.

[Humates are weather-resistant organic polymers with a molecular weight of about 1.5×10^5 g. They are relatively insoluble in water, and generally found in soils. Concentrations of all organic material found in the granitic Lac du Bonnet batholith are very small, and no significant effects of complexation by humates are expected. (Geochemical and hydrogeological data for the postclosure assessment of the reference disposal system are chosen to be consistent with information from the Whiteshell Research Area, which includes the granite of the Lac du Bonnet batholith.) This factor is discussed further under Complexation by organics. See also Fulvic acid and Microbes. Related discussion is provided under Biological activity, Complexation by organics and Long-term physical stability in the list of vault factors (Table 1), and under Bacteria and microbes in soil in the list of biosphere factors (Table 3).]

Hydraulic properties - evolution P FT EV X G

The precipitation and dissolution of material could affect the groundwater flow regime by plugging or opening pores and fractures. This process could be enhanced by differential solubilities in a thermal gradient. The minerals available for sorption could also change.

[The major cause of changes to precipitation and dissolution would be the thermal gradient produced by the vault. We believe overestimates of impact would be obtained if we do not explicitly consider the changes that might result from this thermal gradient. For example, precipitation is more likely than dissolution as groundwaters move to cooler conditions far from the vault. Precipitation would tend to reduce permeabilities in the geosphere, and thereby reduce groundwater flow and contaminant transport. Moreover, it is expected that the solids that might precipitate would be similar to those already found within the geosphere, such

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
as calcite and gypsum. These issues are discussed in more detail under Groundwater - evolution. We have therefore assumed that no further consideration is required for the postclosure assessment of the reference disposal system. See also Earthquakes, Groundwater composition, Precipitation and Dissolution, and Vault heating effects. Related discussion is provided under Backfill evolution, Buffer evolution and Seal evolution in the list of vault factors (Table B-1).]					
Intrusion (magmatic)	E	FR	U	X	-
Magmatism near the disposal facility could lead to substantial changes to existing groundwater flows and rock properties.					
[This factor is included with the discussion under Metamorphic activity and Volcanism.]					
Intrusion (mines)	E	FRT	A	IX	GS
Intrusion into the disposal system could occur through the construction of a mine downgradient of the vault or near the vault. Possible effects include changes to groundwater flow regimes, rock integrity and transport pathways. The critical group might be miners.					
[These events are very much dependent on the characteristics of the disposal site, and the potential likelihood and impacts of mining should be evaluated on a case-by-case basis during site selection. In general, however, drilling and mining into or near the vault is unlikely because the site selection process would favour host rocks that were of no economic interest (Davison et al. 1994b). This is by and large the case for the plutonic host rocks of interest for the disposal of Canada's nuclear fuel waste (Eedy and Hart 1988). Most other reasons for deliberate intrusion are unlikely because of the magnitude and cost in time and money of the operation that would be required. It may be assumed that any future society that wished to recover materials such as plutonium from the vault would also have the technology to understand and avoid the hazards. We have assumed that most aspects of this factor do not require further evaluation in the central scenarios for the postclosure assessment of the reference disposal system, although some aspects should be examined in the inadvertent human intrusion scenarios. Two similar factors, Wells and Wells (high-demand), cover situations where wells may intrude into the host rock. See also Borehole - well, Boreholes - exploration and Solution mining. Further discussion is provided for intrusion in the lists of vault and biosphere factors (Tables B.1 and B.3).]					

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Isostatic rebound	E	FR	E	X	G

The presence of heavy loads on the earth's surface, such as several kilometres of glacial ice, may compress and depress the underlying rock, followed later by rebound effects when the load is removed.

[Consideration of this factor is included under Glaciation and Topography (future).]

Magmatic activity	E	FR	U	X	-

Magmatism could occur in the vicinity of the vault, leading to substantial changes to groundwater flow and rock properties.

[This factor is included with the discussion under Volcanism.]

Magnetic poles (reversal)	E	F	E	X	-

Reversal of the earth's magnetic poles could lead to changes in the earth's ionization layer, with subsequent evolution of the climate.

[This event occurs very rarely, and is also expected to have no significant impact on the performance of the geosphere. See also Climate change. Further discussion is provided under Climate change and Flipping of earth's magnetic poles in the list of biosphere factors (Table B-3).]

Matrix diffusion	P	T	E	CX	G

Contaminants may diffuse into surrounding rock from contaminated water in a fracture zone or from contaminated rock into a nearby fracture zone, due to matrix diffusion.

[Matrix diffusion generally refers to the diffusion of contaminants in a direction that is transverse to the direction of convective transport (and into the surrounding rock matrix). We expect that diffusion would be the dominant transport mechanism in some regions of the geosphere, particularly in the regions of low-permeability sparsely fractured rock surrounding the reference disposal vault. In this instance, contaminant transport by diffusion should be considered. In other regions, where convective transport is dominant or equally important, we have concluded that convection and longitudinal diffusion should be considered, and that it is acceptable to ignore transverse diffusion. That is, diffusion in the direction of the convective transport should be modelled, but diffusion in directions perpendicular to convective transport can be ignored. This conclusion is based on our groundwater tracer tests and field evidence of geochemical patterns, which do not show much evidence of matrix diffusion effects. If

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

matrix or transverse diffusion is ignored, simpler transport models can be used; moreover, overestimates of impact will result because the effect of matrix diffusion would be to remove contaminants from groundwater flow paths, and thereby reduce contaminant transport. We have therefore assumed that this factor can be excluded from scenarios requiring quantitative evaluation in the postclosure assessment of the reference disposal system. See also Convection and Diffusion.]

Metamorphic activity	E	FR	U	X	-

Metamorphic activity could cause activation, creation, or sealing of faults; changes in topography; changes in rock stress; deformation of rock; and changes in groundwater temperatures.

[Metamorphic activity is not expected for long periods of time on the stable portions of the Canadian Shield that would be favoured for a disposal site. No such activity is certainly expected over the next 10^4 a, the time frame for quantitative evaluation in the postclosure assessment. We have therefore assumed that no further quantitative evaluation is required for the postclosure assessment, although some consideration may be required for longer time scales. See also Earthquakes, Topography (current) and Volcanism.]

Meteorite impact	E	FRT	U	X	GP

Meteorite impact could cause activation, creation and sealing of faults; changes in topography; changes in rock stress; and deformation of rock.

[Impacts from meteorites large enough to cause significant changes is very improbable; for example, Merrett and Gillespie (1993) report that such events would occur on the order of 2×10^{-11} events per year. This very low probability of occurrence would make a negligible contribution to the risk associated with the disposal facility. We have therefore concluded that no further evaluation for the postclosure assessment is warranted. See also Bomb blast and Earthquakes. Related discussion is provided under Collisions, explosions and impacts in the list of factors for the biosphere (Table B-3), and under Sabotage and improper operation in the list of factors for the vault (Table B-1).]

Methane	F	T	U	X	-

Methane in deep groundwaters may be a resource and the object of mining activities, or methane may modify the mobility of contaminants (methylation).

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

[Methane is not found in sufficient quantities in a crystalline rock pluton to warrant consideration as a potential resource or as an unusual source of methylation. We have therefore concluded that no further evaluation for the postclosure assessment is required. See also Complexation by organics and Microbes. Related discussion is provided under Biological activity, Complexation by organics and Long-term physical stability in the list of vault factors (Table B-1), and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table B-3).]

Microbes F T E X G

Incorporation of contaminants into or onto microbes or bacteria could affect the rate of transport of contaminants. The activity of microorganisms could affect the mobility of contaminants by methylating heavy metals, releasing organic ligands with a high complexing capacity, affecting the groundwater pH and redox, and reducing permeability in fractures.

[At the present time we do not have sufficient data to demonstrate the effects that microorganisms could have on increasing (or decreasing) contaminant mobility. The importance of this factor is, however, likely to depend on the specific characteristics of a given disposal site. Data for the postclosure assessment of the reference disposal system are chosen to be consistent with information from the Whiteshell Research Area, and studies at this Area reveal that only extremely small quantities of microbes and bacteria exist in the groundwaters at disposal vault depths. Stroes-Gascoyne and West (1994) have evaluated the potential effects of microorganisms in the context of the concept for disposal of Canada's nuclear fuel waste. Expansion of either introduced or indigenous microbiological communities within the open excavations could be controlled by good housekeeping. The most likely effect of microbiological activity on the geosphere would be the development of biofilms on available aerated surfaces (e.g., open fractures and microcracks in the excavation damage zone) immediately behind the surface of the excavations. If this did occur, it would tend to reduce the transport porosity and permeability of the region and could be potentially beneficial. Stroes-Gascoyne and West (1994) consider it unlikely that microbiological activity would cause any significant geochemical changes in the geosphere because of the very large buffering capacity in the geosphere and the low nutrient availability (indigenous microbial populations are presumably in equilibrium with the geochemical conditions at the site). If biofilms were developed by introduced microbes or by expanding populations of indigenous microbes (the likely situation if microbes are present, because biofilms improve the chance for survival in nutrient poor conditions), they would tend to retard the transport of vault

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TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

contaminants by fixing contaminants by sorption. Biofilms may also compete with colloids for sorption of vault contaminants, thus tending to reduce the already negligible effect that colloids would have on contaminant transport if radiocolloid formation was reversible (Vilks et al. 1991b). Microbes and bacteria could exist in the vault itself but it is expected that they would not pass through either the buffer and backfill materials of the vault or the intact rock surrounding the vault because these materials would act as filters to microbes, colloids and bacteria. On the basis of these considerations, we have assumed that no further evaluation is required for the postclosure assessment of the reference disposal system. See also Complexation by organics. Further discussion is provided under Biological activity, Complexation by organics and Long-term physical stability in the list of vault factors (Table B-1) and under Bacteria and microbes in soil, and Biological evolution in the list of biosphere factors (Table B-3).]

Mines	E	FRT	A	IX	G

Mines constructed in the vicinity of the disposal vault could affect groundwater flow regimes, rock integrity and transport pathways.

[This factor is discussed under Intrusion (mines). See also Borehole - well, Boreholes - exploration, Solution mining, Wells and Wells (high-demand).

Open boreholes	E	FT	AV	O	GV

Boreholes that were left open, improperly sealed or reopened for some reason, could modify flow and transport properties, including transport within the borehole and within the damaged zone surrounding the borehole. Similar effects could occur for the vault shafts.

[This event is thought to be unlikely, because the engineering designs for the disposal facility call for the permanent sealing of all boreholes, including those drilled during site characterization and facility operation. Scoping studies suggest that the situation with greatest risk is where an open borehole was drilled from the surface and passed close to a vault room that contained nuclear fuel waste. We have concluded that this factor should be examined further in the open-borehole scenarios for the postclosure assessment of the reference disposal system, and the assessment should evaluate the effectiveness of quality assurance measures that would decrease the likelihood of a borehole being left open at the time of vault closure. See also Borehole seal failure and Shaft seal failure. Related discussion is provided under factors on intrusion in the lists of vault, geosphere and biosphere factors (Tables B.1 to B.3).]

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	T/E/P	Comp.	Mech.	Treat.	Ref.
Ozone layer	E	F	E	X	G

Destruction or damage to the earth's ozone layer may lead to significant changes to the climate, affecting properties of the geosphere, such as groundwater flow patterns.

[Discussion of this factor is included with Climate change.]

Precipitation and dissolution	P	T	EV	X	G

Contaminants, primary minerals and rock alteration products, could be subjected to precipitation and dissolution at different points along their flow paths, as a result of changes in temperature (thermal gradients), groundwater chemistry, flow rates and mineralogy, or the presence of microbes.

[The major driving force for these processes would be the thermal gradient produced by the vault. However, the expected thermal gradient is not large: the maximum temperature rise would be about 35°C within 50 m of the vault (Chan et al. 1986). Precipitation is likely to be more important, which would tend to reduce permeabilities in the geosphere and thereby reduce groundwater flow and contaminant transport. It is expected that the rock alteration products that precipitate would be similar to those already found within the geosphere, such as calcite and gypsum. The extent of these processes are difficult to predict, but we have concluded that overestimates of impact would result if they were ignored. We have therefore assumed that no further consideration is required for the postclosure assessment. See also Earthquakes, Groundwater composition, Groundwater - evolution, Hydraulic properties - evolution, Sorption and Vault heating effects. Related discussion is provided under Chemical gradients, Chemical interactions, and Precipitation and dissolution in the list of vault factors (Table B-1).]

Pseudo-colloids	P	T	E	X	G

The formation of pseudo-colloids could affect the transport of contaminants.

[Pseudo-colloids are naturally occurring particles, such as clay, that contain sorbed contaminants. Discussion of this factor is included under Colloid formation.]

Radiation effects	P	RT	V	X	G

Radiation damage and radiolysis products could affect the properties of the rock, including structural integrity, sorptive capabilities and the chemistry of the groundwater.

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor **F/E/P** **Comp.** **Mech.** **Treat.** **Ref.**

[Radiation damage would occur mostly from g-irradiation. However, experimental evidence shows that g-irradiation has little or no effect on the structure of clay minerals in the buffer material (Oscarson and Cheung 1983). No significant effects are expected on the surrounding rock, which would be more distant from the used fuel containers than the buffer in the vault. Radiolysis is the dissociation of molecules caused by the absorption of high-energy radiation. Most of the products of radiolysis would be generated by alpha decay of heavy nuclides (such as uranium and plutonium), which would be localized mostly to the vicinity of the used fuel container. It is expected that most of these radiolysis products would be consumed within the vault, and have no significant effect on the properties of the rock and groundwater in the geosphere. Radiation damage and radiolysis effects from decaying radionuclides that escaped from the vault would also be insignificant, because concentrations of such nuclides are expected to be extremely small. We have therefore assumed that radiation effects on the geosphere do not require further consideration in the post-closure assessment. Related discussion is provided under Radiation damage and Radiolysis in the list of vault factors (Table 1.2).]

Radioactive decay P W E C G

Radioactive decay, including the ingrowth of progeny, would affect the movement and concentrations of contaminants. Members of a radioactive decay chain may have different sorption and transport properties in the geosphere, which would lead to differences in their transport.

Recharge groundwater P T E CX G

Different sources of recharge water could change the chemistry of the groundwaters passing through the vault. Mixing of these waters with other groundwaters could result in precipitation, dissolution and altered chemical gradients.

[Groundwater compositions in plutonic rocks of the Canadian Shield are controlled to a great extent by rock-water interactions that cause the chemistry of the recharging water to gradually evolve toward high salinity and a Ca-Na-Cl composition with greater depth and longer travel lengths along the groundwater flowpaths (Davison et al. 1994a). Most aspects of this factor are included in the central scenario, but some may be excluded. See also Colloid formation, Complexation by organics, Geochemical interactions, Groundwater composition, Groundwater - evolution, Microbes, Precipitation and dissolution, Salinity effects on flow, Saturation, Sorption, Speciation and Vault heating effects. Related discussion is provided under Chemical gradients, Chemical interactions and Chemical kinetics in the list of vault factors (Table B-1).]

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Rock properties	F	T	E	C	G

Expected features of the rock that should be modelled include porosity, tortuosity, permeability, active (open) fracture joints or zones, inhomogeneities and structures such as layers or zones of different rock. Rock properties, such as permeability, measured in the laboratory may be significantly different from in situ values. (Most features of the rock that affect contaminant transport such as fractures and faults and their physical and chemical properties are determined in situ using field testing procedures. Some rock properties are determined in the laboratory and these studies are performed so as to account for the disturbance that occurs when the sample is removed from its in situ environment. See also Conceptual model - hydrology, Damaged zone, Hydraulic properties - evolution, Open boreholes, Rock properties - undetected features, Shaft seal failure, Topography (current) and Topography (future).)

Rock properties - undetected features	F	T	E	X	G

Undetected but important features may be present and may have significant impacts. These features include unknown active fracture zones, inhomogeneities, faults and features connecting different zones of rock, different geometries for fracture zones, and induced fractures due to the construction or presence of the vault.

[The time required for the selection, construction, operation, decommissioning and extended monitoring stages of an actual disposal facility would take several decades. During this time, site characterization activities would continue, and contribute to the development of a complete understanding of important properties of the disposal system. We expect that, over these long time frames, a calibrated and thoroughly tested conceptual model could be developed, and that any remaining undetected features would have no significant effects. Also, the importance of detected features, and possible or plausible features, could be evaluated through sensitivity analysis studies, using both detailed research codes and performance assessment codes. We have assumed that there are no features that are both undetected and important for the postclosure assessment of the reference disposal system, and therefore no further evaluation is required. See also Conceptual model - hydrology, Damaged zone, Hydraulic properties - evolution, Open boreholes, Rock properties, Shaft seal failure, Topography (current) and Topography (future).]

Sabotage	E	F	A	X	-

Acts of sabotage, during or after closure, may affect flow properties.

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
[Acts of sabotage occurring after closure are not likely to occur, and should not significantly affect the performance of the geosphere. Acts of sabotage occurring during or before closure could be mitigated if they were significant, and it would be more appropriate to deal with them in the preclosure assessment. We have therefore assumed that further evaluation for the postclosure assessment is not warranted. See also Bomb blast, Blasting and vibration and Explosion. Related discussion is provided under Sabotage and improper operation in the list of vault factors (Table B-1), and under Collisions, explosions and impacts in the list of biosphere factors (Table B-2).]					
Salinity effects on flow	P	F	E	C	G
Deep groundwater flow may be influenced by density gradients due to varying salinities.					
Saturation	P	T	E	C	G
The available sorption sites may be saturated by an over-abundance of contaminants or natural competing species. See also Sorption and Sorption - nonlinear.					
Sea level change	E	FT	E	X	-
Climate changes and different stages of glacial cycles would raise and lower sea levels, possibly affecting groundwater flow and contaminant transport.					
[This factor may be of concern for disposal facilities located near a sea. This is not the case, however, for the reference disposal system evaluated in the postclosure assessment; the nearest body of sea water is hundreds of kilometres distant. We have therefore assumed that no further evaluation is required for the postclosure assessment.]					
Shaft seal failure	E	FT	AV	CX	VG
Failure of the shaft seals and grouts could modify flow and transport properties, including enhanced transport within the shafts (possibly with percolation) and between the seals and rock.					
[Following detailed investigation by the Vault Model Working Group, it was concluded that seal failures should be included in the central scenarios through variability in parameter values (see Uncertainty). However, the group also concluded that no significant changes in groundwater flow are expected due to seal degradation, because the vault design includes a redundant combination of bulkheads, seals and backfill in the shafts, which would control and limit groundwater movement for long periods of time. Signifi-					

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

cant changes would be possible only in the very unlikely event of complete failure of several of these redundant elements (Chan and Stanchell 1990, Johnson et al. 1994). In addition, the shafts would be remotely located from any vault room containing used fuel waste (typically 100 m or more), further reducing any possible effects on the movement of contaminants in the geosphere. We have therefore assumed that no further evaluation is required for the postclosure assessment. See also Borehole seal failure, Conceptual model - hydrology, Damaged zone and Hydraulic properties - evolution. Related discussion is provided under Percolation in shafts, Seal evolution and Seal failure in the list of vault factors (Table B-1).]

Solution mining	-	E	FRT	A	X	-

Solution mining or other new mining techniques might be used near the vault, affecting flow regimes, transport pathways and/or rock properties.

[Solution mining of the crystalline rock is expected to be improbable, because of the very low permeabilities and because site selection would favour a site that has no economic value as a source of minerals. (Davison et al. 1994b). No further evaluation for the postclosure assessment is warranted. See also Intrusion (mines).]

Sorption	P	T	E	C	G

Sorption of contaminants would depend on factors such as the nature of the contaminant, minerals involved, mineral surface area, pH, electrochemical potential, salinity and available complexing ligands. See also Colloid formation, Geochemical interactions, Groundwater composition, Precipitation and dissolution, Saturation, Sorption - nonlinear and Speciation. Related discussion is provided under Chemical interactions, Sorption and Sorption - nonlinear in the list of vault factors (Table B-1).

Sorption - nonlinear	P	T	E	C	G

Sorption of contaminants may show a non-linear dependence on factors such as contaminant concentration. The extent of sorption along a flowpath may also change in response to different combinations of minerals and groundwater chemistry. See also Colloid formation, Geochemical interactions, Groundwater composition, Precipitation and dissolution, Saturation, Sorption and Speciation. Related discussion is provided under Chemical interactions, Sorption and Sorption - nonlinear in the list of vault factors (Table B-1).

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Speciation	P	T	E	C	G

Speciation of contaminants in waters containing different inorganic and organic components would affect mobility and sorption. See also Colloid formation, Complexation by organics, Geochemical interactions, Groundwater composition, Precipitation and dissolution, Recharge groundwater, Sorption and Sorption - nonlinear.

Topography (current)	F	T	E	C	G

Present-day topographical features should be modelled, including outcrops and hills, water-filled depressions, wetlands, recharge areas and discharge areas. See also Conceptual model - hydrology, and Topography (future).

Topography (future)	F	T	E	X	G

Changes affecting topographical features should be modelled or estimated, so that subsequent effects on flow can be taken into account.

[Processes that change topographical features may be classified according to whether they affect regional or local areas. Regional processes are of no concern, since they would not have significant effects on the relative hydraulic heads that drive groundwater flow past the vault. Local processes are expected to be of little concern, since they would also not significantly affect hydraulic heads. We have therefore assumed that no further quantitative evaluation is required for the postclosure assessment. See also Dams, Earthmoving, Earthquakes, Erosion, Glaciation and Topography (current). Related discussion is provided under Earthmoving projects, Flooding and Water management projects in the list of biosphere factors (Table B-3).]

Turbulence	P	FT	U	X	-

Turbulent flow of groundwater could affect its transport capabilities.

[This factor is very unlikely because groundwater flow velocities at disposal vault depths in the Whiteshell Research Area are very small and well below the range where turbulent flow would occur (hydrological data for the postclosure assessment of the the reference disposal system are chosen to be consistent with information from the Whiteshell Research Area). See also Cavitation.]

Uncertainties	EFP	all	all	C	BGPV

The geosphere system is very difficult to model because it is difficult to access. For example, it would not be possible to

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

directly observe concentrations of minerals and groundwater flows in all regions affected by the disposal vault. Considerable uncertainties exist in describing its current behaviour, and extrapolating this behaviour for thousands of years into the future. The effect of these uncertainties should be included in the postclosure assessment, using techniques such as sensitivity analysis and probabilistic systems assessment. Virtually all of the factors in this list have associated uncertainties that should be addressed in a quantitative fashion.

Unsaturated rock	F	FT	AU	X	GV

Portions of the geosphere may be naturally unsaturated or become unsaturated because of dewatering during construction of the vault. Consequently rock temperatures may rise and an unsaturated transport may be important.

[It is expected that the geosphere would consist of saturated rock at all times, except for a small volume of rock near the vault during and just after excavation. This rock should resaturate quickly because the reflooding transient is expected to be relatively short (see Reflooding in the list of Vault factors). In addition, the use of saturated transport models is expected to lead to overestimates of impact, because corrosion of the containers and the release and transport of contaminants requires the presence of water. We have therefore assumed that further evaluation for the postclosure assessment is not required. See also Dewatering. Related discussion is provided under Reflooding and Unsaturated transport in the list of Vault factors (Table B-1).]

Vault closure (incomplete)	E	FT	AV	X	GV

Incomplete or improper closure of the vault could lead to significant changes to anticipated flow in the geosphere.

[The time frame for the postclosure assessment begins after decommissioning and closure of the disposal vault. Thus this factor is outside the scope of reference of the postclosure assessment, and we have assumed that no further evaluation is required. However, this factor may warrant further consideration in the preclosure assessment, which deals with construction, operation, closure and decommissioning of the disposal facility.]

Vault heating effects	P	FR	V	C	G

Groundwater flow would be affected by the time-varying heat source in the vault; the resultant inhomogeneous geothermal gradient may result in the formation of convection cells. Thermally induced stresses superimposed on existing shear stresses might induce fracturing and fracture displacement, with subsequent alteration

TABLE B-2

GEOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
of flow paths and flow properties. See also Hydraulic properties - evolution, Geothermal gradient effects, and Precipitation and dissolution. Related discussion is provided under Backfill evolution, Buffer evolution, Chemical gradients, Chemical interactions, Precipitation and dissolution, and Seal evolution in the list of vault factors (Table B.1).					
Volcanism	E	FR	U	X	-
Volcanism (hot-spots and rifts) and magmatic activity could cause activation, creation and sealing of faults; changes in topography and in rock stress; deformation of rock; changes in groundwater temperatures; and severe perturbation to the integrity of the vault.					
[These processes are very unlikely for plutonic rock in the centre of the Canadian Shield. There are no hot-spots on the Shield at present and there is no evidence that plate tectonics will move the Canadian Shield over any hot-spots in the next 10^4 a. The site selection process would avoid seismically active regions of the Canadian Shield that might be of potential concern (Davison et al. 1994b). We have therefore concluded that no further evaluation for the postclosure assessment is warranted. See also Earthquakes, Faulting and Metamorphic activity.]					
Wells	F	FT	A	C	BGP
One or more wells drilled to supply domestic or irrigation water may intersect the contaminant plume. The central scenarios should deal with wells that have a low to medium demand, because well water use by members of the critical group is expected to be modest. It is expected that wells in this class and located in the Whiteshell Research Area (the site of the reference disposal system) would not substantially perturb existing groundwater flow fields during periods of maximum demand. See also Borehole - well, and Wells (high-demand). Related discussion is provided under the factors for intrusion in the list of vault and biosphere factors (Tables B.1 and B.3).					
Wells (high-demand)	F	FT	A	C	BGP
One or more wells drilled to supply domestic or irrigation water may intersect the contaminant plume. The "high-demand" qualification for this factor implies that existing flow fields would be substantially perturbed as a result of large volumes of water being drawn from the well(s). For a well located in the Whiteshell Research Areas, such perturbations would occur for well demands of the order of 10^4 m^3/a (Reid and Chan 1988, Reid et al. 1989). (Geochemical and hydrogeological data for the postclosure assessment of the reference disposal system are chosen to be					

TABLE B-2

GEOSPHERE FACTORS (concluded)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
consistent with information from the Whiteshell Research Area). It was first thought that the effects of this factor would have to be represented by a separate geosphere model for a separate (alternative) scenario, compared with the geosphere model used to represent the central scenario for the postclosure assessment of the reference disposal system. It was subsequently concluded, however, that the geosphere model could be developed to include perturbations caused by high-demand wells (Davison et al. 1994a). Thus this factor is included within the central scenarios for the postclosure assessment of the reference disposal system. See also Borehole - well, and Wells. Related discussion is provided under the factors for intrusion in the list of vault and biosphere factors (Tables B.1 and B.3).					

TABLE B-3

BIOSPHERE FACTORS FOR THE REFERENCE DISPOSAL SYSTEM

The headings **F/E/P**, **Comp.**, **Mech.**, **Treat.**, and **Ref.** use the following abbreviations:

F/E/P - classified as **F**eature, **E**vent or **P**rocess.

Comp(onent) - classified for route to man (**C**ontact, **I**ngestion and **R**espiration (Inhalation)) and cause (**A**nthropogenic, **F**acility or **N**atural).

Mech(anism) - classified as **B**iological, **C**hemical or **P**hysical.

Treat(ment) - recommended treatment for the postclosure assessment. Some factors should appear in the **C**entral scenarios and/or in one of the **O**pen-borehole or **I**nadvertent human intrusion alternative scenarios. Others may be e**X**cluded from scenarios because they would not contribute significantly to estimated impacts.

Ref(erence) - reports on the **A**tmosphere model (Amiro 1992a), **B**iosphere model (Davis et al. 1993), **F**ood-Chain model (Zach and Sheppard 1992), effects of **G**laciation (Elson and Webber 1991), **P**ostclosure assessment (Goodwin et al. 1994), **S**oil (Sheppard 1992), and Surface **W**ater (Bird et al. 1993).

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Acid rain	F	AIN	BC	C	SW

Acid rain can detrimentally affect aquatic and terrestrial life by interfering with the growth, reproduction and survival of organisms. It can influence the behaviour and transport of contaminants in the biosphere, particularly in surface water and soil. In surface water, it may change the solubility, sedimentation and bioavailability of some contaminants (Santschi et al. 1986, Schindler and Turner 1982, Wang 1987, Schindler et al. 1980). In the soil, it can decrease sorption and thereby increase the mobility of some contaminants (Sheppard and Sheppard 1988). Moreover, it can reduce soil pH and enhance pH degassing of carbon dioxide. (Acid raid should be considered quantitatively, but not necessarily explicitly in the postclosure assessment. See also Bioconcentration, Ion exchange in soil, Precipitation (meteoric), Seasons, Sedimentation in water bodies, Soil sorption, Surface water bodies and Surface water pH.)

Extreme and continuous dry weather can cause the accumulation of salts and contaminants at the soil surface, where water continuously evaporates.

Alkali flats	F	NCIR	CP	X	S

(Alkali flats are uncommon, or occur only temporarily, on the Canadian Shield because precipitation is relatively high and this tends to leach soils. Such areas do not support much vegetation or may be completely bare, and thus would not likely be used as

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
gardens or forage fields by the critical group. Given these considerations, we have assumed that further evaluation is not required in the postclosure assessment. See also Capillary rise in soil, Climate, Climate change, Dust storms and desertification, Erosion (wind), Greenhouse effect, Precipitation (meteoric), Seasons, and Soil leaching.]					
Animal diets	F	AIN	BC	C	F
Various domestic and wild animals have different diets, and there can be both qualitative and quantitative differences. These are important factors in determining contaminant intake and concentration. Less important are special dietary aspects, such as food supplements, man-made salt licks and medication. See also Animal soil ingestion, Bioconcentration, Carcasses, Critical group - pets, Fish farming, Game ranching, Human diet, and Scavengers and predators.					
Animal grooming and fighting	P	CIN	B	C	F
Terrestrial animals may become externally contaminated with radionuclides from contact with water, soil or air. Radionuclides may then be ingested by the animal itself or by another animal through a variety of activities, such as grooming, preening and fighting. These exposure pathways are likely to be of minor importance compared with direct intake of water, soil and air. In aquatic animals, such as fish, pathways related to grooming and fighting are likely even less important than in terrestrial animals. Thus pathways related to animal grooming and fighting deserve to be considered quantitatively, but not necessarily explicitly. See also Burrowing animals, Critical group - pets, Dermal sorption (except tritium) and Dermal sorption (tritium).)					
Animal soil ingestion	P	CIN	B	C	F
Terrestrial animals routinely ingest soil inadvertently or sometimes purposefully to meet nutritional needs (Zach and Mayoh 1984). Soil may be ingested directly or through contaminated plants. Soil from natural salt licks formed by discharge of deep groundwater is particularly attractive to animals. Soil ingestion can lead to the intake and absorption of contaminants, which can be significant for contaminants that are not readily taken up and transferred via plants. Aquatic animals, such as fish, may ingest sediments and thereby contaminants. See also Animal diets, Erosion (wind), Human soil ingestion, Soil and Terrestrial surface.					
Ashes and sewage sludge fertilizers	F	AIR	BCP	C	F
These materials, which may be contaminated with contaminants, may be applied to land to increase plant yield. Contaminants may then					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

be taken up by plants and enter various food webs. While in the soil, the radionuclides may expose humans and other organisms to external radiation. In addition, ash may be used in the manufacturing of building materials, which could also result in external radiation exposure. All these exposure pathways, which are likely of minor importance, are related to recycling of contaminants. Recycling is an important process and thus the application of ash, sewage sludge and fertilizer needs to be considered quantitatively, although not necessarily explicitly. See also Building materials, Crop fertilizers and soil conditioners, Fires (agricultural), Herbicides, pesticides and fungicides, Peat and leaf litter harvesting, Recycling and Soil.

Bacteria and microbes in soil	F	NCIR	BC	C	FS

These organisms help to decompose organic matter in the soil and liberate contaminants, which may then be leached or recycled. Bacteria and microbes may also chemically transform contaminants and thereby change their mobility in the environment (Loewen and Flett 1984). Clearly, these organisms can play an important role in the behaviour and transport of contaminants in the environment, and their effects must be considered quantitatively, but not necessarily explicitly. See also Chemical precipitation, Ion exchange in soil and Soil sorption. Further discussion is provided under Biological activity, Complexation by organics and Long-term physical stability in the list of vault factors (Table B-1), and under Complexation by organics, Methane, and Microbes in the list of geosphere factors (Table B-2).

Bioaccumulation	P	NCIR	B	C	BF

Contaminants may accumulate in different organisms, including members of the critical group, affecting impacts. (This factor is discussed under Bioconcentration.)

Bioconcentration	P	NCIR	B	C	BF

Contaminants may concentrate in different organisms, including members of the critical group, affecting impacts. Bioaccumulation and biomagnification are related processes and are often confused with bioconcentration (Zach and Sheppard 1992). Bioconcentration refers to the ability of an organism to concentrate a contaminant from its environment, usually from water or soil. Bioaccumulation refers to the tendency of an organism to continue to bioconcentrate throughout its lifetime. Finally, biomagnification refers to the occurrence of a contaminant at successively higher concentrations with increasing trophic level in the food web. All these processes are important in the food-chain transfer of contaminants and need to be considered quantitatively, although not necessarily in detail. See also Scavengers and predators.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Biogas production	P	AR	BC	X	A

Heating needs may be met with biogas from biological reactors fueled by plant materials, faeces and refuse, or from trapping natural methane from garbage disposal sites, bogs and sediments. These fuels may be contaminated with radionuclides and this may lead to radiation exposure.

[These heating methods would lead to increased suspension of radionuclides in the atmosphere. However, they are likely of minor importance compared with the use of wood or peat (Amiro 1985). We have therefore assumed that biogas production need not be treated explicitly in the postclosure assessment. See also Gas leakage into basements, Household dust and fumes, Radon emission, Space heating, and Suspension in air.]

Biological evolution	P	IN	B	X	BF

Organisms are subject to biological evolution in an everchanging environment. Evolution may affect not only anatomical features, but also physiological processes. The rate of evolution varies for a given organism, depending on the rate of change in the environment. It also varies between organisms and it can be very rapid in bacteria and microbes, which have short generation times.

[Biological evolution is driven by natural selection, which, in turn, is based on random genetic variation. Thus many aspects of biological evolution are unpredictable and direct quantitative evaluation would be difficult. However, it is likely that evolution will not lead to new or unusual exposure pathways, partly because a wide variety of representative pathways are explicitly included within the description of the biosphere. Moreover, the Atomic Energy Control Board has indicated that it is reasonable to ignore biological evolution in the postclosure assessment, and to assume persistence of present day conditions (AECB 1987a). We have therefore assumed that no additional evaluation is required for the postclosure assessment. See also Climate change, Critical group - evolution and Mutagenic contaminants. Further discussion is provided under Mutation in the list of vault factors.]

Biomagnification	P	NCIR	B	C	BF

Contaminants may occur in higher concentrations in organisms that are further up the food chain. (This factor is discussed under Bioconcentration.)

Biotoxicity	P	CIN	BC	CX	BFG

Radionuclides can be radiologically and chemically toxic.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

[Evaluation of these effects for humans and other organisms is a key feature of the postclosure assessment. In terms of the behaviour and transport of radionuclides in the environment, biotoxicity can lead to the disruption of food webs. For human dose prediction, such disruptions need not be considered quantitatively because ignoring their effects on food webs would lead to overestimates of dose (Zach and Sheppard 1992). In addition, the human dose limit established by the Atomic Energy Control Board is a small fraction of the natural background dose (AECB 1987a) and this would likely exclude any possibility of biotoxic effects. See also Bioconcentration, Carcinogenic contaminants, Chemical toxicity, Mutagenic contaminants, Radiotoxic contaminants, and Teratogenic contaminants.]

Bioturbation of soil and sediment	P	INR	P	C	SW

Plants and especially burrowing animals can physically displace large amounts of soil. This would promote redistribution and uniform mixing of contaminants in soil and sediment (Robbins and Edgington 1975, Robbins et al. 1977, Durham and Joshi 1984). For agricultural soil, bioturbation has an effect similar to plowing. This type of mixing is important and thus bioturbation of soil and sediment needs to be quantified, although not necessarily explicitly. For example, it may be adequate to assume that contaminants are uniformly distributed in soil and sediment. See also Burrowing animals, Sediment resuspension in water bodies, and Soil.

Building materials	F	ACR	B	C	F

Wooden and inorganic building materials could become contaminated through a variety of processes. This would lead to external radiation exposure of humans, although such exposure would likely result in a relatively low radiation dose compared with internal exposure from ingestion and inhalation of radionuclides. See also Critical group - house location, Groundshine and Urbanization on the discharge site.

Burrowing animals	F	IN	BCP	C	F

Burrowing animals may contact or ingest contaminated soil and some of the soil may then be ingested by humans, resulting in direct contaminant transfer from soil. Soil ingestion by humans is a potentially important exposure pathway (Hawley 1985) that needs to be considered quantitatively, although individual contributors to this pathway need not necessarily be considered explicitly. See also Animal soil ingestion, Animal diets, Bioturbation of soil and sediment, and Human soil ingestion.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Capillary rise in soil	F	ACINR	BCP	C	SB

Capillary rise involves the drawing up of soil water, above the water table, in continuous pores of the soil until the suction gradient upward is balanced by the gravitational pull downward. It is a key process in soil solute transport; for example, contaminants dissolved in soil water can be transported upward with capillary rise (Sheppard 1992). See also Soil and Soil leaching.

Carcasses	P	INR	B	C	F

The bodies and remains of contaminated animals could lead to new routes of exposure. Humans do not usually scavenge carcasses, but if they did, the effects would be similar to ingesting meat from animals killed for meat purposes. This should be treated quantitatively. Rotting carcasses may also return contaminants to the surrounding soil. This type of recycling is an important ecological process that needs to be considered quantitatively, but not necessarily in great detail. See also Bacteria and microbes in soil, Human diet, and Scavengers and predators.

Carcinogenic contaminants	F	ACIR	BC	C	BFGP

Besides heritable effects, carcinogenesis is the major concern in radiation exposure (ICRP 1977, 1991). Similarly, some elements that are part of nuclear fuel waste may be chemically carcinogenic. Carcinogenesis has focussed mainly on humans but it should also be considered for animals in a general way. See also Biotoxicity, Chemical toxicity, Cure for cancer, Mutagenic contaminants, Radiotoxic contaminants and Teratogenic contaminants.

Charcoal production	P	AR	CP	C	AB

Charcoal may be produced from wood contaminated with radionuclides, and the charcoal may then be used as a source of heat or as a filter material. Charcoal production and burning would drive off some radionuclides, but others may remain with the ash. Ash, as well as charcoal filter material, would have to be disposed of and this may result in the contamination of the environment. This type of disposal relates to recycling of materials and contaminants. The suspension of contaminants to the atmosphere through charcoal production and use is equivalent to direct burning of wood, and therefore it may be adequate to include charcoal production implicitly with the burning of wood. The same is true for recycling of ash and used filter material. See also Ashes and sewage sludge fertilizers, Fires (agricultural), Fires (forest and grass), and Space heating.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Chemical precipitation	P	NCIR	C	C	BSW

An important determinant in the transfer of contaminants in the environment is mobility. Highly mobile contaminants tend to reach humans and other organisms, and increase radiation exposure. Chemical precipitation in surface water, wetlands and soil tends to reduce mobility and thereby doses. On the other hand, chemical precipitation in the soil rooting zones may result in larger transfers of contaminants to edible plants. See also Ion exchange in soil, and Soil sorption.

Chemical toxicity	F	AIR	C	C	BFP

Some elements in nuclear fuel waste can be chemically toxic to humans and other organisms, including plants. Chemical toxicity can involve teratogenic, mutagenic or carcinogenic effects and thus interfere with reproduction, growth and survival. Although chemical toxicity has often been focussed on humans, it should also be examined for plants and animals. See also Biotoxicity, Carcinogenic contaminants, Mutagenic contaminants, Radiotoxic contaminants and Teratogenic contaminants.

Climate	P	NCIR	BCP	C	ABFSW

A wide variety of climatic factors, such as temperature, precipitation and wind speed, can directly or indirectly influence the behaviour and transport of contaminants in the environment. For example, temperature influences heating fuel needs, which in turn may influence radionuclide concentration in indoor air and the inhalation dose to humans. Climate is an important driving force for contaminant transport through the soil (Sheppard 1992) and the atmosphere (Amiro 1992a). Similarly, short-term natural fluctuations in climatic conditions, as might occur over the next 10^4 a on the Shield, need to be considered quantitatively. These influences of climatic factors on dose prediction argue for their quantitative consideration in the postclosure assessment. See also Alkali flats, Climate change, Dust storms and desertification, Flipping of earth's magnetic poles, Glaciation, Greenhouse effect, Irrigation, Ozone layer failure, and Seasons.

Climate change	P	NCIR	BCP	CX	BG

There could be massive climate changes on the Shield due to anthropogenic and natural causes. Here the focus is on natural causes and in particular the occurrence of further continental glaciations.

[There are many uncertainties in evaluating the potential effects of climate change on the behaviour and transport of radionuclides in the environment, and radiation doses to various organisms. In spite of this, some specific changes may require quantitative

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
evaluation in the postclosure assessment. Others may be excluded; for example, the next onset of a major glacial episode is expected about 2 x 10^4 a or more from the present (Eronen and Olander 1990, Davis et al. 1993). Since quantitative estimates of impact are required for only the first 10^4 a following closure, changes due to glaciation may be excluded. Further discussion of climate and climate change is provided under the headings for Climate, Dust storms and desertification, Glaciation and Greenhouse effect, under Climate change in the list of geosphere factors (Table B-2), and under Global effects in the list of vault factors (Table B-1).]					
Collisions, explosions and impacts	E	ACINR	P	X	-
A variety of disasters might happen that could compromise the integrity of the disposal system: an aircraft could crash on the earth's surface above the vault; a nuclear device could be detonated near the vault during testing or in a war; a large meteorite may strike near the vault, open it and disperse its contents over a wide area. These, and other events, could significantly change the way the biosphere functions, and dramatically increase the potential radiation dose to humans and other organisms.					
[The effects of these events on the biosphere are difficult to predict. It appears, however, that such events are improbable or would not substantially affect the overall effectiveness of the reference disposal system. For example, there are no known explosive devices capable of breaching the reference disposal vault, located at a depth of 500 m in a granite pluton; and impacts by meteorites large enough to cause significant damage are of the order of 2 x 10^{-11} per year (Merrett and Gillespie 1983). It is therefore assumed that no further evaluation is required for the postclosure assessment. See also Earthquakes, Intrusion (deliberate) and Intrusion (inadvertent). Further discussion may be found under Bomb blast and Meteorite impact in the list of factors for the geosphere (Table B-2), and under Sabotage and improper operation in the list of factors for the vault (Table B-1).]					
Colloids	F	INR	C	C	SW
Colloids consist of small organic or inorganic particles, ranging in size from 1 to 1000 nm in diameter. Because of their small size, colloidal particles remain suspended in the media, usually water. However, under certain circumstances they can agglomerate and settle out (Lush and Hynes 1973). Radionuclides can become strongly attached to colloidal particles and this can influence their behaviour and transport in the environment, particularly in surface water and soil. For example, highly immobile radionuclides can become mobile as part of colloidal particles (Means					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

et al. 1978, Cleveland and Reese 1981, Choppin 1988). Thus colloids should be considered in the postclosure assessment, although an implicit treatment may be satisfactory. See also Capillary rise in soil, Dispersion, Sedimentation in water bodies, and Soil sorption. Further discussion is provided for Colloids in the list of vault factors (Table B-1) , and for Colloid formation in the list of geosphere factors (Table B.2).

Convection, turbulence and diffusion (atmospheric)	P	NCIR	P	C	AB

Air-borne radionuclides can be directed, diluted and dispersed by convection, turbulence and diffusion. This in turn can strongly influence dose predictions for various organisms. See also Deposition (wet and dry), Dispersion, Dust storms and desertification, Erosion (wind), Suspension in air, and Wind.

Correlation	P	NCIR	BCP	C	ABFSW

Model parameters are not always independent; that is, given a value for one parameter, the value for another may be restrained or fixed. For example, the amount of food a person consumes is related to the amount of water consumed, and the degree of root uptake of a contaminant is related to the solubility of the contaminant in the soil (Sheppard and Sheppard 1989). These relationships can be conveniently expressed as correlations, and consideration of correlations avoids the selection of unreasonable combinations of parameter values.

Critical group - agricultural labour	P	AI	B	C	ABF

Soil may become contaminated with radionuclides and these radionuclides may then become suspended in the atmosphere and inhaled by farmers. This could be a potentially important exposure pathway because plowing, cultivation and harvesting can create a great deal of dust. Thus inhalation of dust by farmers should be considered quantitatively in the postclosure assessment, although not necessarily in an explicit manner (Amiro 1992a). See also Dermal sorption (except tritium), Erosion (wind), Fires (agricultural), Human soil ingestion, Soil, Soil sorption and Suspension in air.

Critical group - clothing and home furnishings	F	ACR	B	X	BF

Clothing and home furnishings of the critical group (Zach and Sheppard 1992) could become contaminated with radionuclides and result in external radiation exposure.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp	Mech.	Treat.	Ref.

[There are a wide variety of such external exposure pathways which, traditionally, have not been considered explicitly in radiological assessments because of their minor importance. They are usually considered as part of other, more important pathways, such as air immersion, water immersion, ground exposure and exposure from building materials. This is particularly appropriate when these pathways include conservative assumptions that tend to inflate dose predictions. We have assumed that this type of treatment would be appropriate in the postclosure assessment and that no explicit quantitative consideration is required. See also Building materials, Critical group - house location, Groundshine, and Household dust and fumes.]

Critical group - evolution	F	ACIR	B	X	BF

Basically, humans are subject to biological evolution in the same way as other organisms, although humans may have escaped biological evolution to some extent by exerting control over natural selection and by modifying the environment to suit their needs.

[Evolution of the critical group is largely unpredictable, and direct quantitative evaluation would be difficult. However, it is unlikely that evolution would lead to characteristics that would be substantially different from the pessimistic characteristics that are explicitly evaluated in the postclosure assessment. Moreover, the Atomic Energy Control Board has indicated that it is reasonable to assume present day characteristics for members of the critical group (AECB 1987a). The case is similar for cultural evolution with its scientific and technological advances, which may eventually totally prevent or cure radiation-induced cancers. Conversely, there could also be a loss of scientific and technological knowledge due to global war or other factors. We have assumed, for the postclosure assessment of the reference disposal system, that humans and their lifestyle and activities remain much as they are now. See also Biological evolution and Cure for cancer.]

Critical group - house location	F	AR	B	C	BF

The exact location of a house can be an important determinant in the radiation exposure to its occupants, particularly external exposure from the ground and internal exposure from radon gas. By definition, the house occupied by the critical group must be located such that radiation exposure is higher than for any other group of humans. See also Building materials, Gas leakage into basements, Household dust and fumes, Radon emission, and Urbanization on the discharge site.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Critical group - individuality	F	AIR	BC	C	BF

People vary anatomically, physiologically and especially in their habits, such as food preference (Guthrie 1983). This type of variability can impact on dose predictions and, therefore, should be treated quantitatively, either implicitly or explicitly. The same is true for susceptibility to radiation, which may vary in relation to age, sex and reproductive status (ICRP 1977, 1991). See also Building materials, Critical group - leisure pursuits, Critical group - pets, Food preparation, Houseplants, Human diet and Sensitization to radiation.

Critical group - leisure pursuits	F	AC	B	C	BF

Activities such as hockey or curling on contaminated ice, swimming or diving in contaminated water and playing baseball or golfing on contaminated ground could influence external radiation exposure. These types of leisure activities do not necessarily increase radiation exposure in comparison with alternative activities, such as reading, watching television or resting. In spite of this, the influence of leisure pursuits on radiation exposure needs to be considered quantitatively, although not necessarily explicitly or in great detail.

Critical group - pets	F	AC	B	X	F

Furry pets tend to be frequently handled by people during petting and grooming. Such pets could become externally contaminated with radionuclides through a variety of pathways, such as atmospheric deposition. Ingested radionuclides may also be transferred to the body surface and then shed with skin particles or hair. Thus, pets could influence radiation exposure to humans.

[In comparison with other pathways, such as ingestion and inhalation, human exposure from pets is expected to be minor. These minor exposure pathways could be considered implicitly by making conservative model assumptions that tend to inflate dose predictions of the major, explicitly considered pathways. We have assumed that this approach is appropriate for the postclosure assessment of the reference disposal system, and therefore that further evaluation is not required. See also Animal grooming and fighting, Animal diets, and Burrowing animals.]

Crop fertilizers and soil conditioners	P	AI	BC	C	F

Crop fertilizers, such as chemicals, manure, fish meal or minerals, and soil conditioners, such as peat moss or lake sediments, may become contaminated and affect food chains through plant uptake. Fertilizers would likely be of minor importance in contaminant transfer, but some relate to recycling of organic

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

materials. Soil conditioners, which may be used in large quantities, could have a substantial influence on radionuclide transfer in the environment and radiation exposure of humans and other organisms. Note that contaminants in the soil may have an impact on the environment and humans not just through plant uptake, but also through a variety of other exposure pathways. These processes need to be considered quantitatively, although not necessarily explicitly. See also Ashes and sewage sludge fertilizers, Critical group - agricultural labour, Peat and leaf litter harvesting, and Soil.

Crop storage	P	AIC	BC	X	BF

Contamination of stored crops and reduction in radioactivity are the two most important aspects of crop storage. Crops could become subject to seepage or flooding by contaminated water. Radioactivity in stored crops could decrease through radioactive decay. This would be particularly important for short-lived radionuclides.

[It is reasonable to assume that this is a minor pathway because the water may be uncontaminated, or less contaminated than the crops themselves, and because wetted crops may spoil and be discarded. We have therefore assumed that no further quantitative treatment is required. See also Human diet and Water leaking into basements.

Cure for cancer	E	ACIR	B	X	-

Scientific and technological advances may lead to the total prevention or cure of radiation-induced cancers.

[The risk of contracting cancer is a major concern associated with low levels of radiation exposure (BEIR 1990). If such cancers could be prevented or cured, the effect would be to reduce the potential risk from nuclear fuel waste. However, it is not prudent to bank on possible future advances. The Atomic Energy Control Board has also indicated that the postclosure assessment should be based on present day conditions (AECB 1987a). Thus it is appropriate to omit this factor from further consideration in the postclosure assessment. See also Biotoxicity, Carcinogenic contaminants, Chemical toxicity, Mutagenic contaminants, Radiotoxic contaminants and Teratogenic contaminants.]

Deposition (wet and dry)	P	NCI	P	C	ABFS

Air-borne contaminants may settle on surfaces through wet and dry deposition. This could lead to contamination of vegetation, soil and surface water. The importance of wet and dry deposition has

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
long been recognized in contaminant transport, and these processes are well understood (Amiro 1992a). See also Dispersion, Erosion (wind), Precipitation (meteoric) and Suspension in air.					
Dermal sorption (except tritium)	F	AC	BC	X	F
The main concern here is dermal sorption by humans through exposure of the skin to various health and beauty products, such as toothpaste, shaving cream, soap, moisturizer, etc. These products may become contaminated with radionuclides, which could then enter the human body because the skin can be permeable and absorb various substances.					
[Dermal sorption in general is likely to be of minor importance, at least for members of the critical group (or humans in general), compared with the direct ingestion and inhalation of radionuclides. Conservatism built into these major pathways could readily include dermal sorption, and therefore no explicit quantitative treatment of dermal sorption is required. See also Dermal sorption (tritium), and Intake of drugs.]					
Dermal sorption (tritium)	F	AC	BC	C	BF
Dermal sorption of tritium by humans could increase radiation exposure. Studies have shown that skin absorption of tritiated water vapour can be more important than inhalation (Osborne 1966). Thus, dermal absorption of tritium should be considered explicitly. See also Dermal sorption (except tritium).					
Dispersion	P	NCIR	P	C	ABFSW
Dispersion is a fundamental aspect of the transport of contaminants in the environment. It refers to the movement of a contaminant away from its source and its spreading out over space. Dispersion includes advection and diffusion, and water and air are important media for dispersion. Thus, dispersion can strongly influence contaminant concentrations in surface water, soil and air. Besides advection and diffusion, contaminants could also be dispersed in the environment by humans, animals and plant pollen. See also Capillary rise in soil, Convection, turbulence and diffusion (atmospheric), Erosion - lateral transport, Erosion (wind), Fires (agricultural), Fires (forest and grass), Flooding, Flushing of water bodies, Household dust and fumes, Irrigation, Outdoor spraying of water, Radon emission, Runoff, Saltation, Showers and humidifiers, Soil leaching, Surface water bodies, Suspension in air, and Wetlands.					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Dust storms and desertification	P	NR	P	CX	ABS

The focus here is on large-scale desertification as a result of extended drought. Thus, there could be deforestation and much of the grassland could also disappear. The exposed soil would erode and dust storms might become a common feature. Contaminants might move to the soil surface, which could result in the formation of alkali flats. Winds could then readily disperse contaminants. The area might become uninhabitable for humans and the critical group would be located far away from the vault. Desertification would represent a dramatic step away from current conditions on the Shield.

[As indicated by the Atomic Energy Control Board, the postclosure assessment is to be based on today's conditions (AECB 1987b). Thus, no quantitative treatment of desertification is required, although some consideration should be made for periods of low annual precipitation. See also Alkali flats, Capillary rise in soil, Climate, Climate change, Erosion - lateral transport, Erosion (wind), Irrigation, Outdoor spraying of water, Precipitation (meteoric) and Saltation.]

Earthmoving projects	E	ACIR	P	X	S

Major earthmoving projects could alter the landscape and expose subsoil, overburden or bedrock.

[The occurrence of these projects are largely unpredictable, as are a detailed evaluation of subsequent effects on the behaviour and transport of contaminants in the environment. However, it is reasonable to expect that no new or unusual exposure pathways would be created, given the wide range of representative pathways that must be considered in the description of the biosphere. Moreover, such projects would not likely have large effects on deep groundwater flows, and therefore would not significantly alter the performance of the geosphere and vault, nor the overall performance of the disposal system. The possible occurrence and effects of earthmoving projects should be a factor for consideration in the selection of a site (Davison et al. 1994b). Finally, it may well be that major earthmoving projects would be subject to environmental impact statements, which would include implications for existing structures, such as a nuclear waste disposal facility, and perturbations to existing natural systems. We have therefore assumed that further evaluation is not required for the postclosure assessment of the reference disposal facility. See also Intrusion (deliberate), Intrusion (inadvertent), Toxicity of mined rock, and Water management projects. Further discussion may also be found under Dams, Earthmoving, Erosion and Groundwater - evolution in the list of factors for the geosphere (Table B-2).]

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Earthquakes	E	NCIR	P	X	-

Earthquakes could influence the containment of the nuclear fuel waste by opening or closing fractures in the geosphere. This may change the discharge of contaminants from the geosphere into the biosphere.

[Earthquakes are not expected to cause new or unusual exposure pathways. For example, new lakes might be formed, but the description of the biosphere should include such features. In addition, site selection criteria would avoid seismically unstable regions, and therefore the probability of earthquakes would be small (Davison et al. 1994b, Goodwin et al. 1994). For these reasons, earthquakes need not be treated quantitatively as a factor for the biosphere. See also Collisions, explosions and impacts. Further discussion may also be found under Earthquakes in the lists for the vault and geosphere (Tables B.1 and B.2).]

Erosion - lateral transport	P	NCIR	P	C	ABS

Erosion of soil, overburden and bedrock by wind, water or ice may move contaminating radionuclides laterally away from the area occupied by the critical group (Zach and Sheppard 1992) and thus reduce local contamination. Alternatively, erosion may bring uncontaminated soil and overburden into this area and reduce radioactivity through dilution. There could also be lateral transport between fields and lakes. See also Climate, Climate change, Dispersion, Dust storms and desertification, Erosion (wind), Glaciation, Saltation, Soil, Suspension in air, and Terrestrial surface. Further discussion is provided under Erosion in the list of geosphere factors (Table B-2).

Erosion (wind)	P	NCIR	P	X	ABS

Soil and other materials contaminated with radionuclides may be exposed and eroded by wind action, and dispersed in the environment. This would remove radioactivity from the area occupied by the critical group, particularly because radionuclides tend to adhere to small clay particles, which are more easily carried away than the bulk soil.

[It is expected that the critical group would inhabit the area where contaminants discharge, because they would then be most exposed to all routes of potential contamination. Wind erosion would tend to reduce radioactivity in the area occupied by the critical group rather than increase it. Although downwind recipients might then have greater airborne exposures, they would be less likely to be exposed by other routes (such as ingestion of well water) that are expected to be more significant. To simplify the postclosure assessment, it is therefore deemed acceptable to ignore this process. See also Convection, turbulence and diffu-

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
sion (atmospheric), Critical group - agricultural labour, Dispersion, Dust storms and desertification, Erosion - lateral transport, Saltation, Soil, Soil sorption, Suspension in air, and Wind.					
Fires (agricultural)	E	ACIR	P	C	AB
Fires are routinely used to clear land for agricultural use, to reduce peat, to kill weeds and to remove stubble. The material being burned could be contaminated with various radionuclides which, upon burning, would be injected into the air as gases or particulates. This in turn could influence radiation exposure of humans and other organisms. Agricultural fires occur fairly frequently on the Shield, and quantitative consideration is required. However, it may be acceptable to deal with this factor without going into great detail (Amiro 1992a). See also Ashes and sewage sludge fertilizers, Critical group - agricultural labour, Critical group - house location, Dispersion, Fires (forest and grass), and Suspension in air.					
Fires (forest and grass)	E	AINR	BCP	C	AB
Most forest and grass fires are started accidentally or by natural causes. Forest fires are an important natural feature of the Shield, and they occur fairly frequently and regularly (Amiro and Davis 1991). Contaminating radionuclides may be injected into the atmosphere on burning trees or grass, which may enhance radiation exposure of various organisms through several pathways, such as inhalation and air immersion. See also Ashes and sewage sludge fertilizers, Charcoal production, Dispersion, Fires (agricultural), Seasons, Suspension in air, and Wind.					
Fish farming	P	ACI	B	C	BF
Fish farming is practised only to a limited extent on the Shield, but it is a growing industry elsewhere. While being raised, fish could absorb contaminants from the surrounding water and, if present, from sediments. They could also be fed with contaminated feed. Ingestion of these fish could then increase radiation exposure of humans. There is nothing fundamentally different in the ways wild and captive fish can be contaminated. Therefore, fish farming could be considered quantitatively together with wild fish. See also Animal diets, Game ranching, Human diet, Hydroponics, and Technological advances in food production.					
Flipping of earth's magnetic poles	E	NCIR	P	X	-
Flipping of the magnetic poles could lead to temporary changes in the earth's ionization layer and to increased solar radiation.					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
[Flipping occurs only infrequently and it is not expected that it would permanently influence or change the biosphere. It is also expected to have no significant impact on the performance of the geosphere and vault components of the disposal system. For these reasons, quantitative treatment is unnecessary for the postclosure assessment. See also Climate change and Magnetic poles (reversal) in the list of geosphere factors (Table B-2).]					
Flooding	E	ACINR	BP	X	B
Short-term flooding can alter the landscape and may destroy, or help to create, agricultural land. Flooding could be caused by intentional or accidental human actions. There could also be natural causes of flooding, such as beaver activity. On flooded land, vegetation may disappear and this might influence the behaviour and transport of some contaminants. It is well known that the mobility of mercury can greatly increase when lands are flooded by hydroelectric dams. Flooding could also result in the removal of soil or the deposition of new material that might be uncontaminated.					
[It is difficult to predict whether or not flooding will occur and to describe its effects in detail. It is expected that flooding may lead to some changes in the biosphere that should be included in the postclosure assessment, notably the use of lake sediments as arable farm land. On the other hand, no significant changes are expected in the performance of the geosphere and vault components of the disposal system. Aspects of this factor requiring explicit evaluation are described in more detail under other headings. See also Climate, Climate change, Earthmoving projects, Earthquakes, Lake infilling, Precipitation (meteoric), Seasons, Soil, Soil leaching, Surface water bodies, and Water management projects. Further discussion is provided for factors such as Climate change and Groundwater - evolution in the list of geosphere factors (Table B-2) and for Hydraulic head in the list of vault factors (Table B-1).]					
Flushing of water bodies	F	ACINR	C	C	BW
Flushing is a basic feature of water bodies such as lakes, and it is important in determining contaminant concentrations in water (Cornett and Chant 1988, Cornett and Ophel 1986, Bird et al. 1993). Flushing usually means dilution and dispersion of contaminants. Flushing rates are variable and some water bodies on the Shield are stagnant with little or no flushing. Such water bodies could have a high potential for accumulating contaminants. See also Artificial lake mixing, Industrial water use, Irrigation, Precipitation (meteoric), Runoff, Surface water bodies, Water management projects, Water source, and Wetlands.					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Food preparation	P	AI	CP	C	BF

Food preparation, such as peeling, boiling and frying, can influence contaminant concentrations in food (Lofti et al. 1989). Concentrations could be enhanced or decreased, depending on the circumstances. It is also possible that contaminants in cooking utensils or fuel could be transferred to the food, but this is likely unimportant in determining the total dose to humans. Food preparation should be considered quantitatively, but not necessarily in great detail. See also Crop storage, Human diet, Human soil ingestion, Plant roots, and Technological advances in food production.

Game ranching	P	ACI	B	C	BF

Game ranching has increased in some areas of Canada, particularly with respect to bison and elk. Game ranching could become more popular in spite of various environment and health concerns because many wild animals have much leaner meat than domestic animals. Moreover, there are lucrative markets for other game products, such as antlers. Game ranch animals could become contaminated through the intake of contaminated feed, water, soil or air. These sources of contamination would be similar to those for domestic animals, as would other considerations. Thus game ranching is just another type of animal husbandry that does not differ in any fundamental way from more traditional animal husbandry, and therefore game ranching could be implicitly included in the quantitative treatment of various domestic animals. See also Animal soil ingestion, Animal diets, Fish farming, Human diet, and Technological advances in food production.

Gas leakage into basements	F	AR	P	C	AB

Gaseous radionuclides may infiltrate from the ground into houses and increase radiation exposure of the occupants. Studies have shown that this can be an important pathway for radon (Amiro and Davis 1991). See also Biogas production, Critical group - house location, Household dust and fumes, Radon emission, and Water leaking into basements.

Glaciation	E	NCIR	P	X	BG

Continental glaciation may influence the disposal system and bring about massive disruptions in the biosphere.

[It is likely that the the next glacial episode will occur about 2×10^4 a from now (Eronen and Olander 1990, Davis et al. 1993, Davis 1986), beyond the 10^4 a period of quantitative assessment established by the Atomic Energy Control Board (AECB 1987a). The potential effects of glaciation on the disposal system are mixed. For example, it is likely that glaciation would have a profound

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

effect on the biosphere, but much less effect on the geosphere, and no effect on the vault (Heinrich 1984). We have therefore assumed that quantitative treatment of glaciation is not required in the postclosure assessment of the reference disposal system for evaluation of radiological risk up to 10^4 a. However, it would be prudent to examine the possible effects of glaciation on the biosphere for times beyond 10^4 a, to determine (for example) whether there is the potential for sudden and dramatic increases in the release rates of radionuclides. Glaciation is therefore excluded from any scenarios, although additional analysis is indicated to determine potential impacts on the biosphere. See also Climate, and Climate change. Further discussion is provided for Glaciation in the lists of vault and geosphere factors (Tables B.1 and B.2).]

Greenhouse food production	P	AIR	P	C	BF

Greenhouse production of tomatoes and cucumbers is common in favourable areas of Canada, but not on the Shield. While growing in greenhouses, these and other plant crops could become contaminated with radionuclides through root uptake, water, fertilizers, etc. This method of food production is much the same as for outdoor garden and field crops. Therefore greenhouse food production could be considered quantitatively as part of plant crop production in general, and there may be no need for detailed explicit consideration. See also Ashes and sewage sludge fertilizers, Bioconcentration, Crop fertilizers and soil conditioners, Herbicides, pesticides and fungicides, Hydroponics, and Technological advances in food production.

Greenhouse effect	P	ACIR	BCP	X	AB

The greenhouse effect refers to the presence of carbon dioxide and other gases in the atmosphere that tend to transmit solar radiation through to the earth's surface and retain the generated energy. Thus, these gases act much as the glass of a greenhouse, with the earth as the greenhouse. A significant human-produced increase in these gases in the atmosphere over the last 150 a has led to concern of a possible massive climatic change. For the Shield, this might mean a warmer and drier climate for, perhaps, hundreds of years. The duration of the stronger greenhouse effect would depend on further contributions to the greenhouse gases, such as from burning fossil fuels, and the rate of disappearance of the gases into peat, the seas and sedimentary deposits.

[The greenhouse effect would not likely influence the overall integrity of the disposal system, although it would change some characteristics of the biosphere. However, there are no obvious reasons that these changes would lead to increased radiation exposure of humans and other organisms. We have therefore assumed that further quantitative treatment is not warranted in the post-

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
closure assessment. See also Climate, and Climate change. Further discussion is provided for Climate change in the list of geosphere factors (Table B-2) and for Global effects in the list of vault factors (Table B-1).]					
Groundshine	F	CN	P	C	BF
When outdoors, humans and other organisms may be externally exposed to a variety of radiation sources. These may include contaminated vegetation, animals, rocks, and buildings, but chief among them is the ground. Ground exposure, or groundshine, can represent a significant source of radiation, and therefore quantitative treatment is required. See also Critical group - agricultural labour, Lake infilling, Rivercourse meander, Soil, and Terrestrial surface.					
Heat storage in lakes or underground	P	AR	B	X	-
Although currently quite unimportant on the Shield, lakes and underground materials could be used for storing large amounts of heat. This in itself may influence the behaviour and transport of contaminants in the environment, but there would also have to be a circulating media, such as water, to recover the heat. The media could become contaminated itself, as well as promoting contaminant transport.					
[There are many possibilities regarding the use of heat storage systems; however, it is expected that such systems would be limited in scope. This is particularly the case for heat storage deep underground, given the low hydraulic permeability and porosity of plutonic rock (for a discussion of a related topic, see Dewatering in the list of geosphere factors, Table B-1). It is expected that heat storage in lakes would have significant effects only on local elements of the biosphere, with no significant effects on the overall performance of the disposal system. If heat storage involved deep underground elements of the geosphere, it is reasonable to expect that any deleterious impacts would be much less significant than (for example) the extraction of groundwater for use as drinking or irrigation water. Finally, it is likely that such projects would be subject to environmental impact statements that would address implications for an existing nuclear waste disposal facility and examine perturbations to existing natural systems. We have therefore assumed that no further evaluation is warranted for the postclosure assessment. See also Artificial lake mixing, Industrial water use, Space heating, and Water management projects.]					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Herbicides, pesticides and fungicides	P	ACI	BC	C	F

Agricultural chemicals could become contaminated and pass contaminants onto plants and into various food chains. This is likely a minor pathway in comparison with contaminant uptake by plants from soil and leaf deposition. It may be sufficient to include these chemicals in an implicit fashion, through conservative treatment of other major pathways involving contaminant transfer. See also Critical group - agricultural labour, and Crop fertilizers and soil conditioners.

Household dust and fumes	P	AR	P	C	AB

Household dust and fumes can arise from a variety of indoor and outdoor sources, and some of them may contain contaminating radionuclides. Dust and fumes would allow suspension, transport and deposition of radionuclides, and these processes may enhance human radiation exposure. Of chief importance would be inhalation of contaminated air because this may lead to the internal deposition of radionuclides. See also Building materials, Critical group - clothing and home furnishings, Critical group - house location, Critical group - pets, Fires (agricultural), Fires (forest and grass), Gas leakage into basements, Radon emission, Smoking, Space heating, and Water leaking into basements.

Houseplants	F	ACR	B	X	-

Contaminated household plants and soil could introduce radionuclides into houses. This could increase external exposure to humans. The radionuclides could also become dispersed during repotting or plants could be accidentally dropped, opening up several other potential exposure pathways.

[Household plants are likely of minor importance in determining human radiation exposure, compared with other pathways involving ingestion and inhalation. It is also expected that no new types of exposure pathways would be involved. We have therefore assumed that no further quantitative treatment is warranted in the post-closure assessment. See also Critical group - pets, Household dust and fumes, Human diet, Human soil ingestion, and Showers and humidifiers.]

Human diet	F	AI	B	C	BF

The diet of humans can vary greatly, both qualitatively and quantitatively (Guthrie 1983). For example, food types include cultivated and wild fruit, domestic animals, wild game, fish, mushrooms and spring water. This variability can influence dose predictions, and must be considered quantitatively. See also Fish farming, Food preparation, Game ranching, Greenhouse food produc-

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
tion, Human soil ingestion, Hydroponics, Scavengers and predators, Tree sap, Urbanization on the discharge site, Technological advances in food production and Water source.					
Human soil ingestion	F	AI	C	C	F
Humans may ingest soil with food or from the hands (Hawley 1985). This can lead to the transfer of contaminants, as has been observed for lead in children living in inner cities or around certain industrial installations. There can also be pathological soil ingestion, or pica, due to mineral deficiency, but the focus here is on coincidental ingestion. Soil ingestion can be particularly important for contaminants that have low biomobility. See also Animal soil ingestion, Human diet, and Soil.					
Hydroponics	P	AIR	B	X	F
The raising of certain greenhouse crops using hydroponics, that is, without soil, has increased in importance. Plants are grown in a hydroponic medium consisting of water and all the other essential macro- and micronutrients. Thus, plant crops could become contaminated through this medium and also through the confined atmosphere.					
[Hydroponics are relatively unimportant on the Canadian Shield, and there is no reason to believe that such crops, which are grown under highly controlled conditions, would become more contaminated than garden or field crops. Thus we have assumed that no further explicit consideration is required for the postclosure assessment. See also Critical group - agricultural labour, Greenhouse food production, and Plant roots.]					
Industrial water use	P	ACIR	CP	X	-
Water has a variety of industrial uses in agriculture, mining, the pulp and paper industry, and electricity generation. The establishment of large water use systems could influence the behaviour and transport of contaminants in the environment, and exposure to humans and other organisms. Both the public and industrial workers might be affected.					
[These effects are expected to be limited to local changes to the biosphere (excluding potential impacts due to the industry itself), with no significant impacts on other elements of the disposal system. It is also expected that no new or unusual exposure pathways would result. Finally, development of any large water use systems would likely be subjected to an environmental impact statement to examine the implications for an existing waste disposal system and perturbations to the natural system. We have therefore assumed that no further evaluation is warranted for the					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
postclosure assessment. See also Artificial lake mixing, Earthmoving projects, Heat storage in lakes or underground, Irrigation, Surface water bodies, and Water management projects. Further discussion is provided for Dams and Earthmoving in the list of geosphere factors (Table B-2).]					
Intake of drugs	E	AI	BC	X	-
A variety of drugs may be locally produced and become contaminated with radionuclides. Upon injection, ingestion, inhalation or external application, the drugs may then lead to radiation exposure of humans and domestic animals.					
[This pathway would likely be of minor importance, especially because most drugs are subject to stringent quality control. In addition, it may be considered that the conservative treatment of other ingestion pathways would implicitly include ingestion of drugs. We have therefore assumed that no further quantitative evaluation is required for the postclosure assessment. See also Critical group - individuality, Critical group - pets, Dermal sorption (tritium), Human diet, Human soil ingestion, and Smoking.]					
Intrusion (deliberate)	E	ACIR	P	X	BG
Humans could deliberately intrude into the vault, driven by curiosity, the desire to recover valuable materials or to perform remedial actions. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere.					
[We have assumed that deliberate intrusion need not be considered quantitatively because it would likely require government permission, considerable resources and technological know-how. There may also have to be an environmental impact statement, addressing the potential consequences of such events. It is reasonable to assume that humans engaged in deliberate intrusion would be fully aware of all the dangers, and the need to protect themselves and the environment (Nordman and Vieno 1989). See also Earthmoving projects, Heat storage in lakes or underground, and Intrusion (inadvertent). Further discussion is provided for intrusion in the lists of vault and geosphere factors (Tables B.1 and B.2).]					
Intrusion (inadvertent)	E	ACIR	P	CI	-
Humans could accidentally intrude into the vault or the rock surrounding it. This might happen during scientific, mineral or geothermal explorations.					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

[Some elements of inadvertent human intrusion should be considered in the central scenarios. For example, one likely reason for intrusion into the geosphere would be to search for drinking water, and the postclosure assessment should consider such events. On the other hand, other reasons for intrusion may be very unlikely. For example, the siting criteria would avoid host rocks that may be of economic value (Davison et al. 1994b), and thus inadvertent intrusion in search of minerals is not expected (Eedy and Hart 1988). If inadvertent intrusion into the vault were to occur, the intruders might be exposed to relatively high radiation exposures. In addition, radionuclide release rates to the biosphere might be increased if the breach of containment were not repaired. These unlikely possibilities should be examined in the inadvertent human intrusion scenarios, similar to those studied by Wuschke (1991, 1992). See also Collisions, explosions and impacts, Earthmoving projects, Earthquakes, Heat storage in lakes or underground, Water management projects, and Water sources. The lists of vault and geosphere factors (Tables B.1 and B.2) include further comments on intrusion and wells.]

Ion exchange in soil	F	ACINR	BCP	C	SB

During ion exchange in the soil, contaminating radionuclides may become sorbed to soil materials by displacing other ions. Thus, ion exchange relates to the mobility of contaminants in soil, as do other processes, such as chemical precipitation. Mobile contaminants are of more concern than sorbed ones because they can more readily enter plants and food chains. See also Acid rain, Bioconcentration, Chemical precipitation, Soil, Soil leaching, Soil pore-water pH, and Soil sorption.

Irrigation	P	ACIR	P	C	BFS

Watering of gardens is common practice on the Shield, but large-scale commercial irrigation is not. However, this possibility cannot be excluded (Sheppard 1985). Irrigation water drawn from surface water or wells could become contaminated with radionuclides, which may then contaminate plants through root uptake or leaf deposition. Thus, irrigation might significantly increase radiation exposure of humans through food-chain transfer. See also Critical group - agricultural labour, Outdoor spraying of water, Runoff, Seasons, Surface water bodies, Water management projects and Water source.

Lake infilling	P	ACINR	P	C	SB

Shield lakes may gradually fill in and be transformed into wetlands and eventually into dry land with rich soils suitable for agriculture. Lakes may also be drained to use their sediments for farming. Alternatively, sediments might be dredged to enrich poor

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
soils. In all these cases, soils could be contaminated with contaminants from sediments. This could be significant because sediments may become contaminated from below through discharges from the geosphere, and from above through deposition from the water column. See also Critical group - agricultural labour, Crop fertilizers and soil conditioners, Rivercourse meander, Sedimentation in water bodies, Soil type, Surface water bodies, and Wetlands.					
Lake mixing (artificial)	P	ACIR	P	C	W
Artificial processes, such as aeration, wave making, purifying and thermal storage, may affect contaminant concentrations in lakes. These processes could accelerate mixing of water or stirring up of sediments. Artificial lake mixing needs to be considered quantitatively, but not necessarily explicitly. See also Bioturbation of soil and sediment, Sediment resuspension in water bodies, Sedimentation in water bodies and Water management projects.					
Mutagenic contaminants	F	ACIR	BC	C	BFP
Radionuclides are known to be mutagenic, that is, they cause mutations that may lead to cancer or, if the reproductive cells are affected, hereditary effects that may be detrimental and transmitted to future generations (ICRP 1991). Various elements are associated with the used fuel and some of them could be mutagenic through chemical, rather than radiological toxicity (Friberg et al. 1979). Of all the elements, arsenic, cadmium, chromium, lead, mercury and selenium have been of greatest health and environmental concern, although not all of them are mutagenic. See also Biotoxicity, Carcinogenic contaminants, Chemical toxicity, Radiotoxic contaminants, Teratogenic contaminants and Toxicity of mined rock.					
Outdoor spraying of water	P	AR	P	C	ABFS
Water may be sprayed outdoors for a variety of reasons, such as cooling of buildings, watering plants and controlling dust. Spraying may result in aerosol formation and suspension of contaminating radionuclides in the atmosphere (Amiro 1985). This in turn could enhance various exposure pathways that lead to increased environmental and human radiation exposures. See also Deposition (wet and dry), Dispersion, Fires (forest and grass), Industrial water use, Irrigation, and Suspension in air.					
Ozone layer failure	E	AC	C	X	-
Certain industrial chemicals may lead to the destruction of the earth's ozone layer. The prime culprits are chlorofluorocarbon compounds (which are not found in nuclear fuel waste). The ozone					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
vicinity of the critical group or are entirely used up. The recycling process is discussed separately under factors that include Ashes and sewage sludge fertilizers, Bacteria and microbes in soil, Carcasses, Charcoal production, Crop fertilizers and soil conditioners, Peat and leaf litter harvesting and Soil.					
Rivercourse meander	P	IN	P	C	B
Rivers can change their beds, especially after a glaciation episode. This may expose sediments for farming. Exposure of sediments can greatly influence the behaviour and transport of contaminants in the environment. This process is analogous to the gradual exposure of sediments through lake infilling; the actual mechanism by which sediments become exposed is of secondary importance. It may therefore be adequate to include this factor implicitly with a factor such as Lake infilling. See also Crop fertilizers and soil conditioners, Earthmoving projects, Lake infilling, Sedimentation in water bodies, Soil, Soil type, Surface water bodies, and Wetlands.					
Runoff	P	NCIR	P	C	SW
Runoff refers to precipitation water that runs off laterally, at or below the surface, to drain into a water body. Thus, runoff is important in determining the flushing rate of surface water bodies (Bird et al. 1993). Runoff may also carry contaminants, scavenged from the atmosphere or leached from the soil, to water bodies. Runoff is therefore an important vehicle for the dispersion of contaminants. Moreover, runoff is an important component in the water balance, which, together with precipitation, infiltration and evapotranspiration, determines irrigation water needs for optimal crop production. See also Dispersion, Flushing of water bodies, Irrigation, Precipitation (meteoric), Seasons, Soil leaching, and Surface water bodies.					
Saltation	P	NCIR	P	C	A
Saltation refers to the process by which soil particles become temporarily suspended into the atmosphere by wind action and then bounce along the soil surface (Male 1985). Thus, saltation can be an important factor in wind erosion and the dispersion of contaminants in the environment. It may also, together with many other natural and anthropogenic processes, increase the air concentration of radionuclides (Amiro 1985). This in turn may enhance several exposure pathways to man and other organisms, most notably inhalation. See also Dispersion, Dust storms and desertification, Erosion - lateral transport, Erosion (wind), Soil, and Suspension in air.					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Scavengers and predators	F	NCI	B	C	BF

Scavengers and predators are an integral part of food webs and they may become contaminated through the ingestion of meat. Unlike many other contaminants that are organic and fat-soluble, or inorganic and capable of forming fat-soluble species (Parks 1988; Hoffman et al. 1990), radionuclides do not tend to greatly accumulate at higher trophic levels. For example, wolves have a cesium-137 concentration of up to a factor of six higher than their prey (Zach et al. 1989). Uptake of radionuclides by fish varies with feeding habits, but is not necessarily highest in predatory species (Poston and Kopfer 1986). Humans routinely consume predatory fish, such as northern pike and walleye, but not avian and mammalian predators and scavengers that occur on the Shield. An exception might be black bear, which is occasionally consumed. Because of their importance in food webs, scavengers and predators should be considered quantitatively in the post-closure assessment, although not necessarily explicitly. See also Animal diets, Bioconcentration, and Carcasses.

Seasons	P	NCIR	BCP	C	ABFSW

Seasons on the Shield affect many aspects of the natural and human environments. Because of temperature changes that lead to freezing, photosynthesis, which is at the bottom of most food webs, comes to a virtual standstill during winter. This is true for the natural environment and also for agriculture, with the possible exception of greenhouse culture. Besides food production, seasonality also influences the behaviour and transport of contaminants in the environment. Water flow is reduced in winter because of freezing, and there can be substantial runoff during the spring. This can flush accumulated contaminants into surface waters, which, in the case of acid rain, can have serious consequences. In winter, contaminant transport in soil is greatly reduced, but it can then be greatly enhanced with spring flooding. Atmospheric suspension of contaminants is usually greatly reduced during winter because of snow cover, but it may be greatly enhanced during dry springs when forest fires become common. See also Capillary rise in soil, Climate, Climate change, Critical group - agricultural labour, Critical group - leisure pursuits, Crop storage, Dispersion, Dust storms and desertification, Erosion - lateral transport, Erosion (wind), Fires (agricultural), Fires (forest and grass), Flooding, Flushing of water bodies, Human diet, Irrigation, Outdoor spraying of water, Precipitation (meteoric), Runoff, Soil leaching, Space heating, and Suspension in air.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Sediment resuspension in water bodies	P	NCIR	P	C	BW

The surficial layer of sediments, and the associated contaminants, may become resuspended through wave action (Brunskill et al. 1984) and through perturbation by fish (Jackson et al. 1980) and other organisms. Thus, sedimentation becomes a two-way process and, in order to determine appropriate contaminant concentrations, it could be quantified in terms of a net sedimentation rate that may vary from contaminant to contaminant. Although sediment resuspension needs to be considered quantitatively, it could be treated implicitly through a net sedimentation rate. See also Artificial lake mixing, Bioturbation of soil and sediment, Flushing of water bodies, Sedimentation in water bodies, and Surface water bodies.

Sedimentation in water bodies	F	ACINR	C	C	BW

Contaminants may adhere to various particles suspended in the water column and settle to the bottom. The tendency of radionuclides to attach to particles varies, and some, such as cobalt-60, are much more particle reactive than others and therefore settle out more readily (Santschi et al. 1986). Upon settling, contaminants become part of the surficial layer of sediments, which is subject to perturbation by wave action and the activity of various organisms. The latter is referred to as bioperturbation. Beneath the surficial layer, which is not very deep, are the compact sediments, which can be very deep, depending on the age of the water body and the rate of sedimentation. Ordinarily, contaminants enter the sediments from the water column only, but in the case of nuclear fuel waste management, they could also enter from below with discharging groundwater from the geosphere. Depending on the exact circumstances, contaminants may sorb onto sediments, to a lesser or greater extent before entering the water column. See also Bioturbation of soil and sediment, Flushing of water bodies, Lake infilling, Rivercourse meander, Sediment resuspension in water bodies, and Surface water bodies.

Sensitization to radiation	P	AIR	BC	C	F

Human and other organisms may become sensitized to radiation exposure so that its effects are more severe. This might involve the presence of other mutagens, which can cause genetic damage similar to radiation exposure. In this way, the DNA repair mechanism might become over-taxed, resulting in more cancers and genetic effects than expected. Similar arguments can be advanced with respect to suppression of the immune response system when challenged simultaneously by several cancers, or cancer-producing agents. The importance of sensitization to radiation is difficult to predict and it is reasonable to assume that sensitization is part of the existing database used to establish risk factors for radiation exposure (ICRP 1977, 1991). Thus, it would be treated

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
quantitatively, although not necessarily explicitly. See also Carcinogenic contaminants, Chemical toxicity, Herbicides, pesticides and fungicides, Mutagenic contaminants, Radiotoxic contaminants, and Teratogenic contaminants.					
Showers and humidifiers	E	ACR	P	C	ABF
Household water could become contaminated with radionuclides, which may then be released indoors and contaminate the air. This could enhance pathways, such as inhalation and air immersion. Showers and humidifiers might be important sources of radionuclides, especially gaseous ones. Showers and humidifiers are not expected to be of major importance in determining the total dose to humans. Therefore it may be adequate to deal with this factor without going into great detail. See also Gas leakage into basements, Household dust and fumes, Radon emission, Space heating, Suspension in air, Water leaking into basements and Water source.					
Smoking	P	AR	BC	X	BFS
Human exposure to radionuclides in tobacco can result from smoking (Watson 1985). Tobacco plants could take up radionuclides from contaminated soil or through leaf deposition. Upon smoking, radionuclides might attach to smoke particles, which could then be deposited and absorbed from the respiratory tract.					
[It is suspected that health problems from smoking, unrelated to radiation, far outweigh those from radiation. For this reason, we have assumed that no further evaluation is warranted for the post-closure assessment. See also Carcinogenic contaminants, Chemical toxicity, Mutagenic contaminants, Sensitization to radiation, and Suspension in air.]					
Soil	F	ACINR	BCP	C	BFS
Soil is the basis of terrestrial food webs because it is required by plants that carry out photosynthesis. Soil is also important in the recycling of materials through the action of various invertebrates and microbes. Soil is thus important in the natural environment and also in agriculture. When soil becomes contaminated, a variety of exposure pathways are opened up, most notably root uptake. See also Alkali flats, Animal soil ingestion, Ashes and sewage sludge fertilizers, Bacteria and microbes in soil, Bioturbation of soil and sediment, Climate change, Critical group - agricultural labour, Crop fertilizers and soil conditioners, Deposition (wet and dry), Dust storms and desertification, Erosion - lateral transport, Erosion (wind), Groundshine, Herbicides, pesticides and fungicides, Human soil ingestion, Ion exchange in soil, Irrigation, Peat and leaf litter harvesting, Plant roots,					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.

Precipitation (meteoric), Rivercourse meander, Runoff, Saltation, Seasons, Soil depth, Soil leaching, Soil porewater pH, Soil sorption, Soil type, Suspension in air, Terrestrial surface, Urbanization on the discharge site, and Wetlands.

Soil depth	F	ACINR	BCP	C	SB

Soil depth refers to the distance from the soil surface down to the water table (Sheppard 1992). This depth can vary considerably, from a few centimetres to several metres. In addition, the depth may vary seasonally with the water table. The soil profile, encompassed by the depth, is not uniform and there are distinct layers. There may be an organic litter layer on top followed by a mixed layer with decaying organic matter. The lowest layer is usually mineralized. Contaminants may move up and down the soil profile through capillary rise and leaching. See also Dispersion, Plant roots, Soil, Soil leaching, Soil type, and Terrestrial surface.

Soil leaching	F	ACINR	BCP	C	SB

Contaminants residing in the soil profile may be leached through precipitation or irrigation. Thus, they may move downward or laterally with runoff to eventually discharge into a surface water body or wetland. In order to be leached, contaminants need to be free to move, which implies desorption. Leaching of contaminants is a complex and important process that needs to be considered quantitatively, although not necessarily in great detail. See also Capillary rise in soil, Colloids, Precipitation (meteoric), Soil, Soil sorption, and Soil type.

Soil pore-water pH	F	ACINR	BCP	C	S

The pH of soil pore water is an important factor in determining the behaviour and transport of contaminants in the soil because it affects sorption to soil solids (Sheppard and Thibault 1990, 1991). Generally speaking, sorption of contaminants decreases with decreasing pH through such processes as ion exchange. Decreased sorption means higher mobility and this may open up a variety of exposure pathways. See also Acid rain, Capillary rise in soil, Chemical precipitation, Crop fertilizers and soil conditioners, Ion exchange in soil, Soil, Soil leaching, Soil sorption, and Soil type.

Soil sorption	F	ACINR	BCP	C	SB

Soil sorption refers to the process whereby contaminants adhere to or are taken up in soil solids and become essentially immobilized. This is important because sorbed contaminants cannot be taken up by plants, and cannot leach or move upward by capillary rise.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
This means that they become excluded from many, but not all, of the exposure pathways leading to humans and other organisms. Many factors affect soil sorption, including soil type, pH and precipitation. See also Acid rain, Bioconcentration, Capillary rise in soil, Chemical precipitation, Colloids, Ion exchange in soil, Soil, Soil leaching, Soil porewater pH, and Soil type.					
Soil type	F	ACINR	BCP	C	S
Several soil types occur on the Shield, including sand, loam, clay and organic (Sheppard 1992). These soil types support various natural ecosystems and agriculture. The soil types differ in various physical and chemical attributes, such as organic matter content and pH, which in turn influence the mobility of contaminants. Mobility is of key importance in the transport of contaminants in the soil and in root uptake by plants. See also Alkali flats, Climate, Climate change, Crop fertilizers and soil conditioners, Irrigation, Lake infilling, Peat and leaf litter harvesting, Rivercourse meander, Soil, Soil depth, Soil leaching, Soil porewater pH, Soil sorption, and Terrestrial surface.					
Space heating	F	AR	B	C	AB
Space heating, involving burning of fuels, can increase indoor and outdoor contamination of the atmosphere. Of particular importance here are local fuels, such as wood and peat, that could become contaminated with radionuclides. Upon burning, radionuclides may be released as gases or attached to smoke particles. They could become dispersed in the environment, but could also contribute to exposure pathways such as inhalation and air immersion. Space heating is not anticipated to be of major importance. Thus it should be considered quantitatively, but not necessarily in great detail (Amiro 1992a). See also Ashes and sewage sludge fertilizers, Household dust and fumes, and Seasons.					
Surface water bodies	F	ACINR	C	C	W
Surface water bodies are of key importance in the behaviour and transport of contaminants in the environment. It is likely that contaminants released from an underground vault would first enter the biosphere through discharge of deep groundwater into a lake or river. The fate, and environmental and human impact of contaminants, would then depend to a large extent on the physical, chemical and biological attributes of the surface water body. Important attributes might include size, flushing rate, pH, sedimentation rate and productivity. A variety of exposure pathways, such as transfer to fish, ingestion of drinking water by humans and other organisms, and water immersion, relate to surface water bodies. See also Artificial lake mixing, Bioturbation of soil and sediment, Climate, Climate change, Deposition (wet and dry),					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Flooding, Flushing of water bodies, Heat storage in lakes or underground, Industrial water use, Irrigation, Precipitation (meteoric), Rivercourse meander, Runoff, Seasons, Sediment resuspension in water bodies, Sedimentation in water bodies, Water management projects, Water source, and Wetlands.					
Surface water pH	F	ACINR	C	C	W
In conjunction with acid rain, the pH of water bodies on the Shield has become of major concern (Harvey et al. 1981). These lakes are poorly buffered so that acid rain can effectively depress the pH. This can detrimentally affect aquatic life, and lakes can become clear and less productive. The pH can also influence sedimentation of contaminants through the availability of suspended particles and the reaction of contaminants with these particles (Santschi et al. 1986). The pH of Shield lakes is not very variable and most are circumneutral, with a value between 6 and 7. The pH of surface water needs to be considered quantitatively, but not necessarily explicitly. See also Acid rain. Industrial water use, Precipitation (meteoric), Sedimentation in water bodies, Soil leaching, and Surface water bodies.					
Suspension in air	P	ACINR	P	C	ABFS
There are a wide variety of pathways through which contaminants released from an underground vault could become suspended as particulates or gases in the atmosphere (Amiro 1985). The two major sources for suspension might be surface waters and soils, and many processes could be involved, such as degassing, wind erosion, plowing and irrigation. Forest and other fires can also become potent agents for injecting contaminants into the atmosphere. Once in the air, contaminants could become dispersed or deposited to underlying surfaces. By contributing to the air concentration and through deposition, suspension can increase doses to humans and other organisms in several ways. See also Biogas production, Charcoal production, Convection, turbulence and diffusion (atmospheric), Critical group - agricultural labour, Deposition (wet and dry), Dispersion, Dust storms and desertification, Erosion (wind), Fires (agricultural), Fires (forest and grass), Gas leakage into basements, Household dust and fumes, Irrigation, Outdoor spraying of water, Radon emission, Saltation, Showers and humidifiers, Smoking, Space heating, and Wind.					
Technological advances in food production	F	ACIR	B	X	BF
Most of the feed and forage for farm animals, and of the food for humans is produced with traditional methods. There are some relatively new methods now practised, such as fish farming, game					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/?	Comp.	Mech.	Treat.	Ref.

ranching and hydroponics. In the future, there could be novel technological advances brought about by an ever-increasing human population.

[The relatively new methods do not substantially deviate from traditional methods, and it is expected that any novel advances would not be subjected to new types or degrees of contamination. In fact, the new and novel methods are likely to be more controlled, and therefore less likely to be affected by contaminants from a disposal facility. Moreover, the Atomic Energy Control Board (AECB 1987a), has specified that the postclosure assessment is to be based on current-day conditions. We have therefore assumed that technological advances in food production need not be considered further for the postclosure assessment. See also Critical group - evolution, Fish farming, Food preparation, Game ranching and Hydroponics.]

Teratogenic contaminants	F	ACIR	BC	C	BFPG

Radionuclides, and other contaminants associated with fuel waste, could be teratogenic, that is, cause developmental disturbances in humans and other organisms. High radiation exposures can cause serious malformations, but the situation is less clear at lower doses, especially those at or below background radiation levels. At these levels, the most likely teratogenic effect in humans might relate to brain development and mental capacity (ICRP 1991). See also Carcinogenic contaminants, Mutagenic contaminants, Radiotoxic contaminants, and Teratogenic contaminants.

Terrestrial surface	F	NCIR	P	C	ABFS

Land areas on the Shield include rocky outcrops, bare soil, grassland, bush and forest (Rowe 1972). Each of these types of areas has unique physical, chemical and biological properties that may influence the behaviour and transport of contaminants. For example, grasslands usually have deep soils, runoff is high on rocky outcrops, and bare soils tend to have particularly high erosion rates. Moreover, each type of area supports different plant and animal communities. See also Alkali flats, Erosion - lateral transport, Irrigation, Runoff, Soil, Soil depth and Wetlands. Related issues are discussed under Topography (current) in the list of geosphere factors (Table B-2).

Toxicity of mined rock	F	AIR	C	X	-

Excavation of the vault may result in the production of tailings, which may subsequently release toxic contaminants.

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
[In general, the toxicity of the tailings is expected to be of no concern. For example, site selection criteria would avoid host rocks that have any economic value (Davison et al. 1994b), implying the absence of large concentrations of heavy metals and related contaminants. The host rock would typically consist of granite or gabbro, which mostly contain minerals such as feldspar and quartz. These minerals and their leachates are not regarded as toxic. Other environmental concerns, such as acid drainage, are not associated with granites or gabbros. Finally, there may be some concern for toxic releases of byproducts from any explosives used to construct the disposal vault. However, it is reasonable to expect that such releases would be of short duration, and adequately evaluated in the preclosure assessment. We have therefore assumed that further consideration is not required in the postclosure assessment. See also Chemical toxicity and Radiotoxic contaminants. Related topics are discussed under Sabotage and improper operation in the list of vault factors (Table B-1).]					
Tree sap	P	NCIR	BP	C	F
Tree sap could become contaminated through root uptake and leaf deposition of contaminants. Tree sap is used in the production of resins, tars and syrup, most notably maple syrup. It is of local importance on the southern edge of the Shield. This factor is not expected to be a major route of exposure, and therefore it may be adequate to deal with it in an implicit fashion or without great detail. See also Animal diets, Bioconcentration, Human diet and Seasons.]					
Uncertainties	FEP	all	all	C	ABFPSW
The biosphere is complex and it involves a wide variety of interacting physical, chemical and biological factors. The biosphere is constantly changing over time in an often unpredictable way, and this raises additional uncertainties. In addition, knowledge, in the form of models and parameter values, for predicting the behaviour and transport of contaminants can never be complete, even with a constant biosphere, and this also raises uncertainties. This factor is accentuated by the need to make quantitative predictions over thousands of years. Virtually all factors in this list have associated uncertainties that should be addressed in a quantitative fashion.					
Urbanization on the discharge site	P	ARC	P	X	-
By definition, the critical group receives a higher risk than any other group of individuals. As such, it is likely that the critical group would be located in the immediate area of groundwater discharge from the vault, where dilution and dispersion of					

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
released contaminants would be minimal (Zach and Sheppard 1992). The critical group could be urban or rural. This could have important implications for dose predictions because the two types of groups could be exposed to different pathways, or the same pathways might differ in importance. [An important characteristic of rural groups is that they tend to be more self-sufficient than urban ones, relying more on local water, food and other resources. This is particularly so in the case of farm communities. In general, resources produced local to the discharge areas would be more likely to be contaminated than resources that were imported. Moreover, there would most likely be more exposure pathways, each with greater importance, for a rural group than for an urban group. These considerations suggest that the characterization of the critical group should be based on a rural lifestyle, as opposed to an urban lifestyle. We have assumed that this is the appropriate situation for the postclosure assessment, and that urbanization does not require explicit evaluation. See also Critical group - agricultural labour, Critical group - clothing and home furnishings, Critical group - house location, Critical group - individuality, Critical group - leisure pursuits, Human diet, Human soil ingestion and Water source.					
Vault heating effects The heat released from radioactive decay of the nuclear fuel waste would increase the temperatures at the surface above the disposal vault. This could result in local or extensive changes in flora and fauna. [Scoping calculations indicate that the expected temperature rise would be very small, typically less than 1°C (Amiro 1992b). The heat energy from the vault would be much less than natural geothermal and solar energy affecting the same area. We have therefore assumed that vault heating effects may be excluded from further consideration in the postclosure assessment. Further discussion is provided under Temperature effects in the list of factors for the vault (Table B-1), and under Vault heating effects in the list of factors for the geosphere (Table B-2)].	F	F	P	X	-
Water leaking into basements Water, contaminated with radionuclides, could leak into basements and contaminate houses. This might involve groundwater or water from a flood. [Water leaking into basements is likely a minor exposure pathway. For example, it is reasonable to expect that ingestion of drinking water and exposure to groundshine would involve similar, but much	F	ACR	P	X	F

TABLE B-3

BIOSPHERE FACTORS (continued)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
more significant exposure pathways. We have therefore assumed that it may be excluded from further consideration in the post-closure assessment. See also Critical group - house location, Flooding, Gas leakage into basements, Groundshine, Household dust and fumes, Human diet, Radon emission, Showers and humidifiers, and Water source.					
Water management projects	F	ACIR	P	X	W
The focus here is on large-scale water management projects, such as diversions and dams for hydroelectric generation or irrigation. Such projects could have a major influence on the behaviour and transport of contaminants in the biosphere.					
[The occurrence of these projects are largely unpredictable, as are a detailed evaluation of subsequent effects on the behaviour and transport of contaminants in the environment. However, it is reasonable to expect that no new or unusual exposure pathways would be created, given the wide range of representative pathways that are considered in the description of the biosphere. In addition, such projects would not likely have large effects on deep groundwater flows, and therefore would not significantly alter the performance of the geosphere and vault, nor the overall performance of the disposal system. The possible occurrence and effects of water management projects should be a factor for consideration in the selection of a site (Davison et al. 1994b). Finally, it may well be that major water management projects would be subject to environmental impact statements, which would include implications for existing structures, such as a nuclear waste disposal facility, and perturbations to existing natural systems. We have assumed that further evaluation is not required for the postclosure assessment of the reference disposal facility. See also Earthmoving projects, Flooding, Intrusion (deliberate), Intrusion (inadvertent), and Surface water bodies. Further discussion may also be found under Dams, Earthmoving and Erosion in the list of factors for the geosphere (Table B-2).]					
Water source	F	ACIR	C	C	BFSW
Potential water sources for humans, such as lakes, rivers and wells, could be contaminated with radionuclides to different degrees, and thus radiation exposure may depend on the exact water source. This could be particularly true for drinking water of humans and farm animals, because drinking is a direct pathway with few delays and intermediaries. Similar comments apply to chemically toxic elements. See also Critical group - house location, Industrial water use, Irrigation, Outdoor spraying of water and Surface water bodies. Further discussion is provided under Wells and Wells (high-demand) in the list of geosphere factors (Table B-2).					

TABLE B-3

BIOSPHERE FACTORS (concluded)

Factor	F/E/P	Comp.	Mech.	Treat.	Ref.
Wetlands	F	NCIR	BC	C	AFSW

Various forms of wetlands, such as marshes and fens, which include peat bogs, are common on the Shield. Contaminants released from a vault would likely discharge in deep groundwater to a surface water body, but it could also be to a wetland. Wetlands may also be drained to provide agricultural land, and peat might be mined to be used as a fuel or soil amendment, or burned for fuel (Amiro 1992a). Of course, wetlands are important ecosystems that support in many ways a wide variety of unique organisms. See also Flooding, Flushing of water bodies, Lake infilling, Peat and leaf litter harvesting, Rivercourse meander, Runoff, Soil, Soil type, Surface water bodies and Terrestrial surface.

Wind	P	NR	P	C	A

Wind is a major environmental force in both the dispersion of contaminants through soil erosion and the transport of contaminants suspended in the atmosphere. Thus, it can help to dilute contaminants, but can also move them laterally. Wind could also have indirect effects on the behaviour and transport of contaminants through such processes as evapotranspiration, fires and leaf deposition. Key aspects of wind are its velocity and direction, particularly in relation to sources of contaminants, such as chimneys or fields, and recipients of contaminants, such as humans and other organisms. See also Convection, turbulence and diffusion (atmospheric), Dispersion, Erosion (wind), Fires (agricultural), Fires (forest and grass), and Suspension in air.

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