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The Potential Significance of Permafrost to the Behaviour of a Deep Radioactive Waste Repository

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Contents

1 Introduction 1

2 Distribution of permafrost 3

2.1 Introduction 3

2.2 Properties of frozen ground 5

3 The hydrogeology of permafrost areas 6

3.1 Introduction 6

3.2 Position of "aquifers" relative to permafrost 6

3.2.1 Introduction 6

3.2.2 Suprapermafrost Aquifers 9

3.2.3 Intrapermafrost Aquifers 10

3.2.4 Subpermafrost Aquifers 11

4 Groundwater movement 12

4.1 Infiltration and recharge 12

4.2 Lateral movement 13

4.3 Discharge 14

4.3.1 Introduction 14

4.3.2 Springs 15

4.3.3 Baseflow 15

4.3.4 Icings (Naledi or Aufeis) 15

5 Geochemistry 16

5.1 Effects of low temperatures 16

5.2 Groundwater geochemistry 16

5.3 Chemistry of Icings 18

5.4 Surface water chemistry 18

6 **Water supply in permafrost areas** **18**

6.1 Introduction 18

6.2 Surface water supplies 19

6.3 Groundwater supplies 19

6.4 Natural factors which effect the hydrogeology of permafrost terrains. 20

7 **Future climatic states over the next million years** **21**

8 **Permafrost behaviour around a repository** **25**

8.1 Statement of the thermal problem 26

8.2 Assumptions made in calculating the effect of the repository 27

8.3 Results 31

9 **The significance of permafrost on the performance of a repository** **43**

9.1 Introduction 43

9.2 The effect of permafrost on groundwater infiltration and recharge 43

9.3 The effect of permafrost on discharge 46

9.4 Lateral groundwater flow 47

9.5 The effect of permafrost on the chemistry of the groundwater 47

9.6 The influence of permafrost on the release of gas from a repository, and on the formation of clathrates (gas hydrates). 49

9.6.1 Introduction 49

9.6.2 Clathrates 50

9.6.3 Discussion 53

9.7 The influence of permafrost on the repository engineered barriers 53

9.8 The influence of permafrost on the biosphere 55

10 Permafrost scenarios **56**

10.1 Introduction 56

10.2 Radionuclide release via springs 56

10.3 Release via a sub-lacustrine open talik 58

10.4 The combination of thermal buoyancy combined with a sub-lacustrine open talik 59

10.5 The combination of thermal buoyancy, together with shaft seal failure and a sub-lacustrine talik 59

11 Structure of scenario to be analysed **59**

12 Recommendations for repository designs **61**

12.1 Aspects of repository design and location influenced by permafrost 61

References **63**

List of Tables

Table 7.1 23

1 Introduction

Permafrost is one of the scenarios that is being considered as part of the groundwater flow and transport modelling for the Project-90 assessment. It is included as one of the primary Features, Events and Processes (FEPs) which are being kept outside the PROCESS SYSTEM in the SKB/SKI scenario development project (Andersson at al, 1989). There is a large amount of evidence that Sweden has suffered several cycles of permafrost development over the Quaternary, approximately the last 2My, and climatic predictions for the next hundred thousand years suggest that similar climatic cycling is likely to occur. The presence of permafrost could have important effects on the hydrogeological regime and could therefore be important in modifying the release and dispersion of radionuclides from a repository. The climatic conditions of permafrost would also influence radionuclide migration and accumulation in the biosphere and the associated radiation exposure of man. These biosphere aspects are not considered here but the implications for discharge into the biosphere are examined, including the abstraction of groundwater by man in permafrost regions.

In order to structure the list of FEPs, it was found necessary to introduce the concepts of the PROCESS SYSTEM and external conditions. The PROCESS SYSTEM comprises the complete set of deterministic physical and chemical processes that might influence the release of radionuclides from the repository to the biosphere. The external conditions are events and processes that are not induced by the repository and can occur independently of the processes in the PROCESS SYSTEM. Using these definitions, most of the FEPs on the original list were assigned to the PROCESS SYSTEM. and only a small number, approximately 50, were left as FEPs representing external conditions. These remaining FEPs have been grouped (lumped) into a few (10) primary FEPs of external conditions, permafrost being one of these ten. This report reviews the evidence relating to permafrost development and discusses the possible implications for the long-term safety of a deep repository.

Continuous permafrost is present to great depths in the Spitzbergen area and in Siberia, and although there is currently no such development of continuous permafrost within Sweden, except in some mountainous areas, it is highly probable that permafrost will be developed, probably repeatedly, within the next few tens and hundreds of thousands of years.

Permafrost can have a major influence on the recharge and discharge of groundwater, and could be significant in localising the return of radionuclides to the environment. Permafrost can produce changes in groundwater chemistry and result in the formation of very saline groundwaters, especially at the base of the permafrost zone, and this could be significant in radionuclide migration. In addition, depending on the depth of the permafrost, the repository structure itself could be affected. Calculations demonstrate that if the glacial period is of sufficient length, permafrost could, in theory, develop to depths in excess of 500m, though such a possibility is thought to be extremely improbable. What seems more probable is that permafrost could affect engineered barriers within the shafts to depths of up to 200m, and this in turn could be significant in increasing the potential for shaft seal failure.

It is likely that one, and perhaps several, periods of permafrost will develop during the thermal phase of the repository. In this situation it might be thought that the rock above the repository would remain unfrozen, whilst the surrounding rock would freeze. The resulting concentration of the thermally driven advection in the rock immediately above the repository could then result in very much shorter transit times to the surface, and these times could be further reduced in the event of any failure of the shaft seals, especially if the shaft is directly above or close to the repository. It will be argued that this situation is in fact very unlikely to occur, except in special circumstances which, if the site is chosen accordingly, can be avoided.

Permafrost may result in a concentration of radionuclides in the groundwater beneath, or within, the permafrost zone, which may subsequently be released as a concentrated pulse when thawing takes place. The geochemistry of groundwaters that may transport radionuclides could be substantially modified after long periods of permafrost, with the presence of higher concentrations of complexing species. Gases derived from deeper within the rock mass may become frozen as clathrates within the permafrost zone or may be trapped as a gaseous phase beneath the permafrost. Gas accumulation could lead to enforced outflow of groundwater from the repository, though this is thought to be of minor significance. The influence of any gas cushion on the groundwater flow field is considered possibly more important. Clathrates are not normally found in crystalline rocks and their significance is not at all clear in the context of a repository for spent fuel.

Permafrost has a major effect on the biosphere, and hence on the types of communities that may be present above the repository. The reduced volumes of potable groundwater that are available in areas of continuous permafrost preclude the development of large communities, except in the situation found in Siberia, where major rivers which have their headwaters south of the permafrost continue to flow through the permafrost zone. On the other hand, the location of any community is most likely to be in an area of discharging groundwater, which is more likely to be where any radionuclides from a repository would be released to the environment. Permafrost could result in more concentrated or localised release to the biosphere. The scope for this to occur in the Swedish case will be examined along with some outline discussion of the implications of this more localised release for predictions of radiation dose.

This report is divided into two main sections. The first is a summary of the nature of the permafrost environment, describing factors that would need to be taken into account in a repository performance assessment. The second endeavours to construct a number of scenarios which are thought to be those of most significance to the release of radionuclides from the repository and the subsequent transport through the geosphere to the biosphere.

2 Distribution of permafrost

2.1 Introduction

Permafrost is defined as ground, soil or rock, with temperatures which remain continuously below 0°C for two or more years. It occurs in areas with mean annual air temperatures below 0°C and is generally overlain by an *active layer*, which is subject to seasonal freezing and thawing. The occurrence of permafrost is controlled by the surface heat balance, which in turn is influenced by the properties of the ground surface, such as relief, slope aspects, vegetation, snow cover, moisture content, soil and rock type and the presence of surface water bodies (Brown, 1970). Kersten (1959) has derived an empirical formula relating the depth of frost penetration to the square root of the number of days per year with air temperatures below 1.6^{0}C. Locally, moving groundwater can have a significant influence on its development. Near the margins of a permafrost area the permafrost consists of thin, isolated masses and, in the northern hemisphere where most of the current information is derived, is more likely to be present under north facing slopes with thin winter snow cover. Towards the north, the areas in which permafrost occurs gradually become larger, and the depth to the base of the permafrost can increase to depths in excess of 500m at high latitudes.

Sloan and van Everdingen (1988) have defined four zones of permafrost of increasing thickness and persistence. The first zone comprises areas not perennially frozen, but which lie within the permafrost region. In the second zone, individual islands of permafrost do not exceed 15m in depth. Because the permafrost is thin and ground temperatures are close to 0°C, it is particularly susceptible to degradation and aggradation, and it may disappear over a periods of a few decades. In the third zone of discontinuous permafrost the thicknesses do not exceed 35m. Unfrozen areas are present, but frozen ground predominates, and is older and more stable than that within the second zone. The fourth zone contains continuous permafrost, except where it is absent within taliks (see below).

The length of time during which intense periglacial conditions have prevailed is as significant as the increase in latitude. Great thicknesses of permafrost found in the fourth zone require several tens of thousands, and perhaps as much as a hundred thousand years, to develop. Consequently, maximum thicknesses will only be found where former ice sheets did not provide an insulating cover from cold air (Ives, 1974). In some parts of arctic North America present day permafrost is thickest where ice sheets were absent during the last (Wisconsin) glaciation, and that in the Mackenzie delta of northern Canada is older that 40ka (Washburn, 1980).

Much of this review is based on work carried out in Canada and Alaska, which itself draws on a larger amount of research in Siberia where extremely large areas of continuous and discontinuous permafrost are present in areas that support large populations. The relatively recent increase in mining and oil development has resulted in an increased interest in the properties of permafrost. Data have also been taken from a review of geomorphological processes likely to occur in Britain in periglacial times (Pitty, 1988).

The hydrogeological aspects of permafrost have been summarised in papers by van Everdingen (1987) and Sloan and van Everdingen (1988). One problem in using these reviews is that they describe the situation in areas within northern Canada and Alaska, which, although at similar latitudes to central Sweden, have far more marked continental climates. It is difficult to make universal generalisations about permafrost development, as each of these areas has distinct regional characteristics. The north of inland Yukon, for example, has remained largely unglaciated throughout Quaternary times. The possible persistence of permafrost over this period contrasts sharply with the repeated cyclic changes involving glaciation, periglaciation and temperate interglacial conditions experienced in western and north–central Europe. Lapland and Spitzbergen, for example, have mean annual temperatures 6-10°C higher than other regions of the same latitude due to the ameliorating affects of the North Atlantic Drift.

2.2 Properties of frozen ground

When water bearing soil or rock is frozen a number of its physical properties are changed. Electrical and hydraulic conductivities decrease by several orders of magnitude, apparent specific heat capacities decrease and thermal conductivities increase (Anderson and Morgenstern, 1973). Any water remaining in the liquid phase, due probably to the depression of its freezing point by the concentration of its dissolved constituents, will have an increased viscosity. Permafrost, which is defined solely on the basis of temperature, is not necessarily frozen. It may be dry and contain no ice or water. It may contain only unfrozen water; if the freezing point depression is large enough to prevent freezing it may contain a mixture of unfrozen water and ice or it may contain ice exclusively. The ice may be segregated into lenses, layers or, perhaps, ice wedges.

Unfrozen water can exist in many soils and rocks as thin films adsorbed onto the surface of soil or mineral particles, even when the temperature is well below the initial freezing point of the water (Anderson and Morgenstern, 1973). The thickness of the water films is a function of temperature and is almost independent of the total water content, except in very dry soils.

The term *cryopeg* describes zones in which the temperature is <0°C in which all the water is in the liquid phase. Cryopegs are common features in permafrost and in many places a cryopeg is found immediately above the permafrost base (Tolstikhin and Tolstikhin, 1974, van Everdingen, 1976) (Fig 1).

Frozen ground is not necessarily impermeable, although the formation of ice in pore spaces and fractures and in the form of ice lenses, will significantly reduce its hydraulic conductivity. Freezing of clean, coarse-grained sediments and fractured basement is likely to reduce their hydraulic conductivities to a small fraction of their unfrozen values. Freezing of fine-grained sediments with a high clay content may result in only a minor reduction in their hydraulic conductivity, especially if the temperature falls only slightly below 0°C, due in part to the fact that they already possess relatively low hydraulic conductivities. The formation of cracks, caused either by drying or by thermal contraction during periods of extremely cold weather, can significantly increase the bulk hydraulic conductivity of frozen ground, though this tends to be important only within the active layer. Permafrost will affect the hydraulic regime only if the ground is perennially frozen and its hydraulic conductivity is significantly lower than it would be under unfrozen conditions. Hydraulic conductivities of frozen and unfrozen parts of the same unsaturated ground may be similar when ground temperatures are close to 0°C. With decreasing temperatures below 0°C the hydraulic conductivity of the ground decreases as the cross-sectional area of interconnected films of unfrozen water become progressively smaller. Fracture systems can provide significant additional hydraulic conductivity to the frozen rock mass, whilst the presence of segregated ice, as layers and lenses, may decrease the hydraulic conductivity to the point where the ground acts as though it were frozen, with a marked reduction in its hydraulic conductivity..

3 The hydrogeology of permafrost areas

3.1 Introduction

The hydrogeology of permafrost areas is not very well understood and recent advances in this understanding have only been made because of increased development in areas such as Alaska, northern Canada and Siberia. For large parts of such regions the knowledge of the hydrogeology is confined to observations of groundwater discharge phenomena, observations of karst recharge and data on a small number of shallow wells distributed over a very large area (Zenone and Anderson, 1978; Heath, 1984; Michel and Wilson, 1988). The directions and rates of groundwater flow in the permafrost areas are generally dependent on the same physical parameters as in areas without permafrost. In addition, however, groundwater regimes in permafrost are affected by major climatic effects and by the presence of perennially frozen ground.

3.2 Position of "aquifers" relative to permafrost

3.2.1 Introduction

The terminology used to describe the hydrogeology of permafrost regions has been developed in response to the demands of groundwater supply and the geotechnical problems associated with civil engineering operations in permafrost (Williams, 1965; van Everdingen, 1976) and the same terminology has been used in this review. The term "aquifer", which is used throughout the following description of permafrost hydrogeology, is not commonly used to describe the hydrogeological situation in crystalline basement. It is used here in its general sense, and is not meant to imply zones of the rock mass having higher hydraulic conductivity nor those providing economic groundwater resources.

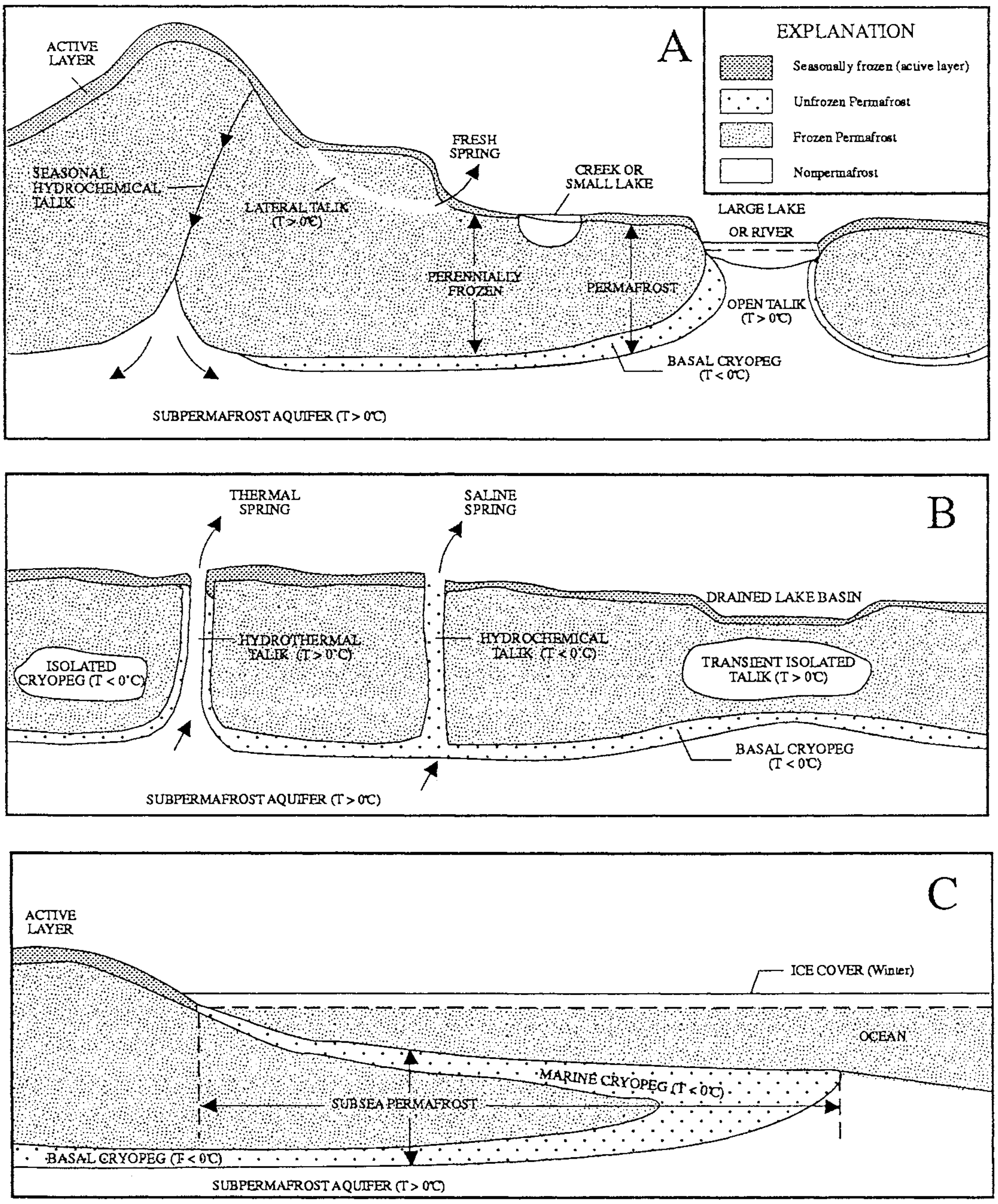

Figure 1: Aquifers and water conditions in permafrost areas. A. Suprapermafrost: active layer; closed taliks. B. Intrapermafrost: open taliks (lake, river, hydrothermal, hydrochemical); lateral taliks; transient isolated taliks; isolated, marine and basal cryopegs. C. Subpermafrost. (From Sloan and van Everdingen, 1988)

It is convenient to group aquifers under three main headings when discussing the hydrogeology of the permafrost region (van Everdingen, 1976; Sloan and van Everdingen, 1988):

1. Suprapermafrost Aquifers - situated above the permafrost, with permafrost generally acting as a relatively impermeable lower boundary
2. Intrapermafrost Aquifers - those found in unfrozen zones (taliks) within the permafrost, and
3. Subpermafrost Aquifers - situated below the permafrost, with permafrost acting as a relatively impermeable upper boundary.

These three types of aquifer are variously interconnected as well as connected to lakes and streams, and each type can be found in both superficial and recent sediments as well as in basement rocks (Fig 1, from Sloan and van Everdingen (1988)). The presence, or absence, of these different types of aquifers could have a major influence on the potential release of radionuclides from a repository.

The different types of talik, several of which are shown in Fig 1, are described below, using the suggested definitions of van Everdingen (1976). Several of them are in fact different types of spring and therefore are of particular significance to the release of radionuclides to the biosphere:

(a) *Thermal taliks* are noncryotic (ie. T>0°C). They include the seasonal thermal talik above the permafrost, also known as the active layer, as well as a number of taliks that all contain suprapermafrost water, and the perennial thermal talik below the permafrost, which contains subpermafrost water. In a few cases a perennial thermal talik may be present between the seasonally cryotic layer and the permafrost.

(b) *Hydrothermal taliks* are also noncryotic; heat from flowing groundwater, often within fracture zones, helps maintain their positive temperature. They contain intrapermafrost water and may be fed by either suprapermafrost water (recharge) or by subpermafrost water (discharge). The recharge type is probably seasonal, and many large rivers in northern Canada, eg the Mackenzie River, are fed from such perennial springs.

(c) *Chemical taliks* are cryotic, and their freezing is prevented by the salinity of the pore water. They can be expected to occur in the basal portion of the permafrost, where they are termed *basal cryopegs*, and also in near-surface sea-bed material.

(d) *Hydrochemical taliks* are also cryotic, their freezing is prevented by the mineralisation of flowing groundwater. They contain intrapermafrost water and are often fed by subpermafrost water.

(e) A *pressure talik* is cryotic; its freezing point is depressed by the high pressure of its pore water. Pressure taliks are likely to freeze rapidly upon release of the pressure.

(f) *Piezochemical taliks* are cryotic; their initial freezing point is depressed as a result of boundary forces related to mineralogy and grain size distribution, as well as by mineralisation of the pore water. They are most likely to be present where thermal gradients are low and temperatures are close to 0°C.

Mackay (1963) observed that where the depth of a channel or lake exceeded the thickness of winter ice the subajacent sediments remained unfrozen. Thus much of the subaqueous half of the Mackenzie delta, which lies within an area of continuous permafrost, and with permafrost depths of up to 365m in the adjacent tundra, could be underlain by unfrozen ground. Gold and Lachenbruch (1973) confirm that the maximum thickness of fresh ice at high latitudes is approximately 2m, and thus all lake and river depths which exceed this could in theory be underlain by perennially unfrozen ground. Even lakes as small as $0.02 km^2$ in Alaska (Kane and Slaughter, 1973) are known to maintain open taliks, and in Antarctica, where permafrost is normally 1km thick, it is absent beneath large solar heated lakes, although the high salinities of the lake waters also have a significant effect (McGinnis and Jensen, 1971). In an area with numerous small lakes, such as characterises some parts of Sweden, it seems likely that many, if not most of these lakes will lie above open taliks if permafrost conditions are not too severe. In such regions there thus could be a general lack of continuity in the permafrost, and this has important consequences for groundwater discharge. With increase in the severity of the permafrost, the number of such open taliks decreases as the shallower lakes freeze completely. Completely frozen, small lakes are found in northern Canada in areas of continuous permafrost.

3.2.2 Suprapermafrost Aquifers

Suprapermafrost aquifers are normally found in low-lying areas in closed taliks beneath lakes and rivers and in elevated areas with little relief. They are less common on slopes, where, in the northern hemisphere, they are usually restricted to those slopes that face south.

Most of these aquifers freeze during winter, and their water normally has a high organic content, since they are often associated with muskegs, cf. peat bogs. Suprapermafrost water plays a significant part in geotechnical problems such as frost heave, the formations of icings (see section 4.3.4) and frost mounds and slope instability.

3.2.3 Intrapermafrost Aquifers

Intrapermafrost aquifers are not subject to seasonal freezing and their extent is affected only by long-term temperature changes. During periods of cooling the extent of intrapermafrost taliks will be reduced by encroaching permafrost, whereas the reverse will be true for periods of warming.

They can be found in *open taliks*, unfrozen zones that completely penetrate the permafrost, in lateral taliks, unfrozen layers within the permafrost, and in *isolated taliks*, unfrozen zones completely surrounded by permafrost (Fig 1).

Open taliks can occupy extensive areas below large lakes and major rivers. Their extent and incidence will decrease with decreasing size of the surface water bodies and with increasing latitude, and eventually open taliks will become closed taliks that gradually decrease further in size, Many open taliks are maintained by convective heat transport by upward flow of slightly warmer and/or mineralised subpermafrost water. Open taliks can also be maintained by downward flow (recharge) of surface or suprapermafrost water.

Lateral taliks can be produced where coarse and fine-grained sediments alternate, eg. in glacial deposits. The temperature of the more permeable horizons is kept above freezing by the heat content of the moving water. The basal parts of thick permafrost is often unfrozen due to the freezing point depression of the highly mineralised water, and such negative temperature taliks are termed basal cryopegs (Tolstikhin and Tolstikhin, 1974).

Isolated taliks develop below the beds of recently drained lakes and abandoned river channels, where permafrost activity is developing from the surface downwards into what were originally closed taliks. Isolated taliks are therefore transient phenomena and can develop high pressures, due to thermo-osmotic effects, giving rise to large pingos–perennial ice-cored frost mounds.

The chemical composition of intrapermafrost water depends on the nature of the taliks. Water in open and lateral taliks is either similar to suprapermafrost water, but with a slightly increased mineralisation and a reduced organic content, or similar to subpermafrost water, which can be highly mineralised. Water in isolated taliks is affected gradually by *cryogenic metamorphism* which causes increased mineralisation with the eventual precipitation of less soluble salts, ion exchange, adsorption and possibly biochemical processes (Tolstikhin and Tolstikhin, op cit). Water temperatures in open and lateral taliks are usually just above 0°C, but can be much higher in taliks that are fed by thermal subpermafrost water. Temperatures below 0°C prevail in basal cryopegs and are found in open taliks that have highly mineralised water.

3.2.4 Subpermafrost Aquifers

Subpermafrost aquifers are situated below the basal cryopeg and therefore have water temperatures above 0°C. In areas of discontinuous permafrost, where permafrost may be thin, subpermafrost aquifers commonly occur in unconsolidated deposits, whereas at higher latitudes they are found predominantly in the basement.

In basement rocks the regime of subpermafrost aquifers can be extremely varied. In discontinuous permafrost such aquifers may receive recharge from rain or snow melt, or from suprapermafrost water in river valleys. Within the continuous permafrost zone they receive recharge almost exclusively from rivers and from intrapermafrost aquifers through open taliks -perhaps almost exclusively associated with fracture zones.

The chemical composition of subpermafrost water within the basement is usually similar to that of the overlying surface and suprapermafrost water. Highly mineralised subpermafrost water may reflect cryogenic metamorphism, and high sulphate concentrations have been found in the vicinity of sulphide mineralisation (Sloan and van Everdingen, 1988).

In the Baker Lake area, Northwest Territories, Canada, a detailed geochemical study has been carried out (Dyck and Car, 1987) over a large He-U anomaly. It was concluded from this study that regional fracture zones were supplying mineralised waters to the lower parts of the lake through an open talik. The estimated permafrost thickness in this area is 500m (Judge, 1973) and there is evidence from nearby that the permafrost is at least 300m thick (Hilger, in Judge (op cit)). The high He content, as high as 26,000 nl l^{-1} in lake bottom waters, indicates that the mineralised water is derived from great depths. In the lake sediments He and U were highly anomalous and paralleled the strong anomaly patterns of He observed in the water. Median and maximum values in the sediments were 57ppm and 396ppm U, and 296 nl l^{-1} and 13,870 nl l^{-1} He. This was surprising as a high U content indicates an oxidising, and hence near surface source. One must therefore conclude that the water entering the lake is oxidising with respect to U and Fe in spite of its deep origin. There are two possibilities, one that involves O_2-rich waters recharging through large open taliks , moving laterally under the permafrost and emerging through the large fracture zones. An alternative hypothesis relies on the radiogenic heat of U to provide the upward convective force for groundwater movement. Because of the low concentrations of Rn the U mineralisation is likely to be at a significant distance from the lake, also indicating lateral groundwater movement.

Subpermafrost aquifers in alluvial deposits below river valleys are widely used as sources of water supply in the basins of the Yukon and Tanana rivers in Canada and Alaska (Williams and van Everdingen, 1973).

4 Groundwater movement

4.1 Infiltration and recharge

Groundwater recharge will be least affected by the presence of permafrost in areas in which the basement outcrops and where sufficiently large zones of higher hydraulic conductivity remain open for most or all of the year (Kane, 1981; Kane and Stein, 1983). In an area of continuous permafrost, in the Mackensie River system in the Yukon, Michel (1988) showed that recharge was significantly affected by the permafrost, except where rock exposure or sinkholes permitted direct entry to the solution channels in this karstic terrain. The continuity of fracture systems with depth is often limited in crystalline basement and hence recharge can be very restricted. The major, intermediate and even minor fracture zones included within the SKI Project 90 reference site could be potential recharge zones within a permafrost regime, as could the areas of higher ground in the western parts of the site.

The presence of extensive *muskegs* (peat bogs) and numerous lakes and ponds in areas where the rainfall is not high, eg in continental arctic Canada, illustrates that infiltration and recharge are severely restricted by permafrost, especially in areas of low relief (Roulet and Woo, 1986, 1988). These wetlands, in a similar manner to those in more temperate climates (Bay, 1969), do not appear to play an important role in long term storage or in the regulation of streamflow, particularly so because the storage capacity for much of the year is very restricted. The storage capacity increases during the thawing process, but the high specific retention of the peaty soils limits the capacity of adsorbing any additional water. Evaporation is the main process which depletes the soil moisture and hence increases the storage capacity in summer.

Many of the larger lakes and rivers are underlain by taliks of variable horizontal and vertical extent. If these taliks completely penetrate the permafrost, pathways are available either for recharge or discharge of sub-permafrost water. Recharge is very limited in areas covered with thick sequences of medium- to fine-grained unconsolidated sediments, such as glacial till (Sloan and van Everdingen, 1988).

The concentration of recharge in smaller areas and at fewer points can lead to high local recharge rates. Measurements are only available from karstic regions of Canada, where, during snowmelt, inflow into individual sinkholes in permafrost near the Great Bear Lake exceeded 1 m^3 s^{-1} (van Everdingen, 1981).

4.2 Lateral movement

The distribution of groundwater flow is strongly influenced by the presence of perennially frozen ground. The types of flow regime present in permafrost areas are illustrated in Fig 1. Lateral movement of groundwater in permafrost areas is confined to: (1) seasonal flow in the active layer during the frost free season, (2) flow in taliks and (3) flow in unfrozen rock below the permafrost (van Everdingen, 1976).

Flow can take place in the unfrozen zones found along the base of some of the larger alluvial fans (lateral taliks) and unfrozen zones containing mineralised water in basal cryopegs, which both form intrapermafrost aquifers for lateral movement of groundwater. Open taliks below large lakes and rivers, and taliks associated with thermal and saline springs, form intrapermafrost aquifers that can allow recharge to and discharge from the basement rock below the permafrost.

At sufficient depths below the permafrost, the groundwater flow regime remains relatively unaffected, except that the volumes of groundwater could be severely restricted if the permafrost is continuous and lasts for considerable periods of time. Compared with the situation of hydrogeological environments in sedimentary rocks, bulk hydraulic anisotropies are not great within crystalline basement and the groundwater flow cells do not normally have great lateral extent. When permafrost is sufficiently extensive, the locations of recharge and discharge are limited, and are likely to have greater lateral separations. The lateral extent of groundwater flow cells is therefore likely to be significantly increased. Within the uncertaintities inherent in the scenario analysis, this may not be considered a significant effect, as gradients may perhaps be halved, and transit times perhaps doubled.

4.3 Discharge

4.3.1 Introduction

Active groundwater flow systems are present in permafrost areas, and the evidence for this activity is very similar to those discharge phenomena which are observed in more temperate regions. The presence of open water in ice covered rivers, the occurrence of icings (Carey (1973) and see section 4.3.4) and the presence of certain types of frost mounds (Acedemia Sinica, 1975) indicate groundwater discharge. Some of these have been used to derive quantitative estimates of groundwater flow (Michel, 1977).

Most of the discharge from all forms of permafrost aquifer takes place through taliks below lakes and streams and through a number of large springs. During the winter, discharge from open taliks can be revealed by pools or reaches of open water and by large icings for some distance downstream. Winter baseflow in rivers can also be substantial. In areas north of the normal tree line, the existence of open taliks below a river is often indicated by the presence of willows or poplars along the river channels.

The discharge from subpermafrost aquifers is generally perennial, whilst discharge from lateral intrapermafrost aquifers may stop before the end of the winter, especially if decreasing flow rates from limited reservoirs allow the outlets to freeze. Discharges from the active layer normally stop at the onset of winter.

Burn (1988) has calculated the rate of incorporation of water into the permafrost over the last 8000 years by downward temperature-induced infiltration of groundwater for some near-surface ground ice at a site in the Yukon. He has demonstrated that the rate of water incorporation into the permafrost has been at least 0.1 mm y^{-1}. The water has built up an ice-rich zone at the base of the active layer, and elevated tritium levels have been detected in ground ice up to 50cm below the base on the active layer (Burn and Michel, 1988), suggesting that downward temperature-induced infiltration of tritiated water, precipitated since the late 1950s has continued well below the active layer. This zone is of significance because its widespread occurrence in permafrost regions implies that it is a substantial hydrogeological reservoir and because it can act as a thermal buffer to climatic warming due to its high latent heat content.

4.3.2 Springs

The discharge from springs and seeps can provide reliable information on groundwater flow. The temperature and chemical composition of a spring's water can provide valuable data on the source and age of the water, ie. whether it is derived from a supra-, intra- or subpermafrost source (Michel, 1977; van Everdingen et al, 1979; Burn and Michel, 1988).

Perennial springs commonly discharge water from subpermafrost aquifers or less commonly from intrapermafrost aquifers. Research in Canada has shown that all thermal springs (T>10°C), most springs with discharge rates exceeding about 5 l s^{-1} and most mineral springs, with more than 1g l^{-1} dissolved solids derive their water from subpermafrost regions via open taliks. Springs with lower discharge rates or producing cooler or less mineralised water may, of course, also be discharging from subpermafrost regions (Sloan and van Everdingen, 1988) .

4.3.3 Baseflow

A first approximation of the rate of groundwater discharge in a river basin in which there are no lakes can usually be derived from the rates of baseflow in rivers, in a similar manner to the methods used in more temperate regions. The groundwater contribution to base flow in drainage basins in the discontinuous permafrost zone generally ranges between 1.0 and 5.0 l s^{-1} km^{-2} in Canada and Alaska (Sloan and van Everdingen, 1988).

4.3.4 Icings (Naledi or Aufeis)

During the winter much of the groundwater flow discharge in the continuous permafrost zone, which would normally maintain winter baseflow in rivers, freezes instead and form icings (a direct translation from the Russian word, *naled* (Carey, 1973)) or *aufeis*. The distance between the point of discharge and the point where icing formation commences is a function of the discharge rate, temperature, concentration of the dissolved components, the gradient of the discharge channels and the meteorological conditions (Michel, 1986).

The source of the groundwater has a significant influence on the duration of icing growth. Icings which are fed by discharge from suprapermafrost water will normally stop growing before the end of the winter, whilst icings fed by intra- or subpermafrost aquifers will commonly continue to grow until the mean daily temperature rises above 0°C in the spring.

Nearly all icings are believed to be related to the discharge of groundwater. During the summer the icings normally melt and the stored water is released, and icings thereby cause seasonal groundwater redistribution. For example, Williams and van Everdingen (1973) have calculated that 123 x 10^6 m^3 of icings accumulated on the Sagavanirktok River basin in Alaska during the eight month freezing period. The volume of ice represents an average groundwater discharge rate of $6m^3s^{-1}$, and melting of the icings during the following two month summer season adds about $24m^3s^{-1}$ to streamflow from the basin. The rate of runnoff from melting icings, from data in Alaska and Canada, appears to be 1.5 to 4 times greater that the groundwater flow rate that causes the icings.

5 Geochemistry

5.1 Effects of low temperatures

The reduction in temperature in itself has probably only limited direct effects on the chemical composition of either surface water or groundwater. Under the lower temperatures prevailing in the permafrost areas the solubilities of carbonates and bicarbonates increase, because of the increased solubility of CO_2, and the same is also the case for some sulphates, but the solubilities of most minerals decrease with decreasing temperature. The dissolution rates (in moles s^{-1}) of the majority of minerals also decrease, but this tends to be offset because the higher viscosity of the groundwater, which reduces groundwater flow velocities and thereby increases residence times.

5.2 Groundwater geochemistry

The chemical composition of suprapermafrost groundwater reflects the influence of rainfall and snowmelt and its relatively short residence time. Dissolved components are generally low, but its organic content is high, reflecting its association with muskeg areas. In cases where suprapermafrost water is partly derived from intra- and subpermafrost aquifers, its concentration of dissolved constituents can be extremely high.

The chemical composition of groundwater discharge into rivers in northern Canada and Alaska has been extensively analysed (Brandon, 1965; Schreier, 1979), as has their isotopic composition (Hitchon and Krouse, 1972). The chemistry of the surface water may vary along the length of the river because of local inflows of mineralised groundwater. There will also be seasonal changes in the water chemistry because of the changing contributions from the snowmelt or rainfall, by discharge from the active layer and by discharge from intra- and subpermafrost aquifers. The storage of groundwater discharge during winter, in the form of icings, tends to have a diluting effect on the resulting river water during their melting. With increasing flow in the spring there can be changes in salinity of the river water of more than an order of magnitude.

Lakes in permafrost areas often display chemical stratification. Hypersaline waters sometimes fill the deepest parts of such lakes and are overlain by meteoric waters, with an intermediate mixed layer. Hypersaline conditions can be caused by several processes, including ice sublimation (Matsubaya et al, 1979), groundwater diagenesis and subpermafrost saline supply. Another possibility in near coastal lakes is that post-glacial uplift has captured seawater in topographical depressions, or that horizontal infiltration of seawater has occurred with the freezing-out of ice (Pagé et al, 1987). Such lakes are likely to desalinate with time.

Intrapermafrost water in lateral and open taliks with downward flow usually resembles subpermafrost water, with slightly increased concentrations of dissolved solids. Intrapermafrost water in open taliks with upward flow, and in basal cryopegs, is often identical to the subpermafrost water in both composition and concentrations.

The composition of the subpermafrost water depends strongly on its residence time and the chemistry of the basement rocks and their fracture coatings and infills. Subpermafrost waters analysed in Canada range from Ca-Mg bicarbonate type freshwater, through sulphurous, brackish and saline waters to sodium chloride brines. In the case of the SKI reference site, it seems unlikely that high concentrations of dissolved constituents would be found.

Lower concentrations of dissolved solids in subpermafrost water normally indicate proximity to recharge areas or a relatively fast flowing pathway within the basement. The concentrations of some ions, particularly bicarbonate and sulphate, may be unusually low where thawing is occurring at the base of degrading permafrost. Low solution rates, due to the low temperatures, and the low solubility of minerals such as calcite in the absence of free CO_2, tend to limit the dissolution of these minerals that may have been precipitated during the formation of the permafrost.

5.3 Chemistry of Icings

The chemical composition of icings can vary substantially throughout the icing because of the uneven distribution of mineral precipitates and mineralised fluid inclusions. During the gradual freezing of the water flowing over the icing the concentration of dissolved solids in the water slowly increases until the saturation point is reached for the least soluble minerals. Precipitation of minerals commences and continues, involving more and more soluble components. The last dissolved component is precipitated, or incorporated, in the ice as brine inclusions at the point at which the last water freezes.

As icings melt the more soluble constituents in the ice (eg. NaCl) rapidly return to solution, whereas less soluble components redissolve much more slowly, forming a mineral slush on the surface and around the edges of the icing. Meltwater from icings is therefore generally lower in dissolved minerals than its source and has a higher chloride: bicarbonate and :sulphate ratio.

5.4 Surface water chemistry

The chemical composition of surface waters in permafrost areas is affected primarily by the slightly increased solubilities of any carbonates and the reduced rates of dissolution. In areas with extensive muskeg, surface waters are often high in humics. The influence on the chemical composition of rivers in permafrost areas caused by the discharge of groundwaters of differing chemistries has been discussed above.

6 Water supply in permafrost areas

6.1 Introduction

In permafrost areas water supplies can be obtained from both surface water and groundwater. Data on production rates for groundwater and surface water are available for the Yukon and the Northwest Territories of Canada (Hess,1984; Brandon, 1965; Trimble et al, 1983). These statistics are somewhat distorted because of the very large amounts of surface water used for placer mining in the Yukon, and the equally large volumes of groundwater extracted during dewatering of mines in the Northwest Territories. The volumes of potable groundwater available in the areas of low relief and in areas with very thick permafrost in the Arctic Islands is very limited. The supply of water throughout the year has important implications for the types of human settlement which could be expected to exist on or close to the reference site.

6.2 Surface water supplies

The reliability of surface water supplies is often limited by seasonal freezing. Many small streams and lakes freeze all the way to the bottom. In larger rivers, in which baseflow is sufficient to provide an adequate water supply, the quality of the water may vary widely with the seasons and the suspended sediment supply can be extremely high during the spring thaw. With increase in latitude in Canada the surface water supplies become more and more unreliable as even larger rivers and lakes can freeze to the bottom.

6.3 Groundwater supplies

Suprapermafrost aquifers in taliks below large rivers and deep lakes could provide supplies of potable water throughout the year. Aquifers in the active layer will, by definition, freeze for part of the year. Intrapermafrost aquifers do not freeze, but their supply may be exhausted before the end of the winter, and their salinity may be unacceptably high. With increase in latitude the size of such aquifers decreases substantially.

A special type of permafrost aquifer can be found in isolated transient taliks that have developed from closed taliks below recently drained lakes and abandoned river channels as permafrost penetrates from the surface. If harsh permafrost conditions continue, such aquifers are likely to decrease in size with time and may become artesian.

Subpermafrost aquifers in principle offer the best sources for groundwater supply, but their salinity is often found to be high in the areas of lower relief in the Canadian plains where continuous permafrost is present. In areas of greater relief, especially if precipitation is higher and groundwater transit times are shorter, potable water can be found (Trimble et al, 1983).

Perennial discharge of groundwater within permafrost areas can result in there being open stretches of water which can allow fish to spawn and overwinter. Such areas normally require significant spring discharges (van Everdingen, 1976) and are likely to be less common in areas of low relief, where groundwater flow rates tend to be less, and with increase in latitude, as the available areas of recharge become more restricted.

6.4 Natural factors which effect the hydrogeology of permafrost terrains.

Perhaps the most significant effect that natural processes can have on the hydrogeology of permafrost areas is in terms of erosion and sedimentation effects. Where ice rich sediments are exposed by erosion of riverbanks, melting of the ice can significantly increase the rates of erosion. Development of a thermo-erosional niche, by heat supplied by the river water, will lead to the eventual collapse of the overlying part of the bank (Neil and Mollard, 1980). The relatively large quantities of silt and clay-sized material released by this process can cause a large increase in the concentration of suspended sediment in the stream and encourages the rapid migration of river meanders.

Where significant thicknesses of ice-rich material are exposed, rapid thawing can produce expanding retrogressive thaw slumps that contribute further to the suspended sediment load of the stream. Such slumping is commoner along the coast. Deposition of the sediments in such structures as alluvial fans and deltas will cause a gradual rise in the "permafrost table", but is unlikely to affect surface runoff.

Natural draining of lakes will allow development of permafrost in the unfrozen sediments of the lake talik. In an originally open talik the permafrost growth may stop the discharge, whilst in a closed talik the water remaining in the decreasing frozen zone will gradually come under increased pressure, which may result in the formation of springs or the growth of a pingo.

It seems likely during the periods of permafrost when ice cover is not extensive, that there will be extensive snowmelt flooding. Estimates of increases in runoff rates during snowmelt for the UK in periglacial times by Pitty (1988) suggest that between 25 and 100 times the current mean annual discharge of a major river would occur during these events, and similar differences can be expected in Sweden. Extensive erosion of any superficial sediments is likely to take place, with deposition of these sediments in the low relief areas of the SKI reference site and on the floor of the drained Baltic.

7 Future climatic states over the next million years

The most reasonable assumption of future climatic states is that glacial conditions are very likely to occur several times over the next million years. A large amount of work in Europe and the US over the last few decades, and especially over the last few years, has concluded that the principal cause of the glacial–interglacial cycles are the periodic changes in the Earth's orbital parameters which cause variations in the distribution of the incoming solar radiation. Much of this work has been collated as part of the UK Nirex Ltd R&D biosphere programme (Goodess et al, 1989) and is generally applicable to the whole of western Europe as well as to the UK. The Milankovitch theory describes these changes and the climatic response and provides the basis for a number of predictive models. All these models confirm that the Earth has recently entered a period of oscillatory cooling, possibly leading to a glacial episode about 60ka AP (After Present) as severe as the last glacial maximum. During such an episode probably all of Sweden will eventually be covered by an ice sheet as much as several kilometres thick and the sea level could be as much as 140m below present levels. The models support the assumption that the range of climatic changes likely to be experienced over the next million years in northwest Europe will be similar to those experienced during the previous million years. The evidence from geology and from models suggests that approximately ten glacial/interglacial cycles will occur over this period.

There is a strong possibility that over the next thousand years the principal mechanism for change may be anthropogenic warming induced by "greenhouse gases". Such warming can be considered to be a "super-interglacial" imposed on the normal glacial/interglacial cycles, and is thought unlikely to have a major influence beyond that time, ie. after perhaps 6 ka AP (Imbrie and Imbrie, 1979, Goodess et al, 1989), although other unspecified anthropogenic effects may also influence the climate after that date.

The range, succession and duration of climate and sea level states likely to be experienced in the UK over the next million years has been estimated (Goodess et al, 1989), and extrapolations can be made to the situation in Sweden. These estimates have used empirical analyses of the past climatic record, and are not in precise agreement with either the Milankovitch model predictions nor with the ACLIN1 index (Kukla et al, 1981). Kukla et al have tentatively reconstructed the past and predicted future temperatures, based on the Milankovitch theory, and produced an astronomical climate index (ACLIN). The predicted surface temperature can be represented by the sum of several harmonic functions determined by orbital variations, which generate a 100,000 year glacial/interglacial climatic cycle.

The empirical analysis of Goodess et al (1989) incorporates, in theory, the influence of all possible periodic and random forcing factors experienced over the proxy data time series, and it is this that is thought to be most appropriate for providing data in a suitable format for input to a safety assessment of a repository site.

Using these data it can be shown that glacial/periglacial cycles are likely to last between 24-60 ka within the UK (Goodess et al, 1989). These periods of time are most likely to be longer in Sweden. The duration of climatic conditions in which the temperature of the ground remains below 0°C is significant because it allows estimates to be made of the generation rate of permafrost and the maximum depth to which it is likely to penetrate. What is also of interest are the relative periods of periglacial to glacial conditions. The release of radionuclides from the geosphere to the biosphere may be very different when thick continental ice is present on the site from when permafrost conditions exist but where there is no ice. These different climatic states need to be differentiated and are now discussed further.

An analysis of the expected climatic states within the UK over the next 10^6a (Goodess et al, 1989) has shown that there is expected to be a gradual cooling from 2ka AP to 35ka AP, and then glacial/periglacial conditions from 35 to 80ka AP before warming begins. These climatic data cannot be applied directly to Sweden, but it can be assumed that climatic conditions are very unlikely to be better than in the UK. With the drop in sea level expected during a cooling period, the UK climate is likely to be under a greater continental influence, and the difference between the climate in the UK and in Sweden may become less pronounced than at present.

The ACLIN curves (Kukla et al, 1981) show that there are likely to be three cooling episodes at 5ka, 23ka and 60ka AP. The extreme at 60ka AP is likely to rival the intensity of the Last Glacial Maximum, and should be followed by a shift towards more temperate conditions. These curves apply to the world's climate, and it can be expected that the Swedish climate will respond to the same forcing factors.

A climatic index constructed by Goodess et al (op cit), based on climatic records from deep sea cores in the Atlantic over the last 472ky, shows that the predicted length of glacial and periglacial conditions are as follows:

Climate state	Range	(K years)	Average	% of Time
Temperate	10-22		12	20
Glacial	24-60	(Incl. periglacial)	45	14
Periglacial	-			33
Boreal (warming)	2-12		6	33
Boreal (cooling)	28-42		33	

Table 7.1 Average climate state lengths calculated from the I84 climate index of Imbrie at al (1984) by Goodess et al (1989).

It could be assumed as a pessimistic case that permafrost conditions could be present in Sweden for the maximum time indicated in Table 7.1, ie. 60ka. This increase in time, above and beyond that used in the calculations of permafrost depth, for potential permafrost development is not thought to be particularly significant when balanced against the pessimistic assumptions made in calculating the depth of permafrost. The precise value of the geothermal gradient has a far more marked effect on the depth of permafrost than an increase in the cooling period of 20ka, and neglecting the influence of the ice cover on the heat exchange between the rock and the atmosphere in the calculations has already maximised its predicted depth. It will take a considerable period of time of sub-zero mean annual temperatures before any noticeable continental ice sheets form, and it will be during this period when the maximum cooling of the ground is likely to take place and when the increase of permafrost thickness will be most rapid.

Goodess et al (op cit) have also constructed a possible sequence of events for the climate of the UK over the current glacial/interglacial cycle, from 10ka BP to 98ka AP:

10ka BP - 2ka AP:	temperate, interglacial
2ka AP - 35ka AP:	boreal - cooling
35ka AP - 80ka AP:	glacial/periglacial
80ka AP - 86ka AP:	boreal - warming
86ka AP - 98ka AP:	temperate , interglacial

with a similar cycle repeating, approximately ten times within the next million years.

A similar analysis of future climatic conditions has been carried for Sweden by relating the output from Imbrie and Imbrie's (1980) response model to evidence from foraminifera from the Denmark area (Lykke-Anderson, 1987) together with evidence from past climatic events. It is calculated that cooling up to 23ka AP is likely to produce continental ice sheets similar to the situation that existed at isotope stage 4 (Imbrie and Imbrie, 1980), when parts of Scandinavia were glaciated (Lundqvist, 1986). There is no reliable evidence to suggest how extensive this glaciation might have been; Lykke-Andersen (1987) states that it did not extend further south than the Göteborg area, whereas Lagerlund (1987) provides evidence for an ice lobe extending as far south as the Polish coast. This glaciation was, however, much more restricted than the one in Late Weichselian times. Therefore, according to the Imbrie and Imbrie (1980) model, parts of Sweden will start to become glaciated within the next 20ka, with a glacial culmination at 23ka. These stadial conditions are likely to be followed by an interstadial climate, and the ice sheet is expected to have melted by 30ka AP. If this interstadial is comparable with isotope stage 5a, and hence with the Tärendö Interstadial in Sweden (Lagerbäck,1988), it would imply that harsh climatic conditions could be expected, at least in the north of Sweden. Extensive permafrost could therefore be expected over most of Sweden. At 50ka AP the main glacial advance is expected to commence, with a maximum glaciation at 63ka AP. This glaciation can be related to isotope stage 2, and is therefore similar to the situation in the Late Weichselian. A further interglacial optimum is expected at 75ka AP with another glacial advance around 100ka AP. This implies that large parts of Sweden will be glaciated three times over the following 100ka.

It is likely that a cyclicity paralleling that described by Goodess et al (1988) will take place, with the extent of the periglacial/glacial events being more pronounced. A northward decrease in mean annual air temperatures of 1°C per 150-200km is usually observed and central Sweden lies 800km north of central UK. Estimates of the average UKtemperatures during the last glacial maximum (about 18ka BP) are at least 10°C below present levels; summer temperatures were below 10°C and winter temperatures below -16 and possibly -20°C (Goodess et al, 1988). Extrapolation to Sweden would suggest that the respective temperatures there were below 6°C and below -20°C.

Using the argument above as a guide to future climatic states in Sweden, it is assumed for the present discussion that periglacial conditions commence 15-20ka AP and continue until 100ka AP. During this period either periglacial or glacial conditions are thought likely to be present in central and northern Sweden for a large part of the time, but the mean annual air temperatures are likely to fluctuate from perhaps -15 to -20°C during a glacial period to perhaps only just <0°C during periglacial times, and several degrees higher at the climatic optimums during interstadials. For the development of permafrost the mean annual air temperature is required to be below -1.6°C, and within the level of uncertainty of future climate states, the most pessimistic assumption could be that this air temperature is not exceeded during the whole of the 80ka period. This may be much too pessimistic because, based on the existing distribution of permafrost in Canada (Johnston, 1981), it is observed that it is only when the mean annual air temperature is < -3 to-5°C approx that widespread discontinuous permafrost is present, and it is only when the mean annual air temperature is <-8°C that continuous permafrost exists. It may be that a discontinuous permafrost case needs to be examined in addition to that of continuous permafrost, with repeated cycles of advance and retreat of the continuous permafrost front. In addition, the advance of continental glaciers may restrict permafrost development only to the periods of time before the glaciers are present on the site, and the most optimistic assumption could be that permafrost only develops for periods of less than perhaps 5 to10ka in the initial cooling, pre-glacial stages of any cooling cycle.

Estimates of permafrost thickness were first made for Canada (Judge, 1973) and relied on knowledge of ground temperature variations, both spatially and with time, the thermal conductivity of the rock and the regional variations in geothermal heat flux. In the last few years more sophisticated calculations and detailed borehole studies have been carried out as development has increased in arctic regions (Lachenbruch et al, 1982; Osterkamp and Payne, 1981; Osterkamp et al, 1985) We have made similar scoping calculations for the situation in Sweden at the reference repository site, and these are described in section 8.

8 Permafrost behaviour around a repository

Scoping calculations have been carried out for the situation of a repository situated at a depth of 500m and assumed to be at the SKI reference site. An approximate solution has been derived for calculating the temperature at depth under permafrost conditions and also for calculating the influence of heat emitting radioactive waste on the effects due to the permafrost.

One of the questions addressed is the possibility of generating a "bubble" of unfrozen water around a repository within an area of deep permafrost. Were such a situation to occur it could have significant implications on

71

the pattern of groundwater flow around a repository, the nature and rates of near-field processes and the far-field transport of radionuclides.

After the approximations used in the thermal calculations have been justified, a general solution to the problem is derived and a few examples of specific repository situations are illustrated.

8.1 Statement of the thermal problem

The thermal problem to be solved can be described as follows:

1. The initial temperature profile in the ground is known from present day measurements. It is not necessarily a steady state since the influence of the last glacial event may still be significant at depth.
2. Due to future glacial events the ground surface will be cooled, inducing a time dependent surface temperature boundary condition, which can be predicted reasonably accurately.
3. Due to the cooling the water contained in the rock will freeze, thereby inducing a thermal sink term equal to the latent heat of freezing.
4. The heat transfer within the rock will be governed by conduction and advection, and the geothermal heat flux will result in temperatures increasing with depth. Natural heat sources are also present in the rock due to the radioactive decay of U and Th and their radioactive daughters.
5. The growth of any surface ice sheet will act as an insulating layer between the atmosphere and the ground
6. The heat emitted by the waste will increase the temperature around the repository.

8.2 Assumptions made in calculating the effect of the repository

All these effects could be included more or less exactly into a coupled numerical model for heat and mass transfer to give an exact solution. It is proposed here to use only an approximate analytical solution to the problem in these scoping calculations, and it will be shown that the phenomena not accounted for by this solution can be considered to be of second order importance.

The following assumptions are made :

1. Both the present initial temperature distribution within the ground and any future temperature at the surface can be represented by assuming that the temperature at the surface can be described by a harmonic function of time. Fig. 2, from Kukla et al (1981), is a tentative reconstruction of past temperatures at the surface for the previous million years, and predictions for the next million years based on the predictions from the Milankovitch theory, described, not in terms of the temperature itself , but in terms of the ACLIN index. The value of the ACLIN index, ie the temperature distribution, can be represented by the sum of several harmonic functions, but for the present calculations only three will be considered, one with a period of 10,000 years, one with a period of 40,000 years and one with a period of 120,000 years. Additional or different harmonics could be used. It is also assumed that the present day conditions are correctly represented by the maximum at point A in Fig 2 and that intense periglacial conditions are continuous for the whole cooling period. This is a very pessimistic assumption, and the calculated thicknesses of permafrost are the absolute maxima. It is very unlikely that such thicknesses will develop due to oscillatory climatic conditions and to the development of a thick ice cover.

2. The latent heat of fusion at the permafrost front will be neglected for the particular case of granite. It would be possible to account for this heat sink, and a solution to this problem is shown in Carslaw and Jaeger, page 282 (1959). Unfortunately Neumann's solution to this problem is non-linear and this makes it more difficult to incorporate it into the present solution.

   In order to demonstrate that this approximation is valid, we need to compare the energy associated with freezing of the granite water system with the amount of energy that crosses the boundary of the system at ground level for a half period of the harmonic function. The volume of water contained within the granite, assuming

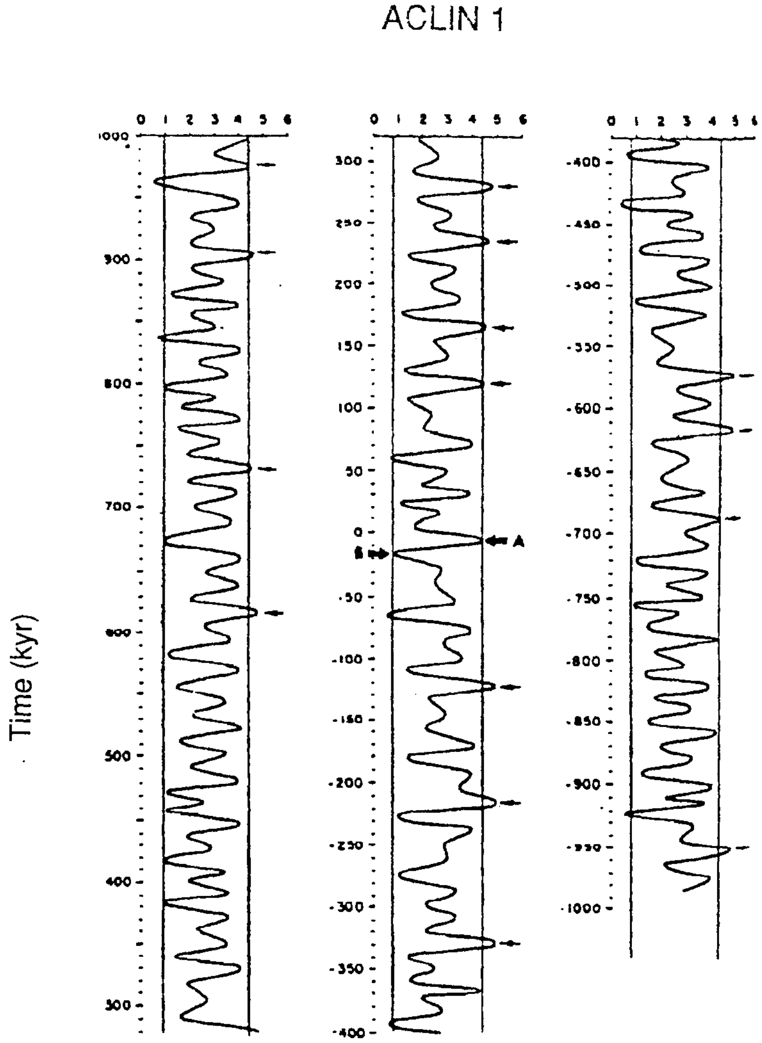

Figure 2: Plot of ACLIN 1 from 1,000,000yr BP to 1,000,000yr AP. Higher value indicates warmer climate. Peak Holocene (A) level of 4.3 defines interglacials marked with arrows. Past peak glacial level at about 17, 000yr BP (B) (From Kukla, 1981).

a porosity of 1%, is for a maximum depth of permafrost of between 500-1000m, 5 or 10 m^3 respectively per square meter of the ground surface. This amounts to a heat sink of 1.7x10^9 or 3.3 x10^9 J m^{-2}, as the latent heat of water is 334x10^3 J kg $^{-1}$. This can be compared with the amount of heat that crosses the ground surface during a half period of the harmonic function, ie. 5,000, 20,000 or 60,000 years, if the sink term is neglected.

The temperature distribution within the ground due to the harmonic boundary function at the surface, and assuming pure conduction, no geothermal heat flux and no repository, is given by:

$$T(x=0,t) = T_0 cos(2\Pi \frac{t}{t_s})$$

$$T(x,t) = T_0 exp(-kx).(2\Pi \frac{t}{t_s} - kx)$$

T = temperature, as a function of x, depth, and t = time
T_0 = half amplitude of the temperature variation
t = time
t_s = period of the harmonic function
$k = \sqrt{\frac{\Pi \rho c}{t_s \lambda}}$
ρc = volumetric heat capacity of granite ($2 \times 10^6 Jm^{-3}\ ^0K^{-1}$)
λ = thermal conductivity of granite (approx $3Wm^{-1}\ ^0K^{-1}$)

(Carslaw and Jaeger (1959), page 64, and values for ρ , c and λ from Tarandi (1983) for Swedish granite). It is easy to calculate the integrated flux at x=0 crossing the ground surface for a half period of each harmonic. It is given by:

$$Q(Jm^{-2}) = T_0 \sqrt{2 t_s \rho c \frac{\lambda}{\pi}}$$

If T_0 = 10°C, the results for the three harmonics are 11.0 x 10^9, 22.0x10^9 and 38.0 x 10^9 Jm^{-2} respectively. The sink term is therefore only approximately 15% at most of the total heat flux and can be ignored in these scoping calculations.

3. Advection will be neglected with respect to conduction. From estimates given in KBS-3, the flow of groundwater at depth in a low permeability rock mass is estimated to be approximately 1 x $10^4 ma^{-1}$. For a temperature difference of 10°C the advective heat flux is therefore of the order of 4.2x10^3 Jm^{-2} a^{-1}; and for times of 5,000, 20,000 and 60,000 years, the flux is 2.1 x 10^7, 8.4 x 10^7 and 25.2 x 10^7 Jm^{-2} respectively. This is negligible when compared with the conductive heat flux of 11.0 x 10^9, 22.0 x 10^9 and 38.0 x 10^9 Jm^{-2} for the same times; and a similar conclusion will be reached for all rocks with hydraulic conductivities less than approximately 1.0 x 10^{-8} ms^{-1}.

4. The growth of the ice cover, as regards its thermal role, will also be neglected. The conductivity and heat capacity of ice are 2.3 Wm^{-1} $^0K^{-1}$ and 1.9 x 10^6 Jm^{-3} $^0K^{-1}$ respectively, compared with the equivalent values for granite of 2.5 to 3.8 Wm^{-1} $^0K^{-1}$ and 2.1 x 10^6 Jm^{-3} $^0K^{-1}$respectively . The presence of the ice cover will therefore lower the heat exchange between the rock mass and the surface. This effect will only be of the order of 20% and will not significantly affect the results of these scoping calculations. By neglecting this factor the depth of permafrost development will be overestimated.

   The assumptions given above result in the problem becoming fully linear, and the effect of the geothermal heat flux and the heat emitted by the repository can simply be added to the temperature calculated with the harmonic solution. The geothermal gradients of 1.5 or 3°C per 100m, used for calculating the depths of permafrost development, corresponds to heat fluxes of 4.5 and 9 Wm^{-2}. The heat emitted by the repository is taken from calculations carried out by Tarandi (1983).

   It is assumed in the present calculations that the existing mean surface temperature in Sweden is 5°C, and that the minimum surface temperature is -15°C during permafrost development. This is a similar temperature to that presently existing in northern Canada in areas of continuous permafrost (Judge, 1973). T_0, half the amplitude of the temperature variation, is therefore 10°C.

   Using the above equation it is now possible to calculate the temperature profile at any time for a specified harmonic function due to the time-dependent surface boundary condition or for any sum of such harmonic functions. To this temperature must be added the geothermal gradient of 1.5 or 3°C per 100m and the influence of the repository.

8.3 Results

The calculations show that, without a repository permafrost, for the first harmonic of 10,000 years, reaches either approximately 500m or 300m depth for the two geothermal gradients of 1.5 and 3°C per 100m respectively, (Figs. 3 and 3b). [1] For the second harmonic, of 40,000 years, it reaches approximately 600m and 350m respectively, (Figs. 4 and 4b). For the third harmonic, of 120,000 years, it reaches approximately 700 and 400m respectively, (Figs. 5 and 5b). These figures are consistent with the estimates and measurements of permafrost thickness in northern Canada (Judge, 1973; Dyck and Car, 1987). A last calculation was made, adding together the three harmonics in order to represent cyclic fluctuations, as described in Fig. 2. The first harmonic (10,000 years) was given a T_0 of 3°, the second (40,000 years) a T_0 of 3° and the third (120,000 years) a T_0 of 4° in order that the total half amplitude of temperature variation remains 10°, as in the previous calculations. Fig. 6 shows the temperature fluctuations with time at ground level for each harmonic with a half amplitude of 10° and Fig. 6b for the proposed weighted sum of the three harmonics. Figs. 7 and 7b show that the permafrost depth reaches approximately 600m and 300m for the two geothermal gradients respectively.

It is also possible to add to the system the heat released by the repository, since the thermal problem has been made linear; using the simplifying assumptions outlined above, one just adds to the previous temperature profiles the temperature increase due to the waste heat. This was done using the one-plane repository design at a depth of 500m of KBS-3 (Tarandi, 1983). The calculated temperature increase with time is shown in Fig. 8. Adding this temperature increase to the eight temperature profiles described above (three periods, one weighted sum, two geothermal gradients) gives eight new temperature profiles through the centre of the repository plane (Figs. 9 to 12). For the first two harmonics, the presence of the repository maintains the permafrost depth above 300m (Figs. 9 and 10). For the last harmonic and the weighted sum, the time of freezing occurs so late that the influence of the repository is no longer very significant (Figs. 11 and 12). However, for the shorter harmonics, the repository could consist, for a period of a few thousand years per cycle of an unfrozen volume of rock lying above the normal level of frozen ground. It can be thought of as an oblate bubble of unfrozen rock.

It therefore seems probable that, assuming a geothermal gradient of 3°C per 100m , which is probably closer to the expected value than 1.5°C per 100m, a repository at 500m depth is unlikely ever to freeze. Using these

[1] All the graphs of the calculated temperatures in this section have been produced by S Ezzedine, from the Paris School of Mines

extremely pessimistic assumptions, the base of the permafrost could come to within perhaps 100m of the upper surface of the repository. These calculations neglect the ameliorating influence of the ice, and take the mean surface temperature as -15°C during a glacial period. In fact, for a large part of the glacial period it seems likely that Sweden will have ice cover, which may be of substantial thickness. The temperature at the base of this ice is very unlikely to be as low as -15°C, and therefore the above calculations result in absolute maximum probable depths of permafrost.

The calculations above have assumed that the periods of the cooling cycles are equivalent to the period of permafrost development. In section 9.8 it is argued, based on a review of climatic data for the UK by Goodess et al (1988), that the situation is not necessarily as simple as this, and that longer periods of cooling could be expected. The longest probable cooling phase is likely to be 60,000 years, ie. a period of 120,000 years for the harmonic function but this increase in cooling is probably balanced by the pessimistic assumptions used for the calculations with regard to the formation of ice cover. The calculation shows that the permafrost depth could reach 700m only for the low geothermal gradient and remain above the repository depth for the high geothermal gradient; but the waste heat will always prevent freezing, for the first 100,000 years at least. Based on climatic predictions for the UK, it does not seem likely that the 10,000 year cooling cycle necessarily introduces intense periglacial conditions, and it is therefore only the longer cooling cycle that is important.

It is not known what the effect of repeated glaciations will be on the maximum depth of the permafrost, and whether the maximum depth could be expected to increase gradually after several cycles of cooling. There is a large phase lag between warming cycles and the downward migration of the permafrost front, such that the permafrost which presently exists at depth in northern Canada and Spitzbergen is probably related not to present climatic conditions, but to previous glacial maxima. Nevertheless, it is thought unlikely that a repository is ever likely to freeze. However, the sealed access shafts will undoubtedly be subject to freezing, and parts of the repository could be intersected by the basal cryopeg, or at least lie within the zone of altered groundwater chemistry.

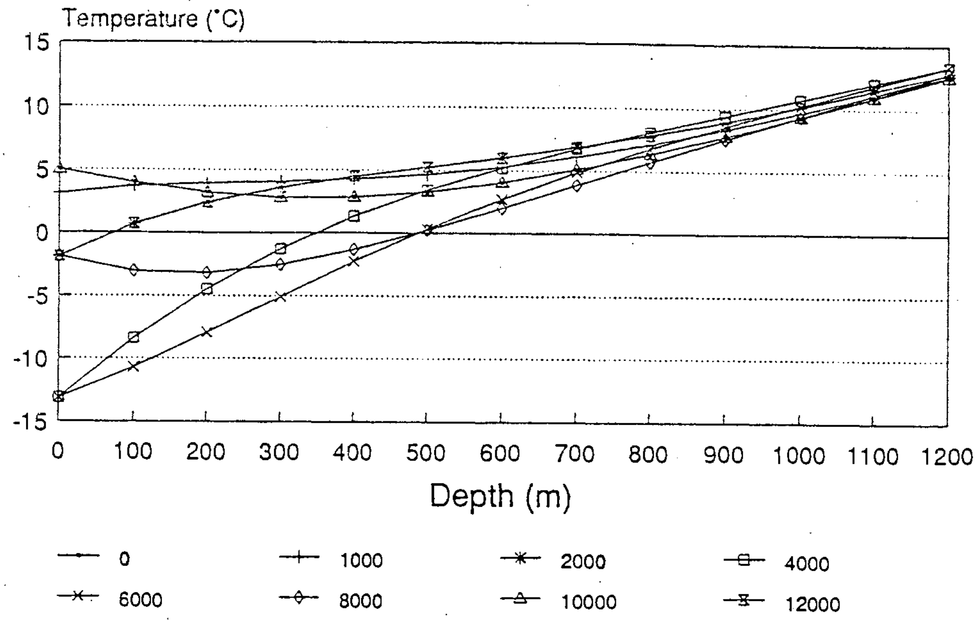

Figure 3. Temperature versus depth(m) and time (years after present)
Period $10,000$ *years*
Geothermal gradient $1.5°C$ *per* $100m$

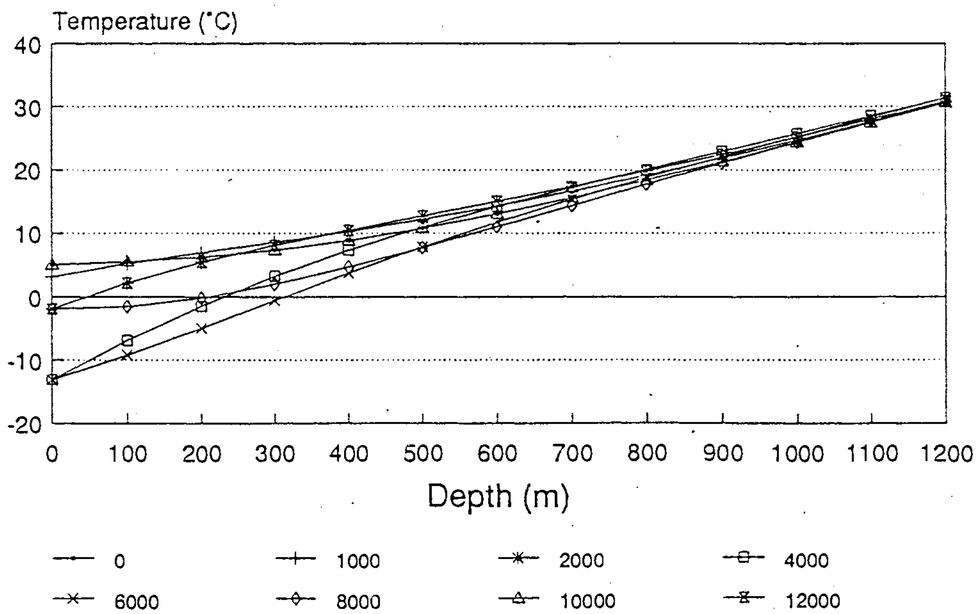

Figure 3b. Temperature versus depth(m) and time (years after present)
Period $10,000$ *years*
Geothermal gradient $3°C$ *per* $100m$

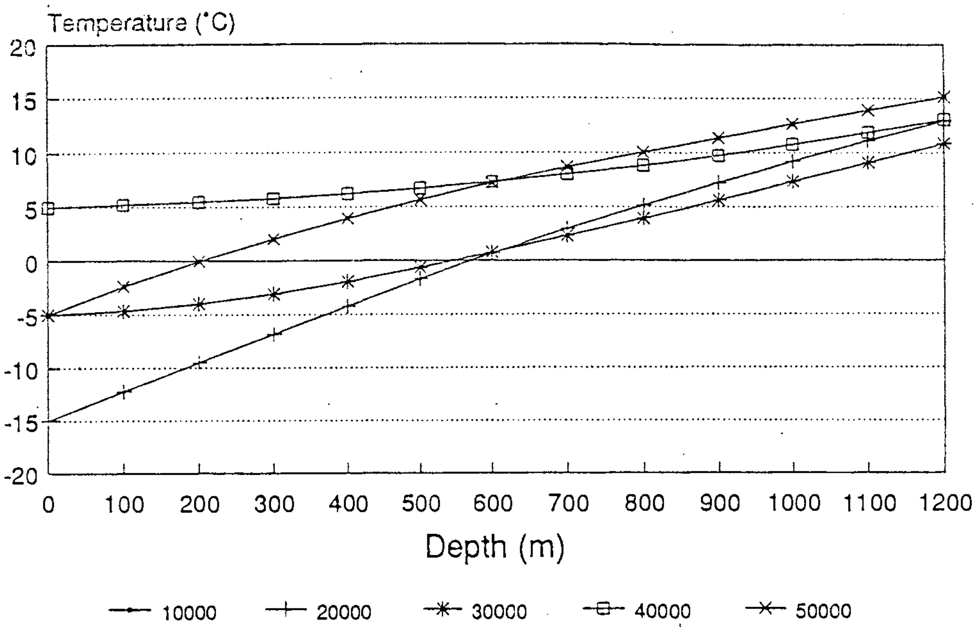

Figure 4. Temperature versus depth(m) and time (years after present)
Period 40,000 $years$
Geothermal gradient 1.5°C per 100m

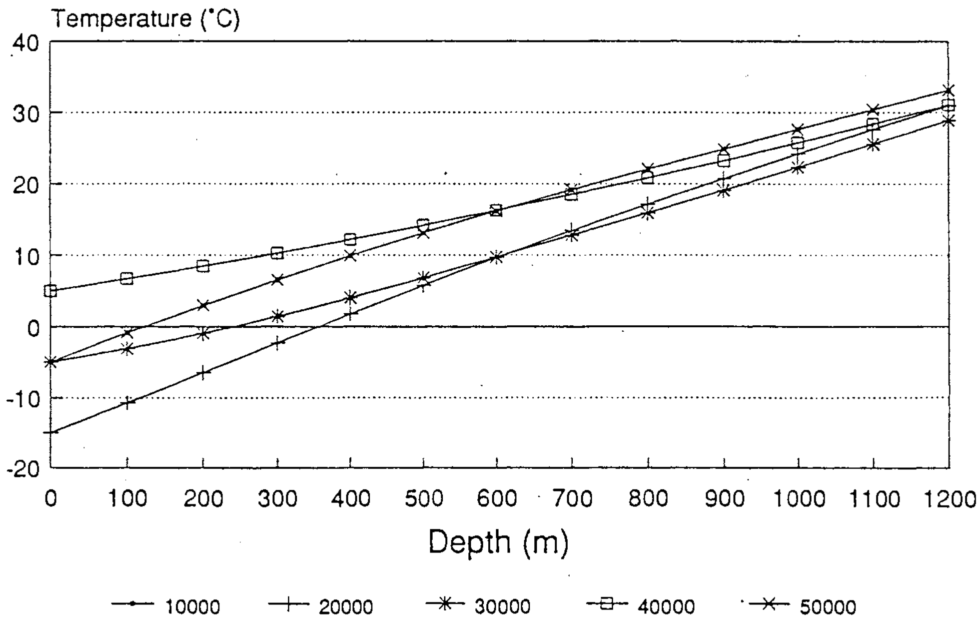

Figure 4b. Temperature versus depth(m) and time (years after present)
Period 40,000 $years$
Geothermal gradient 3°C per 100m

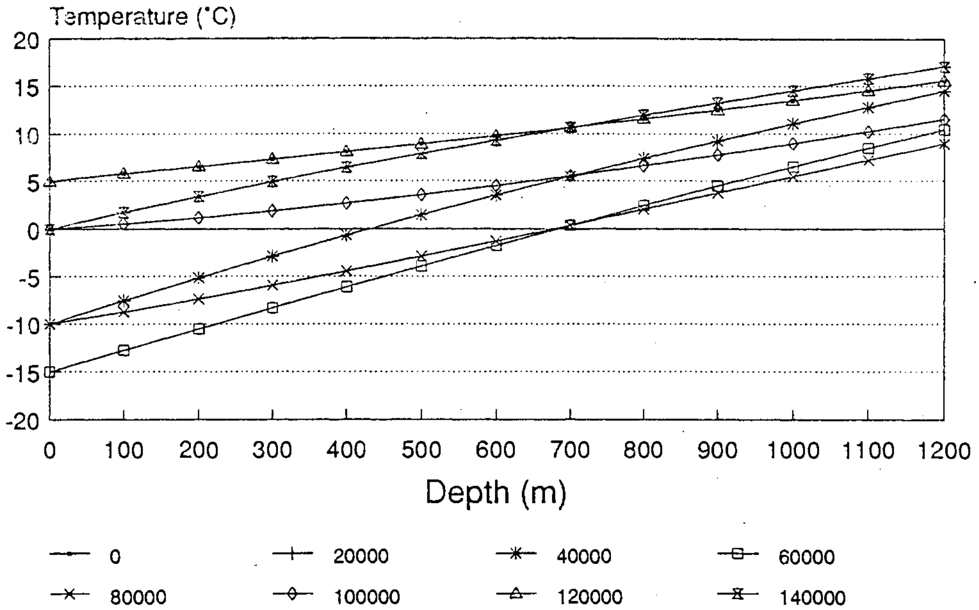

Figure 5. Temperature versus depth(m) and time (years after present)
Period 120,000 *years*
Geothermal gradient 1.5°C *per* 100m

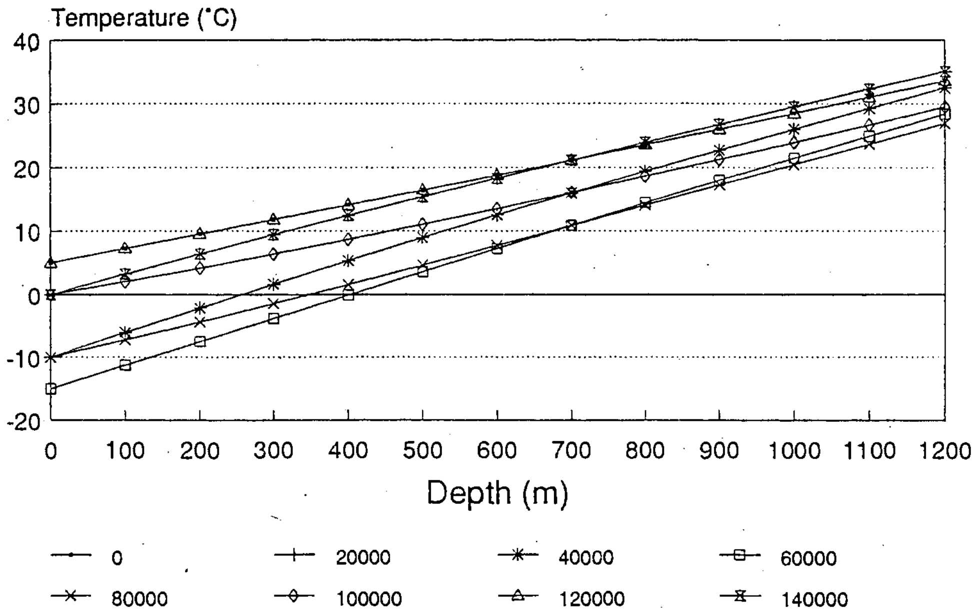

Figure 5b. Temperature versus depth(m) and time (years after present)
Period 120,000 *years*
Geothermal gradient 3°C *per* 100m

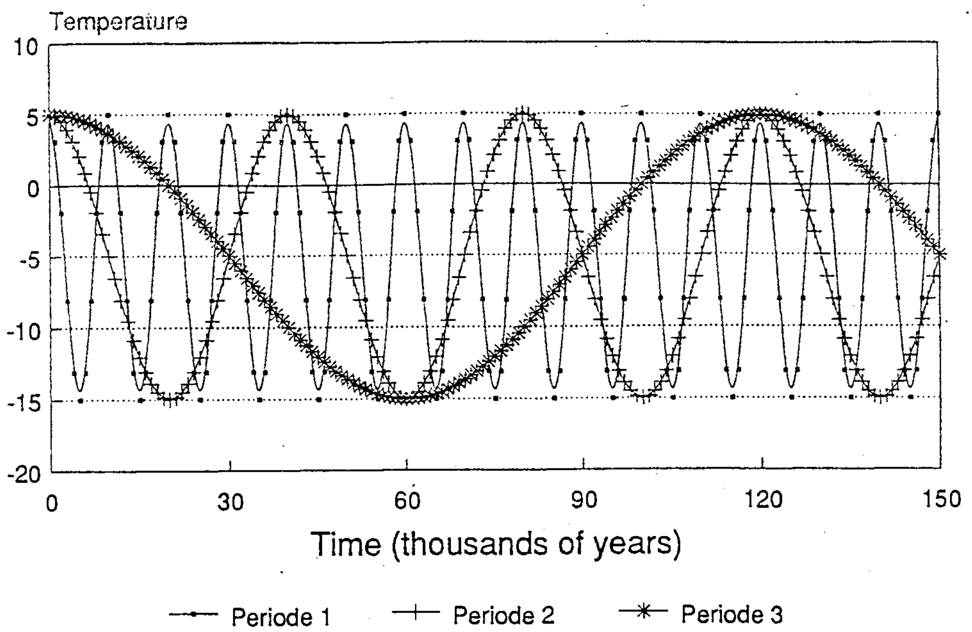

Figure 6. Temperature Variations with time at the ground surface, for each harmonic (period 10,000, 40,000 and 120,000 years).

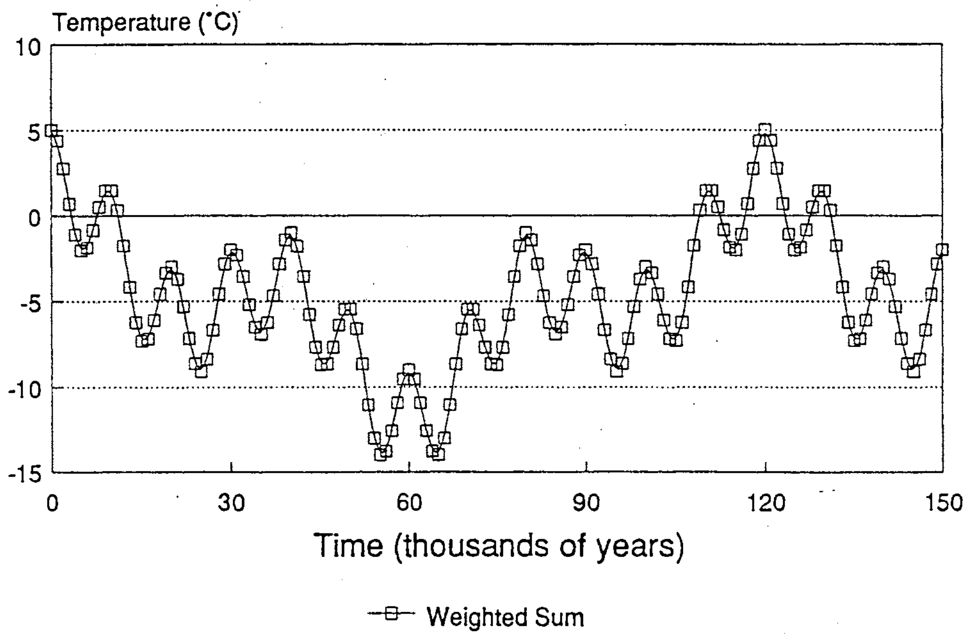

Figure 6b. Temperature Variations with time at the ground surface, for the weighted sum of the three harmonics:
$3°C$ for the $10,000$ *year* period
$3°C$ for the $40,000$ *year* period
$4°C$ for the $120,000$ *year* period

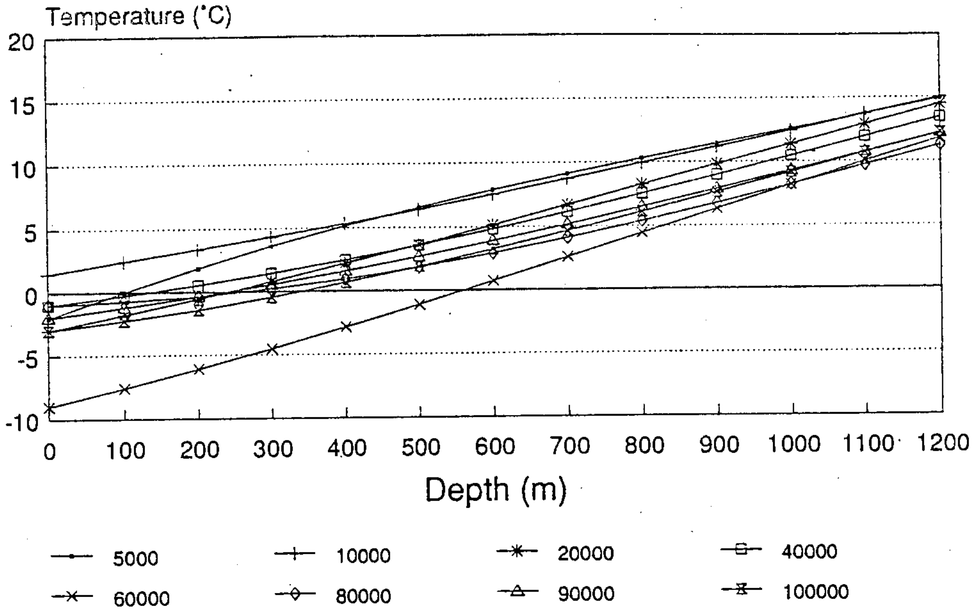

Figure 7. Temperature versus depth (m) and time (years after present)
Weighted sum of the three harmonics
Geothermal Gradient $1°C$ *per* $100m$

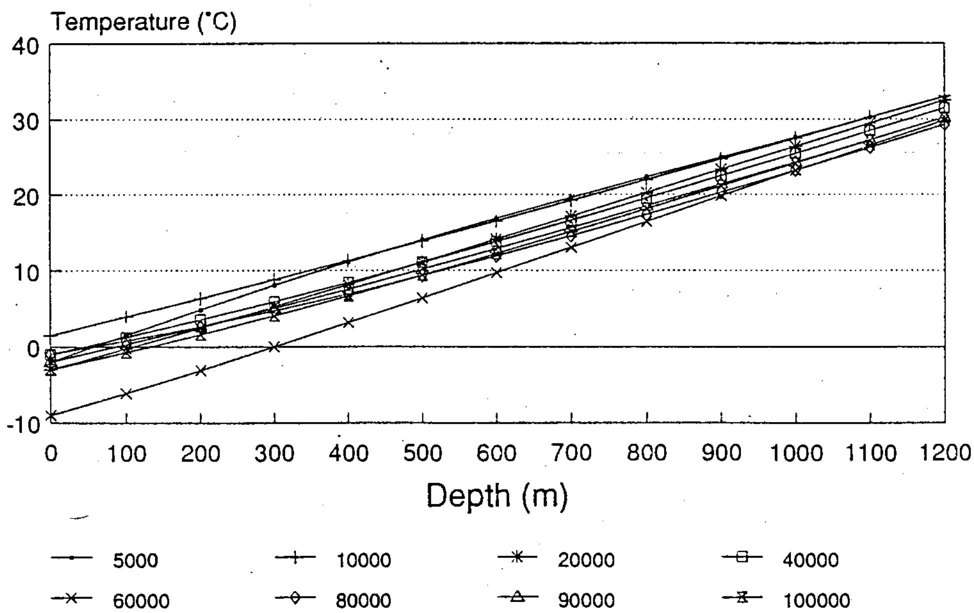

Figure 7b. Temperature versus depth(m) and time (years after present)
Weighted sum of the three harmonics
Geothermal Gradient $3°C$ *per* $100m$

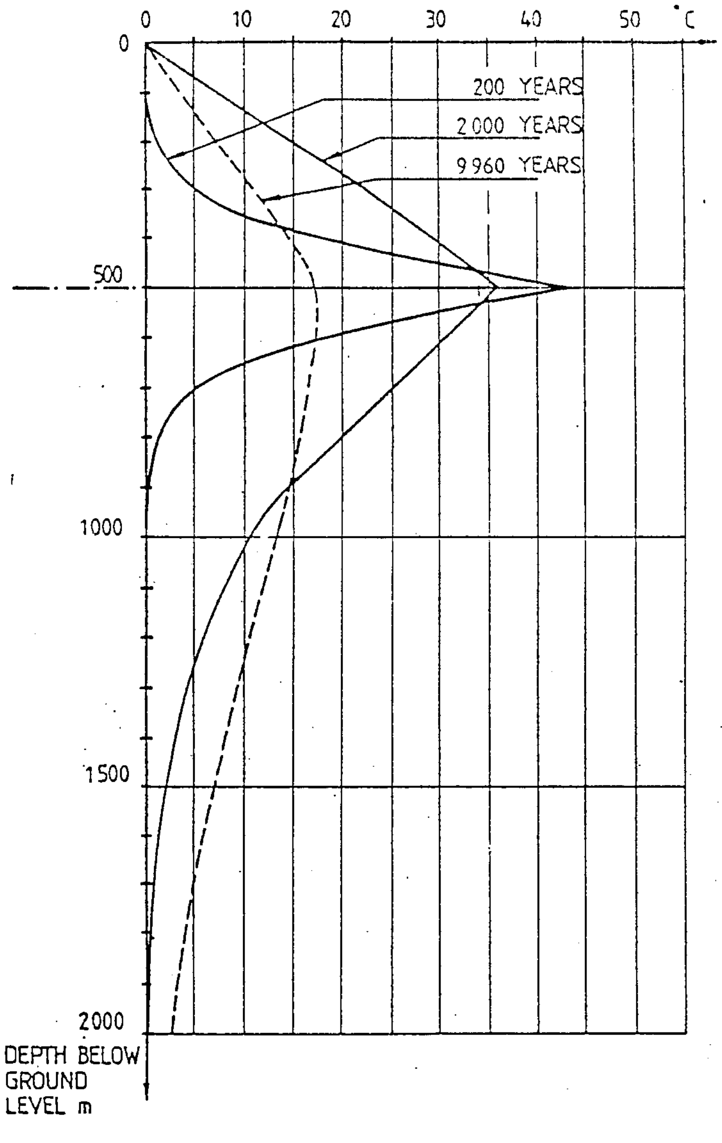

Figure 8, (from Tarandi,1983 (case 1A)). Temperature increase versus depth (m) and time (years after present)
For a one plane repository at a depth of $500m$

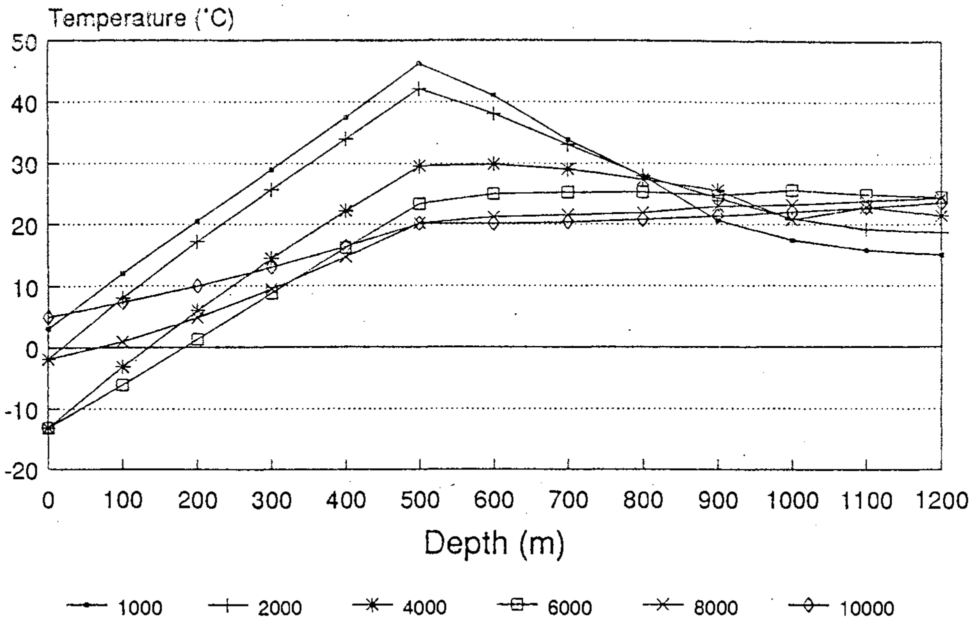

Figure 9. Temperature versus depth(m) and time (years after present) with the repository.
Period $10,000$ *years*
Geothermal gradient $1.5°C$ *per* $100m$

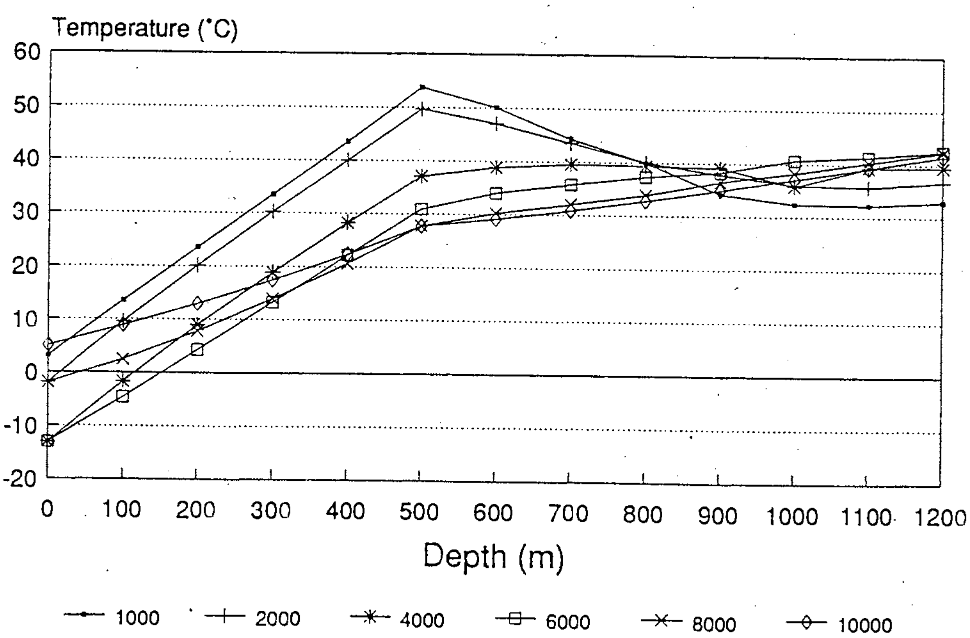

Figure 9b. Temperature versus depth(m) and time (years after present) with the repository.
Period $10,000$ *years*
Geothermal gradient $3°C$ *per* $100m$

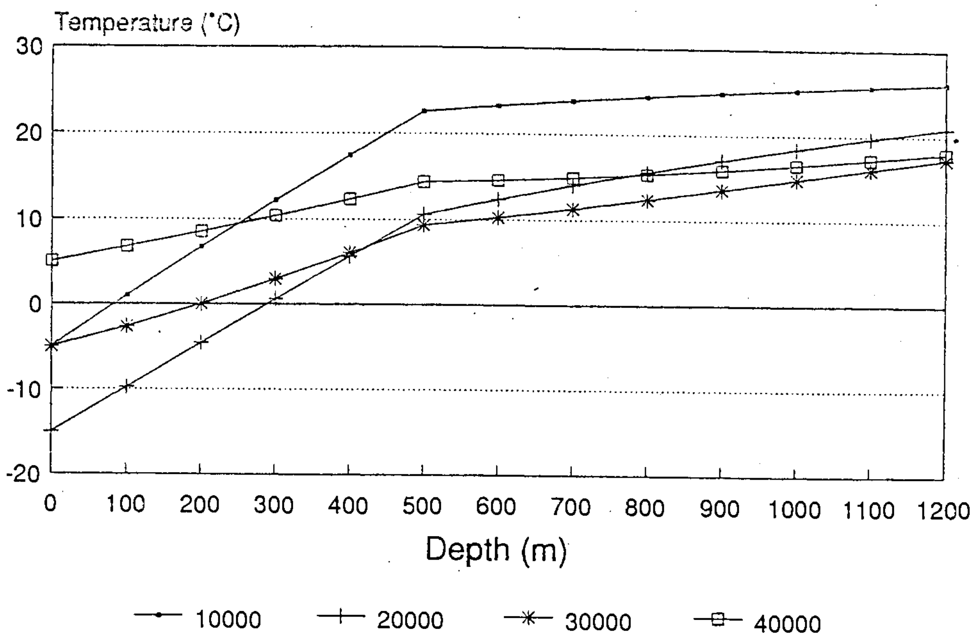

Figure 10. Temperature versus depth(m) and time (years after present) with the repository.
Period 40,000 '*years*
Geothermal gradient 1.5°*C per* 100*m*

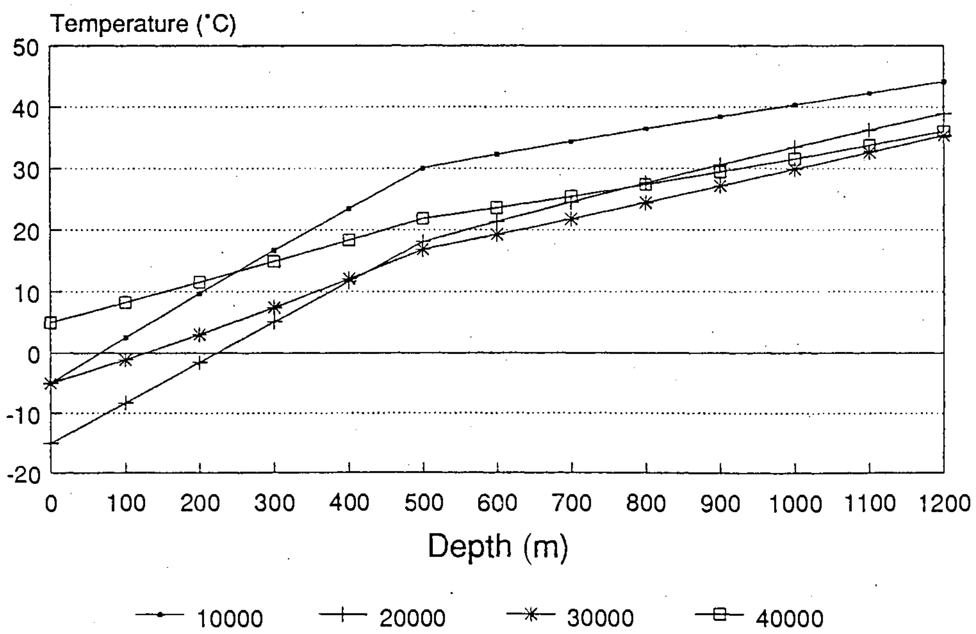

Figure 10b. Temperature versus depth(m) and time (years after present) with the repository.
Period 40,000 *years*
Geothermal gradient 3°*C per* 100*m*

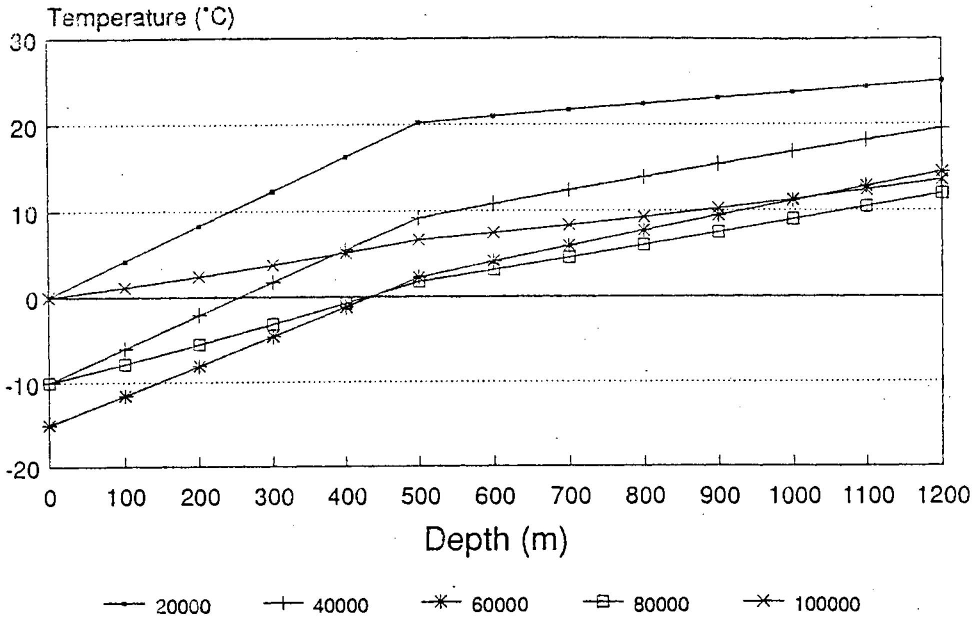

Figure 11. Temperature versus depth(m) and time (years after present) with the repository.
Period 120,000 *years*
Geothermal gradient 1.5°C *per* 100m

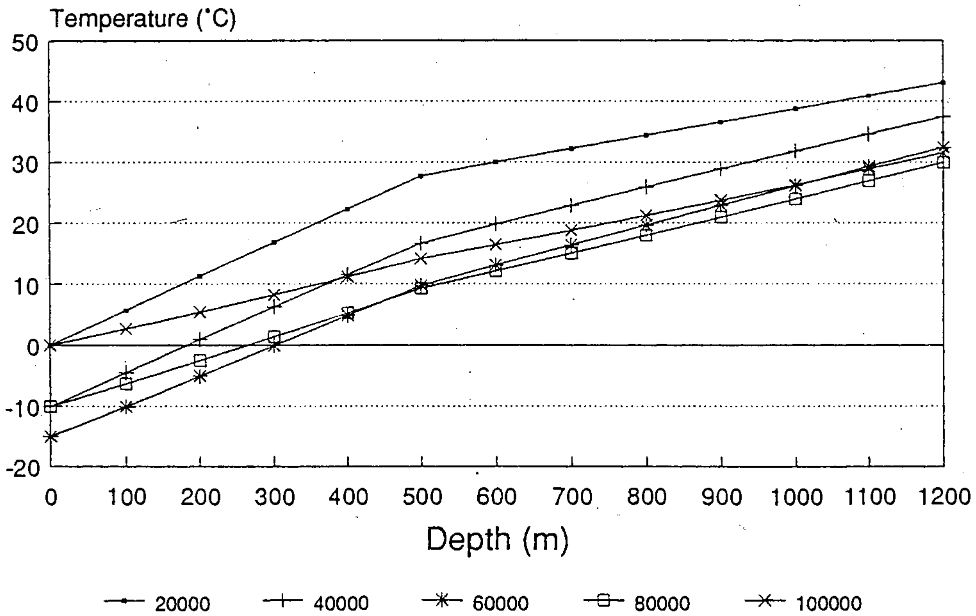

Figure11b. Temperature versus depth(m) and time (years after present) with the repository.
Period 120,000 *years*
Geothermal gradient 3°C *per* 100m

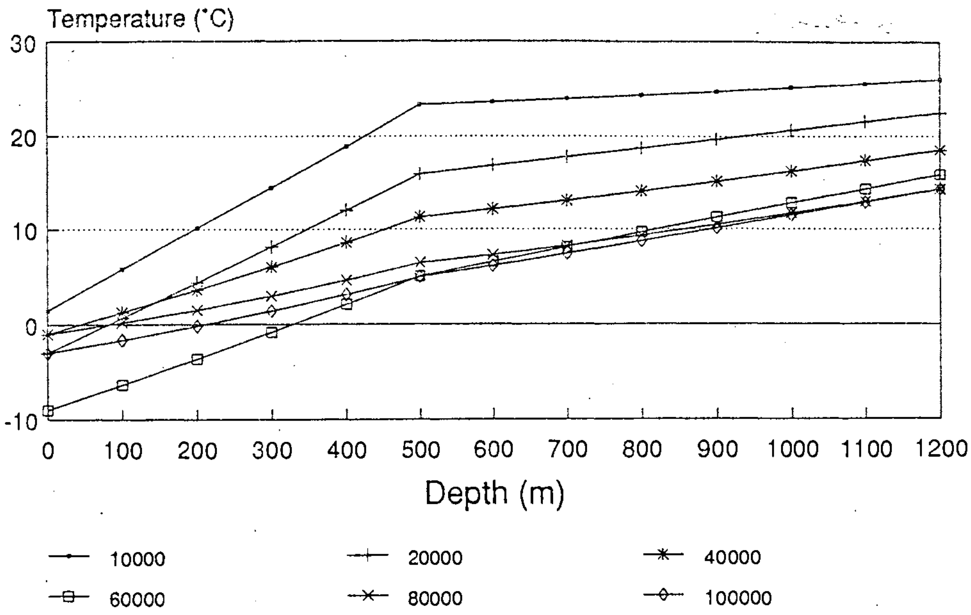

Figure 12. Temperature versus depth(m) and time (years after present) with the repository.
Weighted sum of the three harmonics
Geothermal gradient $1.5°C$ *per* $100m$

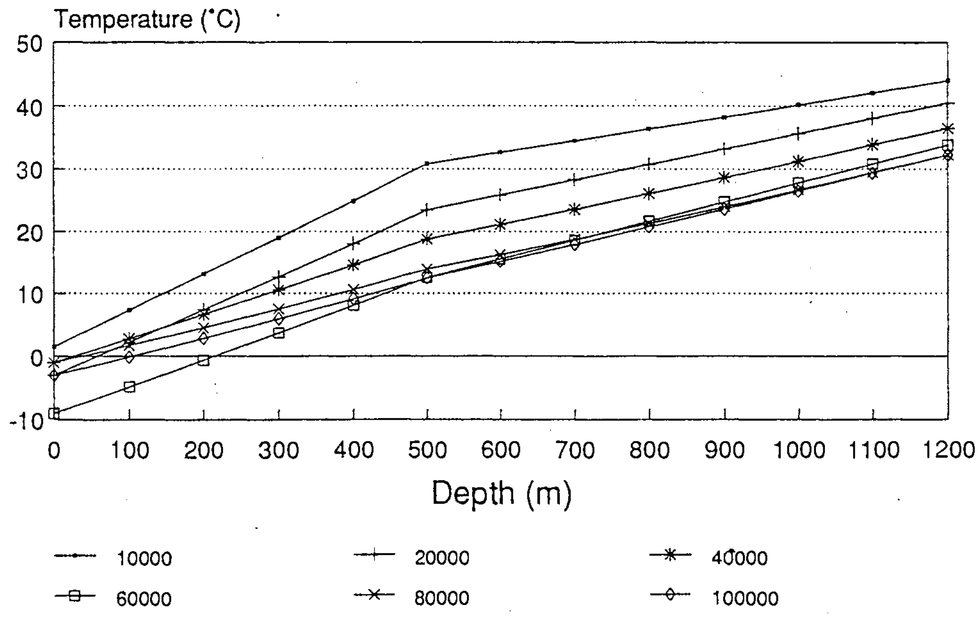

Figure 12b. Temperature versus depth(m) and time (years after present) with the repository.
Weighted sum of the three harmonics
Geothermal gradient $3°C$ *per* $100m$

9 The significance of permafrost on the performance of a repository

9.1 Introduction

The review of permafrost given in Section 2 has illustrated the changes that can occur in near-surface and deep groundwater flow due to freezing of the ground surface. The main effects of permafrost on the performance of a repository can be summarised as:

(a) The effect on groundwater infiltration and recharge

(b) The effect of permafrost on groundwater discharge

(c) The effect on lateral groundwater flow

(d) The effect on the chemistry of the groundwater

(e) The influence on the release of gas and radionuclides from the repository, including the formation of clathrates

(f) The effect on the engineered repository barriers

(g) The influence on the biosphere

(h) The influence on the location and lifestyle of critical groups and on the possibilities of human intrusion

9.2 The effect of permafrost on groundwater infiltration and recharge

The effect of permafrost on groundwater recharge is very dependent on six factors:

(i) The nature and thickness of any existing glacial and recent sediments overlying the basement rocks

(ii) The nature and extent of fracture zones, and their continuation to depth

(iii) The nature and size of any taliks

(iv) The continuity of permafrost

(v) The changes in precipitation associated with periglacial and glacial climatic conditions

(vi) The presence or absence of a substantial ice cover, and the relative periods of continuous permafrost with ice cover and without ice cover compared to the time of discontinuous permafrost.

Fig 1 illustrates the possibilities for recharge in areas of continuous permafrost. In these conditions infiltration and recharge are severely restricted, as is evidenced by the numerous muskegs and lakes in areas of relatively low rainfall in northern Canada, where mean annual precipitation can be as low as 100mm in the arctic islands.

Potential evapotranspiration also exceeds precipitation over a large part of the Canadian permafrost region, and it is expected that precipitation in Sweden will decrease during periglacial and glacial periods, due to a weaker hydrological cycle. Evidence from the UK, based on an analysis of periglacial phenomena in East Anglia (Williams, 1975), indicates that rainfall may have been half its present day value.

The most significant effect of permafrost on recharge is the concentration of the recharge in smaller and fewer points, which tends to lead to high local recharge rates. Many of the lakes and rivers are underlain by taliks of variable horizontal and vertical extent, and if these taliks completely penetrate the permafrost, pathways are available for recharge and discharge of groundwater. Areas of thick medium- to coarse-grained sediments, such as glacial outwash sands and gravels, tend to freeze easily, and in areas of continuous permafrost are likely to prevent completely any recharge. Such sediments are only likely to be found in the low relief areas of the SKI reference site, if at all, and it is not known what the critical thickness of these sediments has to be before such effects become important. Recharge is therefore likely to be limited to the following locations, and will be influenced by the same factors that control recharge in more temperate climates:

(i) Areas of outcropping basement containing major to minor fracture-zones, with the volume of recharge equivalent to the transmissivity of the fracture zone. In Sweden, where areas of lower relief tend to be mantled by a thin veneer of glacial sediments, together with peat, such areas are most likely to be found on the higher ground. Fracture zones may act as seasonal taliks if their transmissivity is not sufficiently high to prevent freezing during the winter. Depending on the continuity of the fracture system at depth, the recharge may be limited to relatively small volumes of the rock mass.

(ii) Areas of higher ground, which are present in the western parts of the SKI reference site. In periglacial and glacial periods the world sea levels will be substantially lowered, by as much as 140m, and this will potentially increase the gradients driving groundwater flow and may change the areas of potential recharge. The Baltic is relatively shallow, except where it has been glacially deepened, with a mean depth of 55m, and it is not known whether this effect of the lowering of world sea levels could influence the hydrogeological situation of western Sweden to any great extent. It seems most likely that once the Baltic has drained, that its depth will represent the maximum increase in hydraulic potential affecting a near-coastal repository site.

In many areas of discontinuous permafrost, areas of enhanced relief are associated with less well developed permafrost, and therefore recharge is less limited. South facing slopes will tend to be free of permafrost, whereas the valleys, which are where the thickest glacial and recent sediments are likely to lie, will contain thicker permafrost. The extent of relief and the proposed sediment cover on the basement on the SKI reference site may not be sufficient to produce this effect.

(iii) Recharge may take place beneath lakes, but it seems more probable in areas of crystalline rock that if lakes are deep enough they will lie above open taliks and be in areas of discharge. If lakes are very shallow they could remain frozen for most of the year, and supply seasonal recharge only in summer. Transient lakes, produced by ice damming, could act as recharge areas, because the location of the lake will probably not be determined by the hydrogeological regime, but it seems unlikely that such a lake would form on the higher ground on the western part of the SKI reference site. The formation of an ice-dammed lake will also tend to increase the hydraulic gradient. It is not known how long such a lake could be expected to last in the situation of the reference site, which might experience several glacial advances and retreats, but combined with the lowering of sea level by 50m (?), an increased head across the site of 100m is the absolute maximum that seems likely.

(iv) Recharge can also take place below the influent portions of rivers. In areas of continuous permafrost, rivers are likely to remain flowing throughout the winter only in groundwater discharge zones, and therefore influent rivers could only supply any recharge during the summer.

9.3 The effect of permafrost on discharge

Active groundwater flow systems are present in areas of continuous permafrost, and the evidence for this activity is very similar to those discharge phenomena which can be observed in more temperate regions. Most of the discharge from all forms of permafrost aquifer takes place through taliks below lakes and rivers and through a relatively large number of large springs.

In a similar manner to recharge, permafrost decreases the possible locations for discharge, especially during the winter. Discharge can be continuous or transitory, depending on the following factors:

(i) whether the discharge is from supra-, intra- or subpermafrost aquifers,

(ii) whether the flow rate, temperature and/or salinity of the groundwater is sufficient to result in perennial flow.

In Section 2 the various types of groundwater discharge phenomena were described, and all of these could be of great significance in localising the release of radionuclides from a repository. In higher permeability environments permafrost has less of an influence on discharge locations, as is witnessed in the Mackenzie River system in the Yukon (Michel, 1986), where karstic conditions are prevalent. However, in low permeability environments and especially those with low relief, discharge could be very severely restricted.

In the SKI reference site the location of the repository, ie. the local domain, has not been fixed, and there are therefore several different possible effects that permafrost could have on the release of radionuclides.

If the repository is located beneath a prominent hill, as is suggested in Lindbom et al (1989), then it is very unlikely to lie below a discharge zone, whatever the future climatic conditions and whatever the influence that the repository might have on the formation of permafrost. A repository located beneath a valley, and particularly one close to the coast or offshore, is more likely to lie beneath a future lake, even one that is only transient, and is therefore more likely to lie below an open talik. If a lake does not form, then such a repository is still more likely to lie closer to a hydrothermal or hydrochemical talik, than one located in an area of greater relief. The path lengths for radionuclide migration may be very differently affected in these two cases by the same change in climatic conditions. It is not known whether the relief at the SKI reference site is sufficient to overcome the reversal in head gradient that might be produced by differential deformation of the rock mass and by sub-glacial groundwater flow beneath a thick glacier.

9.4 Lateral groundwater flow

Near-surface lateral groundwater flow is severely restricted by continuous permafrost, and may only take place within the active zone. At greater depths lateral flow can only occur in open taliks or beneath the permafrost. If permafrost forms to significant depths, and especially if it approaches the repository depth, then much of the lateral groundwater flow which would normally take place around and through the repository may cease. The permafrost will tend to force any lateral groundwater flow to greater depths.

For the case of the SKI Project 90 reference site (Fig 13), it seems very improbable that zone 13 beneath the repository would ever freeze, and it is also improbable that zone 26 will freeze during one of the 40ka or 60ka year climatic cycles. Nevertheless, the effect of the permafrost may be to force, what is likely to be a reduced volume of groundwater because of limited recharge, through the repository region (ie. zones 13 and 26). Depending on the depth of the permafrost with respect to these horizontal and sub-horizontal fracture zones and to open taliks, more or less of the total flow may pass through the repository.

9.5 The effect of permafrost on the chemistry of the groundwater

It is known that the subpermafrost water, especially that lying within or close to the basal cryopeg, can have a very greatly increased salinity. The relationship between the thickness of the basal cryopeg, the thickness of the permafrost, the type of hydrogeological regime and the salinity of the groundwater is unknown. If the base of the permafrost is close to the repository the groundwater in contact with the repository, and hence the waste, may become much more saline during glacial periods. This could influence the solubility and speciation of radionuclides and the potential for colloid formation.

The chemistry of lakes in permafrost areas may be significantly altered from their chemistry during interglacials. There is likely to be a marked increase in their chemical stratification, with the possibility of extremely saline waters being developed in the deeper parts of the lake. Discharges to the lake from subpermafrost groundwaters containing radionuclides from

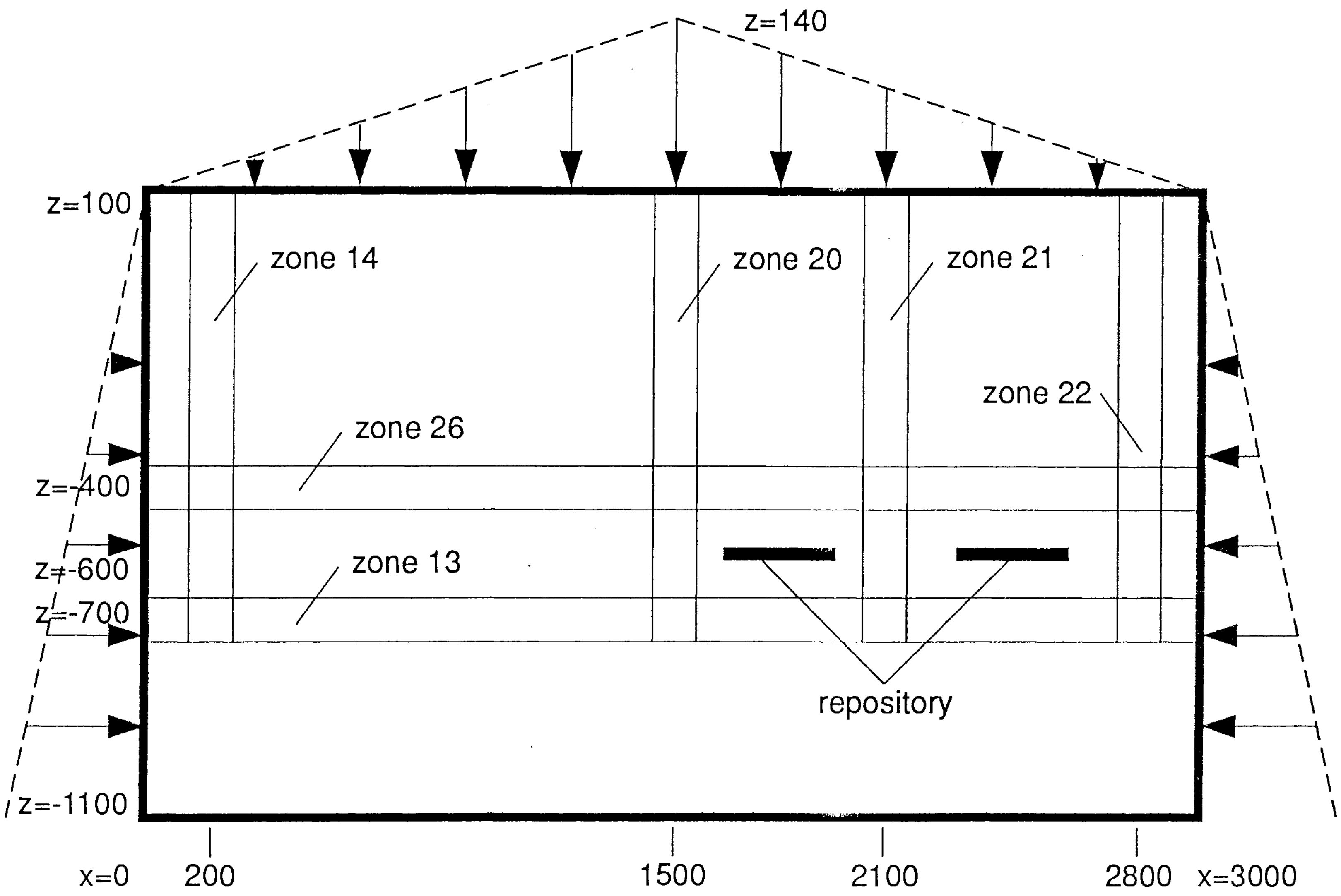

Fig 13. Vertical 2-D cross section used for modelling of the SKI Project 90 reference site, with fracture zones indicated.

a repository may result in there being a build up of radionuclides during glacial periods which could then be released as a pulse during the onset of an interstadial.

The chemical differentiation associated with icings could produce pulsed release of radionuclides to a river system, though probably only on an annual basis. As icings melt, the more soluble constituents in the ice rapidly return to solution, whereas the less soluble components tend to form a mineral slush on the surface and around the edges of the icings. Initial meltwater from the icings has therefore generally a lower salinity. Potential releases of radionuclides to a river system could therefore be concentrated at certain times of the year depending on their solubility. This effect may have a period which is too short to be significant in terms of increased radionuclide release, but it might produce peaks in annual individual doses.

Extremely high salinities, higher than those acceptable for drinking water, can be found in groundwater discharge into the base of rivers and lakes. In the case of rivers, discharges from hydrothermal or hydrochemical taliks which are of sufficient magnitude can produce areas of open water throughout the year. Water supply from such rivers, which can also be associated with winter spawning grounds for fish, could be a more concentrated source of radionuclides from a repository.

9.6 The influence of permafrost on the release of gas from a repository, and on the formation of clathrates (gas hydrates).

9.6.1 Introduction

The accumulation of gases under permafrost has been identified as one of the FEPs in the SKI/SKB scenario analysis (Andersson et al,1989). A very small amount of gas may be generated by the engineered components of the repository for spent fuel, particularly any steel structures whose anaerobic decay could produce hydrogen, and by radiolysis, but the major source of gas is more likely to be rocks at greater depth. Gas production rates from the Swedish basement are likely to be very low, with the dominant gas most likely to be a light hydrocarbon such as methane, but if the ground above the repository is sealed for a sufficiently long period by permafrost, gas accumulation could take place.

An accumulation of gas could have several effects on the groundwater flow regime. It could result in displacement of water from the repository, though this seems unlikely and would require a long time in a rock of low hydraulic conductivity; perhaps longer than the duration of the permafrost. In this case the repository would become partially or fully unsaturated with groundwater, with two phase flow occurring. A resaturation phase would occur as the gas escaped after the permafrost had melted.

The accumulation of gas could also change the pattern of groundwater flow. This could be advantageous, if flow is deflected away from or around the repository and if the length of the flow path to the nearest talik is increased, but the reverse is equally likely. In addition to the trapping of gas beneath the permafrost, if the permafrost reaches sufficient thickness it is likely that clathrates will form. Very much larger volumes of gas can be held within the clathrate structure than is possible if the gas dissolves in the groundwater or forms as a separate phase. In the following discussion it is assumed that methane is the dominant gas, but the same argument is applicable to any of the gases that form hydrates. Hydrogen and helium do not form such structures.

9.6.2 Clathrates

Clathrates, or gas hydrates, are solid, ice-like mixtures of gas and water, which can form at temperatures considerably above the freezing point of water if the pressure is high enough and if there is a sufficient volume of gas within the system to allow for the formation of a separate gas phase. One explanation of the hydrate formation is that the entrance of the gas molecules into the vacant lattice positions in the liquid water structure causes the water to solidify at temperatures above its normal freezing point. About eighteen types of gas will form hydrates, including N_2, O_2, CO_2 and hydrocarbon gases from methane up to isobutane. The lattice work of water molecules is held together by hydrogen bonds and is supported by gas molecules in the "cages", which gives clathrates their name. Two separate molecular configurations are known, giving a 1:20 gas:water ratio for small gas molecules and a 1:24 or 1:28 ratio for large gas molecules. Natural gas hydrates, which are commonly found beneath, and also incorporated within, the permafrost in Alaska and Siberia, have about 90% of their cages filled with gas molecules, dominantly (>99%) methane. Between 170 to 200 volumes of gaseous methane can be held in one volume of hydrate, depending on the void filling ratio.

Bily and Dick (1974) have extensively studied clathrates within the permafrost in the Mackenzie Delta in northern Canada, and have examined the depth/temperature relationships between the formation of clathrates and the thickness of permafrost. Fig 14 illustrates the stability field of methane hydrate with respect to depth and temperature, with an assumed pressure gradient of 9.81 kPa m^{-1} and with pure water. It can be seen from Fig 14 that permafrost must have a minimum thickness of approximately 160m before methane hydrates can form. It is not until permafrost thicknesses reach substantially in excess of this amount that large volumes of hydrate could be present, and for the 11ka harmonic cycle (see section 8.3) and a geothermal gradient of 3°C/100m there is in fact very little possibility of any methane hydrate formation. The presence of other gases, such as other light hydrocarbons, markedly increases the stability field, so that much smaller thicknesses of permafrost are required to produce hydrates, but it is not thought that gases such as pentane and ethane are likely to be outgassing from Swedish basement rocks, at least in any significant amounts, and this situation need not be considered further. Any increase in salinity of the groundwater will reduce the temperature at which the hydrates form, though the effect is not significant within the range of salinities expected in the bulk of the groundwater and at temperatures close to 0°C. The formation of hydrates could be prevented within the basal cryopeg, in which salinities are likely to be markedly increased, but there are no data available to enable the thickness of this cryopeg to be estimated. It is not known whether this structure is significant, but it is difficult to envisage how this cryopeg could be more than a few metres thick, and its influence in this context can probably be ignored.

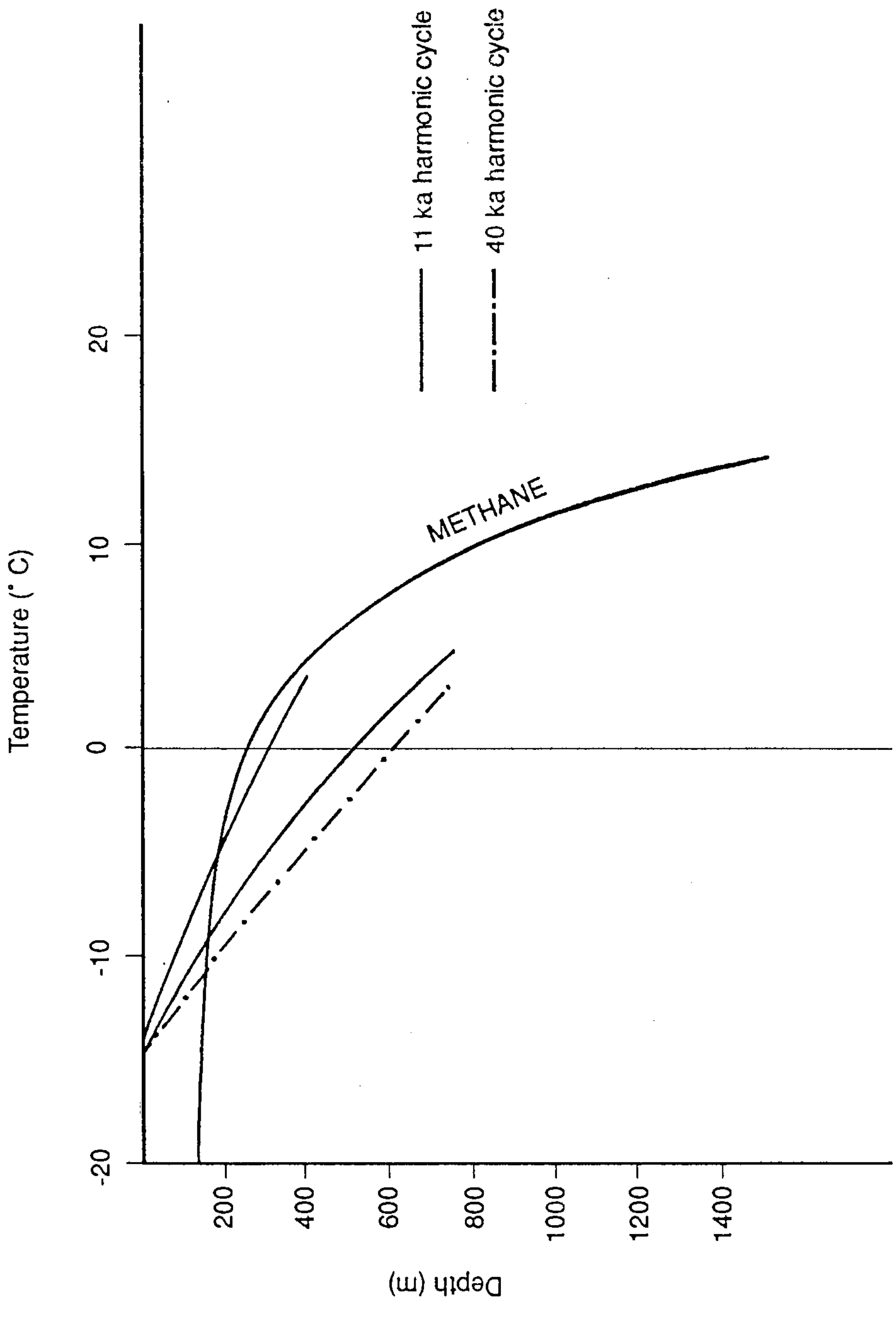

Figure 14: Depth–temperature curve for methane hydrate, with superimposed temperature profiles for 11ka and 40ka harmonic cycles and for geothermal gradients of 1.5 and 3.0°C/100m, showing the minimum depth of clathrate formation.

9.6.3 Discussion

It is therefore only when permafrost has been developing for several thousand years, and when it has reached approximately 300m depth, that clathrate formation needs to be considered, and only when sufficient gas has collected that its solubility limit has been exceeded. Any substantial open taliks will allow the gas to escape, and it may be that the migration of gas within the advecting groundwater will be at a sufficient rate to prevent the accumulation of any gas as a separate phase. This situation could be modelled if the gas flux from the basement rocks could be estimated, and if this were combined with the groundwater flow model of a repository in permafrost conditions, which is described in section 11. Unless it can be shown that natural gas production rates are substantial, it is not thought that this FEP could have a significant impact on the safety case.

9.7 The influence of permafrost on the repository engineered barriers

As was explained in section 8, it seems unlikely that a repository at a depth of 500m and in a regime with a geothermal gradient of 3°C per km is ever likely to freeze. What may freeze, if they are close enough to the surface, are the shaft seals and the seals in the exploratory and monitoring boreholes. Assuming the SKB repository design given in KBS-3 (KBS, 1983), with a bentonite-sand backfill and with bentonite based shaft and borehole seals, it seems that the effect of repeated freezing could only ever affect the upper two thirds, or perhaps half, of the shafts. The concrete, which is planned for the uppermost 100m of each shaft, can be assumed to have been almost totally degraded by the freezing cycles, but the compacted moraine below may be hardly altered.

The effect of freezing on the bentonite blocks in the shaft seals that have previously expanded is difficult to assess. Although at shallow depths the ice formation pressure, caused by thermo-osmosis, is known to cause large ground movements, under higher lithostatic stresses, combined with the high swelling pressure exerted by the bentonite, it seems less likely that significant irreversible effects on the bentonite's sealing capacity will occur. Most of the water which has been taken up by the bentonite during its swelling does not act as free water, because it lies within the field of the surface charge on the clay platelets, and its viscosity and thermal properties are different from that of free water.

Freezing of the bentonite seals is likely to result in the following effects:

(a) Thermo-osmosis will tend to move water out of the clay, though this effect is dependent on the thermal gradient, which at depth is small.

(b) The decrease in temperature towards 0°C will increase the viscosity of the water in the clay's pores and will tend to decrease its hydraulic conductivity

(c) A lowering of the temperature will decrease the clay's pore pressure and will lead to movement of water away from the clay as the freezing front approaches

(d) Thermal contraction of the clay will take place

(e) The clay will become less plastic with decrease in temperature

Many of these effects are thought to be of second order. What may be the most important is the increase in brittleness of the clay which, when combined with its contraction, will reduce its capacity as a seal. This could be significant during deglaciation, when rapid ice removal is likely to result in fault movement and possible dilation of fractures at a time when permafrost may still be present at depth, there being a phase lag between a rise in the air temperature, with the resulting glacial retreat, and thawing of deep permafrost. The bentonite seals in this situation will be less capable of taking up rock movements, and repeated similar actions during each glacial/interglacial cycle could degrade their long-term sealing capability.

Testing of the Boom Clay (Heremans et al, 1984) at temperatures down to -25°C, in order to examine the changes that might be expected to take place in situ during freezing operations for shaft sinking, involved the following tests which are relevant to the expected situation in the shaft seals during permafrost:

(a) Hydraulic testing of the clay in the laboratory at 10°C, after having frozen the clay at -25°C, showed that its hydraulic conductivity had increased ten times, from 10^{-11} to 10^{-10} ms^{-1}.

(b) Triaxial testing of the clay at temperatures of 20°C, -5°C and -25°C, showed that the friction angle decreased from 140 at 20°C, to 70 at -5°C and to 60 at -25°C. There was little change in strength of the clay when tested at -5°C, but when the temperature was reduced to -12°C and then to -25°C there was a marked increase in strength and brittleness. At -25°C the clay behaved in a completely brittle fashion and failed at between 3 and 6% deformation.

Although the Boom Clay is substantially different from pure bentonite, it seems likely that any plastic clay is likely to exhibit a similar deformational response to a decrease in temperature.

9.8 The influence of permafrost on the biosphere

The onset and maintenance of permafrost conditions would influence the consideration of the biosphere within the assessment in two main ways, through modifications to the assumptions made regarding the boundary conditions at the geosphere-biosphere interface and through modifications to the assumptions made for the subsequent migration and accumulation of released radionuclides and the associated possibilities for the irradiation of man.

The scope for especially localised groundwater release to the biosphere during permafrost conditions has been discussed in previous sections and illustrated in Fig 1, and data on flow rates for different types of spring are useful in this context (section 4.3.2). By limiting the availability of near surface aquifers (see section 6), permafrost would tend to promote the use of deeper drilling for water supplies, providing a route to the surface for radionuclides which might otherwise decay in the ground. Activity released to the biosphere during permafrost conditions would be subject to substantially similar processes for migration and accumulation to those pertaining now. However the scale and relative significance of these processes would be significantly modified. Consideration of colder climatic conditions has been suggested for long-term assessments, with corresponding account being given to the potential for different exposure pathways to occur, including the implications of the colder conditions on the level and scope for man to exploit the environment (SKI, 1989). Some consideration has been given previously to biosphere models for different climates (eg. Grogan, 1985; Ashton, 1989). However, this work has not dealt systematically with the processes and effects of permafrost, as discussed above, such as seasonality and the dynamics of the onset and retreat of permafrost.

10 Permafrost scenarios

10.1 Introduction

The discussions which have already been held on permafrost as part of the scenario development programme (Andersson et al, 1989) have identified four possible cases for analysis:

1. Radionuclide release via springs which are present in permafrost conditions.
2. Release via a sub-lacustrine open talik
3. The combination of thermal buoyancy combined with a sub-lacustrine open talik
4. The combination of a sub-lacustrine open talik, together with thermal buoyancy and with shaft failure (included with the well scenario).

10.2 Radionuclide release via springs

It has been assumed during the discussions on the cases that appeared most appropriate for scenario analysis, that groundwater velocities would be sufficiently high within vertical fracture zones 20, 21 and 22 (Fig 13) to allow them to remain as hydrothermal taliks during permafrost. The assumption was based on the expectation that the repository would create sufficient buoyancy to counteract some of the effects of the permafrost. The calculations of the thermal field of the expected SKB repository (Tarandi, 1983) show that the temperature rise at its centre is only 11°C after 25ka, 8°C after approximately 50 ka, and that after 100 ka temperatures on the canister surface are only 3°C above background. The thermal buoyancy is therefore not expected to be significant after perhaps 50ka AP.

The occurrence of geothermal springs within areas of widespread discontinuous permafrost in Canada (Brandon, 1965; Crandall and Sadlier-Brown, 1976) is a useful analogue of a repository in similar conditions. Such springs have been mainly studied in the Mackenzie River system. Many of the springs have a geothermal source, and have exit temperatures well in excess of those that are likely to be associated with a repository during permafrost conditions. But there are springs with temperatures as low as 5°C, and these can continue to discharge for most of the year. It is these springs that are more like those that could be associated with fracture zones 20, 21 and 22.

Such springs appear not to be found in the areas of low relief on the Precambrian Shield in Canada, which tends to be mantled with continuous glacial deposits. This suggests that even where permafrost is not continuous, the fracture zones do not necessarily act as conduits for groundwater flow to the surface except in river valleys, in more mountainous regions and where lakes provide open taliks. The calculations presented in section 8 indicate that permafrost could form above the repository during any part of its thermal phase, and therefore it may not be a suitable case for analysis to assume that the three major fracture zones at the reference site are likely to act as hydrothermal, or even hydrochemical, taliks, except where the repository is also beneath a lake or a river.

There is no evidence that new river systems, of sufficient scale to act in a similar way as that of the Mackenzie, are formed as a result of glacial advances in hard rock terrains. Similarly , there is no evidence that existing rivers are diverted from their course to such an extent that a repository that was not located close to an existing river would find itself beneath, or close to, such a river during or after a glacial advance. It is extremely unlikely that a repository would be located close to a river, of sufficient size to have its own open talik, and therefore the "river case" can probably be dismissed.

A repository is more likely to be situated beneath ground of higher rather than of lower relief, assuming that the relief is not excessive. This is because groundwater travel distances within the geosphere are then more likely to be maximised, as the repository lies beneath a recharge zone, and because an analysis of the rock mass in the vicinity of the proposed repository is made easier due to the thinner superficial cover. Unless this area of higher ground is substantially eroded by glacial action and subsequently becomes an area of low relief, it seems improbable that a lake is likely to form above the repository. The only exception to this could be an ice-dammed or moraine-dammed lake, of inevitably limited existence. Such a lake would need to be of considerable depth and surface area and be sufficiently long lasting before it affected an open talik in previously frozen ground. In an area of relatively low relief, such as any proposed repository site in Sweden, it is highly unlikely that such a lake would have a sufficient volume to produce this affect.

It therefore seems improbable that direct discharge from springs above a repository is a credible case for analysis. What seems far more likely is that discharge will occur in the deeper parts of lakes which act as open taliks. This situation is discussed in the following section.

10.3 Release via a sub-lacustrine open talik

In areas of relatively low relief in the Canadian arctic, the only significant discharge of groundwater appears to be via open taliks beneath sufficiently large lakes or beneath perennial rivers. In areas of discontinuous permafrost such lakes do not have to be very large, and although many lakes in central Sweden are relatively shallow, it is probable that they will all act as open taliks during periglacial and glacial times, especially in discontinuous permafrost.

In section 3.2.4 evidence was presented for the Baker Lake area (Dyck and Car, 1987), where it was concluded that regional fracture zones supply groundwaters containing large amounts of U and He to the lower parts of a deep lake in an area of continuous permafrost. The lake has a maximum depth of 36m and a surface area of 3km^2 and its surface is frozen for most, if not all of the year. Several similar lakes are also present in the same region and are also associated with geochemical anomalies. Based on the arguments of. section 7 regarding the timing of future permafrost, it would appear that if a repository is not situated within a few kilometres of a river, and is not in an area where geothermal activity can produce hydrothermal taliks, that discharge is only likely through lakes in a similar manner to those just described.

The SKI reference site, as described in Lindbom et al (1989) contains several lakes, two of which in particular are of sufficient size that it could be assumed that they would act as open taliks. It seems unlikely that a repository will be situated beneath an existing or a future lake, unless it was a temporary structure produced by damming by ice or a moraine, so it must be assumed that perhaps significant lateral groundwater flow would be required before discharge could take place into the lower parts of the lake.

In conditions of continuous permafrost such lakes are likely to be frozen at the surface for almost all, if not all, of the year. Lakes of sufficient depth tend also to be very distinctly chemically stratified, as has been described in section 5.2, with potential hypersaline conditions forming in their lower parts. Any radionuclides discharged into this environment via fracture zones will tend to remain in the same position, as there is likely to be only limited mixing with the meteoric waters that will predominate in the upper parts of the lake, though, of course, diffusional transfer will occur. In much shallower lakes, where such chemical stratification is not possible, there may be an annual cyclicity in radionuclide release in a similar manner to icings.

At the end of any permafrost period the hydrogeological and hydrological regimes will become more active and there is likely to be a pulse of radionuclides released from the larger, and particularly the deeper, lakes. This pulse may be considerably delayed or reduced in amplitude if many radionuclides are fixed onto the lake bottom sediments. The increased hydrogeological activity might also promote increased movement of contaminated bed sediments. Were the lake to drain for any reason, or if the climate subsequently became significantly drier and the lake level dropped, then a more significant radionuclide pulse could be expected.

10.4 The combination of thermal buoyancy combined with a sub-lacustrine open talik

The discussion in section 10.2 arguing against the probability of permafrost conditions existing during the most significant parts of the thermal phase of the repository, is also applicable in this case. This case is really a sub-set of the previous one, with the possibility that the rate of transport of radionuclides in the groundwater would be probably more rapid than if thermal buoyancy were to be ignored.

As is argued above, it seems highly improbable that a lake would be present, except perhaps for a short period, directly above a repository, and for such a lake also not to be frozen because of the thermal influence of the repository seems even more improbable. Therefore having pursued this case, we believe that it need not be considered further.

10.5 The combination of thermal buoyancy, together with shaft seal failure and a sub-lacustrine talik

In section 10.4 it was concluded that the possibility of there being an open talik directly above the repository was improbable. This case is equally improbable in the context of permafrost for the same reason, and without permafrost is being considered under two FEPs, unsealed boreholes and/or shafts and degradation of hole and shaft seals.

11 Structure of scenario to be analysed

It has been concluded from the discussion in section 10 that the most realistic base case scenario for permafrost is one in which the release of radionuclides takes place via a sub-lacustrine, or perhaps a sub-fluvial open talik. In was suggested in section 10.3 that the situation which currently pertains at Baker Lake in the Canadian arctic is probably a good analogue of this scenario, especially as the release to the lake is from a U deposit.

It is suggested that the scenario needs to have the following structure,which is outlined in terms of the actual scenario that is to be modelled using a similar cross section to that shown in Fig 13, and also with respect to the likely conditions on the reference site during permafrost:

(a) The repository lies between horizontal zones 13 and 26 and between vertical zones 20, 21 and 22 (Fig 13).

(b) During permafrost conditions, vertical zones 20, 21 and 22 are not open at some distance above zone 26, but zone 14 remains open because it lies directly beneath an open lacustrine talik. The lake lies above, but slightly offset from, a groundwater divide, and a no-flow boundary is present immediately to the left of the lake. There is an additional lake to the right on the cross section, at a greater elevation than the first lake and directly above zone 19. The distance above the repository that zones 20, 21 and 22 remain open will vary with the duration of the permafrost. Such calculations could be carried out for different climatic situations, ie different severities and periods of permafrost, and for the situation where thick ice cover is expected, with the possibility that surface temperatures are considerably higher that the -15°C currently assumed.

(c) The lower relief areas of the reference site are permanently frozen during permafrost, except where there are lakes and rivers of sufficient extent to allow for the formation of open taliks. In the cross section all the ground not beneath the lakes is assumed to be frozen. It is assumed that the minimum depth of both lakes would be 5m and that they would have surface areas in excess of $0.5km^2$. The number of lakes on the reference site of sufficient size to maintain open taliks, their size, or probably more important, their volume distribution and their location with respect to the likely groundwater flow directions from the repository could be determined from the situation pertaining in areas of similar topography in central Sweden. It is more difficult to specify the size and flow characteristics of a suitable river, if it were decided to model this situation, though it is thought unlikely that a river of sufficient size is likely to be present on the SKI reference site.

(d) During winter, which is assumed to last 8 months, discharge takes place only into the lower parts of lakes which are underlain by open taliks; in the case of the cross section only in the lake above zone 14. It is also assumed that all lakes with open taliks on the reference site are directly connected to fracture zones at depth. During summer, limited discharge could be assumed to be possible into smaller lakes, into the river(s) as small springs and by the melting of icings. In the modelling of the groundwater flow within the reference site by Lindbom et al (1989) the base case regional modelling assumed that zones 6/9 and 13 would act as the only discharge zones. During permafrost, this situation seems unlikely to occur, and it will have to be decided which of the fracture zones crops out beneath a sufficiently large lake.

(e) Recharge occurs only on the higher ground in the western parts of the SKI reference site, and in particular in the outcrop areas of the larger fracture zones and where the basement rocks have no, or very limited, superficial cover. In the cross section, recharge only takes place beneath the lake above open zone 19. It is not at all certain what the shape of the piezometric surface should be across the reference site during permafrost. It seems most likely that the basement rocks beneath the permafrost will be confined, but the limited recharge may not be sufficient to maintain the groundwater table at the surface in recharge zones. It should be possible to decide which of the fracture zones are most appropriate as recharge areas. From a study of the report by Lindbom et al (op. cit.), it would appear that zones 1, the southern part of 2 and the western part of 12 are the most obvious choices. The cross section to be modelled is not affected by these changes, as it is purposely simplified.

12 Recommendations for repository designs

It has been concluded in the above discussions that a repository at a depth of 500m is very unlikely to freeze at any time during permafrost conditions, but that shaft seals could freeze if they are sufficiently close to the surface. The reasons for and implications of shaft seal failure have been discussed in section 9.6.

12.1 Aspects of repository design and location influenced by permafrost

From a study of the likely affects of permafrost on the release of radionuclides from a repository, it would appear that the following factors need to be taken into account in the repository design:

(a) The repository needs to be located at 500m or deeper if permafrost is confidently avoided within it.

(b) In order to prevent the degradation of the compressed bentonite shaft seals, it is suggested that as many of them are placed at depths where they are unlikely to be subjected to temperatures of less than approximately -10°C, and preferably less than -5°C. This will prevent them from suffering from extensive embrittlement during freezing cycles, which may reduce their capacity to act as seals during what may be a critical phase when glacial retreat is occurring rapidly whilst permafrost may still be present at depth.

(c) The repository should preferably be positioned away from any lakes with sufficient depth and areal extent, and also away from any large rivers, that are likely to be associated with open taliks during permafrost. It should also preferably be positioned beneath a recharge zone which is expected to remain as such during permafrost. In this way the length of the groundwater flow paths between the repository and the discharge zones during permafrost are likely to be maximised.

(d) Although it has been argued that the most significant part of the thermal phase of the repository will take place before the advent of any substantial permafrost, thermal buoyancy effects may still be significant up to at least 10ka AP. For this reason, and for the reason outlined above regarding the degradation of shaft seals, it is recommended that any shafts to the repository are placed at considerable distances from the disposal vaults, with the connecting tunnels parallel to the major fracture zones and normal to the regional hydraulic gradient. This will minimise any effects due to shaft seal failure and thermal buoyancy.

(e) The above recommendations should be viewed in the light of the relatively low significance placed on events occurring greater than 10ka AP in the Nordic Radiation Protection and Nuclear Safety Authorities HLW Criteria Consultative document.

(a) The repository needs to be located at 500m or deeper if permafrost is confidently avoided within it.

(b) In order to prevent the degradation of the compressed bentonite shaft seals, it is suggested that as many of them are placed at depths where they are unlikely to be subjected to temperatures of less than approximately -10°C, and preferably less than -5°C. This will prevent them from suffering from extensive embrittlement during freezing cycles, which may reduce their capacity to act as seals during what may be a critical phase when glacial retreat is occurring rapidly whilst permafrost may still be present at depth.

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