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Groundwater movements around a repository

Final report

Ulf Lindblom et al

Hagconsult AB oktober 1977

KÄRN - BRÄNSLE - SÄKERHET

POSTADRESS: Kärnbränslesäkerhet, Fack. 102 40 Stockholm. Telefon 08-67 95 40

GROUNDWATER MOVEMENTS AROUND A REPOSITORY

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Denna rapport utgör redovisning av ett arbete som utförts på uppdrag av KBS. Slutsatser och värderingar i rapporten är författarens och behöver inte nödvändigtvis sammanfalla med uppdragsgivarens.

I slutet av rapporten har bifogats en förteckning över av KBS hittills publicerade tekniska rapporter i denna serie.

FINAL REPORT

KBS - Kärnbränslesäkerhet

GROUNDWATER MOVEMENTS AROUND A REPOSITORY

Phase 3. Final report

Hagconsult AB
in association with
Acres Consulting Services Ltd
RE/SPEC Inc.

FOREWORD

This report was prepared as the third phase of a study of the groundwater movements around a repository for spent nuclear fuel in the precambrian bedrock of Sweden. It was based on the work performed in the previous two study phases: (1) State of the art and Detailed study plan and (2) Technical Reports. The contract for this work was between Kärnbränslesäkerhet - KBS (Nuclear Fuel Safety) and Hagconsult AB of Stockholm, Sweden. RE/SPEC Inc. of Rapid City, SD/USA and Acres Consulting Services Ltd of Niagara Falls, Ontario/Canada acted as subconsultants to Hagconsult AB.

The principal authors of this report are Dr. Ulf E. Lindblom of Hagconsult AB, Dr. Paul F. Gnirk of RE/SPEC Inc. and Dr. Robin G. Charlwood of Acres Consulting Services Ltd. Portions of the text were prepared and reviewed by Mr. Joe L. Ratigan of RE/SPEC Inc., Dr. Anthony S. Burgess of Acres Consulting Services Ltd and Dr. Håkan Stille of Hagconsult AB.

The opinions and conclusions expressed in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of KBS.

Stockholm, October, 1977

Ulf E. Lindblom
Study Director
Hagconsult AB

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SAMMANFATTNING

Utlakning av radioaktivt material kan äga rum ur det deponerade avfallsglaset om läckage uppstår i omgivande kapslar. Det radioaktiva materialet kan då spridas i en sprickig berggrund genom transport i strömmande grundvatten. Mot denna bakgrund är det klart att studier av grundvattenrörelserna runt ett slutförvar utgör en väsentlig del i en säkerhetsanalys för förvaring av radioaktivt avfall.

Den utredning, som här sammanfattas, har haft till mål att beskriva grundvattenrörelserna runt det slutförvar som studeras för svenskt förglasat högaktivt avfall. Utredningen har genomförts av Hagconsult AB med hjälp av två utländska underkonsulter, Acres Consulting Services, Ltd, Canada och Re/Spec. Inc., USA, samt med bidrag från projektledningen och ett flertal specialister, som anlitats av Projekt Kärnbränslesäkerhet, KBS.

En grundvattenströmningsberäkning för ett slutförvar i sprickigt berg blir av flera skäl komplicerad. Dels är de ursprungliga förhållandena på så stort djup som 500 m svårbedömda då kunskaperna om vattengenomsläppligheten och den av vatten genomströmmande sprickvolymen är mycket begränsade; dels störs strömningen av upptagningen av tunnelsystemet och av den förhöjda temperaturen.

I den första rapporten beskrivs i detalj de olika förlopp som påverkar strömningsbilden och den kunskap man idag har om dessa. För varje förlopp diskuteras tillgång på data, samt metoder för bedömning av grundvattenströmningen och verifikation av resultaten. Den första rapporten ger således en översikt av kunskapsnivån inom för avfallsförvarig aktuella delar av geologi och geoteknik, grundvattenhydrologi, geokemi, värmespridning och bergmekanik.

Hela utredningen bygger på att resulterande grundvattenströmning runt ett slutförvar bestäms av de ursprungligen rådande hydrologiska strömningsförhållandena samt av de störningar i denna

strömning som orsakas av:

A förändringar av vattengenomsläppligheten (permeabiliteten) hos berget genom spänningsomlagring och öppning/slutning av bergsprickor. Sådana spänningsomlagring uppkommer genom utbrytning av bergtunnlarna samt uppvärmningen av berget.

B grundvattenströmning som utöver hydrologiskt betingad strömning uppkommer som följd av temperaturskillnader på olika nivåer i berget (så kallad konvektionsströmning)

C grundvattenströmning mot förvaringsanläggningen under den tid då denna fylls med vatten

D kvarstående permeabilitetsförändringar på anläggningsnivån sedan anläggningen åter fyllts och temperaturerna utjämnats.

De geologiska och hydrologiska förhållandena har exemplifierats med två alternativa lokaliseringar av slutförvaret: vid Kråkemåla nordväst om Simpevarp samt vid Finnsjön väster om Forsmark. Tonvikten vid exemplifieringen har lagts på det senare alternativet.

Bergarterna i den Baltiska skölden är kristallina, hårda och med en kristallmatris som i sig själv är praktiskt taget impermeabel. Skölden är genomdragen av större, tektoniskt betingade krosszoner mellan vilka avståndet kan variera från några hundratals meter till åtskilliga kilometer. Avsikten är att lokalisera slutförvaret på cirka 500 m djup i ett bergparti fritt från dylika starkt vattenförande krosszoner. Vattenföringen runt förvaret sker i det system av mindre sprickor som i ett mosaikliknande mönter genomkorsar bergpartiet.

Fältmätningar av permeabiliteten på stora djup i den Baltiska skölden har tidigare inte utförts. Baserat på vattenförlustmätningar i vertikala borrhål som utförts inom KBS' geologiprogram samt på litteraturuppgifter har det dock varit möjligt att upprätta en nominell "medelkurva" över permeabilitetens variation med djupet.

Enligt denna kurva är permeabiliteten vid markytan ca $10^{-5,5}$ och sjunker sedan exponentiellt till 10^{-7} vid ca 50 m, 10^{-8} vid ca 200 m och 10^{-9} vid ca 1800 m djup. Följande tre fall av permeabilitet har använts parallet under analyserna:

Fall 1 isotrop (lika i alla riktningar), konstant = 10^{-8} m/s

Fall 2 isotrop, varierande enligt den nominella medelkurvan

Fall 3 anisotrop, horisontell varierande enligt medelkurvan; vertikal konstant = 10^{-9} m/s.

Den grundvattenförande sprickvolymen, "porositeten", har mycket sällan bestämts för kristallint berg. I denna utredning har vi antagit en modell av berggrunden med horisontella sprickor av varierande öppning och avstånd för att relatera porositeten till permeabiliteten. Grundvattnets rörelsehastighet i spricksystemet är proportionell mot kvoten mellan permeabilitet och porositet.

Grundvattenytan kan med god noggrannhet antas sammanfalla med markytan, vilket ger god precision i bedömingar av hydrauliska gradienter inom olika partier av berggrunden.

Grundvattenströmningen har analyserats i vertikala sektioner lagda längs de regionala strömningslinjer som passerar genom förvaringsanläggningen. Forsmarksmodellen går 200 km in i landet medan Oskarshamnsmodellen går 100 km in i landet. Båda modellerna har 2 km djup och når 100 km ut i Östersjön. Det befanns att den regionala gradienten mot djupet var ungefär lika med gradienten vid ytan, oberoende av permeabilitetsfördelningen. Jämförelser mellan strömningshastigheterna för permeabilitetsfördelningarna i å ena sidan Fall 1 och å den andra Fall 2 och Fall 3 visar att en zon med markant reducerad vattenrörlighet kan förväntas existera under ett par hundra meters djup i berggrunden i de två senare fallen, det vill säga då den horisontella permeabiliteten avtar mot djupet.

För att klarlägga inverkan av topografin på den djupgående grundvattenströmningen analyserades vertikalsektioner 4 km långa och 1 km djupa. Ur analysresultaten framgår att strömningsbild och strömningshastigheter kraftigt påverkas av permeabilitetens förändringar med djupet. Den tidigare diskuterade zonen med markant reducerad vattenrörlighet kan förväntas förekomma även vid relativt stark topografisk relief, förutsatt att bergets vattengenomsläpplighet avtar mot djupet.

Inverkan av en lutande större spricka genom anläggningen analyserades också i denna grundvattenmodell. I det fall sprickan stiger i strömriktningen finns det en tendens för flödet att öka och följa sprickan ett stycke uppåt och sedan återgå till berget.

En lokal modell för grundvattenströmningen runt det exemplifierade fallet med slutförvar i Forsmark har också analyserats. Modellen är 1750 m lång och 1500 m djup och är representativ för geologin i området med vertikala vattenförande krosszoner som gränser (Finnsjö-förkastningen i väster och Gåvestbo-förkastningen i öster). Baserat på höjderna hos grundvattenytan i randzonerna var medelgradienten $2 \cdot 10^{-3}$ för grundvattenströmningen genom modellen. Topografin gör att strömningen är riktad nedåt i modellens mitt, och tillförseln sker där genom infiltration från markytan. Mot djupet rör sig grundvattnet utåt mot de begränsade krosszonerna i modellränderna, med en något starkare tendens till strömning i riktning med den regionala gradienten. Cirkulationsdjupet för detta lokalt infiltrerade grundvatten beror av randvillkoren samt genomsläpplighetens och porositetens variation med djupet.

Även den lokala strömningsmodellen angav en zon med markant reducerad grundvattenrörlighet under ett par hundra meters djup i det fall permeabiliteten är anisotrop och avtagande mot djupet (Fall 3). De andra förutsättningarna om permeablitet (Fall 1 och 2) gav strömningsrörelser från markytan som når ner till anläggningsnivån på 500 m djup.

De ovannämnda beräkningarna avser ursprungliga förhållanden i berget på de exemplifierade platserna. Anläggningen av förvaret innebär följande förändringar i dessa förhållanden, vilka analyserats i utredningen:

- spänningsförändringar och brott i bergmaterialet
- förändringar av permeabilitet i berget närmast anläggningen
- förändringar i grunvattenströmningsbilden då anläggningen vattenfylls

De bergmekniska analyserna visar att de zoner som kommer i brottillstånd samt undergår nämnvärda förändringar i permeabilitet är mycket begränsade, av storleksordningen en meter från tunnelväggen. Vatteninströmningen till anläggningen beräknades till 30, 18 respektive 4 liter per minut och kilometer tunnel under antagande av de tre nämnda nominella fördelningarna av permeabilitet (Fall 1, 2 och 3). Jämfört med erfarenheter från gruvor syns inströmningshastigheterna vara för höga, vilket skulle innebära att de nominella permeabiliteterna också är för höga. Används resultatet från permeabilitetsmätningar i stor skala i Stripa, ungefär $5 \cdot 10^{-11}$ m/s, blir inströmningen i Fall 3 0,17 l/min, km och återfyllningstiden ca 100 år vid oåterfyllda tunnlar, vilket är i rimlig överensstämmelse med erfarenheten av vattenfyllning i övergivna gruvor.

Värme från avfallet sprids till omgivande berg genom värmeledning i fast berg (konduktion) och transport i det strömmande vattnet (s.k. advektion). Till följd av ventilering i bergrummen under trettio år kommer berget att gå igenom två perioder av upphettning och avsvalning. Temperaturökningen i berget mitt emellan två förvaringsrum når ett högsta värde av 6°C efter tre år i den första uppvärmningen och 20°C efter ca 90 år i den andra uppvärmningscykeln. I större skala blir temperaturökningen maximalt 28°C längs en vertikal symmetrilinje genom anläggningens mitt efter ca 60 år och avtar efter 1000 år till omkring 17°C. Den normala temperaturen på 500 m djup är ca 15°C. Jämförd med värmeledningen i fast berg befanns värmetransporten som ombesörjs av det genomströmmande grundvattnet vara försumbar.

Bergmekaniskt innebär temperaturförhöjningen högre bergspänningar och lägre permeabilitet samt ökade brottzoner runt tunnlarna. Med en horisontell/vertikal sprickorientering i berget är brottzonerna begränsade till området vid tunnelvägg - golv, huvudsakligen i horisontell riktning och till en inträngning av ca 1,5 m. Med lutande 45° sprickriktningar fås en ca 6 m bred och 1,5 m hög brottzon i tunneltaket. Brottzonerna i golvet syns inte utökas nedåt som en följd av uppvärmningen om behållarna placeras i 3 m eller 5 m djupa borrhål, vilket planerats i det senaste förvaringsalternativet, har således ingen betydelse från denna synpunkt. Förändringarna i permeabilitet på grund av temperaturspänningar i berget är av storleksordningen högst 10-15%. Om man medtar viskositetsförändringar hos grundvattnet i permeabiliteten, blir resultatet en fördubbling av permeabiliteten i den omedelbara närheten av avfallscylindrarna. Dessa effekter är dock av underordnad betydelse för strömningsbilden.

Bergmekaniska analyser i stor skala visar inga sammanhängande regionala brottzoner. Maximala höjningen av markytan på grund av termisk utvidgning blir ca 7 cm efter omkring 1000 år. I regional skala har den vertikala permeabiliteten minskat ca 20% efter 100 år inom ett område 50 m ovanför till 100 m under anläggningen. Den horisontella permeabiliteten är i det närmaste oförändrad.

Studierna av de temperaturindicerade, konvektiva grundvattenströmningarna visar, att om de normalt existerande vattenrörelserna antas vara noll, uppkommer ett antal mindre konvektionssystem i närheten av varje rum samt två stora konvektionssystem med en utsträckning om hundratals meter kring anläggningen. Storleken av dessa regionala, konvektiva vattenhastigheter är i verkligheten liten jämförd med den befintliga genomströmningen och ger endast upphov till en relativt blygsam störning av densamma. De lokala konvektionsströmmarna är störst vid inströmningsperiodens slut och avklingar helt efter ca 1000 år. (Under inströmningsperioden förekommer ingen lokal konvektion). Denna konvektionsströmning cirkulerar vattnet i tunnlarna och de närmaste metrarna in i berget. Den är starkt beroende av det lokala sprickmönstret i berget närmast förvaringstunnlarna.

De kvarstående effekterna på den rådande grundvattenströmningen sedan anläggningen återfyllts och temperaturerna utjämnats är små. Den tidigare nämnda, lokala grundvattenmodellen för Forsmark med Finnsjö- och Gåvestboförkastningarna som uppströms- respektive nedströms gränser, har kompletterats med att avfallsanläggningen lagts in som störning på 500 m djup. Återfyllningen har antagits antingen tät eller helt vattengenomsläpplig. För de isotropa permeabiliteterna (Fall 1 och 2) och tät återfyllning är grundvattenströmningen vertikalt nedåtriktad över anläggningen, böjs av horisontellt och mynnar i de vertikala krosszonerna på relativt stort djup. Som nämnts tidigare beror det nedåtgående flödet främst av topografin inom området. Om anläggningen betraktas som helt genomsläpplig sker avböjningar av flödet till horisontell riktning på större djup och tiden för en vattenpartikel att gå från anläggningen till den närliggande krosszonen ökar.

Vid anisotrop, icke-homogen permeabilitet (Fall 3) är strömningen mer horisontell över anläggningen vid tät återfyllning. På 500 m djup är sidoströmningen oberoende av topografin. En annan strömningsbild erhålls om förvaringsanläggningen här betraktas som helt vattengenomsläpplig. Vattnet dras då in i anläggningen på uppströmssidan från en bred zon ovanför och under förvaringsnivån och utträder på liknande sätt från anläggningen på nedströmssidan. Uppåtriktat flöde återfinns upptill 200 m ovanför anläggningen.

Som nämnts tidigare syns de nominella permeabiliteterna vara väl höga jämfört med erfarenhet av inströmning till gruvor samt med de storskaliga permeabilitetsundersökningar som utförs i Stripa. Som ett fjärde permeabilitetsfall (Fall 4) har därför värdena för horisontell permeabilitet i Fall 3 minskats genom parallell förskjutning så att de motsvarar Stripa-undersökningens resultat. Om man antar en tät återfyllning av anläggningen blir den beräknade, årliga vattenströmmen från förvaret i medeltal 0,15 - 0,30 l pr m^2 genomströmmad tvärsnittsarea av berget med permeabilitet enligt Fall 3. I Fall 4 reduceras vattenströmningen till 0,006 - 0,01 l/m^2 år. Detta motsvarar en total vattenmängd om 0,8 m^3 som passerar genom anläggningen på ett år. För genomsläpplig återfyllning av förvaringstunnlarna blir motsvarande vattenmängd 4,6 m^3 per år. Dessa vattenmängder passerar totalt över det kvadratkilometerstora område som anläggningen upptar. Huvuddelen av vattnet passerar sålunda genom pelarna mellan tunnlarna, vilka upptar 86% av ytan i anläggningsplanet.

Det bör påpekas, att vid anisotrop permeabilitet passerar grundvattnet troligen över krosszonen till nästa bergblock och så vidare tills ett område träffas där den regionala gradienten är riktad uppåt. Innan säkra bedömningar kan göras krävs dock bättre kunskap om de djupgående krosszonernas egenskaper och dess inverkan på den regionala hydrologin.

De två viktigaste slutsatserna av utredningen kan sägas vara följande:

- rådande grundvattenströmning syns inte bli nämnvärt störd av värmebelastningen

- grundvattenströmningen över lång tid bestäms principiellt av strömningsbilden före utbyggnaden av anläggningen och kan därför förutsägas genom bestämning av rådande geohydrologiska förhållanden

Vidare har konstaterats att:

- graden av anisotropi hos bergpermeabiliteten i horisontalled har betydelse vid valet av slutförvarets läge och förläggningsdjup. Anisotropin leder till att grundvattnet blir markant mindre rörligt mot djupet

- värmetransporten i berget kan med tillfredsställande noggrannhet anses ske enbart genom värmeledning (konduktion)

- den maximala temperaturstegringen i berget i omedelbar närhet av en avfallskropp är av storleksordningen 40°C med den koncentration av avfallet som antagits i den svenska studien (5,25 W/m^2) och med 30 års ventilation

- av temperaturskillnaderna uppkomna konvektionsströmningar ger endast obetydlig störning av rådande geohydrologisk grundvattenbild i slutförvarets närhet

- risken att nya strömningsvägar för grundvatten från anläggningen skall uppstå som en följd av brott i berget genom utsprängningen och den förhöjda temperaturen är försumbar

- påverkan på berget genom utsprängning och förhöjd temperatur är mycket lokal

- inströmning av grundvatten till tunnlarna kommer att dominera över regionala och konvektiva, lokala grundvattenströmmar under den tid anläggningen fylls upp med vatten

Alla beräkningsresultat i denna utredning finns i detalj redovisade i följande tekniska rapporter:

NR 1: GEOLOGICAL AND GEOTECHNICAL CONDITIONS

NR 2: THERMAL ANALYSES

PART I: CONDUCTIVE HEAT TRANSFER

PART II: ADVECTIVE HEAT TRANSFER

NR 3: REGIONAL GROUNDWATER FLOW ANALYSES

PART I: INITIAL CONDITIONS

PART II: LONG-TERM RESIDUAL CONDITIONS

NR 4: ROCK MECHANICS ANALYSES

NR 5: REPOSITORY DOMAIN GROUNDWATER FLOW ANALYSES

PART I: PERMEABILITY PERTURBATIONS

PART II: INFLOW TO REPOSITORY

PART III: THERMALLY INDUCED FLOW

1. INTRODUCTION

In January, 1977 the Swedish power utilities initiated a special task force, Project Fuel Safety (KBS), to describe in some technical detail how and where solidified high level nuclear waste or spent reactor fuel could be safely handled and stored in an underground repository in Sweden. The overall containment safety assessment involves the study of many factors, including an evaluation of groundwater flow fields around the repository which is of vital importance in the safety analysis. Other important factors, which are presently being studied by KBS, include vitrification procedures, waste handling and packaging methodology, corrosion and mining layouts. KBS has also initiated a geological field test program for determination of geological and hydrological parameters which are important for the long term containment safety. Portions of these investigations are being performed at a depth of 350 m in an abandoned iron mine at Stripa.

In January, 1977, KBS contracted Hagconsult AB for study of groundwater movements around a repository situated in Precambrian bedrock in Sweden. Subsequently, Hagconsult subcontracted RE/SPEC inc. and Acres Consulting Services Limited, and in February produced the first project report entitled "Phase 1. State of the art and detailed study plan".

The Phase 1 report describes in detail the different processes affecting the groundwater regime around a repository and the present state of knowledge of them. For each process, data availability, prediction and validation procedures and monitoring techniques are discussed. The state of the art report reviews flow, geochemistry, heat transfer and rock mechanics. Several changes influencing the project work have occured since the presentation of the Phase 1 report, which in turn lead to changes in the detailed study plan. First of all, it was decided that geochemical questions should not be treated within this study. Secondly, the disposal of reprocessed, highlevel waste became of prime interest, rather than direct disposal of spent fuel. The conceptual design of the repository facility discussed in the Phase 1 report also underwent design modifications.

In the Phase 2 studies, a set of technical reports were prepared in each of the principal phenomenon. Numerical methods were used to analyze the temperature, stress and flow fields, and the results are presented in a series of Technical Reports (TR) as follows:

TR 1: GEOLOGICAL AND GEOTECHNICAL CONDITIONS
TR 2: THERMAL ANALYSES
    PART I: CONDUCTION HEAT TRANSFER
    PART II: ADVECTIVE HEAT TRANSFER
TR 3: REGIONAL GROUNDWATER FLOW ANALYSES
    PART I: INITIAL CONDITIONS
    PART II: LONG-TERM RESIDUAL CONDITIONS
TR 4: ROCK MECHANICS ANALYSES
TR 5: REPOSITORY DOMAIN GROUNDWATER FLOW ANALYSES
    PART I: PERMEABILITY PERTURBATIONS
    PART II: INFLOW TO REPOSITORY
    PART III: THERMALLY INDUCED FLOW

In the detailed study plan, it was recognized that flows are influenced by rock mechanics and thermal conditions. Some of these coupling factors are shown in Figure 1. The initial flow will be determined by the regional hydrology. Various transients will then occur including the mining perturbation, changes in flow permeability, and thermally induced and modified flow in the heated, fractured rock caused by heat generation in the radioactive waste.

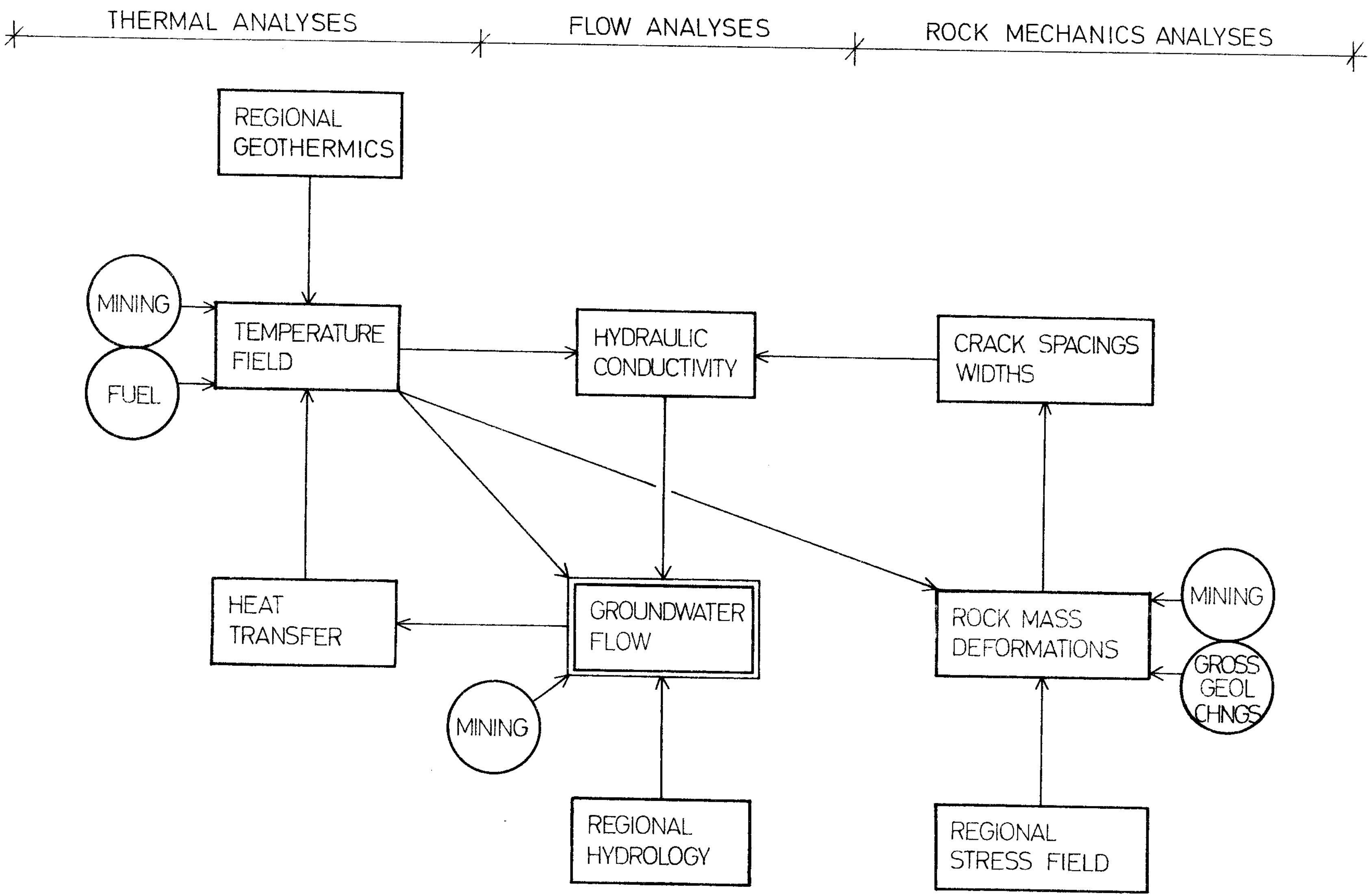


FIGURE 1. INPUT DATA AND ANALYSES REQUIRED TO ASSESS THE GROUNDWATER FLOW.

The long term groundwater flow field can then be partially assessed in terms of the modifications to the initial flow fields caused by the residual effects of the transient perturbations. It is shown that the principal residual effects can be modelled with sufficient accuracy, and that the long term flow fields are determined predominately by the initial conditions wich are insufficiently understood at this time. However, it may therefore be argued conversely, that once the initial conditions are well defined after field work, then the long term performance can be reliably predicted, provided that no major externally-initiated effects occur.

Since the geological and geotechnical conditions determine the groundwater flow and thus the containment, a collection and analysis of known data was presented in TR 1. These data include thermal properties of the rock, the rock mechanics situation at the repository level, and the deformational and flow characteristics of rock fractures. The work presented in TR 1 provides the available ranges for input parameters required in the temperature, rock mechanics and flow calculations. TR 2, assessing the thermal fields around the repository as a function of time, is divided into two parts. Part I reports results of the conduction heat flow calculations for a local model of one tunnel section and for a global model including the entire repository geometry. Part II reports results of the forced convection (advective) heat transfer on the global scale, caused by the crossflow of groundwater at the repository level. In TR 3, an assessment is made of the groundwater regimes at the candidate repository sites at Oskarshamn and Forsmark. Part I reports the initial conditions, prior to repository construction, as they can be best judged from available data. In part II, groundwater flows are predicted considering the residual effects resulting from the transient perturbations during the mining and storage periods.

TR 4 evaluates the thermomechanical stress field in order to assess failure zones in the rock mass and perturbations on the permeabilities caused by the stress changes.

TR 5 describes the effects of the mining and temperature perturbations on the groundwater flow in the vicinity of the repository. In part I, the results from the rock mechanics analyses of report TR 4 are used to assess the perturbations on rock mass permeabilities caused by the thermomechanical effects. Part II reports the flow fields following construction of the repository and water inflow into the excavation. Part III discusses the thermally induced flows in the rock mass surrounding the repository.

This Final Report synthesizes the most important results which were reported in detail in the Technical Reports. These studies are presented in a sequence of time frames following a brief review of the geotechnical conditions and modelling techniques.

Firstly, we summarize our assessment of existing, initial pre-repository groundwater conditions. The transient perturbations caused by construction and thermal loading are then analyzed and the resulting temporary flows identified. It is shown that these perturbations may be assessed by analysis and that the effects are generally acceptable.

Finally, a summary of the availability of data and modelling techniques is given for each phenomenon together with an assessment of the reliability of predictions. The importance of each of these phenomena in terms of its impact on containment is estimated and conclusions drawn on the remaining sources of important uncertainty requiring better definition. These form the basis for the recomendations for further studies.

2. GEOLOGICAL AND GEOTECHNICAL CONDITIONS

In order to assess the groundwater flow around a repository with the numercial methods employed in this study, a number of parameters describing the host rock mass must be known. Examples of such parameters are the general geological and hydrological conditions including joint properties, in situ stress and temperature fields, and thermal and mechanical characteristics of the rock mass and joints. This section gives a brief outline of this type of data and of how the collected data were used within the study.

2.1 Geology and hydrology

During previous gelogical periods, the Baltic Shield was subjected to tectonic disturbances. This has led to the shield being traversed by failure planes, with associated crushed and weathered zones, separating the rock mass into a pattern of competent and only sparsely fractured rock. The lateral distance between these zones can vary from hundreds of meters to several kilometers.

The rocks of the Baltic Shield, being mainly from the Precambrian era, are crystalline, hard and with a crystal matrix devoid of any significant permeability. Thus, water flow in rock blocks between major tectonic zones is thought to be due to water flow conductivity of existing crack systems within the blocks. In geologically recent times, Scandinavia was glaciated and isostatic rebound from the ice load is still taking place. It is the intent in Sweden to construct a repository in a portion of competent rock that is situated between major geological features.

Because of the relatively large amount of precipitation in Sweden as compared to infiltration, the groundwater surface is in general within 3-4 m of the ground surface (1)[x]. For this study, we have therefore assumed that the water table is coincident with the ground surface. A proper hydraulic definition of the vertical features surrounding the repository area is of course very important for the local flow models. More field information is

[x]Numbers in paranthesis refer to references at end of text, section 9.3.

required to determine the natural permeability, potential and flow characteristics of these features. In this study, both constant potential and flowline vertical boundaries have generally been used for comparative purposes at possible vertical feature locations.

2.2 Thermomechanical properties of host rock

The groundwater flow pathways through the crack system within the rock body, are affected by the excavation and thermal stresses developed within the rock mass. It is therefore essential to assess the thermomechanical properties of the host rock mass, including the thermal conductivity, thermal expansion coefficient, elastic deformation moduli, and strength characteristics of the intact rock, and the load-deformation characteristics of the joints.

Thermal data for Fennoscandian granites have been published by The Swedish Mining Society (2) and by Parasnis (3). Within the actual field test program at the Stripa mine, data have been obtained by the University of Luleå (4) and Terra Tek (5). Based on the scatter of these data from rock samples and noting the uncertainties in their application to large scale rock masses with an unknown quartz content, a conservative value for thermal conductivity has been taken as 2.05 W/m,^{o}C. Conduction heat transfer analyses have also been performed with a conductivity of 3.35 W/m,^{o}C, a value which seems to be representative for the average conductivity of small samples. The difference in the temperature predictions in the rock mass surrounding a repository due to this change in conductivity is not significant.

The thermal expansion coefficient for Stripa granite is being determined by the Massachussetts Institute of Technology, U.S.A., and no values have, as yet been released. However, a theoretical calculation for several granites, based on the mineral composition, gave a value for the volumentric expansion coefficient of $24 \times 10^{-6}/^{o}C$. For the linear expansion coefficient, we have used one-third of this value, i.e. $8 \times 10^{-6}/^{o}C$.

Most granites are characterized by quite isotropic mechanical properties. This conclusion was also reached in recent tests on Stripa granite. Hence, the assumption of deformational isotropy was used throughout this study. Young's modulus of elasticity shows a decrease with increasing temperatures (for Stripa granite from 35 GPa at $20^{o}C$ to 31 GPa at $100^{o}C$), but the significance of this effect was judged to be low. Also, Poisson's ratio was considered to be 0.25 , independent of temperature throughout our calculations.

The assessment of strength of the host rock is of vital importance, not only for the support requirements for the tunnels, but also since the induced fracture pattern will have an impact on the flow conditions in the near field of the storage tunnels. With proper reductions in the reported failure strength data for small granite samples, to account for differences in dimensions, loading rates, and water saturation between the sample and the rock mass, the following Mohr-Coulomb failure criterion was employed for the intact rock between the joints:

$$\tau = 19 + \sigma \tan (34^{o}) \text{ (MPa)}$$

where: τ, σ represent the shear and normal stress in the rock.

For the residual strength of intact rock it was assumed

$$\tau_{j,r} = 1.9 + \sigma_n \tan (34^{o})$$

The following relationship was assumed to hold for the shear strength of a joint:

$$\tau_j = 1.0 + \sigma_n \tan (34^{o})$$

Residual strength criterion of a joint was taken as:

$$\tau_{j,r} = 0.3 + \sigma_n \tan (30^{o})$$

2.3 Geohydrological properties of host rock

For the purpose of flow calculations, a parallel plate equivalent continuum model, as proposed by Snow(6), was assumed. The continuum has conveyance properties equivalent to a series of parallel fractures. The rock mass permeability, assuming fractures with effective flow apertures e and spacing s, can be written:

$$K = n \cdot k_j$$

where:

$n = \frac{e}{s}$ is the fracture porosity

$k_j = \frac{\rho g e^2}{12\mu}$ is the permeability of a fracture .

where:

g = gravitional acceleration

ρ = density of the groundwater

μ = dynamic viscosity of the groundwater

Field data on rock mass permeability at depth in the Baltic Shield are very limited. For these analyses, a set of nominal permeability distributions were derived. These were based on recent information from a drill-hole test at Oskarshamn, performed by The Swedish Geological Survey, and data found in the literature. An empirical curve for the variation of permeability with depth was then derived using these data, as shown in Figure 2a. The three cases of rock mass permeability variation with depth wich have been considered are:

Case 1: Homogeneous isotropic permeability ($K = 10^{-8}$ m/s) ;

Case 2: Non-homogeneous isotropic permeability (K varying with depth as per empirical curve) ;

Case 3: Non-homogeneous anisotropic permeability (vertical $K_v = 10^{-9}$ m/s, horizontal K_r varying with depth as per empirical curve).

These distributions are plotted in Figure 2b.

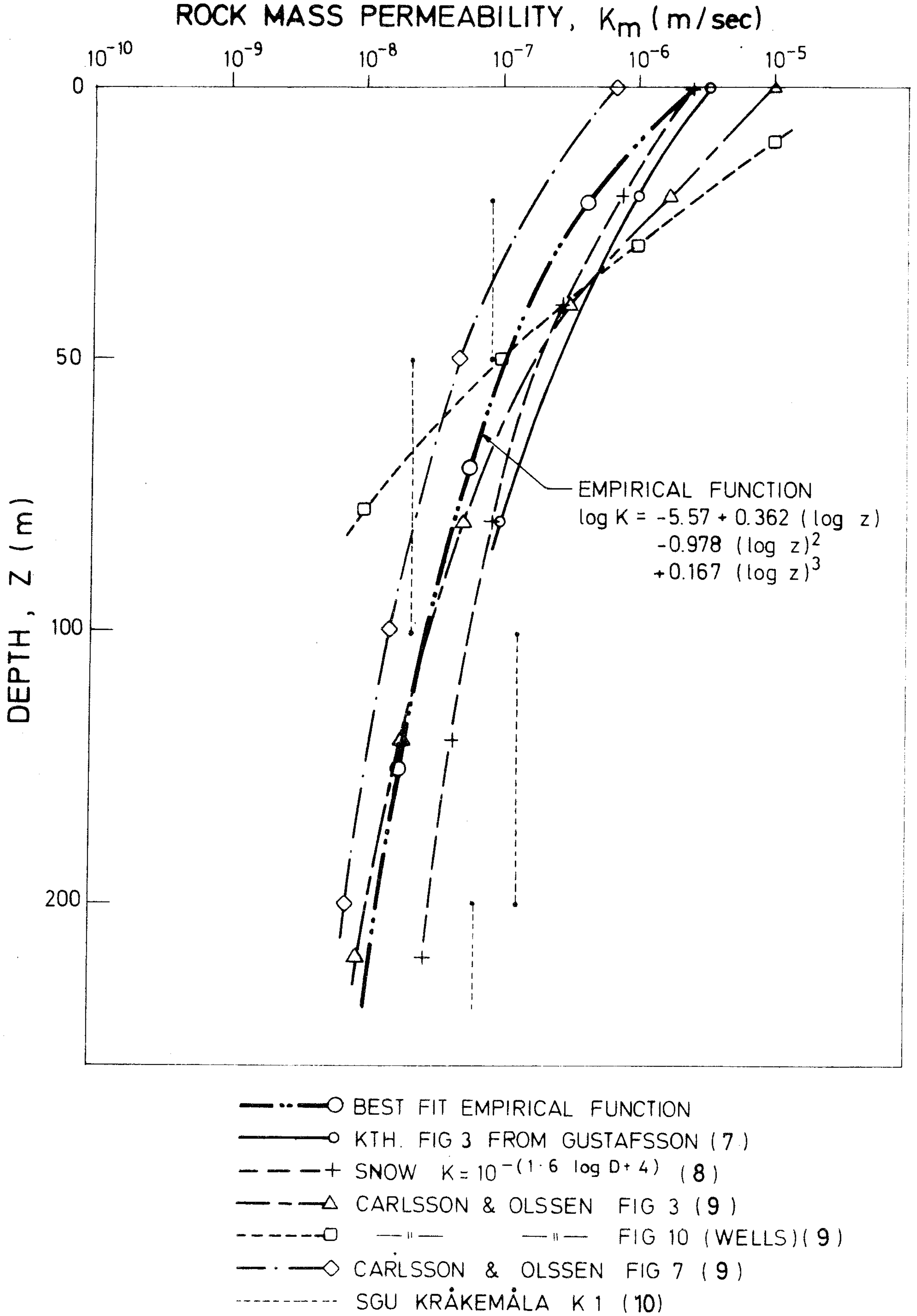
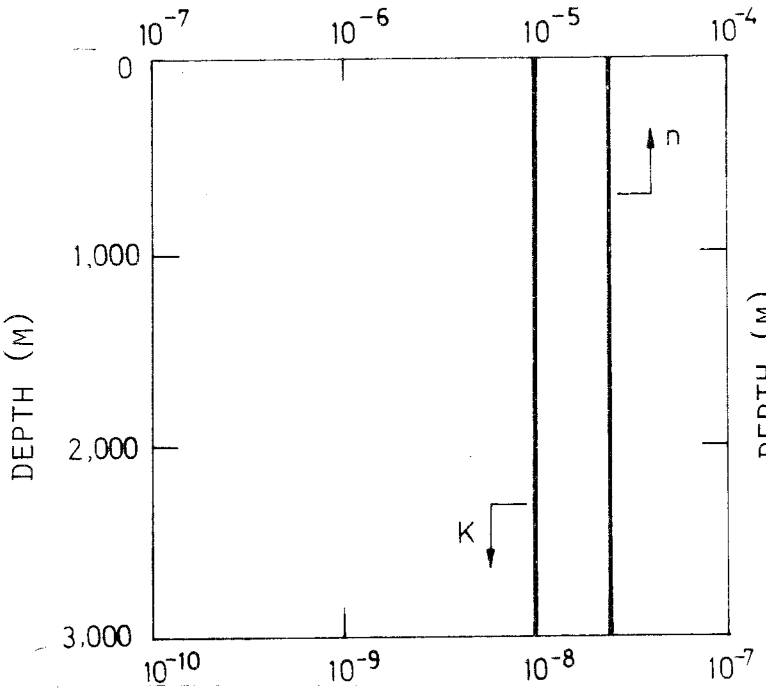
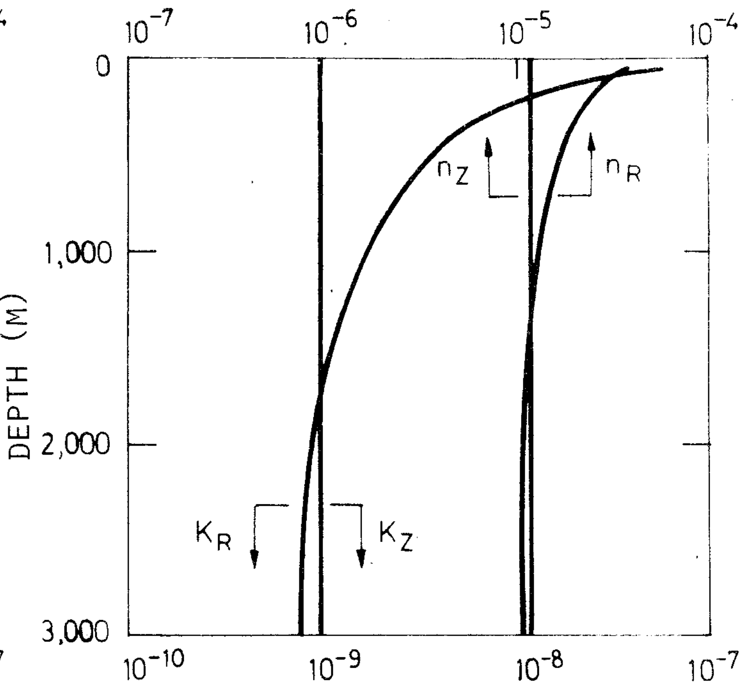


FIGURE 2A. PERMEABILITY V DEPTH



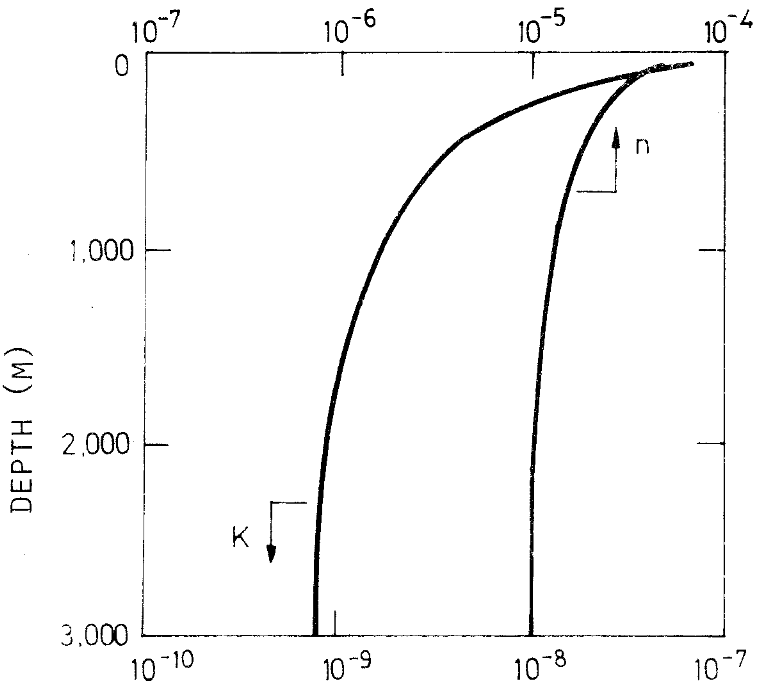
PERMEABILITY K(M/S)

CASE 1: ISOTROPIC, HOMOGENEOUS



PERMEABILITY K(M/S)

CASE 3: ISOTROPIC, NON-HOMOGENEOUS



PERMEABILITY K(M/S)

CASE 2: ANISOTROPIC, NON-HOMOGENEOUS

FIGURE 2B. NOMINAL PERMEABILITY, POROSITORY DISTRIBUTION CASES

An empirical relationship between permeability and stress was also developed. The depth was transformed to vertical gravitational stress, and hence the relation between permeability and stress could be determined. This procedure is considered valid, since measured permeabilities are as a rule obtained from packer tests in vertical drillholes and thus reflect horizontal flow. Horizontal permeability in fractured media is primarily affected by changes in vertical stress.

Selected results of analyses obtained using the three nominal permeability distributions were assessed in the light of recent permeability data from the Stripa hydraulic test.

3. REPOSITORY DESIGN AND MODELLING CONSIDERATIONS

3.1 Elements of the Proposed Repository Facility Design

The design concept is based on a repository situated at a depth of 500 m (with an alternative depth of 1000 m), with storage capacity for 9000 cylindrical canisters of 40 year old PWR reprocessed waste to be emplaced over an operational period of 30 years. The canisters are expected to be 0.4 m in diameter and 1.8 m in length, with a termal power output of 525 W at the time of emplacement. The repository concepts consist of 41 parallel tunnels, situated within an area of 1 km by 1 km, as illustrated in Figure 3. Each tunnel has a length of 1 km, and an approximately circular cross section of 3.5 m diameter, as shown in Figure 4. For a centerline-to-centerline spacing of 25 m, the tunnel system has an extraction ratio of 14%. Access to the repository will be provided by two vertical shafts, each located about 200 m from opposite corners of the storage facility.

The canisters will be emplaced in vertical drillholes in the floors of the tunnels, with one canister per drillhole. After canister emplacement, the drillholes will be backfilled. The drillholes will have diameters of 1 m and depths of 3 m, and will be spaced at 4 m intervals along the length of a tunnel. For a grid spacing of 4 m by 25 m, each canister will have a planar area of 100 m^2 in which to conduct heat to the overlying and underlying rock mass. The corresponding thermal flux density, or gross thermal loading (GTL), will be 5.25 W/m^2 (21.25 kW/acre).

The storage tunnels and the shafts will be backfilled after the emplacement of all of the canisters. The backfill materials, for the tunnels, shafts, and emplacement drillholes, have not yet been selected, and therefore various possible materials have been assumed in the analyses. During the 30 year operational life of the repository, ventilation of the entire tunnel system will be maintained.

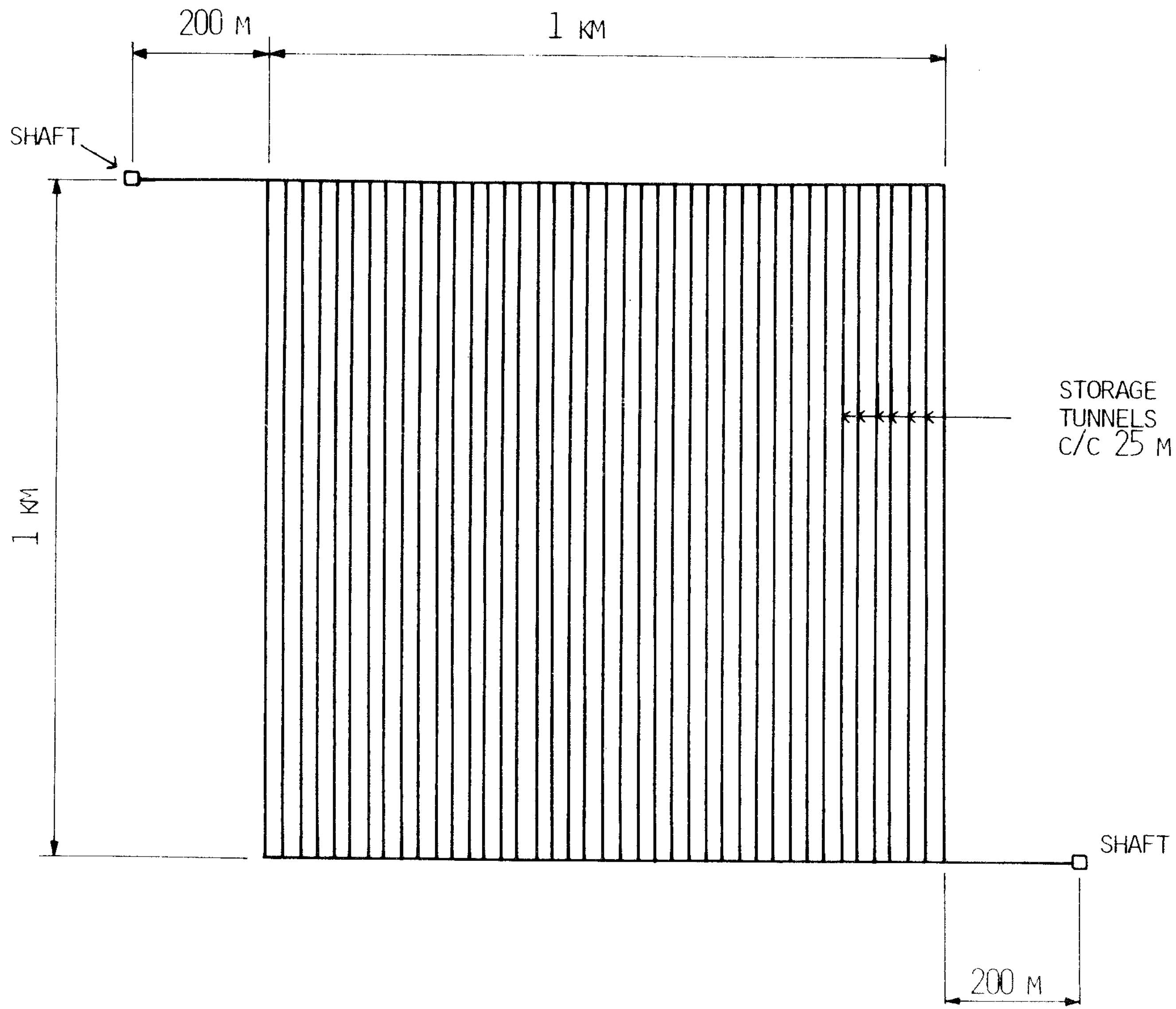


FIGURE 3. TUNNEL AND CANNISTER DETAILS FOR HIGH LEVEL WASTE REPOSITORY

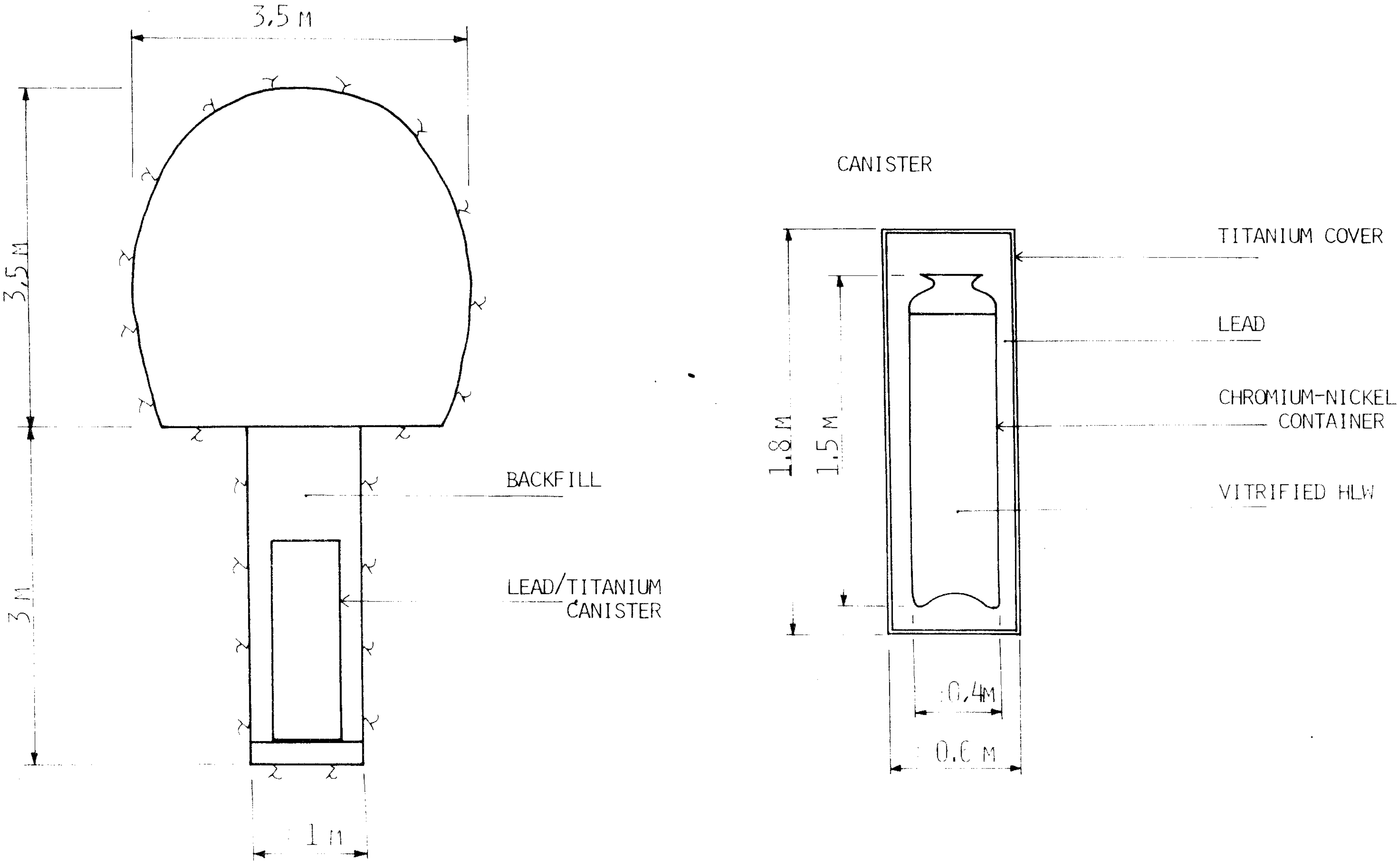


FIGURE 4. LAYOUT OF HIGH LEVEL WASTE REPOSITORY

3.2 Repository Modelling Procedures

Excavation of a repository facility within a rock mass and the subsequent emplacement of heat generating waste will give rise to pertubations of the existing states of in-situ stress and groundwater flow. The coupled thermomechanical-hydrological response of the fluid-saturated rock mass will be time-dependent, principally due to the transient nature of the induced thermal loading. The response will also be nonlinear due to rock fracture and/or flow, joints, and stress/temperature dependent permeability and material properties. In addition, the effect of anisotropic permeability on the groundwater flow system must be evaluated. In order to model this rather complex physical problem in a quantitative fashion, use was made of the finite element method of analysis, with the jointed rock mass replaced by an equivalent porous continuum. The coupling between the various processes was effected by a combination of direct and indirect, or quasi-static, procedures. A flow diagram of the methodology of the composite analysis procedure, including the coupling of phenomena, is presented in Figure 5. The finite element models for the various analyses are categorized as follows:

1) Regional: Utilized for analyses of isothermal, steady state groundwater flow on a regional basis. Plane models with dimensions ranging from 200 to 300 km in length and 2 km in depth.
2) Topography: Utilized for analysis of influence of topography on isothermal, steady state groundwater flow. Plane model with dimensions of 4 km in length by 1 km in depth.

3) Discontinuity: Utlized for analysis of effect of a dipping structural discontinutity on isothermal steady state groundwater flow. Plane models with dimensions of 24 km in length and 2 km in depth.

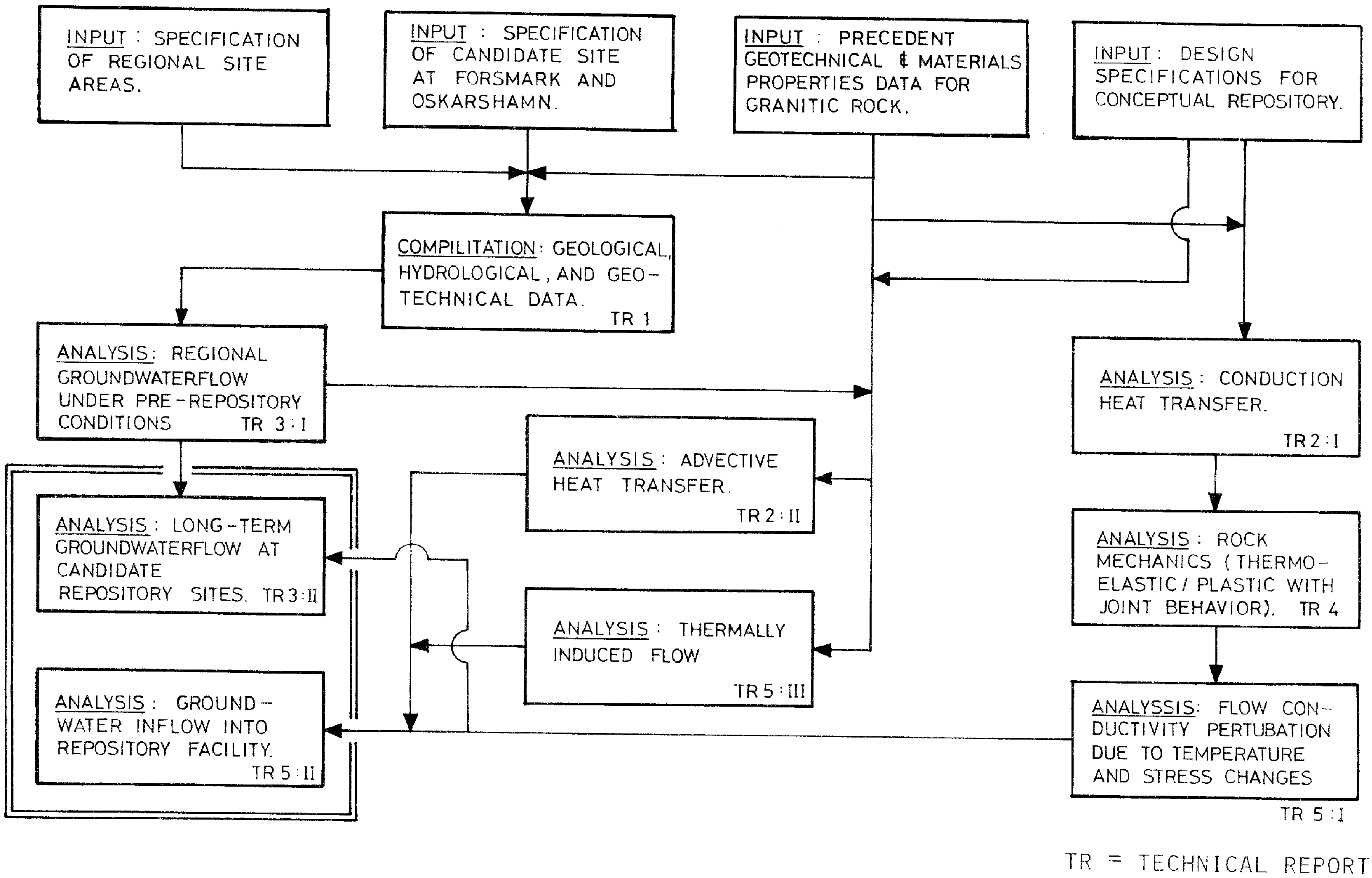


FIGURE 5. METHODOLOGY OF GROUNDWATER FLOW ANALYSIS AROUND A REPOSITORY.

Site: Utilized for analysis of isothermal steady state groundwater flow at the Forsmark site area, both preceding and following repository excavation and waste emplacement. Plane models with dimensions of 1.77 km in width and 1.55 km in depth.

Global (Far Field): Utilized for analysis of transient heat conduction, thermal advection, inflow, thermally induced flow, elastic-plastic and joint behavior, and permeability pertubation. Plane and axisymmetric models with dimensions ranging from 1.5 to 3 km in width (1.5 km in radius) and 3 km in depth.

Local (Near Field): Utilized for analysis of transient heat conduction, inflow, thermally induced flow, elastic-plastic and joint behavior, and permeability perturbation. Plane and axisymmetric models representing a typical strip section through the repository facility and encompassing one-half of a pillar and one-half of a storage room, with demensions of 12.5 m in width (12.5 m in radius) and 50 m to 1.5 km in the vertical.

The various finite element models employed in this investigation are catalogued in an Appendix with details of the computational runs. From a phenomenological viewpoint, the particular finite element models were:

(A) Isothermal Groundwater Flow: Steady state isothermal Darcy flow in fluid-saturated porous media with nonhomogeneous anisotropic permeability. Boundary conditions include water table coincident with ground surface; constant potential or zero flux vertical model boundaries; impervious lower model boundary.

(B) Conduction Heat Transfer: Transient heat conduction with nonhomogeneous, isotropic, temperature-independent thermal properties and time-dependent internal heat generation. Initial temperature field corresponding to geothermal gradient. Boundary conditions include insulated vertical and bottom model boundaries, either constant temperature or convective heat transfer at the ground surface, and either insulated or convective storage room periphery.

(C) Thermal Advection: Transient, advective and conductive heat transfer with nonhomogeneous, isotropic, temperature-independent thermal properties, time-dependent internal heat generation, and constant pore fluid velocity. Initial and boundary conditions are analogous to those described for conduction heat transfer.

(D) Thermally Induced Flow: Transient coupled single phase Darcy flow and heat transfer including fluid thermal expansion and bouyancy in fluid- saturated porous media with nonhomogeneous anisotropic permeability and thermal conductivity. Zero initial temperature and regional initial time and temperature independent potential flow fields. Boundary conditions analogous to those described for isothermal groundwater flow and conduction heat transfer.

(E) Rock Mechanics: Thermoelastic/plastic stress analysis for a jointed rock medium with nonhomogeneous, isotropic, time- and temperature-independent elastic and strength properties, and linear Mohr-Coulomb failure conditions for the intact rock and planes of weakness. Prescribed initial nonhomogeneous stress field with simulated excavation procedures. Boundary conditions include traction-free ground surface, zero horizontal displacement along vertical model boundaries, and zero vertical displacement along lower model boundary.

The analyses of the permeability perturbations in the near and far field domains of the repository used the thermoelastic/plastic stress results, the temperature-dependent water viscosity relation and an empirical relationship between permeability and normal stress. These results were used for assessments of the long-term groundwater flow behavior in the domain of the repository and the inflow into the repository facility.

3.3 Material Properties

In order to employ the material characterizations previously described, the required parameters for each aspect of the investigation are as follows:

(A) Isothermal Groundwater Flow

The nominal permeabilities K of the rock mass (shown in Figure 2b) were:

Case 1. Homogeneous isotropic; $K = 10^{-8}$ m/s

Case 2. Nonhomogeneous isotropic, decreasing with depth Z according to:

$$\text{Log}(K) = -5.57 + 0.362\ \text{Log}(Z) - 0.978\left[\text{Log}(Z)\right]^2 + 0.167\left[\text{Log}(Z)\right]^3$$

Case 3. Nonhomogeneous anisotropic: Vertical $K_v = 10^{-9}$ m/s (constant with depth); Horizontal K_r according to relationship given under Case 2.

By utilizing a joint spacing of 1.8 m and the method proposed by Snow (6), the vertical n_v and horizontal n_r porosities of the rock mass are given by:

$$n_v = 14.503 \times 10^{-3}\ (K_v/2)^{1/3}$$

$$n_r = 14.503 \times 10^{-3}\ (K_v/2)^{1/3} + (K_r - 1/2K_v)^{1/3}$$

(B) Conduction Heat Transfer

Material	Thermal Conductivity K (W/m, °C)	Density ρ (kg/m³)	Specific Heat c (J/kg,°C)
Granite	2.05 3.35	2800 2700	735 800
Vitrified Waste	0.5	2500	735
Backfill	1.0	2800	735
Lead	28.0	12000	130

Ground Surface Film Coefficient = 2.5 W/m², °C

Geothermal Gradient = 20°C/km

Ground Surface Temperature = 5°C

(C) Advective Heat Transfer

Material	Thermal Conductivity K_T (W/m , °C)	Density ρ (kg/m^3)	Specific Heat c (J/kg , °C)
Granite	2.05	2800	735
Groundwater	-	1000	4200

Regional Flux = Porosity x Pore Velocity = 2 x 10^{-11} m/s

Other conditions and properties are the same as used for the conduction heat transfer analysis

(D) Thermally Induced Flow

Material	Thermal Conductivity K_T (W/m , °C)	Density ρ (kg/m^3)	Specific Heat c (J/kg, °C)
Granite	2.05	2800	735
Backfill	1.50	2070	936
Groundwater	-	1000	4180

Permeability of the granite rock mass is the same as used for the isothermal groundwater flow analysis.

Backfill Permeability = $K = 10^{-10}$ m/s

Backfill Porosity = $n = 0.37$

Volumetric Thermal Expansion of Water = $\beta_T = 2.07 \times 10^{4}$ /°C

(E) Rock Mechanics

Modulus of Elasticity = $E = 21000$ MPa

Poisson's Ratio = $\nu = 0.25$

Cohesion of Intact Granite = $S_o = 19$ MPa

Angle of Internal Friction of Intact Granite = $\phi = 34^o$

Cohesion of Joint = $S_j = 1$ MPa

Angle of Internal Friction of Joint = $\phi_j = 34^o$

Residual Cohesion of Joint = $S_j^x = 0.3$ MPa

Residual Angle of Internal Friction of Joint = $\phi_j^x = 30^o$

Coefficient of Thermal Expansion of Granite = $\alpha = 8 \times 10^{-6}$ /°C

Density of Granite = $\rho = 2700$ kg/m^3

In Situ Stress State: Vertical Stress = Density times depth
Horizontal Stess = two times vertical stress

Joint Plane Orientation: Case 1. 0 and 90^{o} from vertical
Case 2. -45^{o} and 45^{o} from vertical

(E) Permeability and viscosity perturbations within repository domain

We use the "engineering permeability" defined as:

$$K = \frac{\rho \cdot g \cdot k}{\mu} \qquad (m/s)$$

where

ρ = fluid density (kg/m^3)
g = gravitational acceleration (m/s^2)
k = intrinsic permeability (m^2)
μ = groundwater dynamic viscosity (kg/m,s)

The stress dependency of K (σ) is defined by:

$$\log (K/K_0) = -5.57 + 0.362 \log (\sigma_n/\sigma_0) - 0.978 \{\log(\sigma_n/\sigma_0)\}^2 + 0.167 \{\log(\sigma_n/\sigma_0)\}^3$$

where: K_0 = unity permeability (m/s)
$\sigma_0 = \rho\ell$
ρ = density (kg/m^3)
ℓ = unity (m)

The relation is valid within the depth range of $0 < Z < 2000$ m

The temperature dependence of the viscosity $\mu(T)$ in the above relation for K is defined by:

$$\frac{1}{\mu(T)} = 5380 + 3800\,A - 260\,A^3$$

where μ = groundwater viscosity (kg/m,s)
$A = (T-150)/100$
T = temperature (^{o}C)

4. INITIAL GROUNDWATER REGIME

4.1 Objectives and Scope of Study

The objectives of this chapter are to present a summary of the concepts and methods of analysis employed and principal conclusions reached in assessments of the initial groundwater flow conditions at the candidate repository sites at Forsmark and Oskarshamn. The analyses of the effects of repository construction, waste emplacement and long term containment are summarized in the following sections. These effects are viewed as perturbations to the initial groundwater regime.

Since the field data obtained to data are very limited,the flow was studied using a set of simulation models based on the regional topography,and surface hydrological system using nominal permeability distributions. Parametric analyses were undertaken in order to study the effect of controlling factors and particularly the flow paths associated with various values and distributions of hydraulic properties.

4.2 Flow Modelling Methodology

A two-dimensional steady state finite element model was used for modelling the initial groundwater fields. The flow is assumed to be saturated, isothermal, and Darcian. This assumption was adopted, since the scale of the models is large and the flow, which is in fact through fracture systems, can therefore be adequately simulated with a porous continuum. Parametric studies were made of the effect of singular features on the porous media flow system using line elements in finite element grids.

Deterministic models were used for these analyses. The possibility of using stochastic models was assessed, but it was concluded that they were not appropriate for modelling spatial variability. The primary source of data variability is at present due to the limited knowledge of the parameters, in particular the permeability and porosity of the rock mass at great depths. A stochastic analysis was, however, used to assess the resulting variability in velocity predictions due to uncertainty in estimates of the flow parameters considering each flow parameter as a single, spatially independent random variable. Permeability, porosity and hydraulic gradient distributions were estimated within expected ranges and the resulting computed probability distribution of pore velocities is plotted in Figure 6. It can be seen that the 95% confidence limits include variations of almost three orders of magnitude in velocity predictions.

PARAMETER	VALUE RANGE		UNITS
K	7.9×10^{-10}	3.2×10^{-9}	m / s
n	1.0×10^{-5}	6.3×10^{-5}	
i	5.0×10^{-4}	8.0×10^{-3}	

$$Vp = \frac{K}{n} \cdot i$$

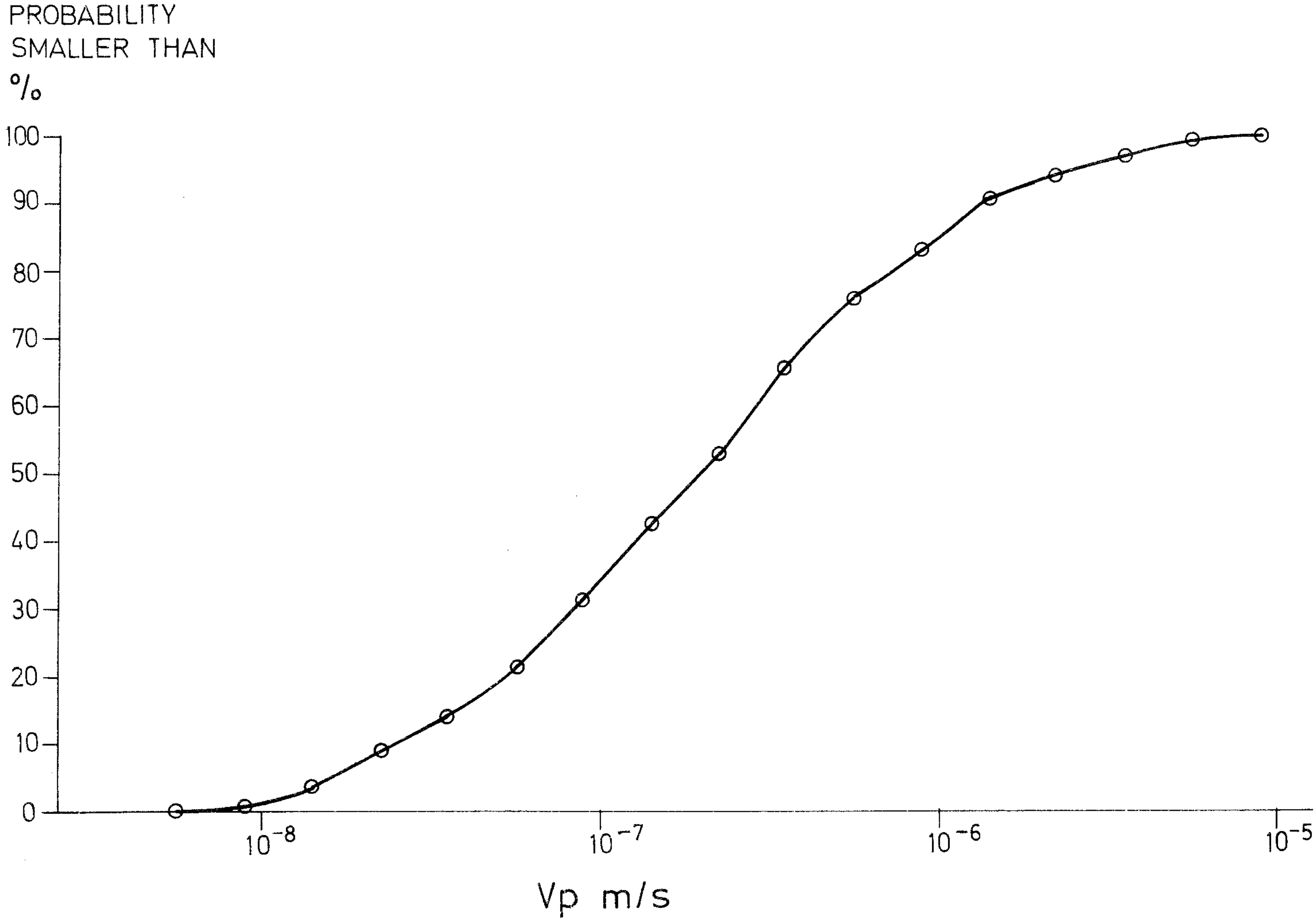


FIGURE 6. PORE VELOCITY RELIABILITY ANALYSIS

4.3 Flow Models

4.3.1 Forsmark site geology

The candidate site at Forsmark is located in an area of subdued local relief with vertical topographical variations generally less than 10 m. The low lying areas are occupied by lakes and drainage is poorly developed. The average ground surface is at an approximate elevation of 35 m.

The bedrock is generally Precambrian Svecofennian gneisses and gneissic granites. In the immediate site area the bedrock is an even grained weakly foliated granite. Worked deposits of iron in leptites occur nearby, although the extent and possible effects of these workings was not studied. Surficial deposits comprise tills overlain by post glacial clays. The major structural features deduced from field mapping and air photo interpretation are shown in Figure 7. Dextral shear movement has been inferred in the Gåvestbo and Finnsjön linear features on the east and west sides of the candidate site. Secondary second-order shearing occurs around the northern end of the site.

The site is thus bounded on three sides by major structural features, the depth and nature of which have not yet been investigated in the field.

Precipitation and infiltration measurements and the existence of many lakes indicate that the regional groundwater levels are generally close to the ground surface. The estimated values of the groundwater levels are shown in Figure 8. In the Uppland area, the regional surface groundwater gradient is approximately 1:1000. Flow lines are shown to indicate general trends, although it is recognized that the main flow will be along structural features.

4.3.2 Oskarshamn site geology

The Oskarshamn area exhibits a highly dissected relief of about 20 m at an average elevation of about 20 m above sea level.

The bedrock of the Oskarshamn region comprises Precambrian Gothian rocks, the Småland-Värmland intrusions, primarily granitic and granodioritic in composition. The candidate site is located within an intrusion of younger sub-jotnian granite.

The joint patterns in the intrusion include radial, tangential, diagonal and flat-lying systems. A north-south reverse fault with a lateral extension of more than

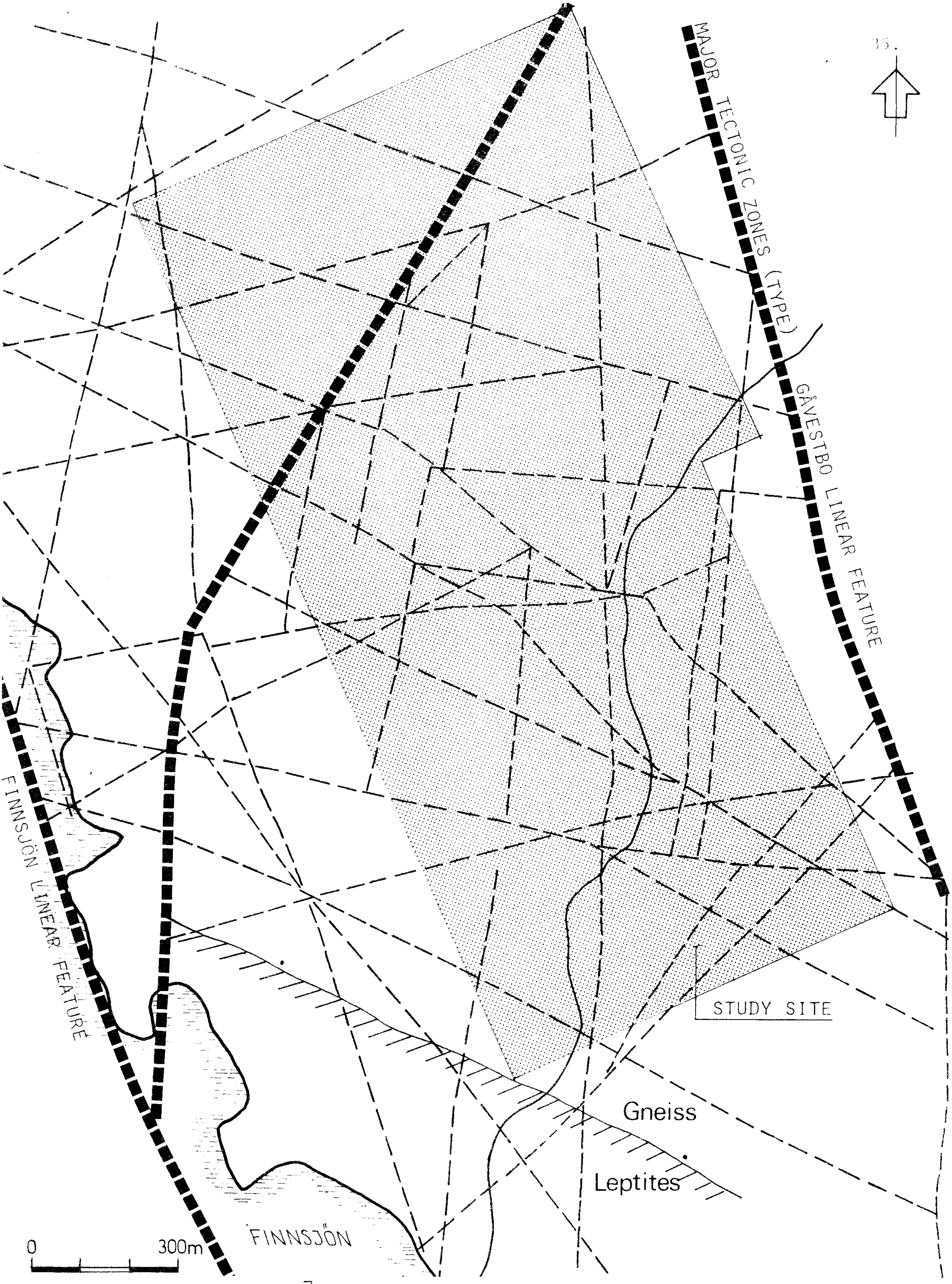


FIGURE 7. MAJOR STRUCTURAL FEATURES AT THE FORSMARK STUDY SITE.

25 m is located 500 m west of the candidate site.

The regional groundwater levels for the Oskarshamn area are shown in Figure 9. The groundwater surface gradient at the site area is approximately 2:1000.

4.3.3 Regional models

Two-dimensional vertical section models were analyzed and located along flow paths passing through the candidate sites in order to study regional flow gradients at depth in the site areas. The location of the Forsmark regional model is shown in Figure 8. and extends from 200 km inland to 100 km into the Baltic with a depth of 2 km.

The location of the Oskarshamn regional model is shown in Figure 9 and extends from 100 km inland to 100 km into the Baltic with a depth of 2 km. Various permeability and porosity distributions, as described in section 4.4.1, were simulated.

4.3.4 Local topography and discontinuity models

Two-dimensional vertical section models were created in order to study the effects of local relief on flow at depth and the modifications to flow cause by a postulated inclined singular feature.

The topography model was 4 km long with depth of 1 km and a central local rise of 50 m. Flow patterns were developed for various permeability and porosity distributions, see section 4.4.2.

The discontinuity model was 24 km long and 2 km deep with a 1 m wide singular feature of various higher permeabilitites dipping at 1:4 either towards or with the main flow direction. Again, various permeability and porosity distributions were modelled with both zero flux and potential boundary conditions. The results are displayed in section 4.4.2.

4.3.5 Site models

A two-dimensional local model for the Forsmark site was developed. The model was 1750 m long and 1500 m deep and is intended to be representative of transverse sections in the southern end of the site area and is bounded by vertical faults for the full depth.

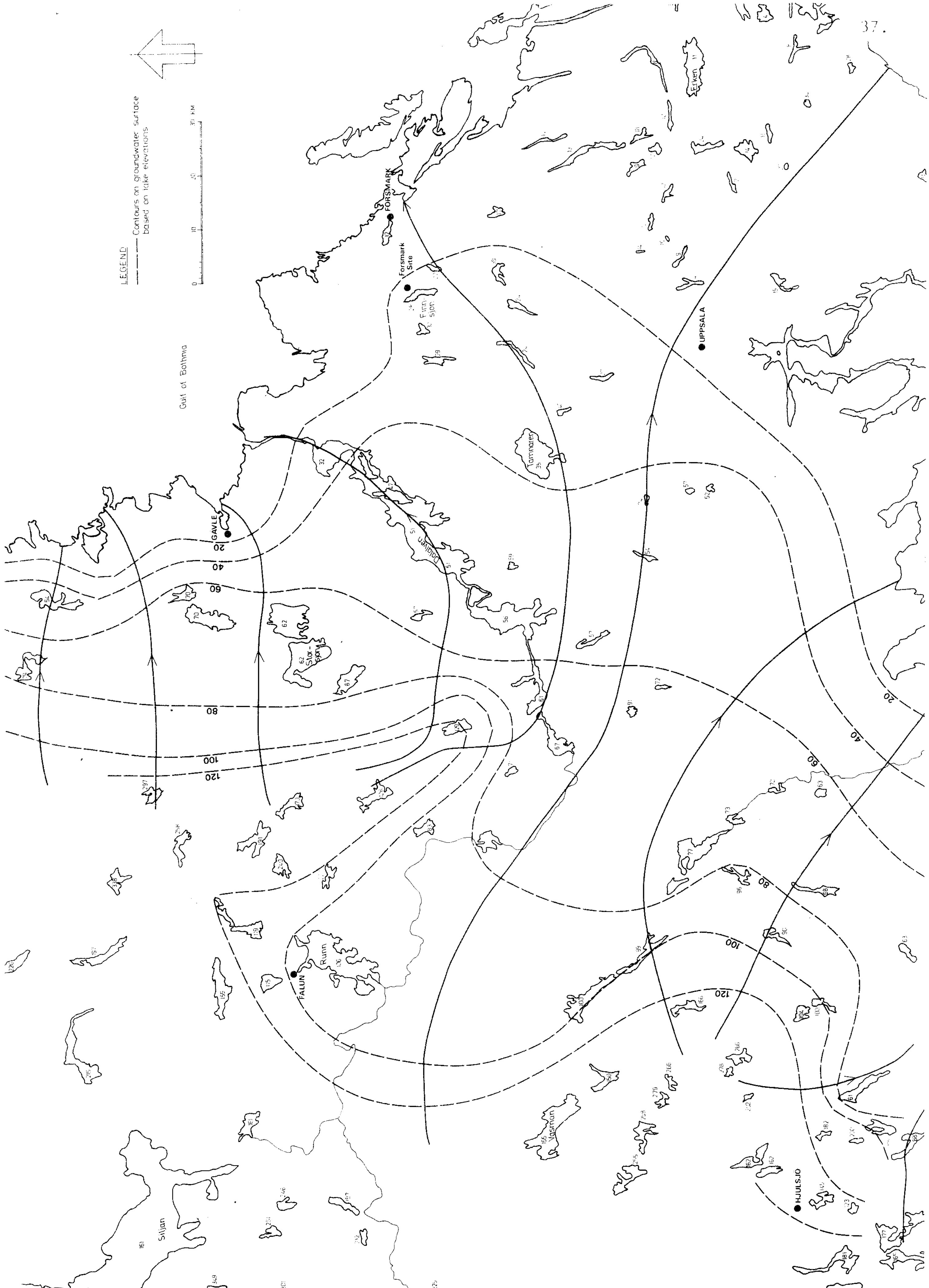


FIGURE 8. REGIONAL POTENTIALS FORSMARK

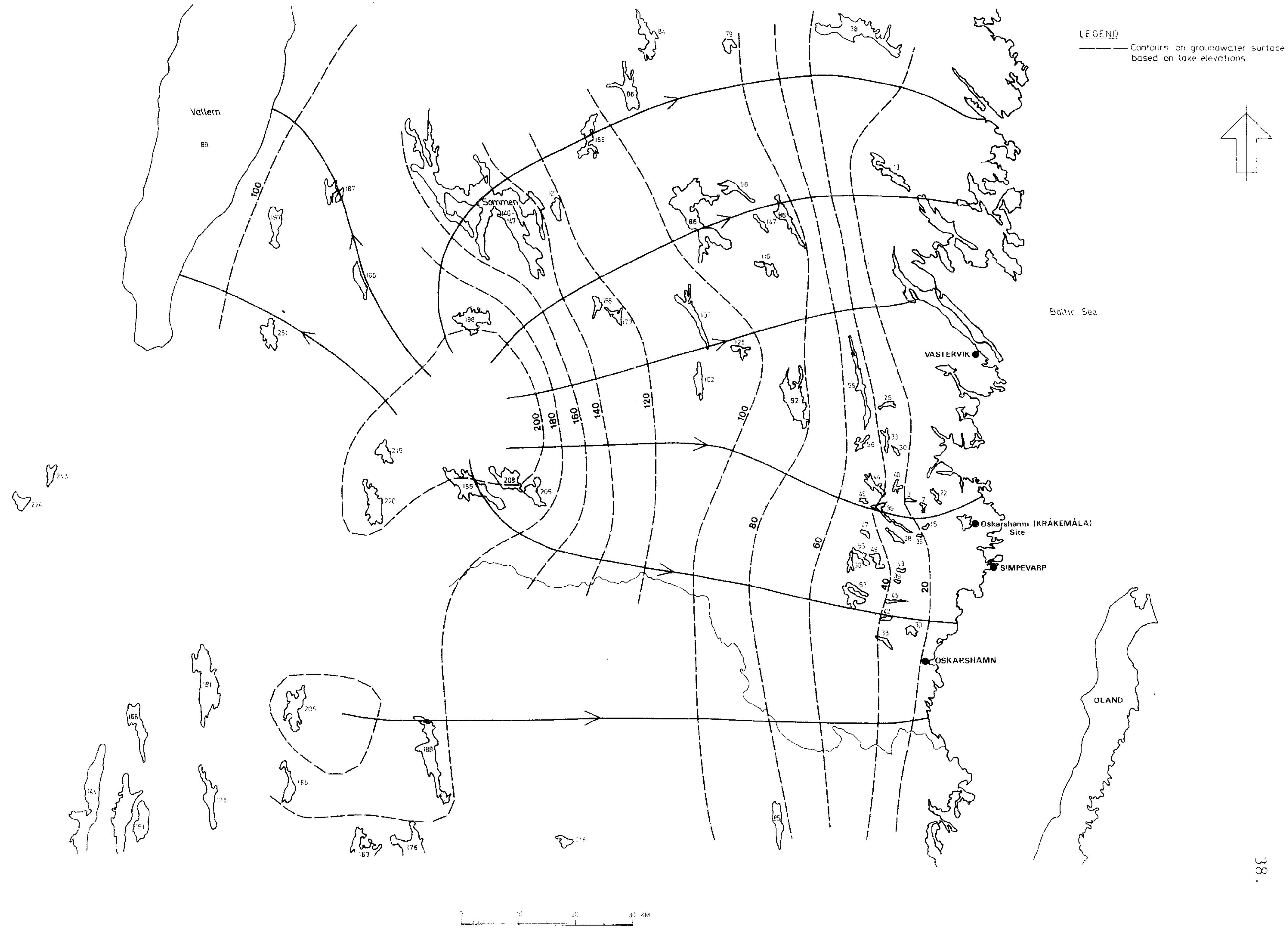


FIGURE 9. REGIONAL POTENTIALS, OSKARSHAMN

4.4 Results of Analysis

4.4.1 Regional models

The flow models used were described in section 4.3.3. The equipotentials were found to be essentially vertical for each of the permeability and porosity distributions. Thus the regional gradient at depth may be expected to be approximately equal to the surface gradient. The resulting flow vectors are shown in Figure 10.

The flow velocities decrease to approximately zero offshore for all permeability and porosity distributions.

Comparisions between the isotropic homogeneous case and the non-homogeneous cases at Oskarshamn (Figure 10) suggest that what might be called a relatively "quiescent zone" can be expected to exist if the permeability and porosity decrease with depth to approximately the degree assumed. The necessary conditions for the existence of this "quiescent zone" were studied with the other models, as described below.

4.4.2 Local topography and discontinuity models

Flow models for these analyses were presented in section 4.3.4. The results of the analysis with isotropic homogeneous and anisotropic non-homogeneous permeabilities for both zero flux and fixed potential boundary conditions for the topography model are shown in Figure 11.

It can be seen the flow paths and magnitudes are strongly effected by the inhomogeneity in permeability. It is concluded that these reductions in permeability and porosity with depth preserve the "quiescent zone" even when fairly large local topographic variations occur.

The two boundary conditions discussed above are the expected extremes and the actual condition should lie between them. The flow patterns are essentially independent of these conditions and the velocity magnitudes vary by a factor of 2 between these cases.

The results of the analysis with the discontinuity model are shown in Figure 12 for various fracture permeabilities, orièntation, and intact rock properties. In the case where the discontinuity dips toward the flow it can be seen that there is a tendency for the flow to increase and be diverted up the discontinuity.

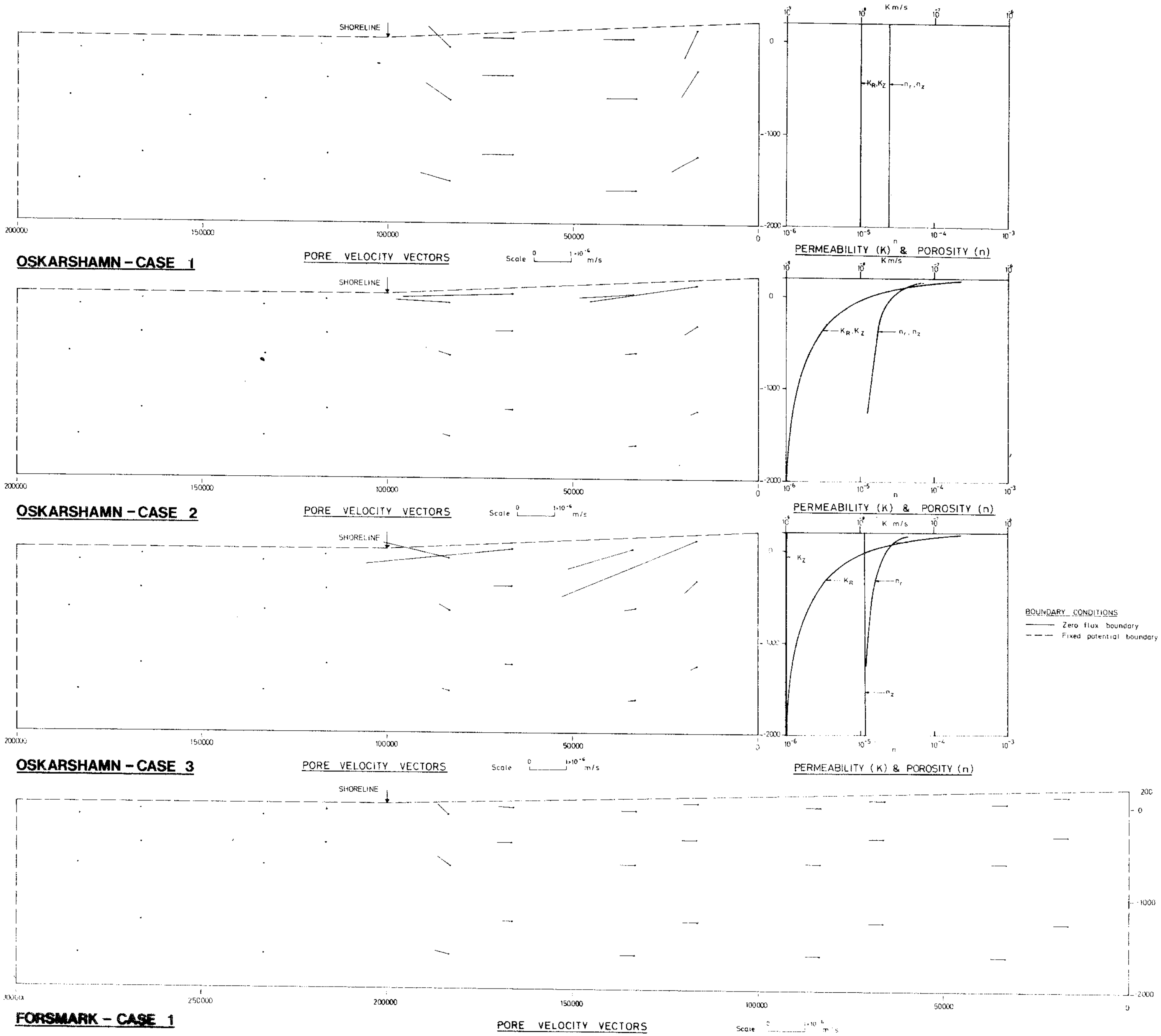
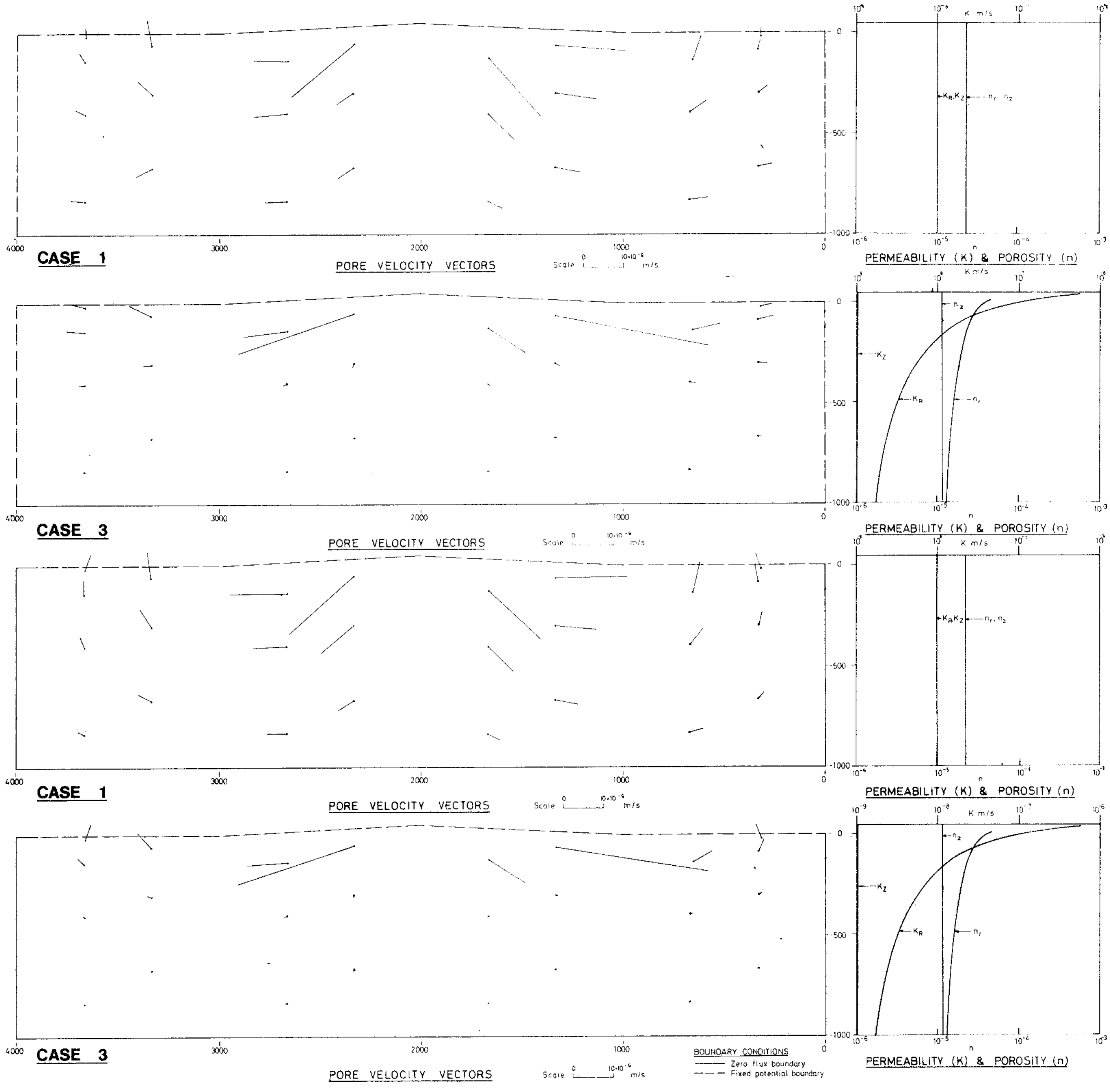


FIGURE 10. REGIONAL MODELS



FIRURE 11. TOPOGRAPHY EFFECTS

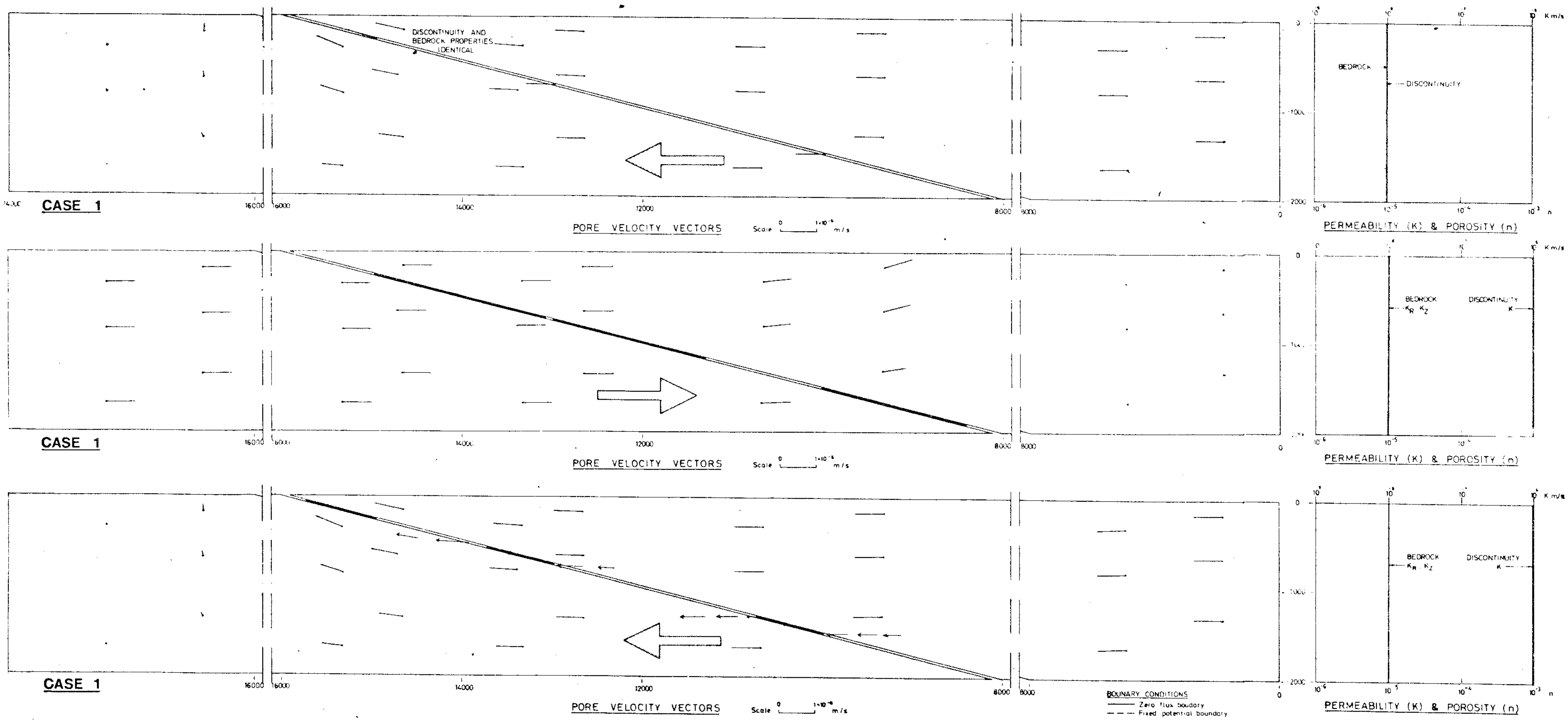


FIGURE 12. DISCONTINUITY EFFECTS

The flow magnitudes are strongly dependent on the relative permeabilities and porosities. However, the flow will exit from the fracture back into the "intact" rock at some distance above the entry point, although containment transport may persist up to the fracture due to dispersion (mixing). The opposite conclusions may be drawn when the discontinuity dips with the flow.

In the case when permeability and porosity decrease with depth, the concept of the "quiescent zone" can be seen to be preserved when a fracture is present although a small vertical shift will still occur at depth.

Since the equipotentials are almost vertical, it can be concluded without further analysis that vertical discontinuities would not disturb the flow paths and the existence of a "quiescent zone". However, dispersion may be present vertically.

4.4.3 Site models: Forsmark

The flow model for these analyses was described in section 4.3.5. The objective of these analyses was to study flow patterns at this candidate site in the intact rock zone into which a repository may be placed. The side boundary conditions will approximately simulate the effect of the neighbouring discontinuity on the intact rock. The flow behaviour in these discontinuities was not studied.

Figure 13 shows the computed flow velocity vectors for the three standard permeability and porosity profiles for the two extreme boundary condition cases. The groundwater surface was assumed coincident with the ground surface. The average cross site gradient was estimated to be 2×10^{-3} using the surface elevations at the Finnsjön and Gåvestbo features.

It can be seen that the flow pathways are down in the centre, with surface recharge, and out into the neighbouring faults with a slight preference for flow in the direction of the regional gradient.

The depth of penetration varies with the boundary conditions and property profiles. A "quiescent zone" can be expected in the anisotropic, non-homogeneous case for both of the boundry condition cases. However, in the case of the isotropic non-homogeneous properties with the no-flux boundary conditions, a "quiescent zone" does not occur in this model. In the isotropic, homogeneous case the no-flux

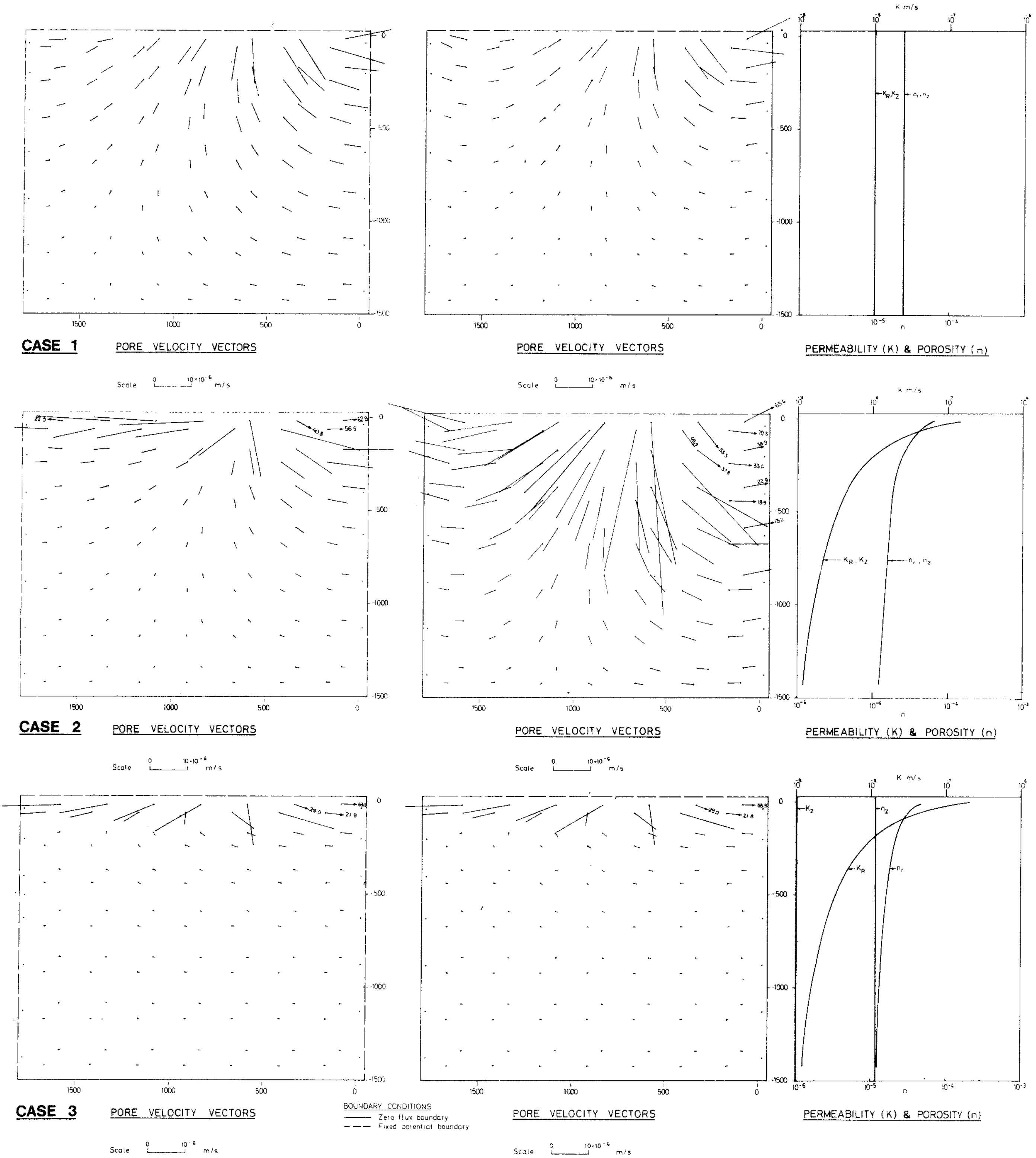


FIGURE 13. FORSMARK - REPOSITORY SITE MODELS

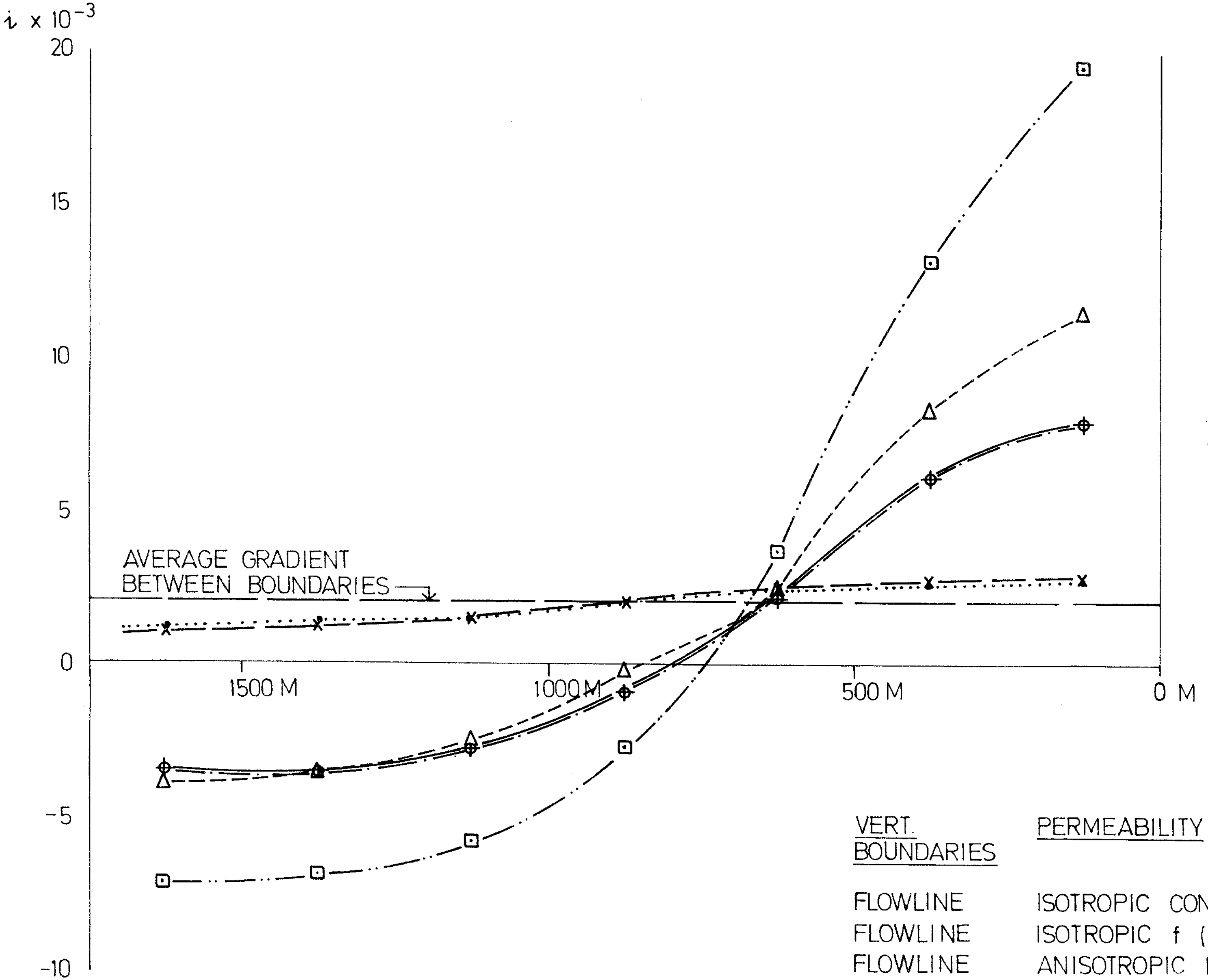
conditions give appreciable flows at the repository level. The potential gradient distributions at the repository level for these cases are summarized in Figure 14. where the same phenomena can be seen.

4.5 Summary and Conclusions

The equipotentials in the regional model were shown to be almost vertical, allowing use of local models with simple boundary conditions.

There is a good possibility that a "quiescent zone" will exist at the repository depth. This was shown in all levels of modelling, even with significant local topographical variations and discontinuities, provided that the horizontal permeability decreases considerably with depth.

The effect of material property profiles is strong. Particularly, the assumed anisotropic case, which includes a significant reduction in horizontal permeability with depth, has a strong tendency to develop a "quiescent zone" at depth.



VERT. BOUNDARIES	PERMEABILITY	CASE No	SYMBOL
FLOWLINE	ISOTROPIC CONSTANT	1	——o——
FLOWLINE	ISOTROPIC f (z)	2	—·+—·
FLOWLINE	ANISOTROPIC K_R=f (z)	3	······•·····
CONST. POTL	ISOTROPIC CONSTANT	1	——Δ——
CONST. POTL.	ISOTROPIC f (z)	2	—··□—··
CONST POTL	ANISOTROPIC K_R=f (z)	3	——x——

FIGURE 14. FORSMARK SITE MODEL HORIZONTAL POTENTIAL GRADIENTS AT ELEVATION - 500 M.

5. REPOSITORY CONSTRUCTION EFFECTS

5.1. Objectives

The repository construction will involve preparation of the underground facilities for waste emplacement and subsequent sealing. In particular, this would include shaft sinking, and the excavation of shaft station, haulageways, ventilation drifts, and storage rooms. These mining activities will give rise to perturbations in the in situ states of stress and groundwater flow in the domain of the repository facility.

The objectives of this chapter are to present an evaluation of:

(1) the stress perturbations and potential rock failure around the storage rooms and in the general domain of the repository facility;
(2) the local and global changes in rock mass permeabilities due to construction.
(3) the perturbation of the groundwater flow regime and the corresponding flow of water into the facility.

The perturbation to the regional groundwater flow is caused by the performance of the excavation as a water sink, and by the local and global changes in rock mass permeability. The permeability changes arise from stress perturbations due to excavation of the facility in an initially-stressed rock mass. The stress perturbations induced by water flow within the porous medium are assumed to be comparatively negligible. Water inflow into the facility will be removed by pumping and ventilation which may also cause some drying of the peripheral regions of the excavations.

5.2 Methodology of the Rock Mechanics Analysis

In this rock mechanics analysis, we modelled the mechanical state of the rock mass surrounding a storage tunnel as a consequence of excavation, prior to the emplacement of the heat-generating radioactive waste. Quantification of the zones of potential rock failure around the tunnels, and the corresponding rock permeability changes, due to construction are of particular interest.

The rock mass is assumed to be elastic-plastic and to contain orthogonal joint planes (or planes of weakness). The failure of the intact rock is characterized by the linear Mohr-Coulomb criterion, with joint failure also governed by a condition of the Mohr-Coulomb type. For both the intact rock and the joints, any strength failure is followed by an assignment of residual strength to the region of failure. Numerical values for the elastic and strength properties are given in Section 3.3 (F). The permeability-normal stress relation is discussed in Sections 2.3 and 3.3 (F)..

The two-dimensional, plane strain finite element model consists of one half of a room and one half of a pillar, as illustrated in Figure 4. This geometrical configuration is representative of a typical single room, or tunnel, with adjacent pillars situated within an infinite sequence of tunnels and pillars. The in situ vertical stress is taken to be equal to the weight of the overburden, with the in situ horizontal stress being twice the vertical stress. The influence of two joint orientations, namely 0 and 90^o, and -45^o and $+45^o$ from the vertical, on the mechanical behaviour of the rock mass during tunnel excavation has been analyzed.

The modelling procedure, using elastic, strength, and permeability properties of the intact, jointed, and failed rock, is based on available laboratory data for granitic materials, as described in Sections 2 and 3.3. The stress perturbations and regions of strength failure, which occur in the rock as a consequence of excavation, are obtained by negating the normal and tangential shear stresses which existed along the tunnel periphery prior to excavation. By means of an iteration process, the stress states that violate the failure condition are progressively transferred to adjacent regions of the rock mass which have not experienced failure, until a state of equilibrium is achieved.

5.3 Results of the Rock Mechanics Analysis

Figure 15 illustrates the regions of potential failure in the rock around a storage tunnel prior to waste emplacement, for the two joint plane orientations. In both instances, the regions of potential failure are separated and localized along the periphery of the tunnel cross section. The depth of penetration of any of the failed zones into the rock mass does not exceed approximately 1m.

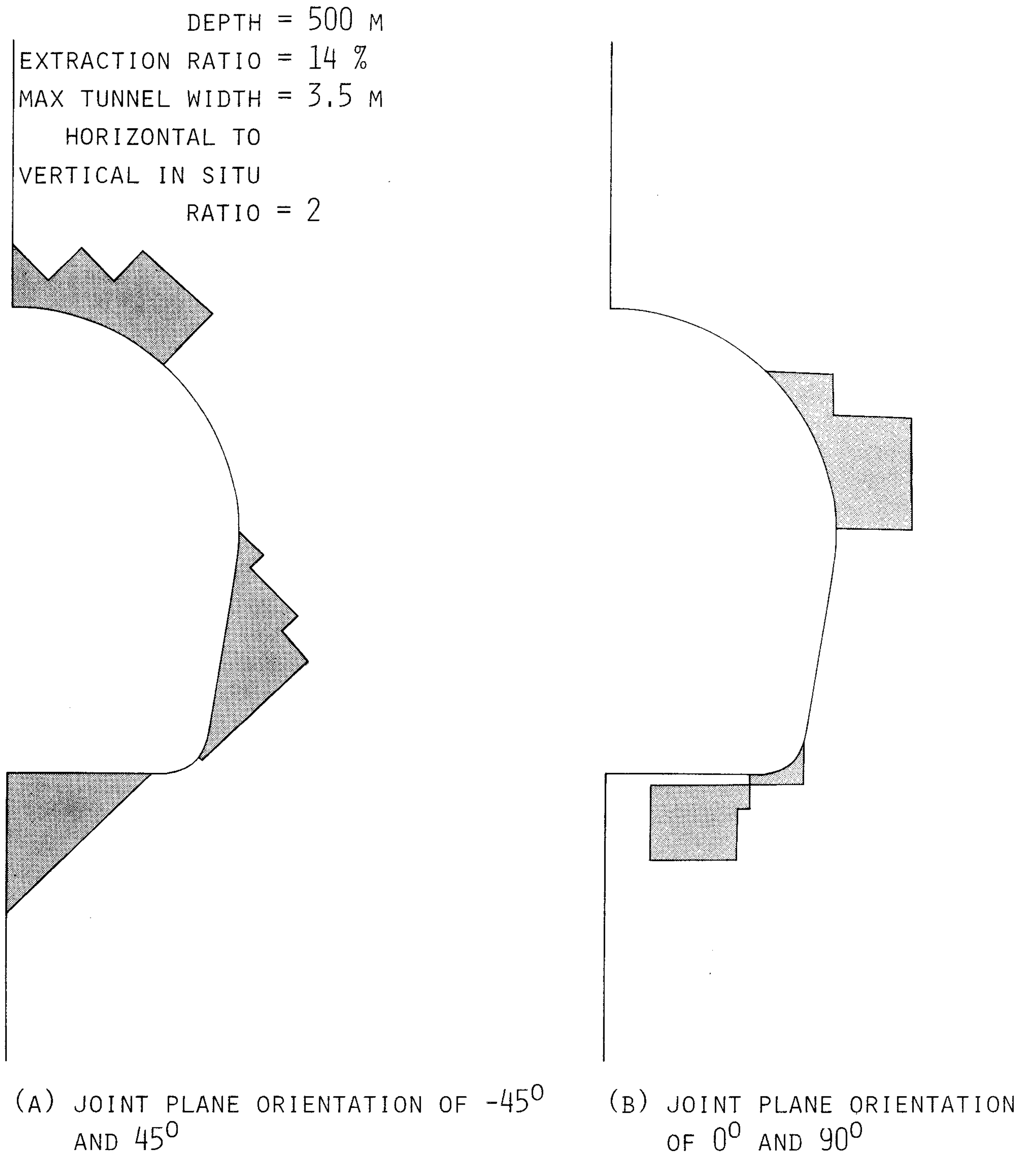


FIGURE 15. FAILED REGIONS AROUND A STORAGE TUNNEL PRIOR TO WASTE EMPLACEMENT.

The joint plane orientation does, however, influence both the location and extent of the regions of potential failure. For a joint plane orientation of $0/90^{\circ}$ from the vertical, localized failure zones develop in the springline and floor-rib intersection regions of the tunnel. On the other hand, for a joint plane orientation of $-45^{\circ}/45^{\circ}$, localized failure zones appear in the crown, lower rib, and floor of the tunnel. It must be noted that these failed regions are strictly due to joint plane failure, as failure of the intact rock itself was not observed in the simulations. Additionally, the joint planes are assumed to have some residual cohesion after failure has occured. Hence, it would appear that rock bolting may be required in the roof and lower rib of tunnels situated in rock with inclined joint planes, in order to minimize the potential for roof falls and pillar slabbing.

Figure 16 illustrates the permeability changes in a rock mass with $0/90^{\circ}$ joint planes around a storage tunnel as a consequence of excavation. The most dramatic changes occur in the horizontal component of permeability in the roof and floor, involving increases above the in situ value by several orders of magnitude. On the other hand, the vertical component of permeability is slightly decreased in the roof and floor, but significantly increased by several orders of magnitude in the rib. However, the extent of the zone of significant change is restricted to 1 m or less from the periphery of the opening. These permeability perturbations are due primarily to the imposed tangential stress field around the tunnel opening. In effect, the results indicate that only a relatively thin shell of highly permeable rock with a thickness of the order of 30% of the tunnel diameter, exist around the excavated opening.

In summary, we may conclude that the zones of potential rock failure and significant permeability change around the storage tunnels after construction will be relatively localized, of the order of 1 m. This i based on a repository depth of 500 m and an extraction ratio of 14%.

5.4 Inflow Modelling Methodology

Analyses of inflow into the repository were made in order to asses flow rates and inflow periods. Precipitation and infiltration were shown to be generally sufficient to prevent drawdown of the water table and therefore steady state analyses were appropriate. An equivalent porous media model assuming saturated conditions was used.

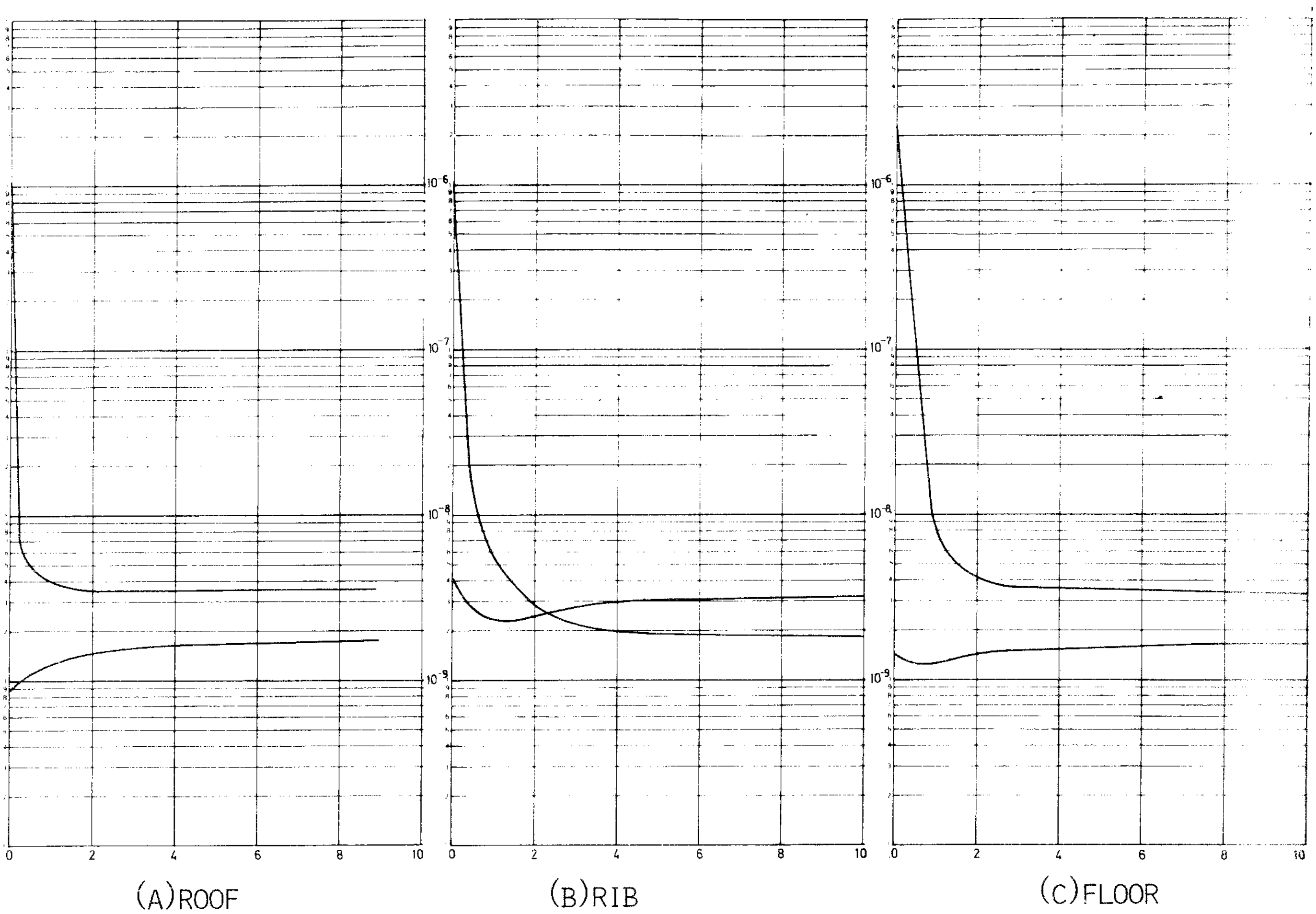


FIGURE 16. PERMEABILITY CHANGES AS A FUNCTION OF DISTANCE INTO THE ROCK MASS AROUND A STORAGE TUNNEL PRIOR TO EMPLACEMENT.

The three nominal permeability distributions presented in Chapter 2, plus two additional stress dependent distributions based on the stress/permeability relationship given in Chapter 3, were used. The analyses were based on rooms without backfill and considered both free inflow and the effect of back-pressure due to trapped air.

Global and local two-dimensional vertical section models were used to allow sufficiently remote boundaries and local detail to be included where necessary.

The inflow was assumed to be independent of regional flows since the inflow velocities were 1000 times larger than the regional cross flows.

The reliability of inflow rates is directly dependent on the in situ permeability estimates which are quite uncertain at this time. The inflow rate predictions were compared with previous mine inflow measurements.

5.5 Results of Inflow Analysis

The inflow rates and related infilling periods are given in Table 1 for the various permeability distribution cases analyzed.

Case	Permeability	K_z at 500m (m/s)	Inflow Rate (ℓ/min, km)	Inflow Period (gears)
1	Isotropic Homogeneous	$1.0.10^{-8}$	28.8	0.64
2	Isotropic Non-homogeneous	$3.7.10^{-9}$	18.0	1.02
3	Anisotropic Non-Homogeneous	$1.0.10^{-9}$	4.17	4.39
4	Initial Stress State	$1.7.10^{-9}$	6.28	3.17
5	Post construction Stress State	$1.7.10^{-9}$	6.34	3.14

Table 1 Computed Inflow Rates and Periods.

A plot of the inflow velocities for Case 1 permeability distribution is shown in Figure 17. Velocities above the center of the repository were found to be essentially vertical and approximately 50% less than those at the outer limits of the repository. The inflow rates can be seen to be strongly correlated with vertical permeability at the repository level, K_Z, for all cases.

Comparison of the inflow rates for cases 4 and 5 shows that the construction stresses have only a very small effect on total inflow.

The effect of back pressure in the repository was analyzed and the results for the permeability Case 1 are shown in Figure 18. The decrease in room void fraction (air space) and inflow fluxes are shown as a function of time. Results of Cases 2 and 3 are similar and may be obtained by multiplying the time scale by factors of 1.6 and 6.9, respectively. The filling curves are essentially the same for Cases 1, 2 and 3. The pressurized flux curve shows that the flux reduces to 1% of the free flux one year after the free filling time. The relatively minor nature of the back pressure effect is due to the fact that the recharge pressure is approximately 50 atmospheres under 500 m of water.

The inflow rates computed in this study were compared with the results of the survey of inflows into mines in the Canadian Precambrian Shield by Raven and Gale (11). The relevant results of the survey are summarized in Table 2. The fluxes were converted to litres per minute per kilometer length of room ℓ/min, km. It can be seen that the estimated inflow rates into the repository are in the range 4.17 to 28.8 ℓ/min, km while the mine data are in the range 0 to 3 ℓ/min, km. These results suggest that the computed inflow estimates may be high by a factor of 10, thus implying that the vertical permeabilities may be high by the same factor. However, reliable estimates of inflow periods must await further field permeability data.

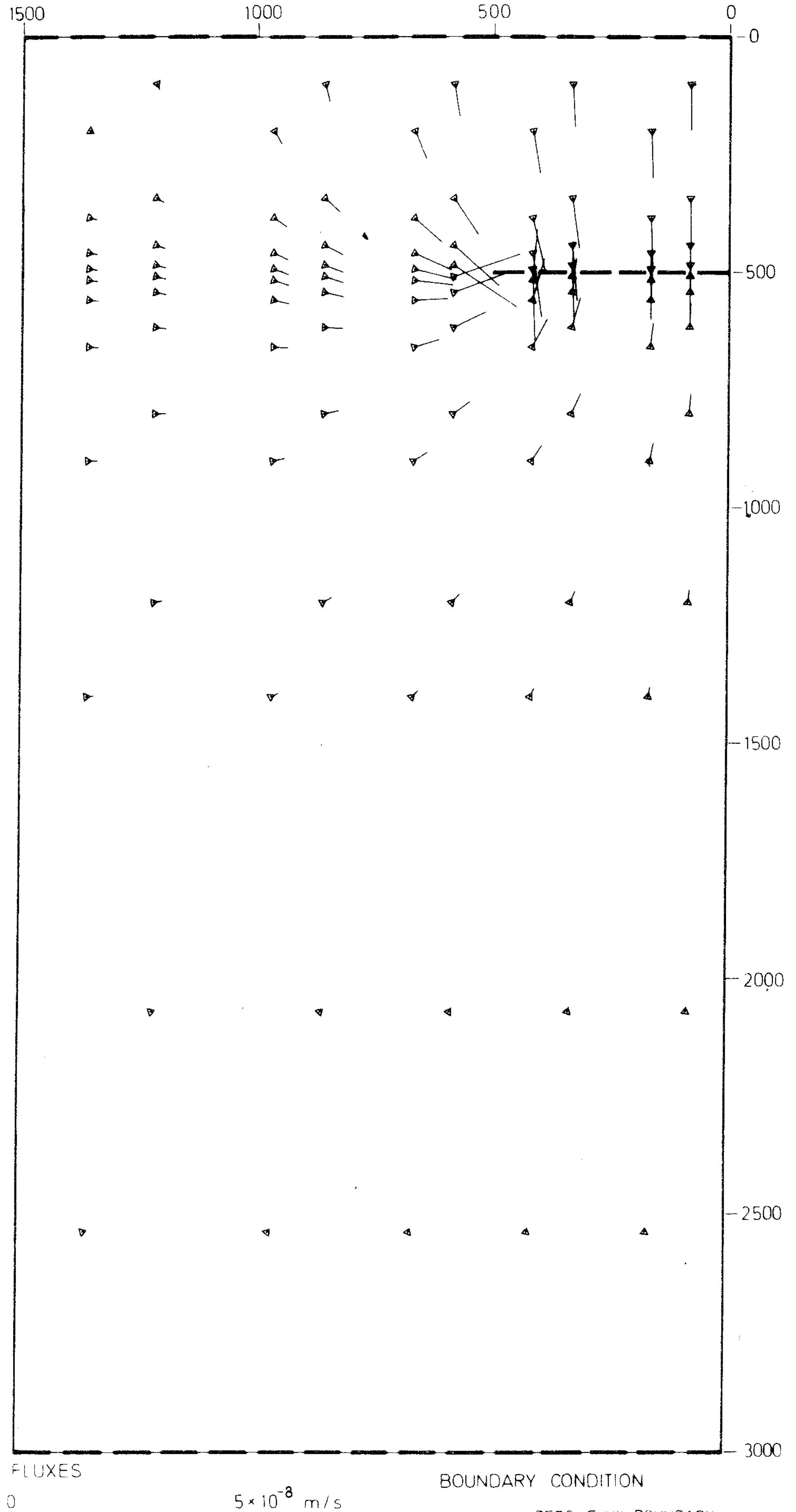


FIGURE 17. CASE 1 FLUX PATTERNS

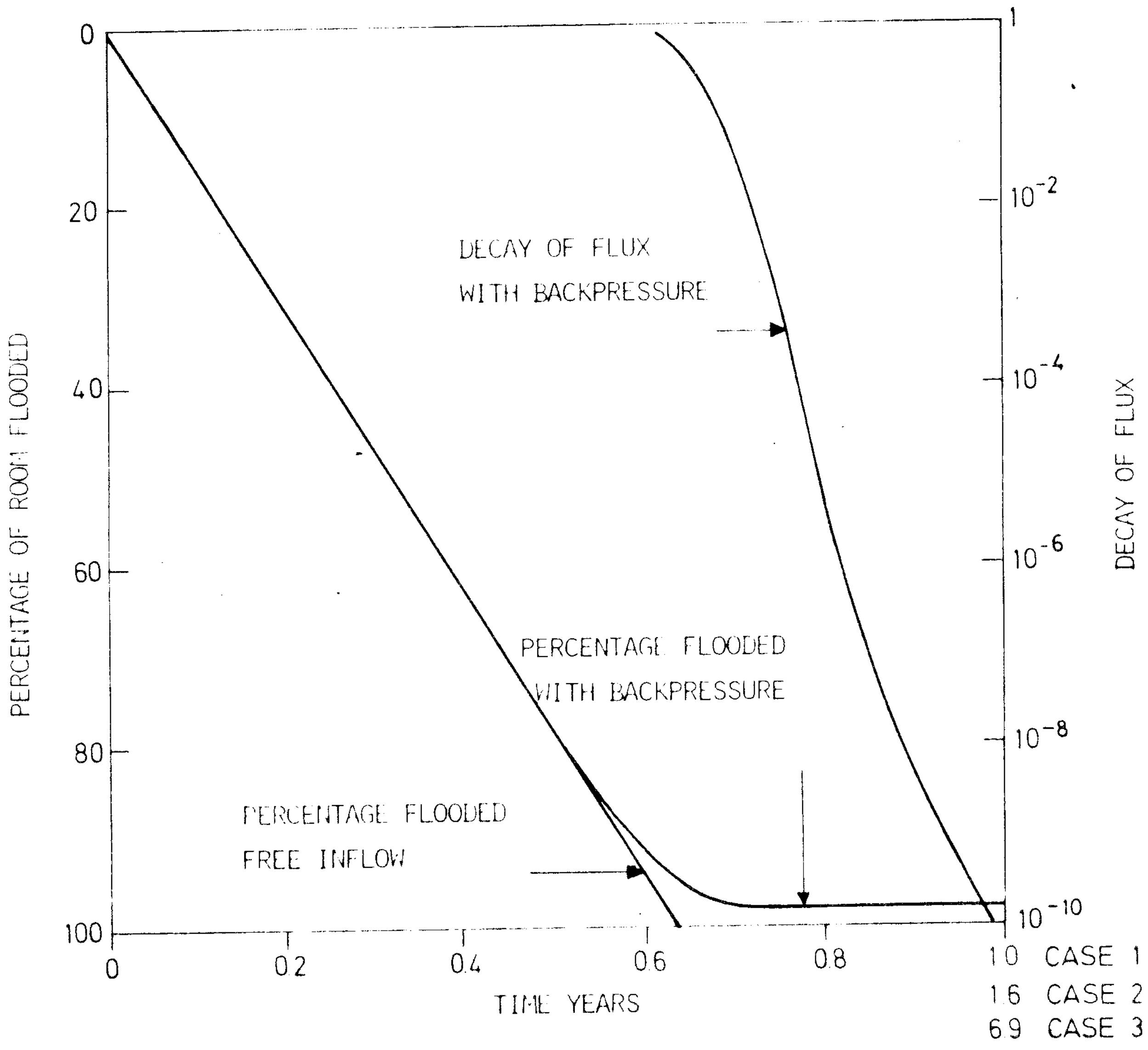


FIGURE 18. EFFECT OF BACKPRESSURE ON INFLOW

TABLE 2. ESTIMATES OF SEEPAGE WATER PUMPED FROM MINES (11).

MINE & DATE OF SHAFT SINKING	DOMINATE ROCK TYPE(S)	SEEPAGE PUMPED 1/min	PERIOD OF PUMPING	DEPTH OF LEVELS PUMPED m	SEEPAGE PUMPED PER KM OF LATERAL DEVELOPMENT 1/min,km	MAXIMUM DEPTH OF VISIBLE CONTINUOUS SEEPAGE m
Macassa (1917)	Augito Syenite	115	1971	150-2100	1.5	>915
North (1955)	Norite	3	1975	777-1200	0.2	>1150
New Quirke (1955)	Meta Conglo- merate Quartzite	0	1975	260-683	0	520
Strathcona (1964)	Granite Gneiss Norite	0	1975	365-915	0	365
Millenbach (1969)	Andesite, Quartz Feld- spar Porphyry	45	1975	716-1224	3.0	355
Langmuir (1971)	Meta Volcanic	6	Oct 1975	154-378	0.6	>378
East Malartic	Greywacke	0	1975		0	
No.5 shaft (1969)	Syenite	680	April-May 1975	1160-1475	61.5	<1160

6. THERMAL PERTURBATIONS

6.1 Objectives and Scope of Studies

The heat generated by the waste is transferred to the host rock by a combination of conduction and advective heat transfer. Most of the heat generation is caused by the fission products which decay to a small percentage of their activity after 1000 years. The resulting temperature cycles have various effects on the groundwater system.

The temperature fields result in stress perturbations which affect the repository structural stability and the local rock permeabiltiy.

Thermally induced flow effects will also be introduced by thermal expansion of the water and bouyant convection forces. The temperature dependence of the groundwater viscosity will also enhance flows in the repository region

These thermal perturbations will then impact on the regional groundwater flow fields as modified by the repository construction. The inflow and recharge of the groundwater regime will be only slightly affected by the initial thermal effects and will dominate thermally-induced flows in the short term. However, once recharge is complete, the thermally induced flows will remain to interact with the regional flow.

The resulting regional flow after recharge and the thermal cycle will be modified by the residual effects of the repository construction the transient phenomena.

In this chapter we summerize the results of studies of heat transfer, thermal rock mechanics and the thermally induced perturbations to the groundwater system. In addition, we present an assessment of the thermo-mechanical stability of the repository design.

6.2 Heat Transfer Methodology

The transient state transfer of heat from the emplaced waste to the rock mass has been analyzed considering both conduction and advection. The conduction analysis involved the use of both local and global models, with consideration of convective heat transfer at the earth's surface, instantaneous and linear time-wise waste emplacement, and storage room ventilation. In addition, the effects of repository depth, waste age, and thermal conductivity of the rock mass were evaluated.

The advection analysis considered the coupled effect of conduction and forced convection due to regional groundwater flow. Use was made of a global model with linear time-wise waste emplacement and a constant regional groundwater flux.

For both analyses, the gross thermal loading was taken to be 5.25 W/m^2 and the geothermal gradient to be $20^{o}C/km$. In addition, the material properties were assumed to be isotropic and temperature-independent.

An analysis of the advective heat transport due to groundwater inflow into the repository was made using the coupled thermally induced flow model described later in Section 6.6.

6.3 Results of the Heat Transfer Analyses

Evaluation of the local, or near field, temperatures as a consequence of heat conduction involved the use of models that represented one half of a storage room and one half of a pillar, in both plane and axisymmetric geometries. The axisymmetric model located about the centerline of a waste canister was used for temperature estimates in the immediate vicinity of the canister. The plane model was used to predict temperature fields in the pillar area. The plane model geometry assumes that the room-and-pillar configuration is situated within an infinte array or rooms and pillars within the repository.

The temperature histories in the waste canister and surrounding rock mass, including the pillar, are presented in Figure 19 for a repository depth of 500 m, 40 year old PWR reprocessed waste, and a period of 1000 years after waste emplacement.

Room ventilation for thirty years causes the rock to undergo two cycles of heating and cooling. The temperature of the drillhole periphery reaches a maximum of 40°C after 3 years during the first cycle, and a maximum of about 43°C at 40 years during the second cycle. Without ventilation, this temperature would rise to a maximum of 56-62°C after 20 to 23 years. During the ventilation period, the pillar attains an average maximum temperature of about 21°C in 13 years; after ventilation ceases, the pillar temperature rises to approximately 35°C after 90 years. Without ventilation, this temperature would peak at 43°C at 55 years.

The maximum temperature difference between the drillhole periphery and the pillar centerline occurs in about 2 years with ventilation, and in about 4 years without ventilation. After 1000 years, all of the temperatures have fallen to about 31 to 33°C, or approximately 16 to 18°C above the in situ rock mass temperature before waste emplacement.

The previous results have been based on a thermal conductivity of 2.05 W/m-°C for the rock mass. For a thermal conductivity of 3.35 W/m-°C and room ventilation for 30 years, the temperatures near the canister are reduced by about 20 to 28%, and in the pillar by 10 to 14%.

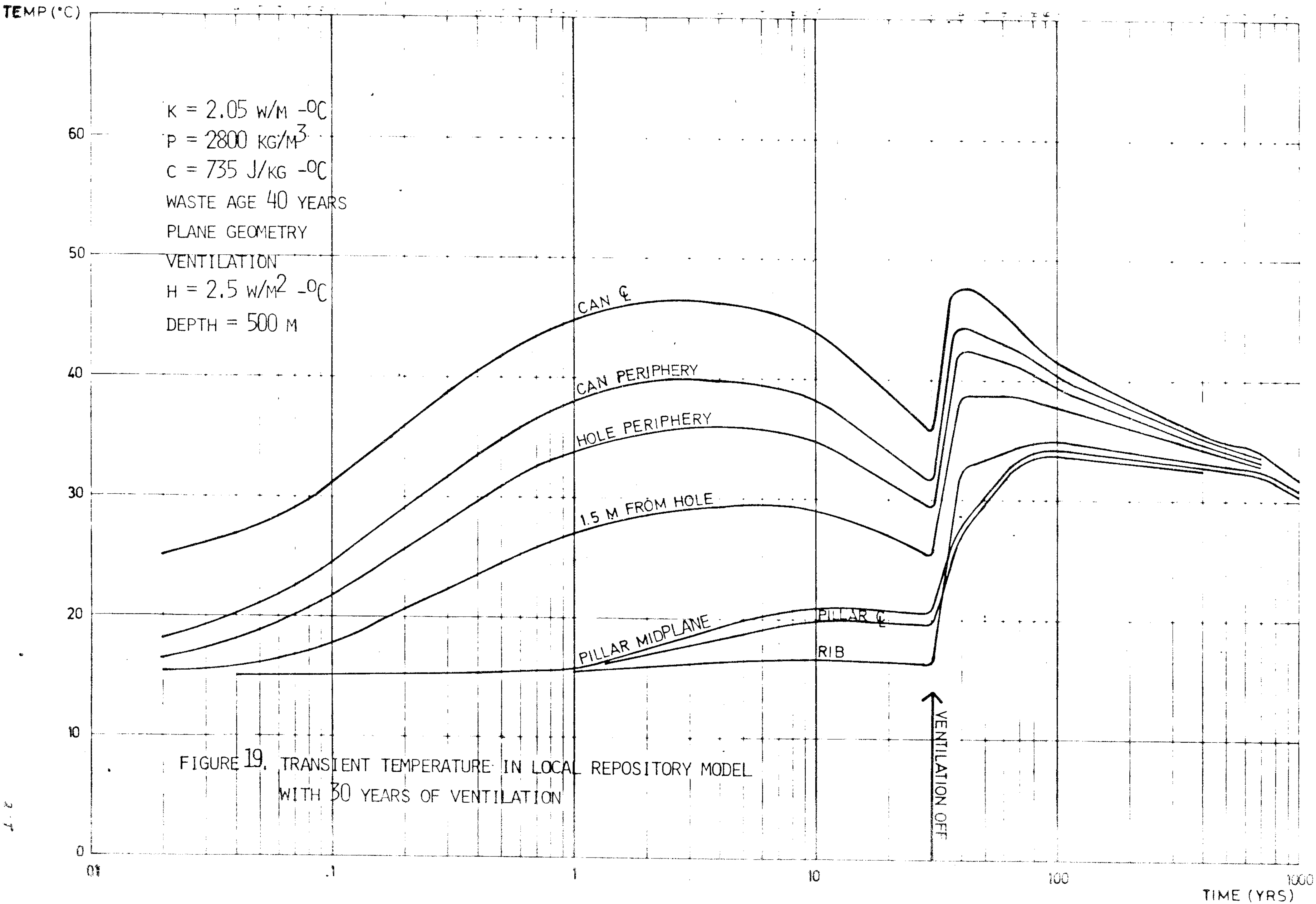


FIGURE 19. TRANSIENT TEMPERATURE IN LOCAL REPOSITORY MODEL WITH 30 YEARS OF VENTILATION

By decreasing the waste age from 40 to 10 years, the temperatures in the rock mass are considerably increased, even with ventilation. In particular, the drillhole perphery reaches a manimum of about 58^{o}C in 3.5 years. These temperatures are 149 % greater than those ocurring for the 40 years old waste. The average temperature of the pillar is also higher, of the orfer of 124 and 137%, during the two heating and coolign cycles,respectively.

The far field temperature distributions resulting from heat transfer by conduction involved models with dimensions of 1.5 to 3 km in the horizontal centerline through an unventilated repository with a depth of 500 m is illustrated in Figure 20 for 10, 100 and 1000 years after instantaneous emplacement. A peak temperature of about 43^{o}C will be attained approximately 60 years after emplacement. After 1000 years, the temperature has decreased to about 32^{o}C, or 17^{o}C above the initial in situ temperature of the rock mass. However, the geothermal temperature profile is perturbed from the surface of the earth to a depth of 1100 m. The transient temperature distributions in the rock mass containing the repository are note influenced by changing the convective boundary condition at the surface of the earth to one of constant temperature.

The transient temperature rises around a repository situated at a depth of 1000 m are nearly identical to those for one situated at a depth of 500 m. For a repository depth of 1000 m, the perturbation of the geothermal temperature field at 1000 years encompasses a depth interval of 250 to 1625 m.

In order to more realistically simulate the sequential emplacement of waste in a repository over a period of 30 years, 40 year old waste was emplaced in a region equivalent to 2 rooms every 1.5 years (linear emplacement). The temperature profiles in the midplane of the repository are illustrated in Figure 21 for time periods ranging from 10 to 1000 years. The horizontal temperature gradients within the repository domain are considerably greater than those for the case of instantaneous waste emplacement, with a gradient reversal after 70 years. Also, the mean temperature differences across the repository are comparatively greater. After about 70 years, the transient temperature distributions in the rock mass for linear emplacement is approximately the same as those for instantaneous emplacement.

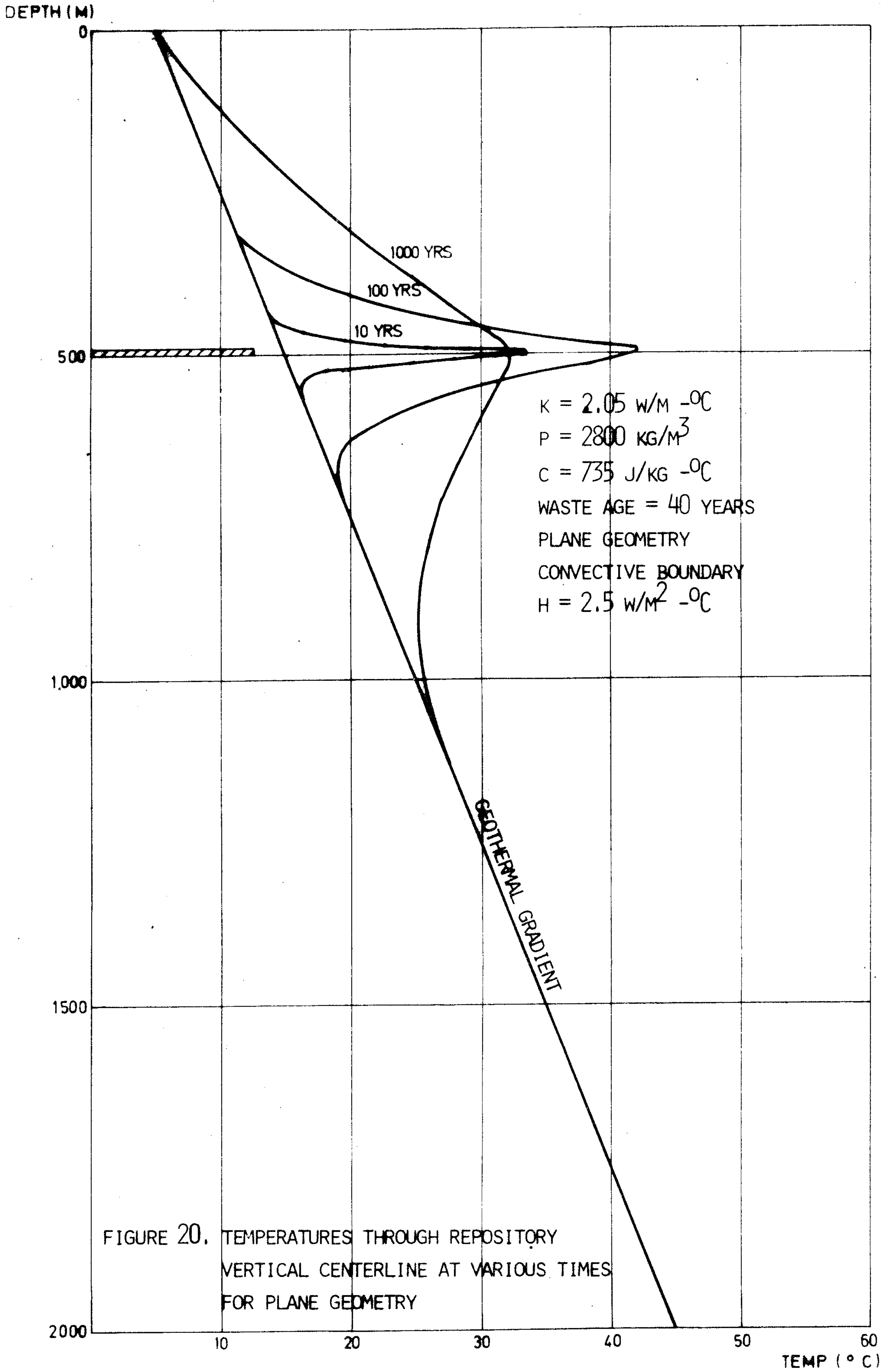


FIGURE 20. TEMPERATURES THROUGH REPOSITORY VERTICAL CENTERLINE AT VARIOUS TIMES FOR PLANE GEOMETRY

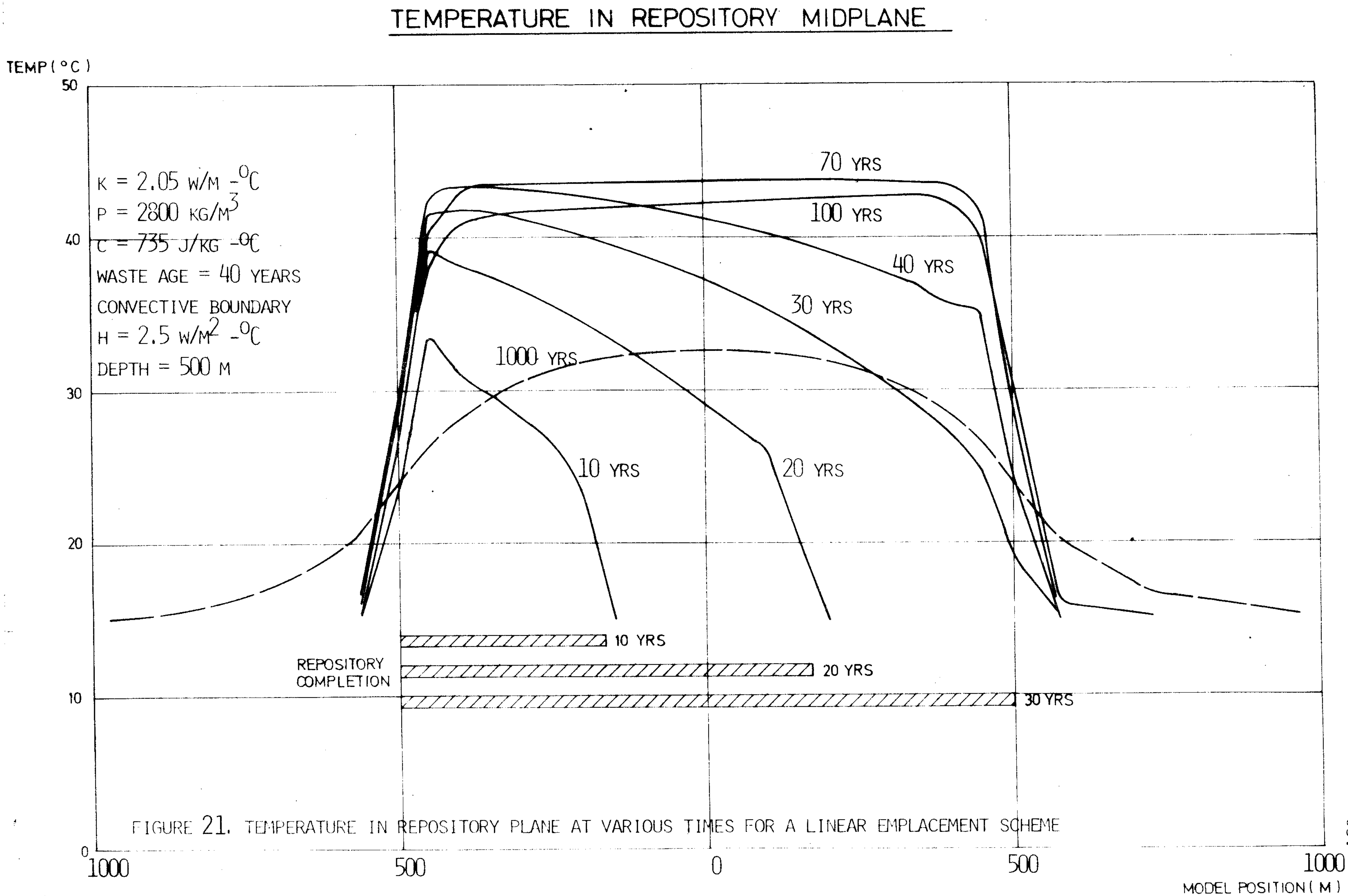


FIGURE 21. TEMPERATURE IN REPOSITORY PLANE AT VARIOUS TIMES FOR A LINEAR EMPLACEMENT SCHEME

In order to assess the influence of regional groundwater flow, i.e. forced convection, on conduction heat transfer, use was made of a global model with linear emplacement of waste over a period of 30 years in a repository situated at a depth of 500 m. Based on analyses of the initial state of groundwater flow, a regional flux (porosity x pore velocity) of 2 x (10^{-11}) m/s was selected on the basis of a rock mass permeability of 10^{-8} m/s and a regional potential gradient of 0.002. For these conditions, the transient temperature history in the domain of the repository was essentially identical to that obtained in the purely conduction heat transfer analysis. In order to quantify the "threshold" regional groundwater flux required for a significant perturbation of the rock mass temperatures, fluxes of 2 x (10^{-10}) and 2 x (10^{-9}) were also employed. As illustrated in Figure 22, the later case produced only 6 to 7^{o} C temperature changes from those obtained previously with purely conduction heat transfer. The only notable feature of increasing the value of the regional groundwater flux was to decrease the time required for the repository domain to return to the initial in situ temperature state; i.e., for each order of magnitude increase in flux, this time was reduced by about 10 000 years.

An assessment of the advective heat transport due to inflow was made using the thermally induced flow program described in Section 6.6. An isotropic homogeneous permeability of 10^{-10} was used which corresponds to an inflow period of 65 years in order that there was a representative overlap between the terminal and inflow periods. It was found that the change in temperature from the 30^{o}C rise predicted by conduction alone at 10 years was 0.1^{o}C. The advective heat transfer effect due to inflow is therefore negligible.

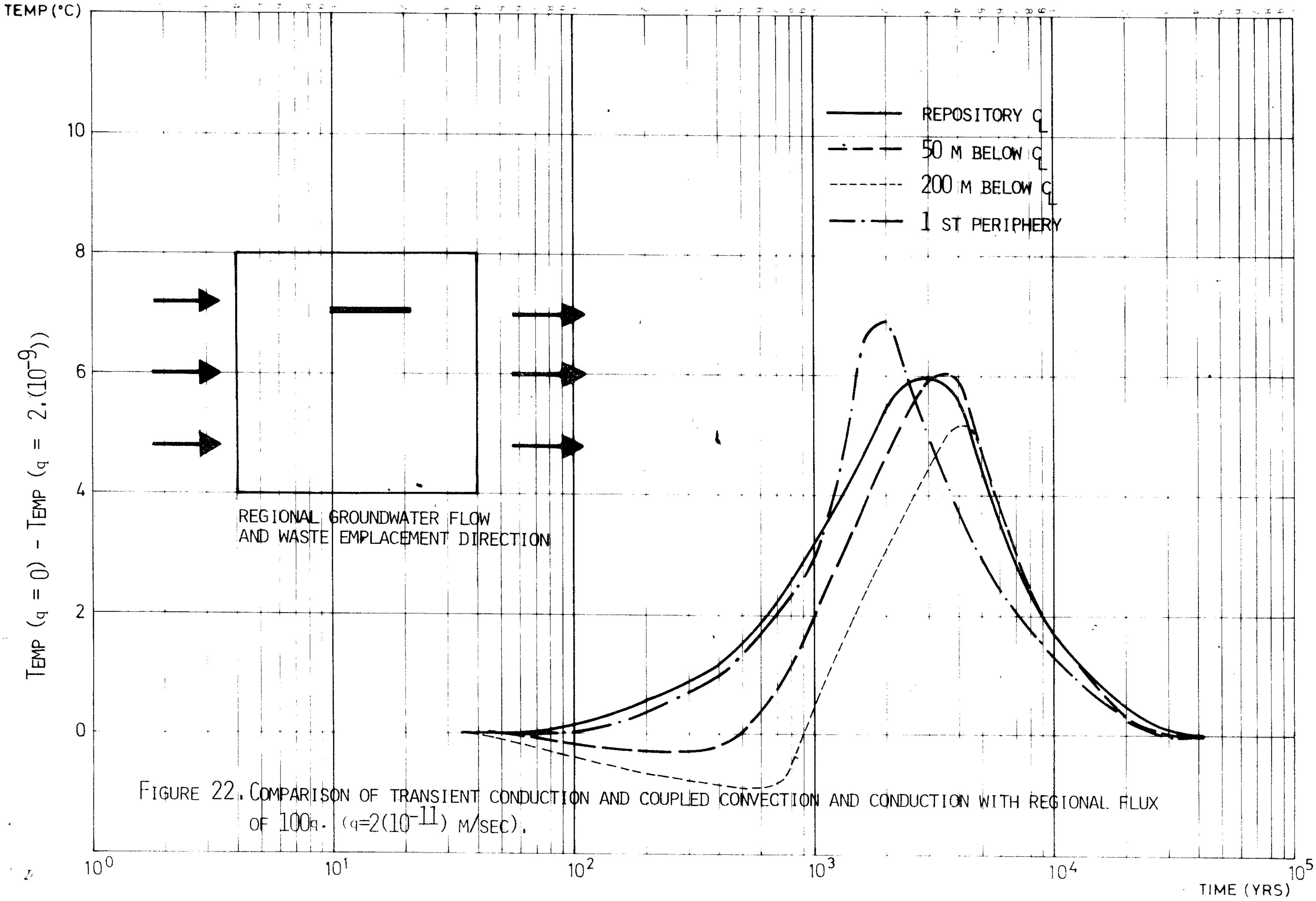


FIGURE 22. COMPARISON OF TRANSIENT CONDUCTION AND COUPLED CONVECTION AND CONDUCTION WITH REGIONAL FLUX OF 100q. ($q=2(10^{-11})$ M/SEC).

6.4 Methodology of the Rock Mechanics Analysis

The rock mechanics analyses has concentrated on an evaluation of the effect of thermal loading on rock failure and permeability change in the repository domain. Use was made of both local and global repository models, involving a representative room and pillar configuration and a vertical section, 3 km wide by 3 km deep, containing the entire repository, respectively. The transient temperature distributions from the heat transfer analysis are utilized as input data for the thermoelastic-plastic and permeability perturbation analyses.

The procedural aspects of the thermoelastic-plastic analysis of the rock behavior are analogous to those described previously in Section 5.2. Assessments of rock failure are made for joint plane orientations of 0 and 90^{o}, and -45^{o} and 45^{o} from the vertical. The material properties are assumed to be both time and temperature independent, with the exception of the groundwater viscosity in the evaluation of permeability perturbation.

In essence, the analysis proceeds from the time of waste emplacement, utilizing the reference stress states developed in Section 5.3 for tunnel excavation. All of the evaluations for the local models assumed that the storage tunnels were not backfilled, with and without ventilation for 30 years after waste emplacement. The global models represented a homogeneous rock mass, in that the excavation geometry for the individual storage tunnels was not included. In all instances the ratio of the horizontal to vertical in situ stresses was assumed to be 2.

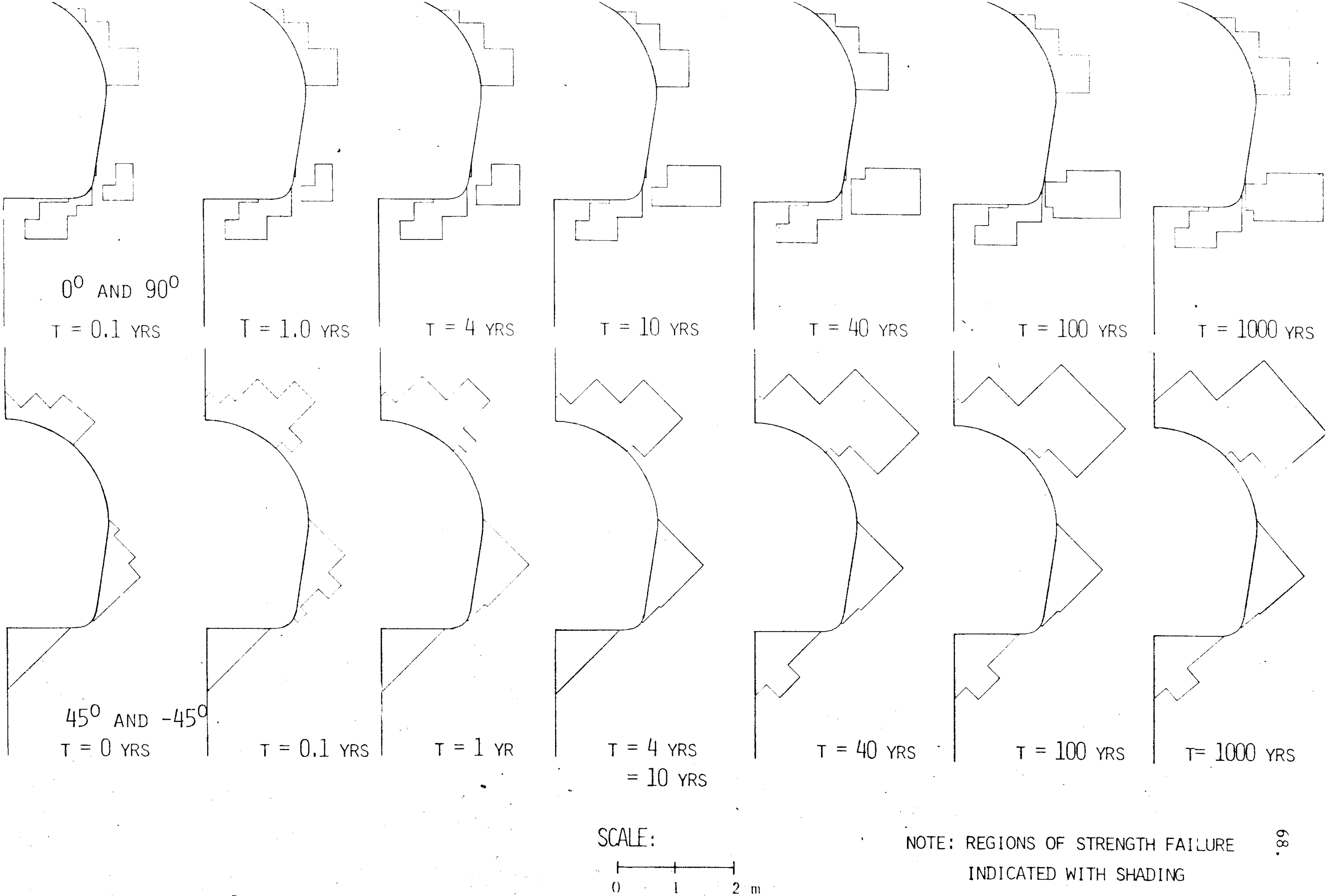
6.5 Results Of The Rock Mechanics Analysis

Figure 23 illustrates the regions of progressive potential failure in the rock around a storage tunnel after emplacement of canisters of heat generating waste in drillholes in the floor. The results for two joint plane orientations, with storage room ventilation, are displayed for time periods up to 1 000 years.

The most striking feature of the progressive growth of potential failure zones around a storage tunnel is the influence of the joint plane orientation. For joint plane orientations of $0/90^{o}$, the progressive growth of failure zones is generally restricted to the region of the rib-floor intersection, predominately in the horizontal direction to a depth of about 1.5 m. For a joint plane orientation of $-45^{o}/45^{o}$, the progressive growth of the failure zone in the crown is relatively extensive, with minor enlargement of the failure zones in the lower rib and central floor. As mentioned previously, the rooms in the repository model are not to be backfilled until 30 years after waste emplacement. Backfilling would probably restrict the growth of the failure zones during the heating and cooling cycle after ventilation shutdown.

It is of particular interest to note that the failure zones in the immediate floor do not grow appreciably downward as a consequence of the thermal loading. The absence of ventilation over the first thirty years of emplacement gives rise to additional, but not significant, failure zone growth, particular in the case of $0/90^{o}$ joint plane orientation. A hypothetical region of influence may be approximately developed around tunnel to encompass the failed zones. The composite cross-sectional area of the influence region and the room would be approximately twice the cross-sectional area of the room.

From the viewpoint of the local permeability perturbations due to thermal loading, the changes in rock permeability due to the thermally-induced stresses are of the order of 10 to 15% at most. These changes are relative to the permeability values after tunnel construction, and are



NOTE: REGIONS OF STRENGTH FAILURE INDICATED WITH SHADING

FIGURE 23. PROGRESSIVE STRENGTH FAILURE DUE TO EXCAVATION AND THERMOMECHANICAL STRESSES

minor compared to the uncertainty in the prediction of initial of in situ permeabilities. The particular joint plane orientation does not appear to appreciably influence the permeability perturbations. As a consequence of the heating of the groundwater, its viscosity is decreased. This decrease may result in a two-fold increase in permeability in the near-field vicinity of an emplaced waste canister.

The thermoelastic/plastic results for the global models indicated the absence of any zones of intact rock or joint plane failure of practical importance in the repository domain. This would be expected due to the extremely localized development of zones of potential failure in the tunnel peripheries. The maximum uplift of the ground surface as a consequence of thermal expansion is only about 7 cm after about 1000 years. This indicates that the global thermomechanical response of the rock mass due to the heat generation from the emplace waste will be essentially elastic and reversible.

Figure 24 illustrates the permeability perturbations in the repository domain due to thermomechanical behavior after 100 years of heat generation. The vertical permeability decreases by about 20% at the level of the repository; the corresponding zone of influence extends from about 50 m above the repository to 100 m below. The deviation of the horizontal permeability from the in situ value at the level of the repository is negligible.

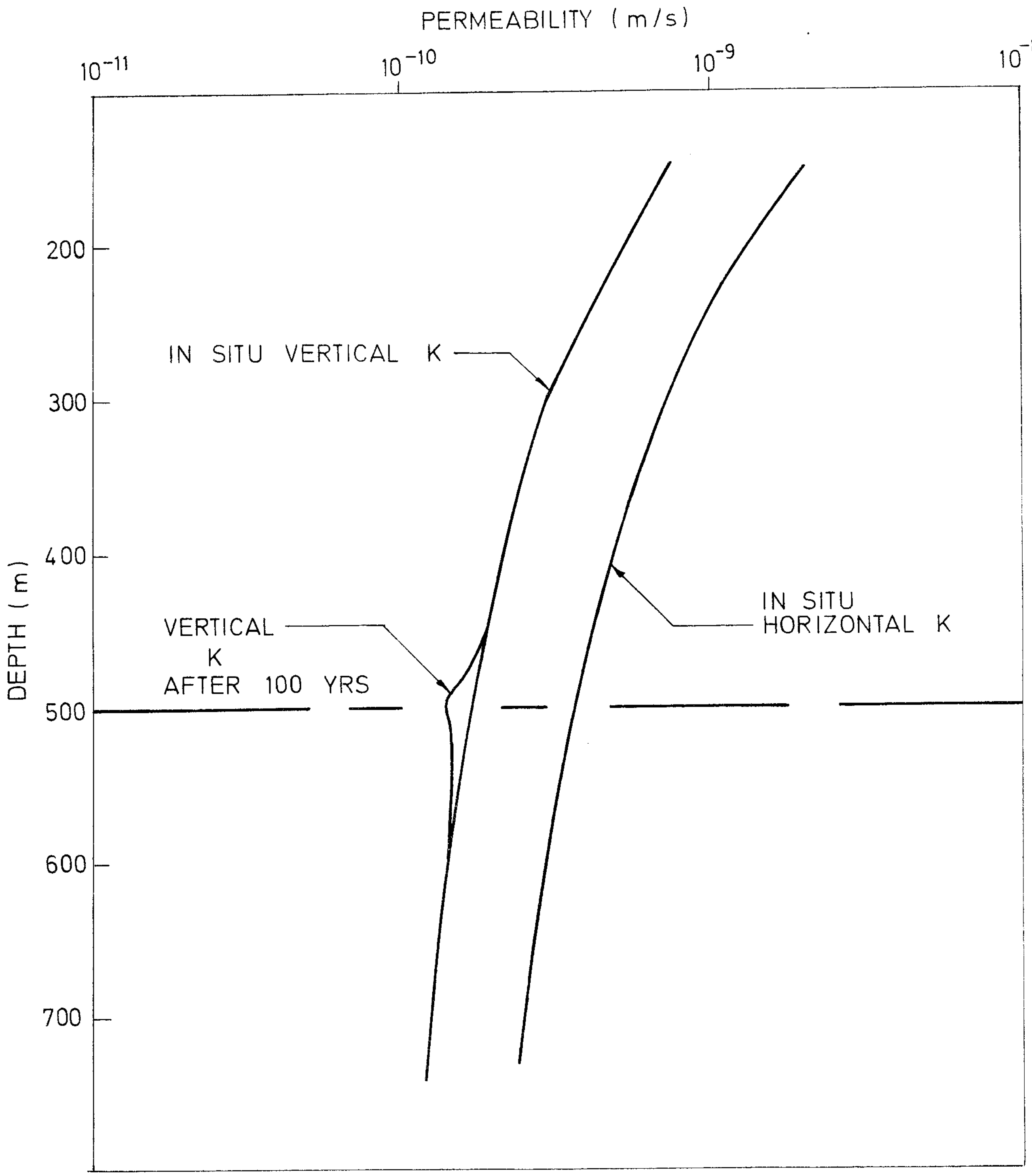


FIGURE 24. PERMEABILITY PERTURBATIONS IN THE REPOSITORY DOMAIN AFTER 100 YEARS OF HEAT GENERATION.

6.6 Thermally Induced Flow Analysis Methodology

The temperature gradients in the groundwater system around the repository will tend to cause free convection currents. The field equations and a numerical analysis procedure are described by Mercer & Pinder (12). This formulation is based on the use of an equivalent anisotropic porous medium in place of the fracture system. The applicability of this assumption depends on the scale of the flow region and the size and spacing of the fracture system. For this initial parametric analysis of the potential for thermally induced flows, the continuum analogy was judged to be adequate.

Thermal convection cells can theoretically develop in a porous media under either vertical or horizontal temperature gradients. The flows associated with a uniform vertical gradient are oscialllatory and can only be initiated above a critical Rayleigh number and are not expected due to geothermal gradients alone (13).

The temperature gradients which are expected around the repository are capable of causing thermal convection flows. These were computed firstly in a static groundwater field to demonstrate the nature of the phenomena and the shape of the cells. Then these flows were combined with the expected regional cross flows and the resulting perturbed flow lines were computed using superposition since the advective effect of regional flows is small.

The analysis also assumed constant parameters. The permeability and porosity values were assumed to be independent of stress and temperature, although it was recognized that these could be subject to variations by a factor of 2 or more. However, until reliable field data are obtained, these nonlinear effects are considered to be relatively unimportant.

6.7 Results of Thermally Induced Flow Analysis.

In order to provide a basis for detailed examinations of the advective heat transfer occurring in the coupled thermally induced flow analysis, an analysis with heat conduction only was made. Subsequent analysis with advection showed that the temperature fields are not sensitive to advection and that for partical purposes the temperature fields presented in section 6.3 are valid outside the rooms. The rooms were considered backfilled with clay in the thermally induced flow analysis.

Thermally induced flow analysis were performed to examine thermal convection cells in a static groundwater system. It was found that cells can theoretically occur at very low horizontal temperature gradients and be initiated at any time. A nested set of pairs fo local cells at each room occurs within a pair of global cells through the entire repository. The velocity vector plot for the nominal anisotropic non-homogeneous permeability distribution (Case 3) at 200 years is shown in Figure 25. In this plot, the model represents a local slice of one half of a room and one of the local cells con be seen. The global model of one half of the repository shows one of the pairs of global cells.

The global cells persist almost indefinitely. Figure 26 shows a plot of the average velocities above the repository as a function of time. It can be seen that the maximum average vertical velocities occur after about 10^3 years and then decay by an order of magnitude after 10^5 years.

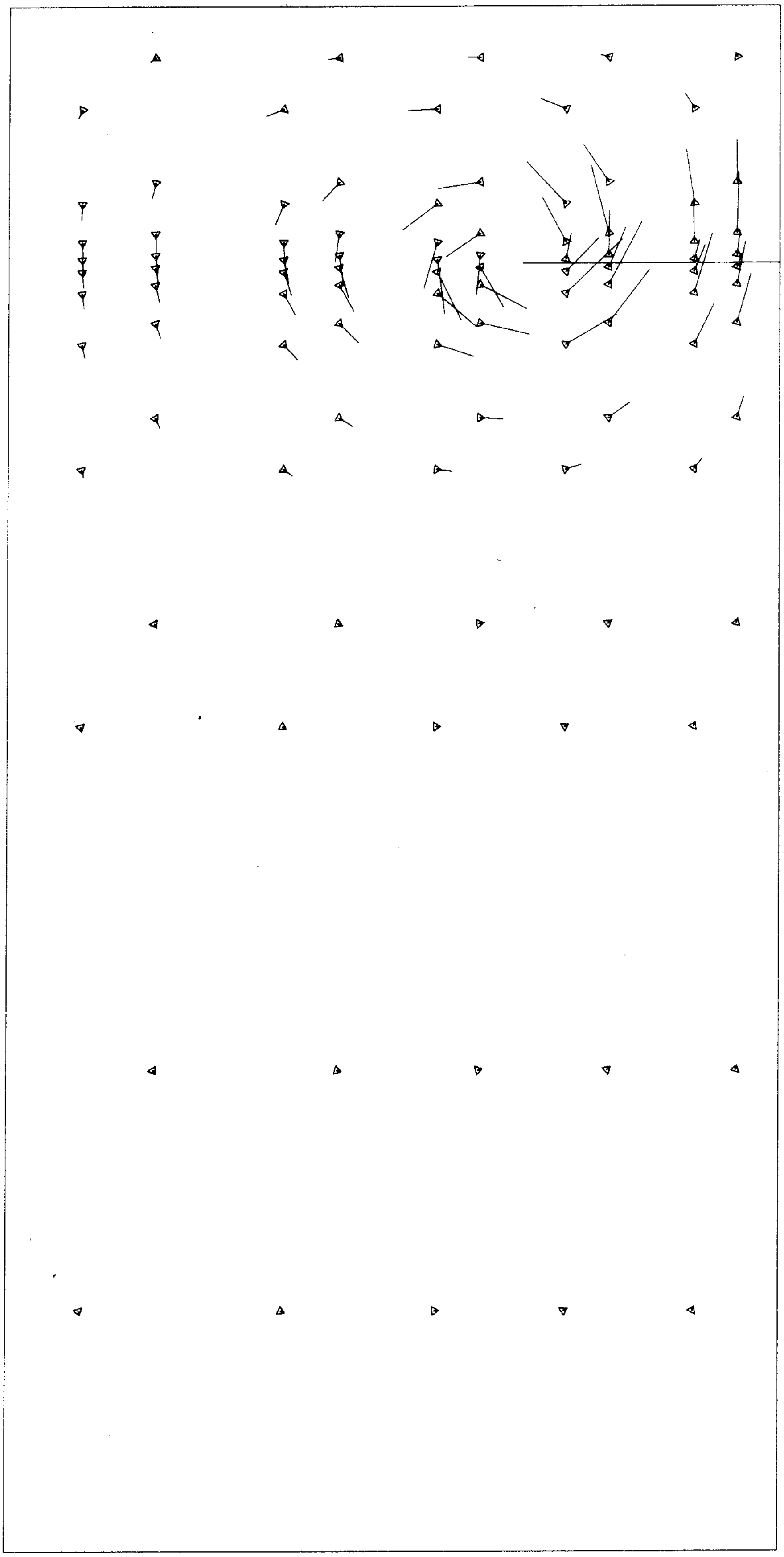
The significant values of velocity predictions for regional, inflow, and pure thermally induced groundwater flows are summarizedin Table 3 for the nominal permeability distributions used in the analysis. The regional flow velocity, V_r, at the repository depth is shown together with the estimated recharge or inflow time t_i, inflow velocity V_i above the rooms, and total inflow Q_i per length of room.

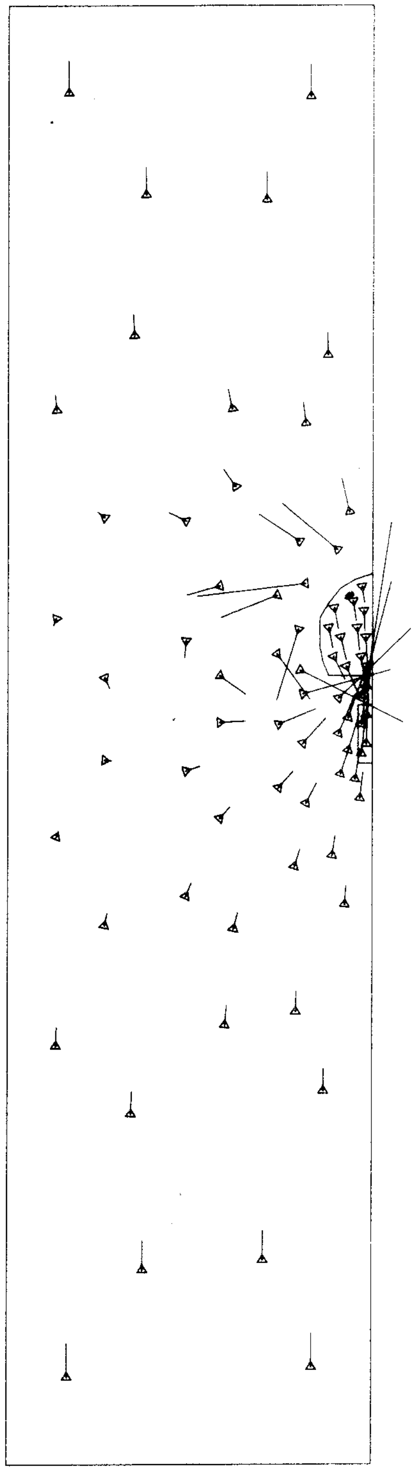
The thermally induced flow velocities v_l due to local cells immediately above the repository are tabulated with global cell velocities v_g above the repository. Also average vertical velocities above the repository $\bar{v}_g$ and corresponding travel times to the surface t_g are shown for various starting times.

The magnitudes of the thermally induced flow velocities are small compared to regional flow velocities and will only appear as minor perturbations. However, in the example of nonhomogeneous anisotropic permeability they correspond to a travel time to the surface of 1000 years starting at time 1000 years, assuming to regional crossflow. For the same fracture spacing, velocities scale approximately to $K^{2/3}$; i.e., a one tenth decrease in permeability decreases the velocity by a factor of 4.6.

TABLE 3 Comparison of Computed Pore Velocities Due to Regional Flow, Inflow and Hydrothermal Flow

	Case 1 Isotropic Homogeneous	Case 2 Isotropic Non-homog.	Case 3 Anisotropic Non.hom.
Properties			
K_R (500m) m/s	$1.\ 10^{-8}$	$3.58.10^{-9}$	$3.68.10^{-9}$
K_Z (500m) m/s	$1.\ 10^{-8}$	$3.68.10^{-9}$	1.10^{-9}
n_R (500m)	$2.48.10^{-5}$	$1.78.10^{-5}$	$1.64.10^{-5}$
n_Z (500m)	$2.48.10^{-5}$	$1.78.10^{-5}$	$1.51.10^{-5}$
Regional Flow			
V_r (500m, i $=2.10^{-3}$) m/s	$0.80.10^{-3}$	$0.41.10^{-3}$	$0.45.10^{-3}$
Inflow			
t_i (recharge, empty room)	0.63	1.02	4.39
t_i (recharge, backfilled)	0.06	0.10	0.44
V_i (10m above room) m/s	$0.49.10^{-3}$	$0.56.10^{-3}$	$1.08.10^{-4}$
Q_i (total inflow) l/min/km	18	15	3
Pure Hydrothermal Flow in a static Groundwater Field			
v_ℓ (roof, t=40) m/s	$1.2.\ 10^{-6}$	x	$0.3.\ 10^{-6}$
v_ℓ (roof, $t=10^3$) m/s	$0.6.\ 10^{-6}$	x	$1.2.\ 10^{-7}$
v (above room, $t=10^2$) m/s	$0.6\ \ 10^{-6}$	x	$1.3.\ 10^{-7}$
v_g (" " , $t=10^3$) m/s	$0.3.\ 10^{-6}$	x	$1.2.\ 10^{-7}$
v_g (" " , $t=10^5$) m/s	$0.5.\ 10^{-7}$	x	$1.2.\ 10^{-8}$
$\bar{v}_g$ (average above rep. $t=10^3$) m/s	$0.8.10^{-7}$	x	$1.6.\ 10^{-8}$
$\bar{v}_g$ (average above rep. $t=10^5$) m/s	$0.8.10^{-8}$	x	$1.6.\ 10^{-9}$
t_g (rise to surface, $t=10^3$) yrs	200	x	2,000
t_g (rise to surface, $t=10^5$) yrs	1000	x	10,000





KBS HYDROTHERMAL RUN GLOBAL 3
K (Z) ANISOTROPIC

LOCAL 3

VELOCITY PLOT

GEOMETRY SCALE 0 — 500 M

VELOCITY SCALE ⊢—⊣ = 0.8 * 10 ** -7 M/SEC

0 5 10 M

200 YEARS

FIGURE 25

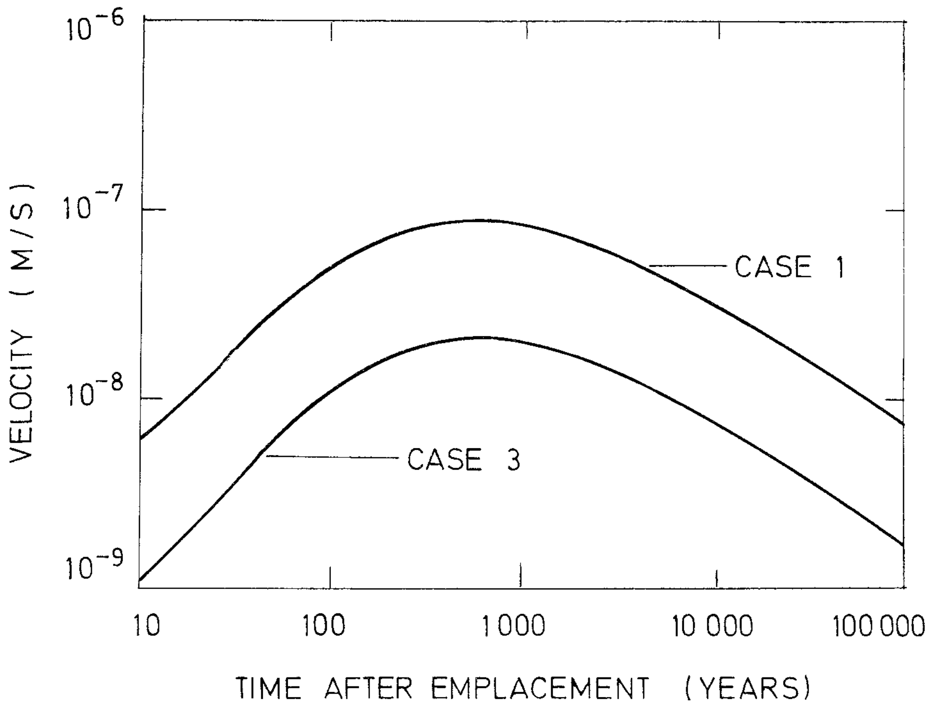
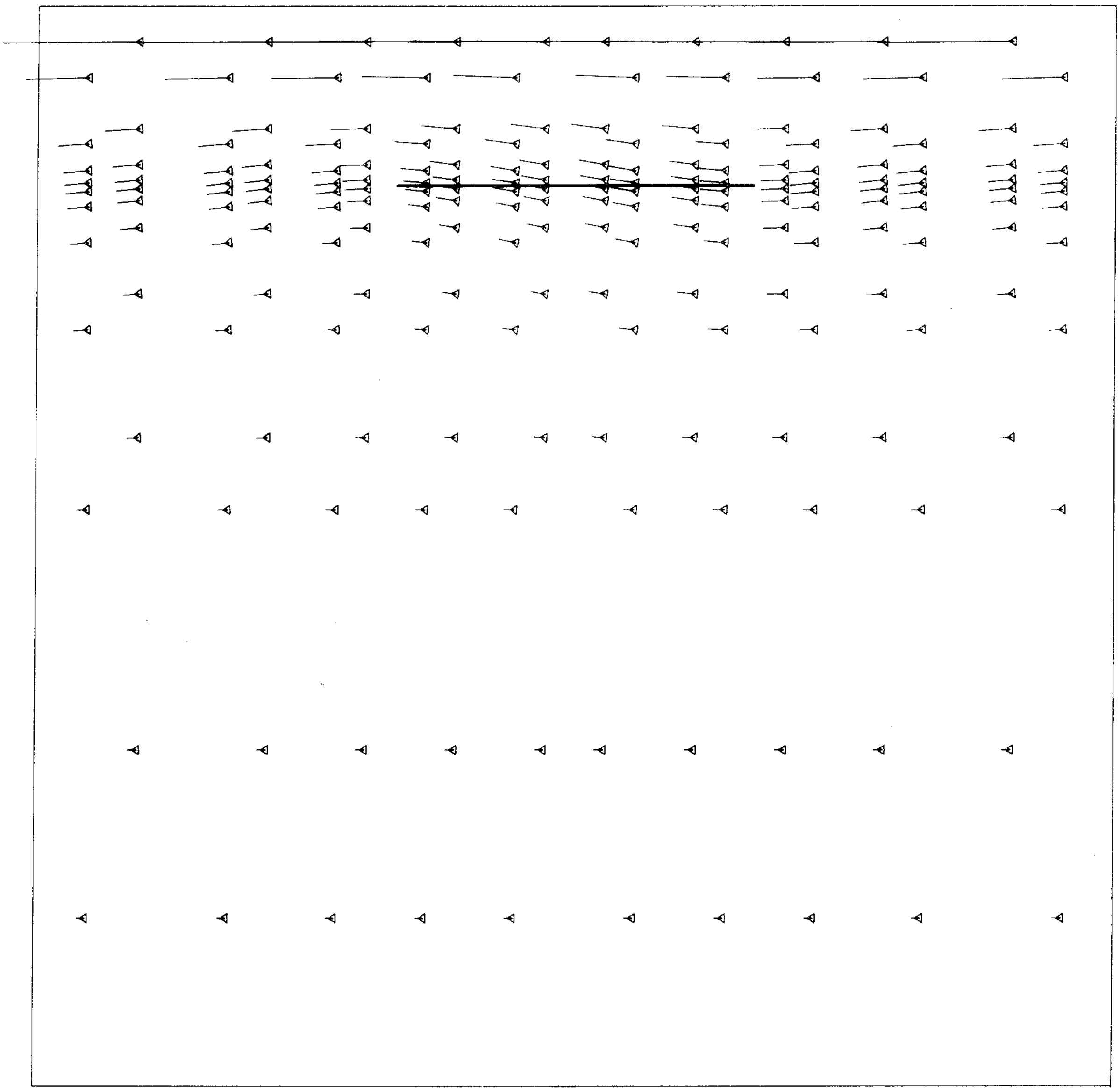


FIGURE 26. AVERAGE HYDROTHERMAL VERTICAL VELOCITY ABOVE THE REPOSITORY

The local cells are strongest at about 40 years and decay to the extent that they almost disappear within 1000 years (after the heat generation effectively ceases). The principal potential effect of the local cells on waste transport may be the channelling of the global flow closer to the canisters, thus increasing the groundwater/waste contact. However, the existence and shape of these local cells will be strongly dependent on the local joint system. This effect, which may be considered a mixing process will diminish after 1000 years.

The inflow velocities will be much stronger than the thermally induced flows by a factor of approximately 10^3, while they last. Therefore the thermal cells can not occur until the recharge is complete. The ratio of inflow velocity to thermally induced flow velocity is almost independent of permeability in the expected range and thus the overpowering of thermally induced flow can be anticipated whatever actual values of permeability are established.However, the time of possible initiation of thermal convection cells is directly dependent on the permeability value since this affects the duration of the inflow period.

A regional gradient is expected and therefore the thermally induced flows and cross flows will interact. Figure 27 shows typical results of the analysis of cross flow under a gradient of 2.10^{-3} and thermally induced flows at time 1000 years for the Case 3 anisotropic non-homogeneous permeability distribution. The regional flows are generally at least 1000 times faster than the purely thermally induced flows and therefore sweep the convection cells laterally. The resulting first potential exit point from the repository rock mass would then be the neighbouring singular feature, rather than the surface above the repository. The relative strengths of regional and hydrothermal flows is largely dependent on the actual values of horizontal and vertical permeabilities, respectively. However, it is expected that the same order of magnitude of relative strengths will be preserved and a regional gradient of this magnitude will exist and therefore the thermally induced flows will only cause minor perturbations to the regional flow.



KBS HYDROTHERMAL RUN GLOBAL 3 WITH CROSSFLOW
K(Z) ANISOTROPIC

VELOCITY PLOT

GEOMETRY SCALE 0 — 500 M
VELOCITY SCALE ⊢—⊣ = 1.0 * 10 ** -6 M/SEC

1000 YEARS

FIGURE 27

7. RESIDUAL EFFECTS IN THE LONG TERM

7.1 Objectives and Scope

An analysis and assessment of the expected initial groundwater regime was presented in chapter 4. The transient perturbations due to repository construction and the thermal loading due to waste emplacement were discussed in chapters 5 and 6. In this chapter, we review the residual effects of these perturbations on the host rock and the groundwater system. These predicted conditions will not, however, be expected until at least 1000 years after waste emplacement by which time the thermal transient, groundwater inflow and recharge will be essentially complete.

The long term behavior is discussed in two categories. Firstly, the residual thermomechanical effects, which include the stresses and failure zones following construction, backfill and thermal loading and relaxation, are reviewed. These determine the long term structural integrity of the repository, modifications to the rock permeabilities and the potential for development of fractures. Secondly, a brief discussion is given on the sources of possible long term geological and environmental perturbations to the groundwater system. The resulting groundwater flow fields around the repository are then discussed for the first category. These include the effects of flow through the backfill and zones of increased permeability around the rooms and haulageways which will tend to attract regional flows through the repository area. Analyses of the second category required the establishment of future environmental and geologic scenarios which were beyond the scope of this study. Consequently,no simulations were performed.

The flow fields predicted in this chapter are derived through modifications to the assumed initial flow fields. The uncertainties inherrent in these assumptions therefore remain, and are compounded by uncertainties in predictions of the modifications. However, the variabilities in the modifications are expected to be relatively small and the need for validation rests primarily in the initial flow field estimates.

7.2 Assessment of the Residual Thermomechanical Effects

The residual thermomechanical effects were analysed using global models of the repository domain for time spans in excess of 1000 years after waste emplacement. The geometrical outline of the individual storage tunnels may be substantially modified depending, to some extent, on the room backfill performance. A zone of disturbed rock will probably encompass the original site of each tunnel. Even with the relatively localized zones of disturbed rock, the domain of the repository will effectively be a homogeneous rock mass in the thermal and mechanical senses.

The temperature in the plane of the repository facility will attain a maximum in approximately 70 years after waste emplacement, and will subsequently subside to approximately the original in sisu geothermal temperature in about 40 000 years. The ground surface will exhibit a maximum uplift of approximately 7 cm in about 1000 years. Since the thermomechanical behavior is elastic in the global sense, the surface uplift is reversible and will be recovered by essentially an equal amount of subsidence over a time period in excess of 40 000 years. This displacement is relative to that associated with either ongoing glacial rebound or renewed glacial loading.

As mentioned above, the original site of each storage tunnel will be represented by a relatively localized zone of disturbed rock. In cross section, the area of the zone may be of the order of two to four times the original tunnel area. The areal extent of this zone will be dependent on the nature and compressibility of the backfill material in the tunnel. According to the thermoelastic/plastic results for the growth of potential failure zones around a tunnel without backfill, the extent of potential rock failure is strongly governed by the orientation of the joint planes, in conjunction with stress perturbations due to excavation. A joint plane orientation of $0/90^{o}$ gives rise to the least failure, restricted to the springline and rib-floor intersection regions of the tunnel. The additional effect of thermal loading on the failure zone growth is generally minimal, compared to that due to construction only. The penetration depth of the failure zones into the floor of a storage tunnel appears to be of the order of 1 m, and is not significantly influenced by the thermal cycle. Interpretation of these quantitative observations in the case when the storage tunnels are back-filled after 30 years, indicates that the disturbed zone in the long term may be expected to extend upward, rather than horizontally and downward. The confinement stress, afforded by the backfill, on the ribs and floor of the tunnel will be beneficial in suppressing the growth of failure zones due to thermal loading and stress relaxation.

The permeability of the damaged zone of the storage tunnel is difficult to quantitatively evaluate in the long term. The two limiting cases used in the analyses considered permeabilities of rubblized rock with moderate packing and of intact rock with joint planes.

7.3 Long Term Geological and Environmental Perturbations to the Groundwater Regime

The long term residual perturbations to the groundwater regime due to the repository design considered in this study are shown to be quite minor and localized. Therefore the question of long term geological and environ-mental perturbations can be considered independently and becomes essentially a matter of forecasting the future of the existing groundwater regime. These forecasts could be analysed by considering the thermal, mechanical and flow response in various scenarios.

A brief discussion of the principal sources of perturbations was prepared. There included glaciation, tectonic activity, erosion and future human activities including use of both the surface and subsurface groundwater systems.

Since various other KBS study tasks are addressing these aspects and no suitably definitive scenarios are available at this time, no analyses of these perturbations were made in this study. Subsequently, it may be possible to quantify certain aspects using global models.

7.4 Methodology for Analyses of the Resulting Long Term Flows

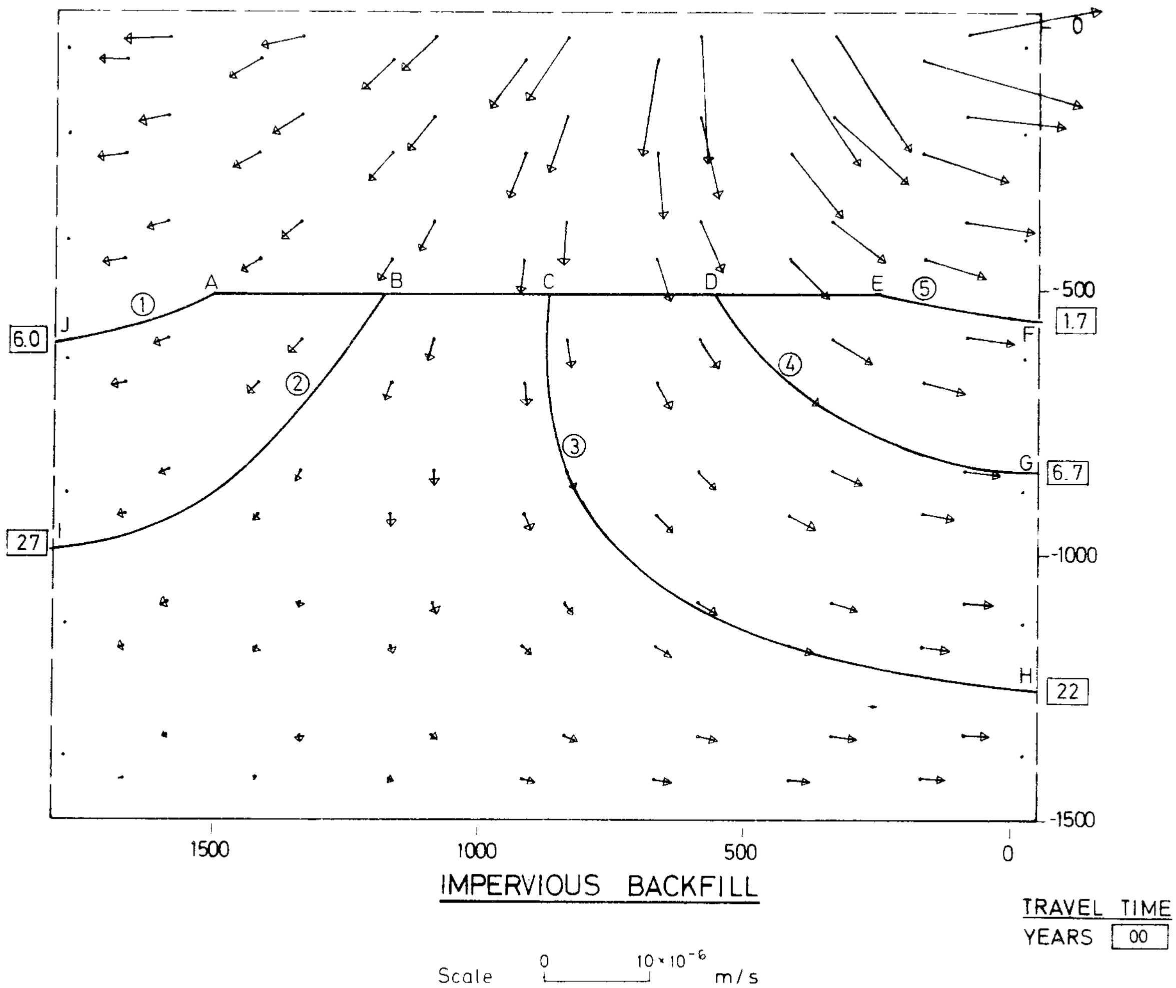
Analyses of groundwater flow in the repository zone were made using the two dimensional local site models previously used in the studies of the initial groundwater regime. These included the repository domain within the boundary discontinuities which were assumed to be equipotential lines. The potential gradients were determined by the surface topography at the site. Nominal permeability distributions used in the initial flow regime studies were used plus a lower permeability distribution based on preliminary results from the hydraulic tests at the Stripa Mine.

The models considered an equivalent uniformly porous layer 5 m deep to represent the repository zone. Equivalent permeabilities and porosities for two extreme cases were computed. One case considered essentially perfect backfilling with no disturbed zones around the rooms and the properties derived in the initial nominal permeability distributions. The second case considered rooms full of crushed rock with a damaged zone, equal to three times the room area, around it with a permeability of 3×10^{-3} m/s and porosity of 0.2.

7.5 Results of Analyses of Resulting Long-Term Flows

Flow fields and travel times along pathways of interest were computed for the Cases 1, 2 and 3 nominal permeability distributions and the Case 3 distribution reduced proportionally to a value of $K_Z = 5.10^{-11}$ at 500 m depth. This value has recently been obtained from preliminary results of the Stripa mine hydraulic tests and is included for comparison purposes. Both the perfect backfill and permeable room zones were considered for each case. Plots of the results are shown in Figures 28 to 30.

For the isotropic distributions for the perfect backfill case in Figures 28a and 29 a the flows through the repository are downwards and reach the lateral boundaries at depth. The downwards flow is due primarily to the particular topography analysed.



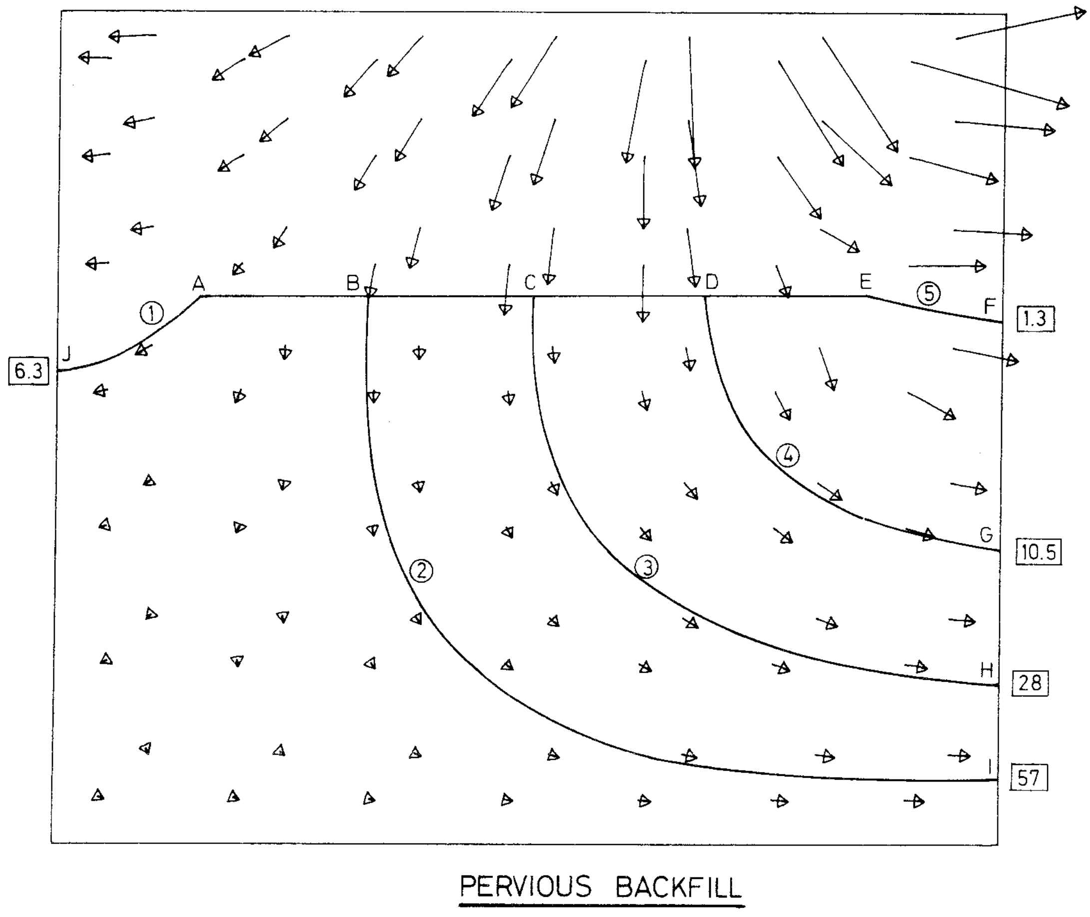


FIGURE 28. PATHWAYS AND TRAVEL TIMES IN REPOSITORY DOMAIN CASE 1

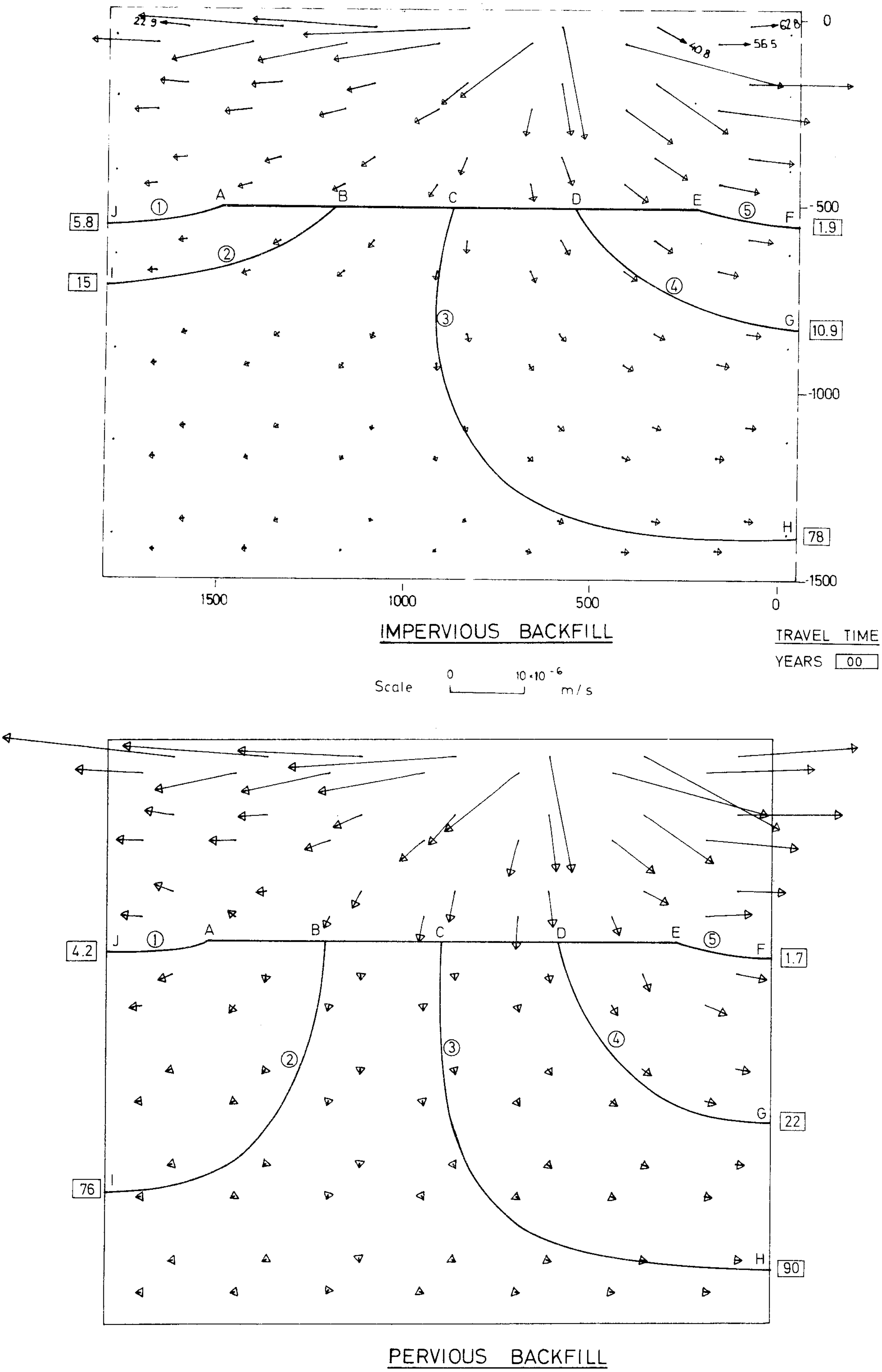


FIGURE 29. PATHWAYS AND TRAVEL TIMES IN REPOSITORY DOMAIN CASE 2

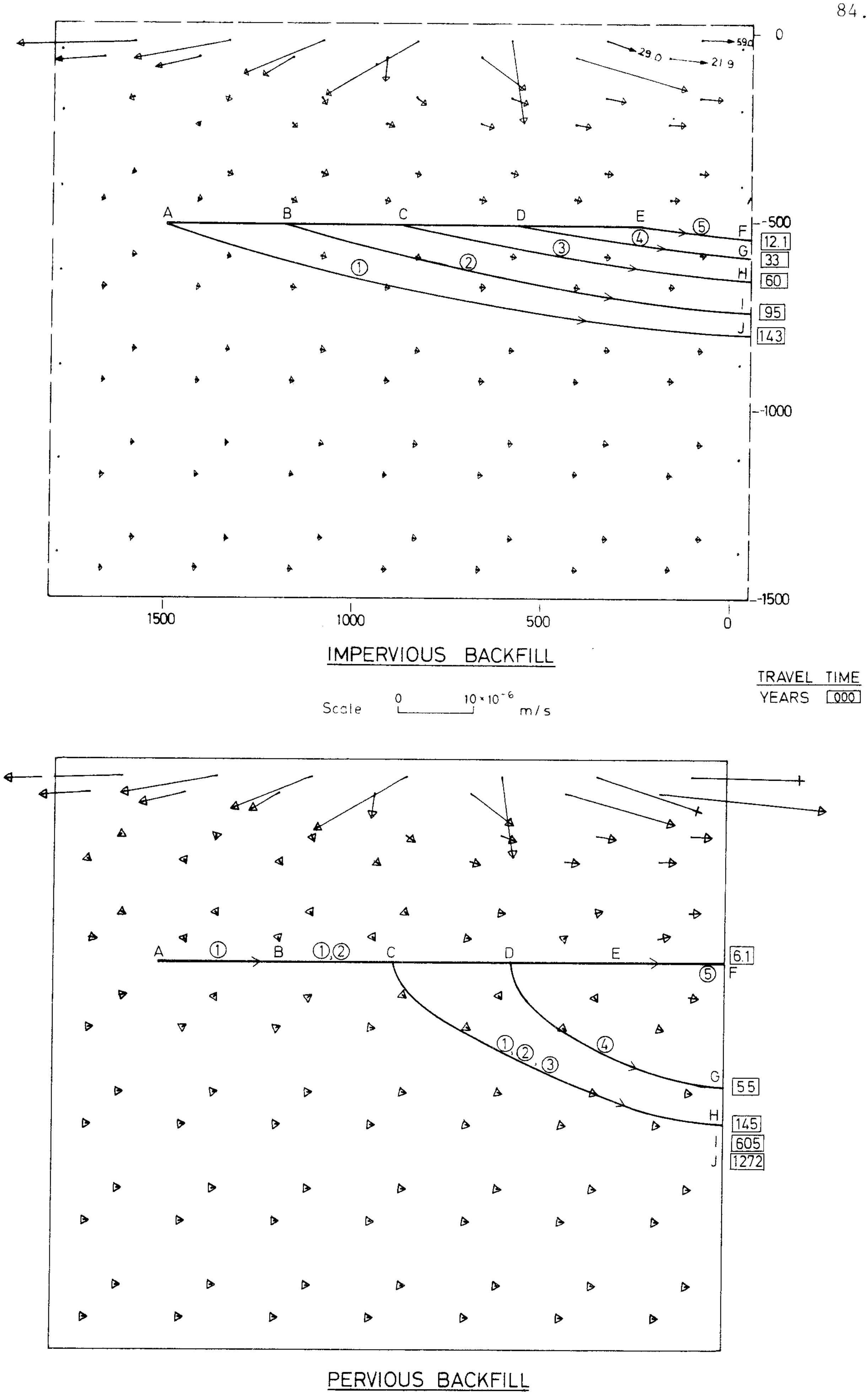


FIGURE 30. PATHWAYS AND TRAVEL TIMES IN REPOSITORY DOMAIN CASE 3.

The introduction of a high permeability repository zone causes the flow lines to be deflected deaper and the associated nominal travel times to be longer. This is shown in Figures 28b and 29b.

In the anisotropic non-homogeneous Case 3 the flows are more horizontal across the repository in the perfect backfill Case 5 shown in Figure 30a. At the repository depth the transverse flow is almost independent of the surface topography. The introduction of a permeable repository zone changes the flowpattern significantly as can be seen in Figure 30b. The flow is drawn into the repository on the upstream side from a wide zone above and below the repository level and discharged on the downstream side. The downstream plume in the permeable room case extends above the repository level to a height of approximately 200 m. However, the nominal travel times along the exit flow lines are increased by a factor of 2.

The nominal travel times for five pathways of interest for the anisotropic permeability Case 3 are listed in Table 4 together with times for the reduced permeability values based on the Stripa test results. These are based on the rooms being parallel to the flow in the place of the model.

TABLE 4 TRAVEL TIME COMPARISONS

Path	Start/Finish location	Permeability Distribution in Host Rock			
		Case 3 Anisotropic		Stripa Test Anisotropic	
		Impervious Backfill	Pervious Backfill	Impervious Backfill	Pervious Backfill
1	A-J (A-C-J for pervious backfill)	143	1127 in backfill 145 in rock 1273 Total	3421	1127 in backfill 3483 in rock 4610 Total
2	B-I (B-C-J for pervious backfill)	96	459 in backfill 145 in rock 605 Total	2288	459 in backfill 3483 in rock 3942 Total
3	C-H	60	145	1443	3483
4	D-G	33	55	789	1317
5	E-F	12.1	6.1	290	146

The pathways 1 to 5 are shortest routes from points A to E, respectively, to the model boundary. The differences between pathways 1 minus 2, and 2 minus 3 between points A to B and B to C are also shown for the permeable backfill cases to show comparable travel times through the repository zone.

In the case of perfect backfill, exit pathways from all locations in the repository are below the repository. The shortest times being 12.1 and 289.5 years for the nominal and Stripa test permeability values respectively.

In the case of the permeable backfill the quickest pathways may be through, above or below the repository depending on the starting point. The shortest time from point E to the boundary is 6.1 or 145.7 years for the two host rock permeabilities. From location D the quickest pathway is above the repository to the boundary. From location C at the center of the repository the quickest pathway is below the repository.

However, the pathway from points A or B is initially through the repository since the zone between points A and C is subject to inflow. Once the flow from points A or B reaches C, then the quickest route is to travel below the repository.

It may also be noted that the velocities through the repository zone are almost independent of the host rock permeability for the high backfill porosity cases but will be strongly dependent on the backfill permeabilities and porosities. Also, the through repository travel times assume that the rooms are orientated parallel to the plane of the model. The actual orientation and effect of haulageways should be taken into account in the final analyses.

Detailed studies of sealing techniques and effectiveness are required in order to further assess the magnitude and character of these possible tunnelling and dispersion effects. This must address the long term performance of both the backfill and the rock around the rooms. The current analyses have only considered extrme cases. These effects are also strongly dependent on the in situ permeabilities and groundwater regime, which awaits further field work.

8. CONCLUSIONS

The overall goal of this study has been to assess the groundwater flow field in the vicinity of a conceptual high-level radioactive waste repository, situated at a depth of 500 m in the precambrian bedrock of Sweden. Finite element modelling procedures have been used employing nominal and extrapolated data for initial groundwater conditions and precedent data for material properties. The coupling of thermal, rock mechanics, and groundwater flow effects has been achieved by means of quasi-static techniques. The results of these interelated processes have been analyzed for the following identifiable periods of the repository time frame: (1) pre-construction; (2) construction, but pre-emplacement of the waste; (3) post-emplacement of the waste through the significant portion of the thermal cycle; and (4) long term.

Assessment of the results of the analysis efforts lead to the following general conclusions:

(1) For the conceptual repository design at 500 m depth with a gross thermal loading of 5.25 W/m^2, the groundwater regime will not be significantly altered by the radiogenic heat dissipation.

(2) The long term flow fields will be determined principally by the flow regime prior to construction and can therefore be reliably predicted through establishment of the existing geohydrological parameters.

From the viewpoint of site selection, the practical design of the repository, and the waste emplacement concept, the following two results are of particular interest:

(1) The degree of anisotropy of the rock permeability is of importance in selecting the repository depth and location. Horizontal anisotropy results in groundwater flow becoming increasingly quiescient with depth.

(2) For a gross thermal loading of 5.25 W/m^2, the maximum rock temperature rise in the immediate vicinity of the waste canisters will be approximately 40^oC if room ventilation is maintained for 30 years after emplacement.

On the basis of the initial groundwater conditions, assumed materials properties and the conceptual repository design specifications, the following conclusions were deduced regarding the relative importance of the principle phenomena:

(1) Heat transfer in the host rock can be satisfactorily modeled considering conduction only since the influence of advective heat transport due to groundwater flow is negligible.

(2) Thermally induced flows will cause only minor perturbations to the regional groundwater regime in the vicinity of the repository.

(3) Inflow will dominate regional and hydrothermal flows during the recharge period.

(4) The potential for the development of pathways from the repository as a consequence of rock failure due to excavation and thermally - induced stresses is negligible.

(5) The change in rock permeability due to excavation and thermally - induced stresses, and to temperature - dependent groundwater viscosity, is localized.

The travel times computed in this study were as a rule based om extrapolatious to depth of data from presently available boreholes. Preliminary results from Field test in the Stripa mine indicate permeabilities 1000 times lower and therefore these travel times may be high by a factor of 100. The reliability of the predictions of groundwater flow will be greatly improved as field data, particularly rock mass permeability and porosity measurements, become available.

9. REFERENCES

In this section, literature and communications refered to in the three study phases are listed. Specifically, sources that are refered to in this Final Report can be found under 9.3.

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A P P E N D I X

FINITE ELEMENT MODELS EMPLOYED IN THE STUDY

				DESCRIPTION	MATERIAL PROPERTIES	
Groundwater Flow	FORS/REG/G W-1	Plane	300 km by 2 km	Forsmark Regional Flow	Isotropic (Case 1)	Prescribed potential B.C.'s
	OSK/REG/G W-2	"	200 km by 2 km	Oskarshamn Regional Flow	Isotropic (Case 1)	Topographic gradient surface B.C.'s
	3	"			Anisotropic and non-homogeneous (Case 2)	
	4	"			Isotropic and non-homogeneous (Case 3)	
	TOP/LOC/G W-5	"	4000 m by 1000 m	Local Topography Effects	Isotropic (Case 1)	Zero flux at sides B.C.
	6	"			Anisotropic and non-homogeneous (Case 2)	
	7	"			Isotropic (Case 1)	Prescribed potential sides B.C.
	8	"			Anisotropic and non-homogeneous	
	DISC/LOC/G W-9	"	24 km by 2 km	Local Discontinuity Effects	Isotropic	Transparent discontinuity
	10	"			Isotropic with $K = 10^{-6}$ discontinuity	Dip against flow
	11	"			Isotropic with $K = 10^{-6}$ discontinuity	Dip with flow
	12	"			Anisotropic and non-homogeneous with $K = 10^{-6}$ disc.	Dip against flow
	FORS/SITE/G W-13	"	1800 m by 1500 m	Forsmark Site Flow	Isotropic (Case 1)	Zero flux side B.C.'s $I_0 = 2.10^{-3}$
	14	"			Anisotropic, non-homogeneous (Case 2)	
	15	"			Isotropic, non-homogeneous (Case 3)	
	16	"			Isotropic (Case 1)	Prescribed potential B.C.'s $I_0 = 2.10^{-3}$
	17	"			Anisotropic, non-homogeneous (Case 2)	
	18	"			Isotropic, non-homogeneous (Case 3)	

PHENOMENON	MODEL	GEOMETRY	DIMENSIONS	COMMENTS		
Conduction Heat Transfer	GLOBAL/CT-1	Plane	1500 m wide by 3000 m deep	500 m Repository Depth	Instantaneous Waste Emplacement	Constant Surface Temperature
	GLOBAL/CT-2	Axisummetric				Convective Heat Transfer at the Surface of the Earth
	GLOBAL/CT-3	Plane				
	GLOBAL/CT-4			1000 m Repository Depth		
	GLOBAL/CT-5		3000 by 3000 m	500 m Repository Depth	Linear Waste Emplacement	
	LOCAL/CT-1	Plane	12.5 m wide by 1500 m deep strip with one-half room/one-half pillar at 500 m depth	No Ventilation	40 Year Old Waste	κ = 2.05 W/m-°C
	LOCAL/CT-2			Ventilation to 30 Years		
	LOCAL/CT-3	Axisymmetric		No Ventilation		
	LOCAL/CT-4	Plane		Ventilation to 30 Years	10 Year Old Waste	
	LOCAL/CT-5				40 Year Old Waste	κ = 3.35 W/m-°C
Thermal Advection	GLOBAL/TA-1	Plane	1500 m wide by 3000 m deep	Linear Emplacement	Regional Flux = $2 \cdot 10^{-11}$ m/sec.	Regional Potential Gradient = 0.001
Hydrothermal	GLOBAL/HT-1	Plane	1500 m wide by 3000 m deep	Conduction Baseline Isotropic Permeability	No Crossflow	Instantaneous Waste Emplacement
	GLOBAL/HT-2		3000 m wide by 3000 m deep	Isotropic Permeability	Regional Gradient $i = 2 \times 10^{-3}$	
	GLOBAL/HT-3		1500 m wide by 3000 m deep	Anisotropic Permeability	No Crossflow	
			3000 m wide by 3000 m deep	Anisotropic Permeability	Regional Gradient $i = 2 \times 10^{-3}$	
	GLOBAL/HT-4		1500 m wide by 3000 m deep	Isotropic Permeability	Advective Inflow	
	LOCAL/HT-1	Plane	12.5 m wide by 50 m deep strip with one-half room & one-half pillar at 500 m depth	Conduction Baseline	No Crossflow	
	LOCAL/HT-3			Isotropic Permeability		
	LOCAL/HT-3			Isotropic Permeability		

PHENOMENON	MODEL	GEOMETRY	DIMENSIONS	COMMENTS		
Rock Mechanics	GLOBAL/RM-1	PLANE	1500 m Wide by 3000 m Deep	500 m Repository Depth	Instantaneous Waste Emplacement	Joint sets at 0 and 90^o Joint sets 45^o and -45^o
	GLOBAL/RM-2			1000 m Repository Depth	Instantaneous Waste Emplacement	Joint sets at 0 and 90^o Joint sets 45^o and -45^o
	GLOBAL/RM-3		3000 m Wide by 3000 m Deep	500 m Repository Depth	Linear Waste Emplacement	Joint sets at 0 and 90^o Joint sets 45^o and -45^o
	LOCAL/RM-1	PLANE	12.5 m Wide by 70 m Deep Strip with one-half Room & one-half Pillar at Depth of 500 m	No Room Ventilation	Joint sets at 0 and 90^o Joint sets 45^o and -45^o	
				Room Ventilation	Joint sets at 0 and 90^o Joint sets at 45^o and -45^o	

FÖRTECKNING ÖVER KBS TEKNISKA RAPPORTER

01 Källstyrkor i utbränt bränsle och högaktivt avfall från en PWR beräknade med ORIGEN
Nils Kjellbert
AB Atomenergi 77-04-05

02 PM angående värmeledningstal hos jordmaterial
Sven Knutsson
Roland Pusch
Högskolan i Luleå 77-04-15

03 Deponering av högaktivt avfall i borrhål med buffertsubstans
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 77-05-27

04 Deponering av högaktivt avfall i tunnlar med buffertsubstans
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 77-06-01

05 Orienterande temperaturberäkningar för slutförvaring i berg av radioaktivt avfall, Rapport 1
Roland Blomqvist
AB Atomenergi 77-03-17

06 Groundwater movements around a repository, Phase 1, State of the art and detailed study plan
Ulf Lindblom
Hagconsult AB 77-02-28

07 Resteffekt studier för KBS
Del 1 Litteraturgenomgång
Del 2 Beräkningar
Kim Ekberg
Nils Kjellbert
Göran Olsson
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08 Utlakning av franskt, engelskt och kanadensiskt glas med högaktivt avfall
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