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Thermal-Hydro-Mechanical Coupled Processes in Safety Assessments

Report of Task 4

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Foreword

DECOVALEX is an international consortium of governmental agencies associated with the disposal of high-level nuclear waste in a number of countries. The consortium's mission is the DEvelopment of COupled models and their VALidation against EXperiments. Hence theacronym/name DECOVALEX. Currently, agencies from Canada, Finland, France, Germany, Japan, Spain, Switzerland, Sweden, United Kingdom, and the United States are in DECOVALEX. Emplacement of nuclear waste in a repository in geologic media causes a number of physical processes to be intensified in the surrounding rock mass due to the decay heat from the waste. The four main processes of concern are thermal, hydrological, mechanical and chemical. Interactions or coupling between these heat-driven processes must be taken into account in modeling the performance of the repository for such modeling to be meaningful and reliable.

The first DECOVALEX project, begun in 1992 and completed in 1996 was aimed at modeling benchmark problems and validation by laboratory experiments. DECOVALEX II, started in 1996, built on the experience gained in DECOVALEX I by modeling larger tests conducted in the field. DECOVALEX III, started in 1999 following the completion of DECOVALEX II, is organized around four tasks. The FEBEX (Full-scale Engineered Barriers EXperiment) in situ experiment being conducted at the Grimsel site in Switzerland is to be simulated and analyzed in Task 1. Task 2, centered around the Drift Scale Test (DST) at Yucca Mountain in Nevada, USA, has several sub-tasks (Task 2A, Task 2B, Task 2C and Task 2D) to investigate a number of the coupled processes in the DST. Task 3 studies three benchmark problems: a) the effects of thermal-hydrologic-mechanical (THM) coupling on the performance of the near-field of a nuclear waste repository (BMT1); b) the effect of upscaling THM processes on the results of performance assessment (BMT2); and c) the effect of glaciation on rock mass behavior (BMT3). Task 4 is on the direct application of THM coupled process modelling in the performance assessment of nuclear waste repositories in geologic media.

This report is the final report of Task 4 about the findings of impacts of the coupled THM processes on the safety assessment of nuclear waste repositories in the views of waste management agencies and regulatory bodies, together with findings achieved during the DECOVALEX III project.

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Summary

A part (Task 4) of the International DECOVALEX III project on coupled thermo-hydro-mechanical (T-H-M) processes focuses on T-H-M modelling applications in safety and performance assessment of deep geological nuclear waste repositories. A previous phase, DECOVALEX II, saw a need to improve such modelling (Stephansson et al., 1999). In order to address this need Task 4 of DECOVALEX III has:

- Analysed two major T-H-M experiments (Task 1 and Task2) and three different Bench Mark Tests (Task 3) set-up to explore the significance of T-H-M in some potentially important safety assessment applications.
- Compiled and evaluated the use of T-H-M modelling in safety assessments at the time of the year 2000.
- Organised a forum a forum of interchange between PA-analysts and THM-modellers at each DECOVALEX III workshop.

Based on this information the current report discusses the findings and strives for reaching recommendations as regards good practices in addressing coupled T-H-M issues in safety assessments.

The full development of T-H-M modelling is still at an early stage and it is not evident whether current codes provide the information that is required. However, although the geosphere is a system of fully coupled processes, this does not directly imply that all existing coupled mechanisms must be represented numerically. Modelling is conducted for specific purposes and the required confidence level should be considered. It is necessary to match the confidence level with the modelling objective. Coupled THM modelling has to incorporate uncertainties. These uncertainties mainly concern uncertainties in the conceptual model and uncertainty in data. Assessing data uncertainty is important when judging the need to model coupled processes. Often data uncertainty is more significant than the coupled effects.

The emphasis on the need for THM modelling differs among disciplines. For geological radioactive waste disposal in crystalline and other similar hard rock formations DECOVALEX III shows it is essential to:

- understand the stress-permeability couplings when interpreting stress and permeability field data,
- understand the coupled processes involved in the re-saturation of the near-field,
- understand the coupled processes involved in the development of an Excavated Disturbed Zone and
- understand the coupled processes involved in the impact of large-scale and significant climatic events, like glaciations and permafrost.

Other couplings may have less direct impact on performance, especially when considered against other uncertainties, and need not be directly included in simulation codes. However, the relatively little importance of THM couplings in hard rock formations may not true for other rock types. Generally, all applications concerned with the rock mass need to at least consider the THM couplings.

Sammanfattning

En deluppgift (Task 4) inom det internationella projektet DECOVALEX III om kopplade termo-hydro-mekaniska (T-H-M) processer har avsett betydelsen av T-H-M modellering vid säkerhetsanalyser av geologiska djupförvar för kärnavfall. I en tidigare fas, DECOVALEX II, konstaterades att sådan modellering borde förbättras (Stephansson et al., 1999). För att studera denna fråga har Task 4 inom DECOVALEX III:

- Värderat slutsatserna från övriga fall inom DECOVALEX III.
- Utifrån en enkät sammanställt och värderat hur T-H-M tidigare (innan 2000) har modellerats säkerhetsanalyser.
- Organiserat och dokumenterat en speciell säkerhetsanalyssession vid varje DECOVALEX III workshop.

Denna rapport utgör en sammanställning av slutsatserna från dessa insatser. Utvecklingen av datorkoder som kopplar T-H-M processer pågår och det är inte uppenbart att de rätt behandlar de väsentliga kopplingarna. Å andra sidan är det viktigt att ha klart för sig att även om geosfären i princip är ett system med koppade processer, behöver detta inte betyda att alla kopplingar måste tas med i numeriska modeller. Modeller och beräkningar görs alltid för specifika syften. Tilltron till modellerna måste relateras till dessa syften.

Modelleringen måste också ta hänsyn till osäkerheter, framförallt konceptuella osäkerheter och osäkerheter i data. Ofta är osäkerheterna i data större än de osäkerheter som uppstår på grund av att försumma kopplade effekter.

Behovet att ta med kopplade THM processer varierar mellan olika tillämpningar. Vid analys av djupförvar i kristallint eller annat ”hårt” berg, visar DECOVALEX III att det är väsentligt att:

- förstå kopplingen mellan bergspänningar och permeabilitet vid analys av fältdata,
- förstå de kopplade processer som påverkar återmättnaden av närområdet,
- förstå de kopplade processer som påverkar utbildandet av den s.k. ”störda zonen” (EDZ), och
- förstå de kopplade processer som påverkar berget vid storskaliga och betydande klimatförändringar, som nedisning och permafrost.

Andra kopplingar kan ha mindre direkt betydelse för förvarets funktion, framförallt jämfört med andra osäkerheter, och behöver inte ingå i datorkoder. Slutsatserna beträffande kristallint berg är dock inte nödvändigtvis överförbara till andra geologiska formationer. Generellt gäller att betydelsen av THM kopplingar alltid behöver värderas.

Contents

1 Introduction

This report presents observations and recommendation as regards the treatment of coupled T-H-M processes in safety assessments of nuclear waste repositories in crystalline and other similar hard rocks. The report builds on the achievements of the DECOVALEX III project.

1.1 Background

A part (Task 4) of the International DECOVALEX III project on coupled thermo-hydro-mechanical (T-H-M) processes focuses on T-H-M modelling applications in safety and performance assessment of deep geological nuclear waste repositories. A previous phase, DECOVALEX II, saw a need to improve such modelling (Stephansson et al., 1999). In order to address this need Task 4 of DECOVALEX III has:

- Analysed two major T-H-M experiments (Task 1 and Task2) and three different Bench Mark Tests (Task 3) set-up to explore the significance of T-H-M in some potentially important safety assessment applications.
- Compiled and evaluated the use of T-H-M modelling in safety assessments at the time of the year 2000 (see Appendix A).
- Organised a forum a forum of interchange between PA-analysts and THM-modellers at each DECOVALEX III workshop.

Based on this information the current report discusses the findings and strives for reaching recommendations as regards good practices in addressing coupled T-H-M issues in safety assessments.

1.2 Objectives and Scope

This report sets out to derive conclusions and recommendations on practices in addressing THM issues in Performance and Safety Assessment Applications, based on the findings of DECOVALEX III. More specifically the report intends:

- to provide concrete examples on when T-H-M couplings may need to be considered in a quantitative fashion in post-closure performance assessment of nuclear waste repositories in hard rock formations and when T-H-M couplings not need to be considered in such assessments,
- to provide a practical approach for the general problem of simplifications of T-H-M analyses such that they can be properly incorporated in Performance Assessment analysis, and to evaluate uncertainties introduced through such simplifications.

However, the conclusion has to consider the limitations in scope of the DECOVALEX III.

The DECOVALEX III project focuses on coupled T-H-M processes in fractured crystalline rock and other hard rocks, and on the interaction between the rock and the Engineered Barriers. Processes only occurring in the Engineered Barriers are not discussed. Furthermore, DECOVALEX focused on mechanical processes and couplings involving mechanical processes. It does not concern uncoupled hydrogeological analyses or coupled hydro-chemical analyses (these processes and couplings are extensively treated in other fora). The conclusions and recommendations presented in this report should be valued with this limited scope in mind.

1.3 What is relevant for Safety Assessment?

Before entering the specific technical discussion on the findings of DECOVALEX III, it is necessary to spend some thought on how to judge the importance of any process, interaction or feature in a Safety Assessment context. Just because there is a THM-coupling does not necessarily mean that it needs detailed study – its effect may be totally insignificant.

1.3.1 What is Performance and Safety Assessment?

The object of a safety assessment (SA) of a deep geological repository for nuclear waste is to produce a *decision instrument* based on a careful evaluation of factors affecting its performance. Such decisions may, for example, concern the need for further studies of a proposed site or concept, the selection of other sites for further characterisation, or ultimately the decision whether the repository at a specific site is (or will be) sufficiently safe to warrant a license for construction, operation or sealing. The OECD Nuclear Energy Agency has explored 10 recently conducted Safety or Performance Assessments (OCED/NEA, 1997a). The study suggests that a ”Safety Case” for the long term performance of a nuclear waste repository consists of:

1. ”A quantitative analysis of a set of processes that have been identified as most relevant to the overall performance of the disposal system and calculations of a measure of overall performance relevant to the given national regulatory regime, e.g. individual dose to members of a critical group, integrated total release of contaminants”
2. ”Testing of arguments that a sufficient subset of processes have been analysed, appropriate models and data used, plus comparison of calculated measures of overall performance to regulatory limits and targets.”
3. ”A full trace of arguments and evidence that a sufficient set of processes have been analysed and appropriate models and data used; relevant overall measures of performance and safety are within acceptable ranges allowing for uncertainties. More qualitative, parallel lines of evidence and reasoning may be used to support results of the quantitative modelling and to indicate the overall safety of the system…”

According to the OECD/NEA study the first two of these steps are the safety assessment, and if the analysis is confined to a part of the repository system it is instead called ”Performance Assessment”. However, it should be recognised that different organisations use these words with slightly different meanings.

In general, it should be understood that a safety assessment and a safety case need not be a complete description of all processes and interactions that take place or will take place in a repository system. Only conditions that have, or could potentially be suspected to have, implications on safety need to be described. Detailed predictions of the evolution of the system are not needed if it can be shown that the evolution and its consequences are insignificant for safety. Simplified models and assumptions could be made provided they can be shown to be "conservative." Furthermore, the arguments and the modelling does not necessarily need to be quantitative – bounding evaluations may be sufficient, even if it is still necessary to demonstrate enough physical understanding of the processes that affect the repository environment and evolution, such that the bounding assumptions could be justified.

1.3.2 Difference between Safety Assessment and Engineering prediction

Designing and managing underground constructions require predictions of rock conditions and responses during constructions. Rock construction implies significant disturbances to the rock, which means that coupled THM effects probably are more pronounced during construction than afterwards during the relatively uneventful post closure phase. Having said this, it needs also be understood that the requirements on engineering predictions are not the same as those made for safety assessment. Engineering predictions are made as support for making decisions on design and (later on) construction. While such decisions may have far reaching practical and economical implications, they do not concern radiological hazards. Many engineering decision do not at all concern issues of long term safety. Furthermore, the adequacy of predictions will be checked against the construction reality. Erroneous predictions may lead to poor engineering decisions, but not to radiological risk. This lead to less strict demands on engineering predictions compared to Safety Assessment, but engineering predictions are not unimportant.

Poor engineering decisions may jeopardise the repository project – no one would be interested in making underground excavations later to be found unsuitable for a repository. Furthermore, even if some engineering predictions concerning issues of little relevance for long term safety, ability to make these predictions would clearly enhance the confidence in the overall ability to make predictions (including those directly related to long term safety).

Consequently, in assessing the relevance of a THM coupling it is important to consider whether its impact concerns engineering issues or safety issues. The latter should acquire special focus, but the former are still important.

1.3.3 Judging the relevance of THM-coupling

When considering the THM mechanisms, it is important to judge whether a given process has relevance to the repository performance, or if increasing the complexity of characterisation and modelling is actually required. The modelling has to be developed to a useable practical scheme, which captures the essence of the required processes. Some THM couplings will be concept, site, and waste-type specific, e.g. whether high-, medium- or low-level waste is being considered

Clearly, it needs to be understood that Safety Assessment concern an evaluation whether a given repository concept in a (more or less defined) siting environment is safe in relation to pre-set safety criteria. Safety Assessment is not a means to describe and predict every aspect of the future evolution of the repository. Furthermore, criteria, concepts and siting environments change. This means that what is important in one concept, may be totally irrelevant in others.

When evaluating the confidence in THM-predictions it is necessary to match this level of confidence with an understanding of *'how much confidence is needed'*. There are three issues:

- the accuracy and precision of the THM prediction,
- the relative inaccuracy (uncertainty) in the THM prediction given the inherent spatial/temporal variability of the domain properties (i.e. geosphere/vault/EBS), and
- the relative importance of uncertainty in the predicted THM process/mechanism to others occurring in the vault/geosphere.

With regard to the first point there needs to be a performance measure against which THM predictability can be judged and to develop means for quantifying the error made by neglecting/simplifying the coupling. Comparison against such measures are essential in order to make reasoned statements on predictability; stating reasonable expectations for THM predictions and evaluating the relative importance of THM processes and/or mechanisms on repository safety. In formulating the different DECOVALEX III Task this need was foreseen and performance measures for each of the tasks were defined. In evaluating the outcome of the Tasks these measures will be assessed as well.

The second point speaks to the fact that the geosphere is heterogeneous and complete characterisation is, well, problematic - so given this, how accurate can our predictions be? If performance measures suggest a divergence between observed and predicted results is this a fundamental problem in understanding and accounting for important THM processes/mechanisms or is it simply an inability to completely characterise the domain and boundary conditions? Lastly, the results should be placed into context with other PA issues relevant to repository safety. It may be in the end that THM process/mechanisms are relatively minor (i.e. compared to uncertainty in geosphere transport, canister failure rates, retardation factors, long-term climate change, parameter up-scaling - etc.). Also these aspect have to be assessed and discussed.

1.4 This report

Chapter 2 of this report discusses some findings, with relevance to safety assessments, from DECOVALEX III. The remaining chapters build on these findings in developing its recommendations.

2 DECOVALEX III discussions on Safety Assessment

This chapter provides an overview of DECOVALEX III discussion on THM and safety assessment. It starts with the assessment of the status on this issue at the time of starting the project and then summaries the content of the discussion sessions held within the project. Chapter will discuss the Safety Assessment implications of the actual modelling work within DECOVALEX III.

2.1 Conclusions made at the completion of DECOVALEX II

The Safety Assessment and Safety case implication of THM-modelling has certainly been in focus also in the earlier DECOVALEX project. In concluding DECOVALEX II, Stephansson et al. (1999) discussed coupled THM-issues related to repository design and performance. They made the following conclusions:

"A predictive THM capability is required to support repository design because precedent practice information is insufficient. Many aspects of THM processes and modelling are now well understood and there is a variety of numerical codes available to provide solutions for different host rock and repository conditions. However, modelling all the THM mechanisms in space and time is extremely complex and simplifications will have to be made — if only because it is not possible to obtain all the necessary detailed supporting information. Therefore, an important step is to clarify the THM modelling requirement within the PA and design context. This will help to indicate the complexity of THM modelling required and hence the models, mechanisms, type of computing, supporting data, laboratory and in situ testing, etc. required. An associated transparent and open audit trail should be developed."

As a result of an elicitation and compilation of the state-of-knowledge statements, and subsequent extensive internal and external reviews Stephansson et al. (1999) identified some outstanding issues. Four of the most important are as follows.

Clarifying the Role of THM Processes for PA .
Although the need to consider the THM processes for PA is understood, it is evident from the information collected that further work is required to identify the type of THM information that is necessary for PA studies. The PA model may well contain overall simplifications of the detailed THM processes and it is not clear how the THM processes should be presented and described.

Demonstration Analysis of Disposal System Stability.
One of the most important aspects of the study of repository design and performance is to ensure that the presence of destabilizing positive feedbacks does not cause the disposal system to become unstable. For example, a natural disturbance to a major rock fracture could enhance the water flow through the fracture which in turn causes further

disturbance and more water to flow. Thus, the long-term effects of perturbations and time should be studied in the system context.

Study of the Scale-Dependent Properties Relevant to Repository Design and Performance.

The importance of this subject is that the parameters and constitutive relations for rock masses are known to be scale dependent. This is a crucial factor for modelling THM processes for repository design and performance. Moreover, the modelling itself may depend on the scale, e.g. discontinuum for the small scale and continuum for the large scale. There is currently no coherent approach to this subject, nor a survey of current understanding of the topic — yet it could well be critical in deciding on the THM modelling strategy.

Technical Auditing Demonstration of the Overall Modelling and a Specific Numerical Cod*e*.

During the elicitation of state-of-knowledge statements and during the subsequent extensive internal and external reviewing of DECOVALEX II a common theme running through many of the comments was to establish which THM processes are actually required in the modelling and whether analysis does capture these processes. For example, does the code include chemical processes? Is 2-way coupling included in the code or not? Are gas processes and multiphase flow included? Further demonstration examples should be developed using the formal methodology for assessing the inclusion of variables and mechanisms in general modelling and as analyzed by a specific code.

These issues were considered for further evaluation and study in DECOVALEX III.

2.2 Conclusions of the Compilation

At the start of DECOVALEX III a questionnaire on the treatment of T-H-M in safety assessment was sent to the participating waste management and nuclear waste regulatory organisations. The answers received during 2000 were compiled (Appendix A). The following conclusions were made:

Most organisations already apply standardised procedures for identifying processes and couplings to be considered in assessments. However, it seems that these procedures are more as a means of stating the confidence in that all relevant (T-H-M) processes are indeed considered in the safety assessment rather than as tools for identifying previously non-considered processes or couplings. Providing a motivated statement of confidence is indeed a crucial part of a safety assessment report, and here the formal approaches are valuable. Judging from the answers the impression is that most T-H-M issues are already identified. One should not expect dramatic surprises if applying such procedures. (It is rather the means of analysing the couplings that needs to be discussed.)

There are several identified problems where T-H-M couplings are shown to be important or are judged to be potentially important to be considered directly in a safety assessment context. Examples of such problems given by the different respondents to the questionnaire include:

- One of the more important pure hydro-thermal couplings concerns the migration of vapour, water and heat in partially saturated systems. These systems seem very hard to describe without considering this coupling.
- Most programs evaluate the mechanical stability of the underground excavations before and during construction. Most analyses can be limited to only consider mechanical processes such as rock burst, rock failure (breakout) and fallout of key blocks. The thermal effect on rock stability after disposal needs to be assessed in the near field, and potentially also in the far-field. In general, the importance of near-field and far-field mechanical stability after closure needs to specified.
- The potential for and the effect of rock creep is studied in some programs. Even if analyses seem to suggest that creep would be limited and its impact small, the process is not discarded from consideration in the safety assessment context.
- Mechanical effects such as rock fall or fracture shear displacements resulting from earthquakes have been analysed and found to be potentially significant to consider. There seems to be fewer studies on the impact on permeability or hydrology in general.
- A potentially important hydro-mechanical coupling concerns the understanding and modelling the formation and resulting hydraulic properties of a disturbed zone (EDZ) around tunnels. Many safety assessments make assumptions on the EDZ based on limited experimental data. A better understanding of the EDZ may affect parameters used in the Safety Assessment and would at any range improve the confidence in the description of the near-field rock.
- There is less clear evidence as to what extent there is a real need to consider stress and stress change impact on fracture hydraulics. There are some field studies indicating such impacts, but it has not really been studied if these effects would be important in a safety assessment context.
- The consequences of a glacial ice cover is another area where hydro-mechanical couplings are potentially very important to consider. Important questions include proper formulation of both hydraulic and mechanical boundary conditions, resulting hydraulic and mechanical response of the rock mass and impact of transients.
- Full thermo-hydro-mechanical couplings, including all such interaction between buffer and near-field rock, need to be considered when analysing the resaturation of the buffer. On a longer time perspective also the chemical interactions need to be considered, for example from the volume changes resulting from the formation of corrosion products.

There are other problems suggested, such as heat pulse driven rock fracturing and permeability changes due to theromechanical deformation of fractures, where a full thermo-hydro-mechanical analysis is potentially needed. So far, such effects have not been included at any depth in safety assessments.

There are also some areas where it is well established that no further modelling is needed and the coupling can be handled by a simplifying abstraction in the Safety Assessment. Still also these processes and couplings should be mentioned in the safety assessment, with reference to the underlying work showing their limited impact on safety.

T-H-M issues are considered in repository R&D, both as regard modelling, field experiments and repository design. Even if there are only a few coupled T-H-M processes, which need direct analyses in a Safety Assessment.

Although PA/SA is built around simplifying abstractions/assumptions, T-H-M modelling coupled with appropriate testing is still needed to understand how the hydrological system works, in order to rationalize the abstractions.

2.3 Presentations at the PA-sessions at DECOVALEX III Workshops

As a part of DECOVALEX Task 4 a forum was been established so that specific PA cases involving THM applications performed outside the project, either underway or completed, were presented by invited PA experts. The presentation and highlights of the discussion were documented following each DECOVALEX workshop to be used as input to the present concluding report

Presentations from a responsible PA-person took place in all full DECOVALEX workshops, i.e. at Meiringen Switzerland, Tokai in Japan, Naantali in Finland and at Toronto in Canada. Below follows a short resume of the topics addressed in these presentations. The following section, compiles the outcome of the discussion on the running set of PA-related THM questions formulated and addressed in the discussions following these presentations.

2.3.1 Safety Case and THM modelling - NAGRA views

Piet Zuidema Nagra, Switzerland discussed the Safety Case and THM modelling needs. The safety case is the set of arguments used to support the statement that a repository will meet all relevant safety criteria. It generally includes a series of documents, which describe the performance, present the evidence used to give confidence in the conclusions of the performance assessment and discuss the significance of any uncertainties or open questions.

Performance assessment is a process and includes development of system understanding, evaluation of available safety and interaction with and guidance of earth sciences and engineering and design. It should help in setting priorities in R&D and how to avoid unsuitable projects. PA serves as a platform for interaction between the different disciplines involved and sets priorities and defines the needed levels of accuracy. PA periodically evaluates and documents the current understanding.

There are several key questions related to Rock Mechanics:

- Can the system be implemented as designed with the required quality (and costs)?
- How does the system evolve with time- early transient phase (T, water uptake, swelling, creep,…) -long term evolution (erosion, glaciation, tectonics, creep).
- Which long term perturbation can occur and how do they affect the system performance (evolution of EDZ, sealing system, gas generation, volume increase in EBS, material interaction…)?
- Can the system be characterised with the needed level of reliability and quality?

Rock mechanical and THM-related issues include:

- The Stress field – how to make best use of it?

- Stability – in most cases not an issue as sound rock is selected for the sites.
- Conventional mining safety – Nuclear facilities are much more critical with respect to conventional accidents.
- Mining precision – backfilling with bentonite blocks may require high precision.
- Retrievability.
- Coupled phenomena – may be important in the early transient phase!
- Convergence of tunnels may lead to displacement of contaminated pore water.
- Self healing – importance of creep and swelling.

In conclusion it is evident that Rock Mechanics (including THM) plays an important role in repository development and PA. The exact type of questions and the needed level of accuracy depend upon host rock, waste type and layout. For the construction and operational phase most rock mechanical aspects are "conventional" but repository specific issues exist (e.g. mining precision, restrictions in material use, minimisation of EDZ). There are several post closure phase challenges. For the early transient phase they concern understanding and obtaining relevant data. For the longterm evolution the challenges concern identifying the spectrum of possibilities with respect to future evolution and to assess the key (kinetic) material properties. The THM specialists should be able to deal with uncertainties and long time scales – to provide spectrum of possibilities, accept that not everything can or needs to be known in all details and interact with PA to inform and set priorities and define needed level of accuracy.

2.3.2 THM issues in the ENRESA 2000 project

Another presentation at the Meiringen meeting was made by Jesus Alonso, Spain. In 20002 ENRESA was concluding the PA-project ENRESA 2000 concerning waste disposal in granitic type media. In general a geological repository must be feasible, safe during pre- and postclosure, retrievable and accepted. Protection of humans and the environment from Radioactive Material and Chemical Toxic Materials are obtained by Isolation and Confinement, through a multibarrier system. Isolation implies protection from external influences and control of environmental (chemical and mechanical) conditions. Repository time scale needs to be considered. In particular, due to the longevity of the canister and the slow dissolution rate of the waste form (UO_2-matrix) most radionuclide releases occur after the early transient phases with temperture gradients and resaturation effects.

The following THM related factors are selected for their interest in THM modelling:

- heat transport, buffer swelling and buffer saturation
- extrusion of buffer material into fractures and erosion
- potential for thermal and chemical alteration
- chemical interactions with groundwater
- mechanical response of the buffer to external forces, hydrostatic pressures, creep deformation of the rock mass, volume change due to corrosion of canister and other metallic materials, canister weight.
- dynamic response to seismic forces
- colloid filtration effect
- flow of gas
- induced fracturation

- thermal convection.

Assessing barrier performance involves both an analysis of the future evolution of the barrier and an assessment of the performance of the characteristic barrier function. The possible future evolution of the barriers includes changes in structure, state and parameter values. For the canister the main performance function to consider is the time to loss of integrity. For the buffer and host rock factors influencing the retentions are the ones to consider.

Generation and flow of gas is an important issue. The corrosion of the carbon steel canister is the main contributor (95%) to the gas generation. The main concerns are overpressure, effects on the integrity of the near field and far field barriers and potentially faster transport of radionuclides with the gas.

2.3.3 Safety Assessment, THM(C) and Monitoring – Japanese experiences

At the Tokai Workshop M. Yui, JNC, Japan made a presentation on Safety Assessment, THM(C) and Monitoring. When assessing the linkage between THM-analyses and Safety Assessment one should consider different aspects of the role of Safety Assessment. It has at least the following two roles:

- System analysis and safety evaluation – Simplifications leading to overestimates of consequences may be justified.
- Confidence building, i.e. demonstrating ability to understand the system - Needs to be based on realistic mechanistic modelling.

It should also be understood that even if the safety evaluation may be regarded as the prime objective of a safety assessment its conclusions need justification. Thus the confidence building aspects and the need to demonstrate understanding is a necessary component of Safety Assessment activities.

Safety assessment and THM(C)

In Japan the focus on Safety Assessment is on the near-field. The waste disposal concept should be robust to a large selection of host rock environments. Regarding THM-processes the attention is on interactions within the Engineered Barrier System (EBS) and interactions with FEPs in the close near-field rock.

JNC have considered FEP interactions in terms of Hierarchical FEP matrices and through influence diagrams. There is still more to be done considering the interactions between FEPs during different time frames. It is also necessary also to put more attention to the coupled chemical effects.

It is necessary to separate between the short term (less than 100 to 1000 years) and the long term. For the short term the aim is to develop a way to handle confidence building and evaluation of monitoring. Such analyses need to be supported by mechanistic (THMC) modelling and predictions. In the long term the focus should be on potential degradation of the EBS/host rock and its effect on radionuclide migration.

Monitoring

The design of the EBS builds on the THM understanding. However, this understanding may not always have been made explicit in Safety Assessment reports. Monitoring the evolution of the EBS and the nearby rock is potentially very important for the confidence in the system and in the Safety Assessment of the system.

The main objective of monitoring is to confirm that changes within the geological environment is within the acceptable ranges and that the engineering system will behave as intended. It is composed of strategic planning, acquisition, interpretation and continuous documentation of the data. It needs to function as one of the management elements of the disposal system of HLW.

Monitoring could thus be seen as a very important aspect of building confidence in the Safety Assessment, but as yet there has been limited consideration on how to design a monitoring system, which would not jeopardise the barrier functions. There is a need for further confirmation / development of the EBS monitoring and in understanding the evolution of the near-field (EBS/host rock).

The target areas for monitoring the geological environment and the EBS are first to assess the initial conditions in the undisturbed area and then to follow the evolution of the excavation disturbed zone (EDZ). The EDZ may be divided into the damaged zone, the unsaturated zone (during operational period) and the stress redistributed zone. Monitoring should comprise THMC-characteristics in order to follow the evolution of the system, in particular during the pre-closure phase.

There are several requirements that needs to be fulfilled by a monitoring system:

- development of long-durability sensors,
- confirmation of relevant range of changes for monitoring,
- level of accuracy of the sensors required to meet the quality control objectives.

Examples of issues to be considered for the degradation of EBS/Host rock are:

- impact of iron corrosion products,
- bentonite alteration,
- impact of high pH plume from cementitious materials, which would alter the water composition and thus also affect the radionuclide migration behaviour in the long term.

The relation between THM(C) and radionuclide transport essentially goes through changes in porosity, permeability and chemistry. However, it is also necessary to consider the temporal and spatial uncertainties.

Conclusions

In conclusion THM(C) models provide confidence in a representative model of performance assessment by pre-closure monitoring. THM(C) models should be extended to the long term considering the impact on radionuclide migration by including the EBS/host rock degradation. THM(C) is a the “starting model” to couple other processes considered in scenario analysis. In short THM(C) modelling and development of monitoring techniques are key points for the near future.

2.3.4 THM Aspects in the POSIVA Safety Case

At the Workshop in Naantali, Finland, T. Vieno, VTT presented an invited lecture for Task 4, with the title of THMC aspects in POSIVA's safety case. The presentation covered:

- Finnish nuclear waste disposal Programme.
- Olkiluoto site geology and groundwater condition, repository constructability.
- Olkiluoto and repository
- Backfilling and sealing with KBS-3 concept and alternatives;
- Safety concept
- THM aspects in RDD programme
- Tentative answers to the Task 4 running set of questions where also provided, see below.

The questions raised during discussion included the use of construction of the repository as a large scale experiment, the need for a baseline report prior to going underground. Other questions concerned considering land-lifting in PA modelling, uniform or non-uniform land-lifting, relevance of earthquakes, consideration of glaciation in THM – PA modelling, permafrost issues.

2.4 Issues discussed at DECOVALEX III Workshops

The PA Sessions were also used for more general discussions on the treatment of coupled T-H-M processes in safety assessments of nuclear waste repositories in crystalline and other similar hard rocks. Clearly addressing this requires a means for judging the importance of any THM process, interaction or feature in a Safety Assessment context and a means to assess its the relevance for the Safety Case? Which, performance measures are used? Are the implications of uncertainties in THM large compared with implications of other uncertainties? A set of issues evolved during the course of DECOVALEX meetings and discussions.

Below follows a compilation of these discussions. They reflect the type of discussion held in DECOVALEX rather that final view of the project. The latter is summarised in chapters 4 and 5.

Are most THM-related FEPs are both identified and sufficiently understood?

At all workshops it was concluded that it appears that most THM-related FEPs are sufficiently understood. In comparison it seems currently not worthwhile to carry out additional exercises for "FEPs identification". It seems much more important to evaluate FEPs and interactions already identified. However, if there are new repository concepts or significantly changed procedures (like an extended period of non-sealed open repository) there may be a need to reconsider this point. Furthermore, many organisations (including Posiva and SKB) plan to rea reassess the completeness of their FEP identifications.

Can we formulate workable performance measures for judging relevance of THM coupling?

The DECOVALEX group has not discussed repository performance at depth. Nevertheless, it is clear that performance measures are needed for judging the relevance of THM-effects. Possible examples of performance measures include:

- THM-evolution which may threatens integrity of EBS,
- significant short term effect on monitoring resaturation etc.,
- significant impact (more than a factor of two) on permeability after closure,
- significant impact (more than factor of two) on data collection,
- significant contribution to understanding of long term evolution.

Can the identified FEPs be managed through the appropriate combination of design, process modelling and scenario analysis?

It seems possible to manage all identified THM FEPs through an appropriate combination of design, process modelling and scenario analysis. Clearly, the uncertainties are managed to an extent allowing for repository programmes to be implemented, rather than being left in an R&D stage.

Do we need to consider coupled HM outside the near-field?

DECOVALEX has not really discussed if there is a need to consider HM-effects outside the near-field. Still, it has to be recognised that most THM effects, currently addressed, concern the short time scale and the short ranges in the repository area. (Effects from climatic changes like permafrost or glaciation do affect the far-field though).

Is there a need to couple THM with transport of RN (apart from the indirect coupling though hydrogeology)?

No evidence suggest there is a need to directly couple THM with transport of radionculides. It is the indirect coupling through hydrogeology which potentially may matter. However, there may be strong THC coupling with direct implications on radionuclide transport, but chemical coupling issues lie outside the scope (and expertise) of the DECOVALEX community.

What do we need to now as regards short term EBS evolution and monitoring and its relation to System Safety?

In most repository programmes there is an increased focus on the shorter time scales. It is likely that repositories would not be allowed to be closed, unless there has been a successful monitoring period. Monitoring is more and more seen as necessary in order to add credit to closure.

There is a need to device schemes on how to act – or not to act on certain monitoring levels. If the monitoring suggest that e.g. barrier functions are jeopardised some remedial actions or possibly retrieval of waste may be needed. On the other hand, such actions could only be motivated if the monitoring really addresses issues related to performance. Furthermore, it will never be possible to fully predict the evolution. A deviation between monitored and predicted values may not necessarily imply that there is any problem as regards safety.

Most THM disturbances are short term and small-scale effects. It could be argued that this evolution has little implication for safety as most repository concepts imply long durability containers with no or very limited radionuclide releases at the time of the THM-evolution, but the short term evolution may have implications on the long term barrier functions. For Safety Assessment modelling there is a need for exploring FEPs and FEP interactions in different time scales. It would not be possible to include all aspects in a single model.

No one has yet looked into the full PA implications of all potential THM-couplings. There may also be a risk of focusing too much on monitoring and confidence building – and too little discussion if there are in fact anything, which could really threaten the barrier functions of the repository.

Monitoring should be seen as part of the need to further enhance the understanding the evolution of the EBS/near-field rock. The following development needs are foreseen:

- There is a need to better understand the EBS/Near-field rock evolution during the (prolonged) pre-closure phase and to understand the safety implications of this evolution.
- There is a need for developing the prediction capability (i.e. modelling) of this (see above) EBS/Near-field rock evolution.
- There is a need for developing reliable ("calibration ability") instruments capable of monitoring phenomena of relevance, without jeopardising the barrier functions.
- There is a need to develop a sound basis for formulating sensible "action" levels in case monitoring results deviate from predictions.

Some of these aspects are illustrated by the various tasks within Decovalex III and it seems justified that Decovalex develops recommendations/observations in this area.

Is the interaction with the "PA-people" actually taking place within your organisation and is it used to inform, set priorities and define needed level of accuracy?

The interaction between R&D and PA-people appears to be improving in many programs. For programs entering an implementing phase there is an increased recognition of the need for interaction between engineering type people, site measurement and safety assessment people. The interaction could still be improved though.

Where should (further) THM-related R&D focus?

Some preliminary thoughts on further THM-related R&D was discussed:

- Work should continue to improve models, measurements of parameter values and confidence building.
- There are open issues in the field of gas flow and related effects and as regards importance of THMC-couplings and the design and constructability of backfill.

More developed recommendations are given in chapters 4 and 5.

3 Findings and implication of the different DECOVALEX III tasks

This chapter summarises the findings of the different Test Cases and Benchmark Test conducted within DECOVALEX III.

3.1 Introduction

DECOVALEX III has involved assessment of two major experiments (Task 1: the FEBEX experiment and Task 2: The Yucca Mountain Heater experiment) and three different BenchMark Tests (BMT1, BMT2 and BMT3). Exploring the significance of THM couplings for repository performance has certainly been the main theme of all DECOVALEX III analyses, but in particular at the BMT:s, which were specifically setup to explore the significance of THM-processes for some PA-relevant issues.
As a part of the overall evaluation of the work, each Task Force (or Test) leader assessed some PA-relevant questions as regards "their" task. These findings, given below, have been discussed at the DECOVALEX meetings following a special format.

3.2 Task 1 – Evaluation of the FEBEX in situ experiments

3.2.1 Overview

The FEBEX (Full-scale Engineered Barriers Experiment in Crystalline Host Rock) "in situ" test was installed at the Grimsel Test Site underground laboratory (Switzerland) and is a near-to-real scale simulation of the Spanish reference concept of deep geological storage in crystalline host rock. A modelling exercise, aimed at predicting field behaviour, was divided in three parts (see Alonso and Alcoverro, 2003). In Part A, predictions for both the total water inflow to the tunnel as well as the water pressure changes induced by the boring of the tunnel were required. In Part B, predictions for local field variables, such as temperature, relative humidity, pore water pressure, stresses and displacements at selected points in the bentonite, and global variables, such as the total input power to the heaters were required. In Part C, predictions for temperature, stresses, water pressures and displacements in selected points of the host rock were required. Eleven Modelling Teams from Europe, North America and Japan were involved in the analysis of the test.
Differences among approaches may be found in the constitutive models used, in the simplifications made to the balance equations and in the geometric symmetries considered. Several aspects are addressed in the paper: the basic THM physical phenomena which dominate the test response are discussed, a comparison of different modelling results with actual measurements is presented and a discussion is given to explain the success of the various predictions.

3.2.2 Main findings

In part A, based on the available geological, hydraulic and mechanical characterizations of the Site as well as on results of hydraulic tests performed on boreholes, a hydro-mechanical model for the zone around the FEBEX tunnel was to be prepared. Using this model, changes in water pressure induced by the boring of the FEBEX tunnel in the near vicinity, as well as the total water flow rate to the excavated tunnel was required.

Widely different models for water inflow were used. Some teams used uncoupled hydraulic transient models to solve the first part of the exercise, whereas others used a coupled HM modelling. It does not seem that the mechanical coupling introduces any advantage in this case. In fact, the reason for some of the better predictions may be associated with previous calibration of the model using other hydraulic data in the same area.

Pore water pressure changes in the vicinity of the tunnel excavation are a direct consequence of changes in the volumetric strain of the rock. Therefore, fully coupled hydro-mechanical analyses are required to try to capture actual measurement. In fact, one-way coupling (hydraulic parameters updated as the rock mass deforms) is not capable of reproducing the observed behaviour. However, the case has demonstrated that even if a fully HM coupled model is used, the difficulties to capture the actual pore pressure of the granitic mass are very high. It was well established that the volumetric behaviour of the rock in the vicinity of the tunnel depends critically on two aspects: the orientation and the intensity of the initial stress field. Since “in situ” stresses often show a large variability incapabilities of model predictions could partly be attributed to characterisation errors.

In part B, based on the characterization of the bentonite and on the details of the process of test installation, a thermo-hydro-mechanical model for the bentonite barrier and the heaters was to be prepared. Using this model, the thermo-hydro-mechanical response of the bentonite barrier as a result of the heat released by the heaters and the hydration from the host rock was required. Local field variables such as temperature, relative humidity, pore water pressure, stresses and displacements, as well as global variables such as total input power to the heaters was required.

Only a reduced number of modeling teams participated in this blind prediction. Models prepared to solve only the thermo-hydraulic part of the problem could not provide predictions for stress development. In some of the models phase change and vapour transfer was not considered and this limitation hampered the correct reproduction of measured variables. In fact, vapour transfer plays a dominant role in the early stages of the test. The three fully coupled models behaved in general terms in a quite satisfactory manner. They predicted quite accurately the evolution of relative humidities inside the barrier.

Stress prediction, however, has proved to be a more difficult task. There is always some concern about the actual reliability of measuring procedures. It appears that the measured radial stresses, which are essentially induced by the progressive hydration of the bentonite, are higher and develop faster than predictions, especially at the end of the considered period.

In part C, based on the characterization of the rock massif and on the details of the process of test installation and performance, the rock response in the immediate vicinity of the buffer was required. The rock was now subjected to the heat released by heaters and to swelling pressures resulting from bentonite hydration. The initial hydrological regime (Part A) is also modified by the presence of the impervious barrier.

Temperature, stresses, water pressures and displacements in selected points of the rock were required.

As in Part B, only a reduced number of modelling teams provided blind predictions for the rock behaviour, once the expansive bentonite barrier was in place. Coupled THM models are also required for this part of the Benchmark although the temperature increase plays a dominant effect on the rock behaviour.

As it is frequently the case, temperature changes are well reproduced in general terms. Rock water pressures were reasonably well predicted by three of the research teams. More limited success was achieved in the prediction of stresses and displacements.

3.2.3 Relevance to safety case?

The work is aimed at gaining confidence on predicting models for barrier performance. Clearly, the bentonite buffer and its interaction with the near-field rock is an essential component of most deep geological repository concepts. This warrants both experimental and theoretical studies as better understanding in general will support statements on the evolution of this repository component. However, for repository performance the outstanding issue is to assess the barrier performance over long times. Details in the re-saturation phase are not necessarily important unless they would imply long term remaining effects. The test case was focused on shortterm effects – and its relevance for long term effects remain to be addressed.

Performance measures?

Given that the Test Case is only indirectly connected to the safety case, i.e. through its potential for enhancing understanding, also the useful performance measures could only be indirectly connected to the ultimate needs. This means that for the Test Case a typical performance measure is to compare model predictions with actual behaviour of the benchmark experiments. Furthermore, it must be understood that gaining confidence requires not only benchmark exercises but good experimental research at a basic level (material behaviour should be understood).

3.2.4 Importance of couplings

Alonso and Alcoverro (2003) makes the following concluding remarks concerning the importance of the couplings considered:

- The development and dissipation of excess pore water pressures in the vicinity of the advancing tunnel (at the time of the FEBEX tunnel excavation) was a clear example of hydro-mechanical interaction. It was concluded that the development of pore pressures was controlled by the initial stress field state, by the rate of excavation and by the permeability and drainage properties of the granite. However, the available information on the intensity and direction of principal stresses in the area was found inconsistent with the actual measurements. The problem posed by this discrepancy was essentially unsettled since a precise determination of the initial stress state in the vicinity of the FEBEX tunnel was not available.

- Predicting the behaviour of the buffer under the combined heating and wetting actions requires a fully coupled THM formulation, which incorporates all the necessary physical processes controlling the bentonite behaviour. Only a partial set of codes could offer the required features. Particularly relevant to predict the early stages of heating was the inclusion of phase changes of water and the vapour transport. Codes incorporating these features were capable of making good predictions. It should be added that the FEBEX in situ test benefits from a comprehensive experimental information on compacted bentonite properties derived from a large variety of laboratory tests on samples and on small-scale hydration and heating cells.

These findings are summarised in Table 3-1.

Table 3-1. Task 1: Assessed Importance of Couplings

Coupling	Rating	Comments
HM and HM	High for pore water pressure	The development and dissipation of excess pore water pressures in the vicinity of the advancing tunnel is a clear example of hydro-mechanical interaction. However, the coupling did not seem important for modelling water inflow.
MT and TM	Low/Med	Stresses and deformations do not modify in a significant way thermal parameters. A limited second order effect comes through the change in porosity due to deformation Thermally induced strains significantly controls stresses in rigid/confined materials. Mechanical constitutive properties are not much affected in the range 20º-80º. Limited information beyond 100º.
THM	High in the buffer	Predicting the behaviour of the buffer under the combined heating and wetting actions requires a fully coupled THM formulation.

3.2.5 Uncertainties

Alonso and Alcoverro (2003) make the following additional concluding remarks:

- The best predictions of the water inflow into the excavated tunnel are found when the hydrogeological model is properly calibrated on the basis of other known flow measurements in the same area. The particular idealization of the rock mass (equivalent porous media, discrete fractures) plays a secondary role
- It has been shown that the hydration of the bentonite buffer was essentially independent of the heterogeneous nature of the rock hydraulic conductivity features. This is explained by the fact that the rock matrix permeability is higher than the saturated bentonite permeability. Some 3D analyses performed, where the heterogeneous permeability features of the rock have been included, tend to support also this conclusion.
- The heating of the rock resulted in a significant increase in rock stresses in the vicinity of the FEBEX tunnel. Water pressures remained however essentially unchanged. The relatively high rock permeability explains the absence of significant pore water pressure transients. Only one of the participating modelling teams was capable of achieving a consistent prediction of all the measured

variables in the rock: temperature, water pressures, rock stresses and radial displacements.

It appears that temperature changes are well reproduced in general terms, rock water pressures were reasonably well predicted, whereas more limited success was achieved in the prediction of stresses and displacements.

3.3 Task 2 - YM-drift scale heater test

3.3.1 Overview

The safety case for the proposed repository at Yucca Mountain in Nevada, USA is predicated on the natural barrier system and the engineered barrier system preventing liquid water from reaching the waste package and the waste in significant quantities, and from leaving them laden with the radionuclides in such measures. The regulations require a demonstration by Total System Performance Assessment (TSPA) that the dose received by a human being at the accessible environment will be below the prescribed level at any time during the period of performance.

Detailed heat-driven coupled processes, such as TH, THM, THC, and THMC, are not directly incorporated in the Yucca Mountain TSPA model; rather the TSPA model is abstracted from numerous detailed process models, and the coupled processes are taken into account in one or more of these process models. The Drift Scale Heater test at Yucca Mountain is a large scale field thermal test conducted to refine and calibrate the coupled process models.

In Task 2 of the DECOVALEX III project the TH, THM and THC responses in the Drift Scale Test are analyzed and studied by comparing modelling results with measurements and observations in the test. The DECOVALEX Task 2 report will reinforce the knowledge base supporting the Yucca Mountain TSPA.

3.3.2 Main findings

The main findings of the Task 2 effort in DECOVALEX III project are that the pore water in the rock leaves an indelible signature on the TH response in the form of a heat-pipe effect at the boiling temperature of water. The results of TH modelling by all three Task 2A research teams support this conclusion. However, for all teams heat-transfer is largely conduction-dominated in both the sub-boiling and above-boiling regime, with heat pipes causing a temporary lull in the temperature increase at the boiling point of water. All teams show that moisture mobilized by the heat is driven away from the heat source, primarily in the vapour phase and condenses on reaching cooler regions. The condensed liquid water, driven by gravity, generally travels downward via fractures in the rock. One or more or all of the teams use models that take into account that liquid water residing in the fractures causes a lowering of the fracture permeability of the rock. Therefore, for these teams, changes in fracture water content cause changes in fracture permeability that may be recovered as the thermal pulse dies, and liquid water drains down emptying the fractures.

As one or more or all of the teams show in the Task 2 report, the effects of THM processes are two-fold. The mechanical effects of increased temperature are changes in stress due to restrained expansion of the rock, which is also manifested as, and is measured as displacements in the rock. One or more or all of the teams show that the other effect of the expansion of the rock is closure of fracture apertures, resulting in lowering of the fracture permeability, an important parameter in the hydrologic process. This is, thus, an example of the coupled THM effect. The changes in fracture permeability due to TH and THM effects may occur at different locations in space surrounding the heat source, and as the Task 2 report shows, for one or more or all of the teams it may be possible to infer which one is which.

The other coupled process studied in Task 2 is THC, and both teams show that gases, especially CO_2 will play an important role in the Yucca Mountain repository, at least during the heating period. The CO_2 concentration directly affects the pH of the water that may come in contact with the waste packages. The chemistry of the water is largely dependent on the mineral assemblages present, and both teams show precipitation of new minerals are likely over longer periods of time, potentially causing changes in the hydrologic characteristics of the rock.

3.3.3 Relevance to safety case?

Task 2 involves developing a good understanding of heat-driven coupled processes such as TH, THM, THC and THMC surrounding a high-level nuclear waste repository. With respect to the safety case for the potential repository at Yucca Mountain, THM processes are considered to have little direct impact on the performance of the potential repository. Studying the heat-driven coupled processes enhances the thoroughness and credibility of the safety assessment by expanding and reinforcing the knowledge base supporting it.

Performance measures

At the highest level the overall performance measure is, of course, the calculated radiological risk (dose) to the public in the accessible environment within the performance period.

At a much lower level the performance measure to assess the relevance of THM processes on the safety case is the nature and quantity of seepage into the drifts and their effects on the performance of the waste package.

3.3.4 Importance of couplings

According to the assessment team, see Table 3-2, there are no highly important THM-couplings going on at the experiment. The evolution could approximately be explained with uncoupled T, H, and M analyses.

Table 3-2. Task 2: Assessed Importance of Couplings

Coupling	Rating	Comments
TH	Medium	Changes in fracture water content cause changes in fracture permeability that may be recovered as the thermal pulse dies, and liquid water drains down emptying the fractures.
TM	Low	
HT	Low	
HM	Low	
MT	Low	
MH	Low	

3.3.5 Uncertainties

The major source of uncertainties in Task 2 is characterising the rock with large spatial variability of properties, especially hydrological properties. The other source of uncertainty is in effectively modelling the consequences of THM coupling capturing all the phenomena of significance.

3.4 BMT1 (WP2) – Safety issues related to near-field T-H-M processes

3.4.1 Overview

In the definition of BMT1, it was proposed that scoping calculations be performed in order to determine how T-H-M processes can influence the flow field, as well as the structural integrity of the geological and engineered barriers in the near-field of a typical repository. The problem is further divided into three sub-tasks: BMT1A- the calibration analysis of coupled THM models and computer codes against the Kamaishi in situ THM experiments (Jing ed., 2001); BMT1B- the simulation of the generic near-field repository behavior without discrete fractures (Nguyen and Jing eds.. 2003); and BMT1C- the simulation of the generic near-field repository behavior with discrete fractures. Scooping calculations of different combinations of coupling mechanisms are performed for BMT1B and 1C, to examine their relative importance of the performance of the near-field repository.

3.4.2 Main findings

As a result of the additional calibration measures, the results from the simplified axisymmetric model used in the re-evaluation of the Kamaishi mine experiment (BM1-A) showed general improvement over the original models used in the prediction phase during the DECOVALEX II project, especially in the following aspects:

- Calculated values of temperature agree very well with the experimental values, for all teams.

- Generally improved stress and strain behaviour in the bentonite, at least qualitatively though, with the measured results.
- The water content near the heater (at point 1) is relatively well predicted by all teams, although the saturation front at the bentonite/rock interface are still predicted to advance much faster than in reality.

In general, the mechanical behaviour of the buffer is complex with forces contributing from shrinking/swelling in all part of the bentonite, external stress from the thermal expansion of the heater and rock, and internal thermal expansion of the bentonite itself. However, a reasonable prediction of the mechanical behaviour can be done if all relevant bentonite properties are known from laboratory tests.

For the typical repository considered in BMT1-B, only the fully THM analysis predicts some localized rock mass failure around the boreholes, which might in turn result in a zone of higher permeability. Other important effects of THM and HM coupling would be on the stress developed in the buffer, which would transfer to the canister and influence its stability. From a safety point of view, engineering measures could be easily carried out to minimize these coupled effects. From the results of the present work, it appears that from a technical point of view the effect of coupling will be either short lived (several decades to 100 years) and would not impact on long term (thousands to hundred of thousand years) safety issues, or could be rectified by adequate design and operation methodology (e.g. avoid over-cooling the galleries).

The influence of the host rock properties (e.g. permeability) on the long-term safety seems to be much more important than coupling, since one has much less control over these properties. However, for confidence building and demonstration purposes, a fully coupled approach is necessary to interpret monitoring data that would be collected the first few decades after repository closure, since coupled processes would prevail during that period of time.

3.4.3 Relevance to safety case?

From a safety point of view, engineering measures could be easily carried out to minimize the coupled effects. From the results of the present work, it appears that from a technical point of view the effect of coupling will be either short lived (several decades to 100 years) and would not impact on long term (thousands to hundred of thousand years) safety issues, or could be rectified by adequate design and operation methodology (e.g. avoid over-cooling the galleries).

3.4.4 Importance of couplings

Table 3-3 (Table 7.6 in BMT1B report) summarizes the effect of different degree of coupling on the key performance and safety indicators in the near field of a repository. The rating of low, medium and high is rather qualitative and arbitrary, as explained in the preceding discussion. The definitions of low, medium and high are qualitative and given in the text. This table is also dependent on the case and scenario being analyzed and no generalization should be done.

Table 3-3. BMT1: The effect of different degree of coupling on the key performance and safety indicators in the near field as assessed in BMT1 (Table 7.6 in Nguyen and Jing eds.. 2003)

	Temperature	Resaturation	Swelling stress	Rock mass stability	Rock mass permeability
THM	Low	Medium/High	High	High	Medium/high
TH	Low	Medium	-	-	Medium
TM	Low	-	Low	Low	Medium
HM		Low	High	Low	Low

From the results of the present work, it appears that from a technical point of view the effect of coupling will be either short lived (several decades to 100 years) and would not impact on long term (thousands to hundred of thousand years) safety issues, or could be rectified by adequate design and operation methodology (e.g. avoid over-cooling the galleries). The influence of the host rock properties (e.g. permeability) on the long term safety seems to be much more important than coupling, since one has much less control over these properties. However, the short term period where coupled processes are important corresponds to the repository construction and post closure monitoring periods for most disposal systems. These periods are crucial for confidence building, demonstration purposes, and public acceptance. In order to interpret and assess the monitoring data collected during the construction and post closure periods, we believe a fully coupled approach is necessary.

3.4.5 Uncertainties

The influence of the host rock properties (e.g. permeability) on the long-term safety seems to be much more important than coupling, since one has much less control over these properties. However, for confidence building and demonstration purposes, a fully coupled approach is necessary to interpret monitoring data that would be collected the first few decades after repository closure, since coupled processes would prevail during that period of time.

3.5 BMT2 (WP3) - Understanding the Impact of Upscaling THM processes on PA

3.5.1 Overview

The Benchmark Test 2 concerns the upscaling THM processes in a fractured rock mass and its significance for large-scale repository performance assessment. For and overview see Andersson et al. (2003). The work is primarily concerned with the extent to which various thermo-hydro-mechanical couplings in a fractured rock mass adjacent to a repository are significant in terms of solute transport typically calculated in large-scale repository performance assessments. Since the presence of even quite small fractures may control the hydraulic, mechanical and coupled hydro-mechanical behaviour of the rock mass, a key of the work has been to explore the extent to which these can be upscaled and represented by 'equivalent' continuum properties appropriate PA calculations.

From these general aims the BMT was set-up as a numerical study of a large scale reference problem. Analysing this reference problem should:

- help explore how different means of simplifying the geometrical detail of a site, with its implications on model parameters, ("upscaling") impacts model predictions of relevance to repository performance,
- explore to what extent the THM-coupling needs to be considered in relation to PA-measures,
- compare the uncertainties in upscaling (both to uncertainty on how to upscale or uncertainty that arises due to the upscaling processes) and consideration of THM couplings with the inherrent uncertainty and spatial variability of the site specific data.

Furthermore, it has been an essential component of the work that individual teams not only produce numerical results but are forced to make their own judgements and to provide the proper justification for their conclusions based on their analysis. It should also be understood that conclusions drawn will partly be specific to the problem analysed, in particular as it mainly concerns a 2D application. This means that specific conclusions may have limited applicability to real problems in 3D. Still the methodology used and developed within the BMT should be useful for analysing yet more complicated problems.

The reference problem concerns the far-field groundwater flow and transport for a situation where a heat producing repository is placed in a fractured rock medium. Radionuclide potentially released from the repository may migrate by the groundwater flow and thus reach the biosphere. Specific issues at stake are:

- how to assess the far-field hydraulic and transport properties when most data stem from small scale (borehole) tests,
- what is the impact of potential mechanical and hydraulic couplings, and
- if MH or HM couplings are significant how would they affect the upscaling?

The relevant data, and boundary conditions, for the rock formations and fault are based on Sellafield data. The data is in the form of statistical distributions of properties. Typically, most of the data concern measurements in small scale, whereas the problem to be studied mainly concerns the large scale.

The study concerns the impact on performance – not was is a 'strictly correct' means of making the upscaling. The significance of different assumptions and methods should thus be compared through specified measures relevant to the performance being explored (far-field flow and migration). Furthermore, also some intermediate measures, i.e. resulting upscaled parameter values are worthwhile to compare.

3.5.2 Main findings

Several conclusions can be drawn from the individual team analyses as well as from the interaction discussions held during Workshops and Task Force meetings.

Interpretation of given data constitutes a major source of uncertainty. During the course of the project it was certainly felt that these interpretation uncertainties could have a large impact on the overall modelling uncertainty.

Differences between teams in estimated effective permeability appear to depend essentially on whether the team used given apertures as input - and then calculated fracture transmissivity using the cubic law – or if the hydraulic test data were used to calibrate the fracture transmissivity distribution. Furthermore, used assumptions as regards fracture size versus aperture (or permeability) are not really validated. Different assumptions on this would, although not really tested in the Task, lead to large differences in upscaled properties.

The calculated effective rock mass deformation modulus differs between teams but all teams include the "given" value of the test case. It appears that this problem is relatively "well behaved".

Despite the preliminary nature of the HM analysis conducted, some general remarks could be made. If modelling uses relaxed initial apertures as input the HM coupling is essential for capturing realistic permeabilities at depth. However, this does not necessarily imply that the HM couplings need to be considered. The fact that the aperture versus stress relation reaches a threshold value indicates that the more normal practice of fitting hydraulic properties to results of hydraulic tests is warranted! A key process, where there still is uncertainty is the relation between hydraulic residual aperture and maximum mechanical aperture, Rb. Evidently this has a strong influence on the impact of the HM coupling. Related to this is the indication found on the significance of the increase of differential stress results in increasing the permeability (when applying the non-linear stiffness model for fractures) and in channelling of flow path (potentially caused by fracture dilation).

Despite the relatively limited amount of large scale analyses conducted within the Task, some general remarks seem possible. It is suggested the stress is so high at the depth of the repository that fractures are almost completely compressed mechanically and the permeability is approaching its residual value. Therefore further stress increase due to thermal stresses would not significantly reduce the permeability. Also the TH effects, due to buoyancy, are relatively limited and would add an uncertainty in the order of a factor of 2 or so.

These observations support the conclusion that it is the uspcaling of hydraulic properties rather than the added complication of T and M couplings, which are the main sources of uncertainty in a problem of this nature. The added disturbance, in relation to in-site stress, is small in the far-field of a deep repository. Yet, understanding the stress/permeability relation is important for understanding the nature of the permeability field.

It can also be noted that most conclusions to be drawn from the large scale analyses could already be drawn from studying the intermediate performance measures such as permeability, deformation modulus and k versus stress relations.

3.5.3 Relevance to safety case?

The scale of PA-models, or at least far-field radionuclide transport models, is usually large compared to the scale where there is some understanding and data on HM couplings. This raises several issues:

- How should coupled processes and associated parameters be upscaled?

- Are the HM couplings significant in relation to the geometrical factors controlling the upscaling of permeability and rock mass mechanical properties (such as deformation modulus)?
- Are couplings at all significant compared to other uncertainties (network geometry, hydraulic properties, fracture constitutive laws)?
- What are the Site Characterisation Implications?

BMT2 is designed to address these issues.

Performance measures

Ultimately, the performance measure for a repository PA would be doses or risk, however, in order not to introduce too many assumptions about the waste, release mechanisms or the retention properties of different species the general performance measures being studied here are restricted to the groundwater specific contribution to retention. The research teams were thus asked to predict:

- Flow related migration parameter in the form of "transit time distributions" and "transport resistance distributions" at two output surfaces.
- Intermediate results of upscaling (effective parameters) like effective permeability and rock mass deformation modulus for different block sizes.

3.5.4 Importance of couplings

Table 3-4 displays the assessed importance of the different couplings in BMT2. In short it is not evident that there are any highly significant THM couplings to be considered for this problem. Upscaling permeability from small scale measurements is indeed a difficult task, but there is little evidence from the test case suggesting the upscaling also needs to consider the added complexity of the THM-coupled effects.

Table 3-4. BMT 2: Assessed Importance of Couplings

Coupling	Rating	Comments
TH	Low	Not significant in large scale
TM	Low	
HAT	Low	
HM	Potentially important	Considered potentially significant. Important starting point in DFN upscaling. Not necessary to consider given other uncertainties, and given that hydraulic data is sampled at appropriate depths.
MT	Low	
MH	Potentially important	See HM

3.5.5 Uncertainties

It appears that the main uncertainties encountered in BMT 2 concern upscaling the parameters of individual processes. The currently listed major uncertainties include:

- Conceptualisation if fracture network data (the resulting upscaling is also very sensitive to this)
- Results sensitive to interpretation of fracture data
- Software limitations especially with hydromechanical codes

THM uncertainty in relation to other uncertainties

The findings certainly suggest that the THM uncertainties in this case are small in relation to the upscaling and geometrical uncertainties explored.

3.6 BMT3 (WP4) – Handling Glaciation in the Safety Case

3.6.1 Overview

BMT3, see Boulton et al (2003) for an overview, is primarily concerned with the coupled hydro-mechanical (HM) impacts of one or more cycles of glaciation and deglaciation on the long-term (up to 100 000 years), post-closure performance of the geosphere in which a repository is located. A performance assessment of a deep repository consists of an analysis of the changes through time in the disposal facility as a consequence of both internal and external forces. Groups of coupled processes are linked together in a description of integrated evolution through time. The primary purpose of BMT3 is to develop modelling tools at a site scale for simulation of climate driven boundary conditions (ice sheet loading, groundwater hydraulics and permafrost) and to illustrate the magnitude of some T-M-H impacts in the far field in the context of a PA. The objectives of the BMT are therefore:

- to study, by analytical and/or numerical modelling the impact of a 100 ka glaciation-deglaciation cycle on the long-term evolution of a fractured rock mass in which a generic repository is located;
- to assess the impact of the glaciation/deglaciation cycle on the coupled thermo-hydro-mechanical responses of the far field system around a repository and on its long-term performance in waste isolation;
- to investigate/demonstrate the technical feasibility of deep geological disposal in hard rocks and improve the scientific basis for safety assessment and the strengthening of public confidence in safety assessment methodology.

The involved teams have focused on simulating glaciation in a way that can be tested by geological observations, and applied the model to suggest subsurface impacts at specific sites to explore the implications for safety assessments. Simulations have been conducted for two sites, the Äspö site in Sweden and the Whiteshell site in Canada, designed to explore the impact of the growth and decay during the last glacial cycle of permafrost and ice sheet development. The successive steps in the simulations are:

- Step 1 – Simulation of the climate drive, where the pattern of climate change is derived from the record from the Greenland ice sheet, adapted to the region using palaeo-climatic data from southern Canada and the northern USA and synoptic extrapolations.

- Step 2 – Ice sheet loading and basal thermal and hydrological regime using a thermo-mechanically coupled, transient ice sheet model (Boulton and Payne, 1994). The model is coupled with the Earth model of Lambeck et al (1998) and driven by the climate function over a prescribed topography. The model computes the temperature at the base of the ice sheet and the rate of basal melting in time and space.
- Step 3 – Determination of permafrost distribution using a transient model of permafrost development (Mikkola & Hartikainen, 2001). The model is driven directly by the climate function when there is no ice sheet present and when the ice overrides the site, the temperature at the base of the ice sheet is used as a boundary condition for permafrost development.
- Step 4 – Simulation of groundwater flow, pressures and states of geosphere stress. The coupling between the permafrost and ice sheet are used to determine the transient response of the groundwater system and the state of rock stress along a 2D section parallel to ice flow. Investigation of groundwater flow and geosphere stresses and strains have also been undertaken for steady state and transient conditions along sections both parallel and transverse to ice flow using the ABAQUS and MOTIF codes.

3.6.2 Main findings

The climate function is used to drive a glaciological model of the Laurentide ice sheet through the last glacial cycle. It suggests that the Whiteshell site was glaciated at about 60ka and during the glacial maximum, between about 22.5ka and 11ka, which is compatible with geological evidence from the region. The maximum ice sheet thickness at the site is modelled as 3000m, which is likely to be an over-estimate. The model computes basal melt rates, and from a simplified, 1D description of hydraulic conductivity, computes the spacing of subglacial channels that would be required to drain the ice sheet bed.

The longitudinal head gradients associated with the ice front and the transverse gradients associated with channels are much greater than modern gradient. This will create flow velocities one to two orders of magnitude faster than modern values and generate strong vertical flow components. Furthermore, the computed ground surface temperature at the ice/bed interface, at 60ka and between 22ka and 11ka are higher than extra-glacial temperatures because of the insulating and heating effect of the ice sheet.

The temperature forcing function has been used to compute the evolution of permafrost thickness through the glacial cycle, together with unfrozen water content, the increase of salinity due to freezing and the magnitude of frost heave. Computed permafrost depths are of the same order as anticipated repository depths. Permafrost progressively decays beneath the glacier.

Strong groundwater flows, up to 2 orders of magnitude greater than in the non-glacial state, are generated beneath the glacier and beneath permafrost that extends beneath the glacier. Where permafrost is thin, significant water overpressures can develop and are enough to generate hydraulic jacking of bedrock. The consequences of glaciation at greater depth are:

- A rapid increase of head during the first 1000 years of glaciation.
- A rapid transmission of these heads through the fracture systems, producing much higher early, transient heads than in the repository zone.
- During the glacier advance over the site, there is a large horizontal hydraulic gradient due to compression of pores by ice loading.
- As the area is completely covered by the ice sheet, a strong downwards hydraulic gradient develops , of as much as 3-5 m/m.
- At depth the excess water pressure is about 1/3 of the ice pressure.
- During ice sheet retreat, the gradient reverses, and is sustained, together with residual excess pressures of as much as 250m at 800m depth.
- Pressures in fracture zones decay rapidly after deglaciation.

The change in effective stress is relatively small as the increase in ice load is largely compensated by the increased groundwater head (however, there is a transient effect, as the former is instantaneous whilst the latter diffuses through the system). There is therefore very little rotation of principal effective stresses. Even in dead-end horizontal fractures, there is no generation of tensile stresses and therefore no hydraulic jacking at depth. No shear failure is predicted.

3.6.3 Relevance to safety case?

Boulton et al (2003) conclude that safety assessments of the disposal of long lived radioactive wastes in the middle to high latitudes of the northern hemisphere must recognise that these areas have been repeatedly glaciated in the recent geological past, and that were it not for the prospect of human induced global warming, would expect an imminent descent into glaciation.

Glaciation has the potential to influence strongly the geosphere to the preferred depths for deep disposal sites of between 500 and 1000m. The strongest potential impacts in periods of glaciation are associated with the extension of ice sheets in and perennial ground freezing to create “permafrost” to depths of several hundred metres. The involved processes are the product of a system driven by the Earth’s climate and characterised by strong thermo-hydro-mechanical coupling, in which both chemical processes and transient phenomena are important.

Boulton et al. (2003) also conclude that although models of glacier-groundwater, glacier-permafrost-groundwater, glacier-groundwater-shallow failure systems have been presented (e.g. Boulton et al, 1995), BMT3 is the first attempt to assess impacts at repository depths using site specific data. The results provide valuable insights into the magnitude and rate of change of site-specific hydrogeologic and geomechanical properties in response to external, transient climate forcing.

The most important general conclusions of BMT2 are that:

- glaciation occur on a depth scale that is relevant to the safety of repositories buried several 100m beneath the surface;
- glaciation occur on timescales that are relevant to safety assessments for long lived waste,
- and assessed impacts implies transient but several orders of magnitude effects on groundwater flow.

Boulton et al. (2003) thus conclude that the coupled processes connected to glaciation must be considered in safety assessments.

3.6.4 Importance of couplings

While the analysis points out several potentially important effects of future glaciations, still only some THM couplings need to be considered. For the analyses of the Whiteshell site Boulton et al. (2003) conclude that:

- the Hydro-Mechanical coupling effects on pore pressure is significant as there are high residual pore pressure for 1000s of years after glacier has retreated from the site,
- the thermal impact on hydrology and mechanics may be significant in terms of permafrost since permafrost may develop at repository depths,
- the Hydro-Mechanical impact in terms of potential hydraulic jacking at depth is unlikely to be important,
- the impact on stress and mechanical stability at depth is minor.

Table 3-5 displays the assessed importance of the different couplings in BMT3. In addition Boulton et al. remarks that the BMT used used four separate components, a climate model, an ice sheet-earth model, a permafrost model and an earth hydro-mechanical earth model. The ice sheet-permafrost models are weakly coupled but the climate and hydro-mechanical earth models are uncoupled from other components. The development of a model in which the system is fully coupled and driven only by global climate, with feedbacks between the ice sheet and local climate is necessary if the full consequences of coupling are to be understood.

Table 3-5. BMT 3: Assessed Importance of Couplings

Coupling	Rating	Comments
TH, HT	Low (High in terms of permafrost)	the thermal impact on hydrology and mechanics may be significant in terms of permafrost since permafrost may develop at repository depths;
TM, MT	Low (High in terms of permafrost)	see above
HM, MH pore pressure	High	high residual pore pressure for 1000s of years after glacier has retreated from the site
HM, MH hydraulic jacking and stress	Low	the Hydro-Mechanical impact in terms of potential hydraulic jacking at depth is unlikely to be important; the impact on stress and mechanical stability at depth is minor;

3.6.5 Uncertainties

The modelling teams note the following main uncertainties related to BMT 3.

- External climate driving ice sheet model.

- Site specific properties (rock type, fracture network geometry & connectivity, hydraulic properties, fracture zone strength) and scaling.
- Boundary Conditions, especially the hydraulic and mechanical state in the ice and in the bedrock at the ice/bedrock boundary, but also the hydraulic boundary conditions at the vertical boundaries.
- Model approximations, e.g. no k(?), no θ (?), influence of salinity on flow omitted, representation of permafrost in HM models, Mesh fineness, model size.

THM uncertainty in relation to other uncertainties

The modelling teams suggest the importance of e.g. spatial variability of rock mass permeability in relation to the process uncertainty is difficult to assess. The uncertainties due to THM coupling are not a subset of uncertainties due to spatial variability. It is judged that the two types of uncertainties are comparable in magnitude for the BMT3 case.

4 Discussion on lessons learned

Both discussions at workshops and findings from the individual DECOVALEX III Tasks demonstrate that the significance of THM couplings is case dependent. This chapter reports some observations and lessons learned from discussions at DECOVALEX workshops and individual Task Force meetings.

4.1 Judging relevance – performance measures

Although the geosphere is a system of fully coupled processes, this does not directly imply that all existing coupled mechanisms must be represented numerically. Modelling is conducted for specific purposes and the required confidence level should be considered. It is necessary to match the confidence level with the modelling objective. For a given underground construction, only some geosphere responses directly affect its function, and minor mistakes made in design may be correctable during the construction phase. In other cases, knowledge of the long term evolution of the geosphere may be required and the associated prediction may require consideration of a wide range of couplings. The modelling style and content depends on the objectives — which are to be judged, inter alia, against performance measures and the confidence required, given the available capabilities in terms of codes and data.

In engineering and applied science it is appropriate, not to judge a model by whether it is absolutely true or not, but to what extent it is relevant to the issues being explored. In order to quantify this, performance measures should be identified, making it possible to explore how assumptions, uncertainties and confidence affect the issues of concern. Useful performance measures should be sought in the context of model predictions that may affect decisions. The decisions may concern a wide range of issues e.g. licensing a nuclear waste repository, selecting a proper grouting scheme or deciding whether a scientific investigation is good enough for publication. A common performance measure for a nuclear waste repository is the yearly risk of death to an individual due to the repository evolution and potential radionuclide releases. Such overall performance measures are usually to be found in regulations. However, useful performance measures can also be related to intermediate conditions potentially affecting these ultimate measures.

The key impact of T-H-M processes as regards repository performance is of course disposal concept and site dependent. Nevertheless, the following T-H-M-related conditions often are linked to overall repository performance:

- the water pressure or water content in buffer and rock
- temperature in buffer and rock,
- formation and properties of an EDZ,
- T-H-M effects on parameter estimation from site or laboratory experiments,
- mechanical stability of emplacement drifts
- significant changes of permeability (temporal and permanent)

In conclusion, when assessing importance of T-H-M for repository performance, care is needed to formulate relevant yet revealing performance measures against which to assess the outcome of the analysis.

4.2 Identification of T-H-M processes

During the course of DECOVALEX III there has been little reason to alter the conclusion made already at the beginning of the work that: *Most processes/issues (i.e. FEPs) where there potentially is need to consider T-H-M-couplings for the currently considered waste disposal concepts are identified.*

However, there is still a need to evaluate to what extent potentially important processes or couplings actually need to be included in an assessment. It is not necessary to develop an all-encompassing model: it is only necessary to include those interactions that will significantly affect the predictive capability. Whether a particular interaction is required to be represented in the computer model depends on the significance of the interaction, given the objective of the modelling.

Furthermore, the uncertainty stemming for potential improper incorporation of coupled processes has to be weighed against the importance of other uncertainties. In particular spatial variability of properties is often a very important source of uncertainty in geologic media. While spatial variability itself is not uncertainty it causes uncertainty as it put high demands on measurements and measurement density. In many crystalline rock applications uncertainties related to spatial variability of e.g. permeability is significantly larger than the uncertainty caused by neglecting HM effects.

Another aspect of model uncertainty in geologic media concerns the basic principles for describing the host rock mass. Among geologists, such principles are often called the conceptual model of the rock mass. Examples of different conceptual models of the rock may be 'typical Swedish low fractured crystalline rock', 'complex deformation zones', 'sedimentary rock', volcanic regions', 'high stress rock' etc. Clearly, the conceptual model affects how data are interpreted and the overall confidence in the system description.

4.3 Examples where T-H-M couplings need to be considered in Safety Assessments

Generally, it appears that the needs for coupled modelling in repository performance assessment are quite well understood. Still, uncertainties remain. The DECOVALEX experiences provide some insight to what extent THM couplings needs to be explicitly included when modelling some performance assessment relevant phenomena with focus on crystalline and other similar hard rock formations. However, the DECOVALEX experience has its limits. Other observations may result in other types of geologic media (notable argillaceous formation) and other performance assessment issues may need to be considered. list of examples is not exhaustive. There may be other modelling needs in performance assessment. Nevertheless, the general approach applied within DECOVALEX may still be applicable in judging the need to include TMH couplings in other cases as well.

4.3.1 Near-field effects

The disturbance caused by a waste repository in terms of e.g. excavation, heat or swelling pressure is most profound in the near-field. This also means that it is in the near-field one would expect the most direct examples of coupled THM-processes affecting performance. DECOVALEX III has also assessed several such potentially important couplings.

Resaturation of the buffer

Task 1 concludes that predicting the behaviour of the buffer under the combined heating and wetting actions requires a fully coupled THM formulation, which incorporates all the necessary physical processes controlling the bentonite behaviour. Particularly relevant to predict the early stages of heating was the inclusion of phase changes of water and the vapour transport. Codes incorporating these features were capable of making good predictions. Understanding the resaturation is important also in safety assessments. However, the only safety implications would occur if the resaturation process implied any long term effects. In many assessments, where container failures happen long after the saturation, the details of the resaturation phase are inconsequential.

Interactions between rock and EBS

The analysis of Task 1, Task 2 and BMT1 demonstrates the saturation of the buffer between the heat producing waste container and the near field rock involves the interaction between heat, vapour, flowing water transport and stress. However, this does not necessarily mean that these couplings need to be considered in the Safety Assessment modelling.

Task 1 demonstrates that the development and dissipation of excess pore water pressures in the vicinity of the advancing tunnel is a clear example of hydro-mechanical interaction. However the development of pore pressures depends on the initial stress field state, which may be more uncertain than the impact of the coupling.
According to the assessment team of Task 2 there were no highly important THM-couplings going on at the experiment. The evolution could approximately be explained with uncoupled T, H, and M analyses.

For the typical repository considered in BMT1-B, only the fully THM analysis predicts some localized rock mass failure around the boreholes, which might in turn result in a zone of higher permeability. Other important effects of THM and HM coupling would be on the stress developed in the buffer, which would transfer to the canister and influence its stability. However, from a safety point of view, engineering measures could be easily carried out to minimize these coupled effects. From the results of the present work, it appears that from a technical point of view the effect of coupling will be either short lived (several decades to 100 years) and would not impact on long term (thousands to hundred of thousand years) safety issues, or could be rectified by adequate design and operation methodology (e.g. avoid over-cooling the galleries).
In general, it seems that the influence of the host rock properties (e.g. permeability) on the long-term safety seems to be much more important than coupling, since one has much less control over these properties. However, for confidence building and demonstration purposes, the coupled effect should be considered.

Long term mechanical stability of disposal vaults

Other potential coupled effects concerns the long term mechanical stability of the disposal vaults. However, this issue has not really been studied within the DECOVALEX III framework.

4.3.2 Far-field effects

The direct repository disturbance affects the near-field. However, despite the heterogeneous nature of the geosphere and the resultant uncertainty in predictions of long-term barrier performance there are still sound lessons in the far-field BMT's. Furthermore, there are potential implications for future site characterisation efforts (see section 4.4).

Groundwater flow in the far-field
The analyses of BMT2 in particular, suggest that modelling groundwater flow in the far-field would generally not need to consider mechanical or thermal impacts, even thought they exist. The effects are small in relation to performance measures and the uncertainties due to spatial variability. However, in understanding the permeability field and its anisotropy, coupled effects may be crucial, as processes like fracture dilatation caused by past stress changes may have a large impact.

Future large scale events (glaciation and permafrost.)
Bench Mark Test 3 of DECOVALEX III demonstrates that future large scale events, like glaciations and permafrost, will mobilise several processes and couplings. Still, it is not evident that all these processes actually need to be modelled, since the details of the glaciation may have little impact on actual performance. Nevertheless, further assessment of the processes affecting hard rock formations during glaciations and other extreme climate effects, like deep permafrost, are warranted.

Need to consider THM directly when modelling radionuclide transport?
Radionuclide transport through the geosphere is essentially controlled by the groundwater flow and the interaction between the flowing water and the solid phase (Neretnieks, 1980). The latter includes processes like diffusion into an immobile rock matrix and sorption (and related processes) onto fractures and mineral surfaces.
In some cases THM related couplings affect the groundwater flow. Examples of this studied in DECOVALEX include the Benchmarks tests (1 to 3) of Task 3. However, in none of these cases were the T or M impacts on H anything but secondary (see previous paragraphs).

TM impacts on the rock matrix aspects of radionuclide migration have not been explored within DECOVALEX, but the effects, if any are judged to be small. In fact, retardation is only sensitive to the square root of matrix diffusivities or sorption coefficients (see e.g. Hedin 2002).
In conclusion, it seems that THM impact on radionuclide migration is manifested through potential THM impacts on the flow. Little suggests other THM couplings need to be considered when modelling radionuclide migration.

4.4 Implications on site characterisation.

There are also coupling implications as regards site characterisation. This concerns the formulation of an appropriate conceptual model and how to interpret what is actually measured in a field test.

Stress-strain relations are important for formulating a reasonable conceptual model of permeability in hard rock formations. For example, a too simplistic stress-permeability relation may suggest an ever decreasing permeability with depth, in contrast to what is actually observed where permeability 'levels off' at depth. In the past there were several examples, see e.g. KBS-3 (1984) of permeability-depth relations used in PA where permeability at depth was extrapolated far outside the measured range as an ever decreasing potential function. Today modern stress-permeability relations include the concept of a 'residual' permeability and the past extrapolation models have been discarded (see e.g. Walker et al., 1998). Such latter model makes much more sense when compared with field data.

As demonstrated both in BMT1 and BMT2 a key process, where there still is uncertainty is the relation between hydraulic residual aperture and maximum mechanical aperture, Rb. Evidently this has a strong influence on the impact of the HM coupling. Related to this is the indication found in BMT2 on the significance of the increase of differential stress results in increasing the permeability (when applying the non-linear stiffness model for fractures) and in channelling of flow path (potentially caused by fracture dilation).

Still, even if understanding coupled phenomena is crucial for formulating appropriate conceptual models, this does not necessarily imply that the actual data analysis needs to be conducted with coupled codes. For example, if modelling uses relaxed initial apertures as input the HM coupling is essential for capturing realistic permeability at depth. However, this does not necessarily imply that the HM couplings need to be considered. The fact that the aperture versus stress relation reaches a threshold value indicates that the more normal practice of fitting hydraulic properties to results of hydraulic tests is warranted! Furthermore, it is also essential to assess data uncertainty and spatial variability. For example, in the BMT2, the means of interpreting fracture information caused more uncertainty than the potential HM-coupling (Andersson et al., 2003).

4.5 T-H-M related to monitoring, retrievability and closure

Coupled processes need also be considered in relation to short term monitoring. Arguably, it will be necessary to explain and predict monitored changes at a repository site, even if these changes may not have implications for repository safety. Confidence in the safety predictions may be in jeopardy in case observed changes in the short term are not reasonably understood. Here, more coupled phenomena, including chemical couplings, may potentially be significant. For example, changes in the water inflow to underground openings are likely to be a function of chemical effects and flow (e.g. precipitation of calcite from water migrating to the drifts), but possibly also for mechanical interactions. Still long term monitoring needs to be connected to issues of relevance to performance. Also decisions not to seal a repository or to retrieve waste from it have long term implications, and such decisions should only be made in case they really can be justified.

4.6 Reporting Safety Assessments - the Safety Case

In making the Safety Case of geological disposal considering THM processes is important for demonstrating understanding. It is necessary for scientific credibility in general but also for the demonstration of the confidence in the understanding of the system. Performance and safety assessments are built around simplifying abstractions (rather than assumptions). It is necessary to acquire a knowledge base supporting an understanding of how the hydrological system works, in order to construct the abstractions. Regardless of the approach selected to PA/SA, evidence should be provided to substantiate simplifying assumptions that consider both time and space. The knowledge base needs to be presented, and reasonable conclusions should be drawn, directly in the PA/SA report.

5 Conclusions

The full development of T-H-M modelling is still at an early stage and it is not evident whether current codes provide the information that is required. However, although the geosphere is a system of fully coupled processes, this does not directly imply that all existing coupled mechanisms must be represented numerically. Modelling is conducted for specific purposes and the required confidence level should be considered. It is necessary to match the confidence level with the modelling objective. Coupled THM modelling has to incorporate uncertainties. These uncertainties mainly concern uncertainties in the conceptual model and uncertainty in data. Assessing data uncertainty is important when judging the need to model coupled processes, but also the confidence in the prediction need to be assessed. Confidence is essentially a qualitative entity, but judgement of confidence can be based on several specific analyses. Even if comparing THM models with real data is a fundamentally difficult problem, it is not impossible, as demonstrated by Task 1 and Task 2 of DECOVALEX III.

The emphasis on the need for THM modelling differs among disciplines. For geological radioactive waste disposal in crystalline and other similar hard rock formations DECOVALEX III shows it is essential to:

- understand the stress-permeability couplings when interpreting stress and permeability field data,
- understand the coupled processes involved in the re-saturation of the near-field,
- understand the coupled processes involved in the development of an Excavated Disturbed Zone and
- understand the coupled processes involved in the impact of large-scale and significant climatic events, like glaciations and permafrost.

Other couplings may have less direct impact on performance, especially when considered against other uncertainties, and need not be directly included in simulation codes. However, the relatively little importance of THM couplings in hard rock formations is not true for other rock types. For example, performance assessments for potential repositories in argillaceous rock (see e.g. Nagra 2002) include substantial consideration of coupled phenomena – and their effects are essential for performance. Generally, all applications concerned with the rock mass need to at least consider the THM couplings.

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Appendix A

DECOVALEX III Task 4
T-H-M in Safety and Performance Assessment Applications
Compilation of answers

Editor: Johan Andersson, JA Streamflow AB

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A1. Introduction

A part (Task 4) of the International DECOVALEX III project on coupled thermo-hydro-mechanical (T-H-M) processes focuses on T-H-M modelling applications in safety and performance assessment of deep geological nuclear waste repositories. A previous phase, DECOVALEX II, saw a need to improve such modelling (Stephansson et al., 1999). But it was also realised that before making useful recommendation on how to develop such modelling, the assembled knowledge on how T-H-M has been treated in existing performance and safety assessments, first needs to be established.

The current document compiles answers to a questionnaire sent out to the eight participating organisations, see table 2-1. A copy of the Questionnaire is enclosed as Appendix 1. The questionnaire was issued on November 1999 and replies have been received between January 2000 and February, 2001. This report therefore represents the state at that time.

The compilation and the questionnaire focus on T-H-M processes with implications for the long-term performance and safety of deep nuclear waste repositories. The following limitations in scope apply:

- The study concerns repositories in fractured crystalline rock or in other similar rock types.
- The study focuses on processes in the rock and on the interaction between the rock and the Engineered Barriers. Processes only occurring in the Engineered Barriers are not discussed.
- The study focuses on mechanical processes and couplings involving mechanical processes. It does not concern uncoupled hydrogeological analyses or coupled hydro-chemical analyses (these processes and couplings are extensively treated in other fora).

It needs also be stated that many of the T-H-M issues discussed in the report are addressed within the DECOVALEX III project. Conclusions from these or other recent studies are not considered in the current report.

A2. Context

Table A2-1 lists the repository concepts, i.e. waste type, waste form, type of rock and general vault geometry considered by respondents. All respondents consider heat producing waste emplaced in vaults constructed at 300 m to 800 m depth in hard (strong) rock formations. The waste type and waste form varies as a consequence of the different national nuclear programmes. The waste types range from spent nuclear fuel, high-level reprocessed waste (HLW) to heat producing intermediate level waste (ILW). The waste is placed in containers of varying durability ranging from different kind of canisters (copper/steel, steel canister, steel overpack, etc.) suitable for spent fuel or vitrified HLW, to steel or concrete containers more suitable for ILW. Most concepts (apart from the US in Yucca Mountain) plan using a repository layout ensuring temperatures below 100 °C. The US is also investigating a repository at lower temperature. All respondents consider hard rock formations as the geologic medium. For all, but the US plans, the repository will be placed deep in the saturated zone. Even if the waste type varies between respondents, the type of rock and the potential thermo-mechanic impact on the rock is fairly similar between respondents. The suggested US concept is an exception, though. Still, the basic processes are the same for all concepts. Consequently, it should be possible to draw some general conclusions on the needs/possibility to handle T-H-M-couplings by learning from experiences of other programmes.

Table A2-1: Repository concepts considered by respondents(Continued on the next page)

Organisation	Waste type and waste form	Type of rock and repository depth	Disposal geometry, buffer, etc
CNSC[1]	Spent nuclear fuel from CANDU reactors. Maximum temperature should be less than 100°C	Granitic rock of the Canadian shield; 500-1000 m depth	In-room or in-floor disposal; vault would cover an area of roughly 2 km x 2 km
JNC	HLW vitrified. 40,000 waste packages with a storage period of 50 years. The initial amount of heat production from one waste package is 350 W. Diameter, height and weight of waste packages: 430mm,1340 mm and 500kg	Disposal site has not been determined in Japan, yet. A range of the physical properties of the rock mass is evaluated by classifying the rock mass into different groups from an engineering perspective. The mechanical properties for hard rock are taken as crystalline rock and Pre-Neogene sedimentary rock. The disposal depth is set by a wide range of technology and material property factors. The disposal depth selected for the design investigation is 1 000 m for the hard rock.	The disposal tunnel horizontal emplacement method and the disposal pit vertical emplacement method are used as reference examples for the review of waste package emplacement type.
Nirex	ILW and some LLW. Moderately heat generating (max. vault temperatures of ~80C). Wastes will be placed in steel or concrete containers conditioned with cementitious grout.	Nirex was originally investigating the suitability of strong, fractured low-permeability rocks at a depth of ~650 m at Sellafield, west Cumbria. Since 1997 Nirex is now considering construction of a generally similar repository in a wider range of rock types	Waste placed in vaults backfilled with a specially designed cementitious backfill.

[1] the Canadian Nuclear Safety Commission

Organisation	Waste type and waste form	Type of rock and repository depth	Disposal geometry, buffer, etc
		along with a consideration of other management options.	
OPG[2]	CANDU (CANada Deuterium Uranium) reactor fuel; sealed in a long-lived corrosion resistant, self-supporting containers. In case studies the maximum temperature was designed to be below 100°C.	An engineered repository excavated at a depth of 500 to 1000 m in stable plutonic rock of the Canadian Shield	Waste containers emplaced in a disposal repository or in boreholes drilled from the rooms; Containers are surrounded by a buffer (bentonite-sand mixture); Each room is sealed with backfill (mixture of crushed rock and glacial lake clay or mixture of sand and bentonite) and other repository seals (e.g., concrete bulk head). Tunnels, shafts and exploration boreholes are ultimately sealed in such a way that long-term safety would not depend on institutional controls.
SKB	Spent nuclear fuel disposal in copper-iron canisters. Maximum temperature design to stay below 100°C	In the crystalline bedrock in Sweden at the depth of about 500 m. Currently three different sites are suggested for Site Investigation.	KBS-3 type repository where canisters are emplaced in vertical deposition holes with pre-compacted bentonite buffer. Alternative repository designs analysed include, for example, horizontal emplacement of canisters.
STUK [3]	Spent nuclear fuel disposal in copper-iron canisters. Maximum temperature design to stay below 100°C	In the crystalline bedrock at Olkiluoto at the depth of about 500 metres	KBS-3 type repository where canisters are emplaced in vertical deposition holes with pre-compacted bentonite buffer. Alternative repository designs analysed include, for example, horizontal emplacement of canisters.
USDOE	Spent fuel and HLW (defence waste) contained in large metal containers.	Potential sub-surface repository at Yucca Mountain in Nevada. Yucca Mountain is underlain by 1000 to 1500 meters of volcanic tuffs formed from the ash of eruptions occurring 8 to 16 million years ago. The repository will be 200 to 350 meters below the surface in the unsaturated tuffs, more than 300 meters above the water table.	A series of emplacement drifts. The central premise behind selecting it as a potential site for a high level nuclear waste repository is that little water will reach the waste packages and little water will leave the packages after contacting the waste. Drip shields.
USNRC	See USDOE answer. (The U.S. Department of Energy is responsible for the design, construction, and operation of the U.S. HLW disposal program. The U.S. Nuclear Regulatory Commission has the regulatory responsibility).	See USDOE answer	See USDOE answer

[2] The OPG answer has been prepared jointly by a team with participants from Ontario Power Generating (OPG) and Atomic Energy of Canada Limited (AECL)

[3] STUK established a team consisting of participants from STUK, VTT, Posiva Oy and Saanio & Riekkola Consulting Engineers Oy to provide the answers to the questionnaire.

A3. Means of identifying T-H-M issues to be considered in PA/SA

Generally, it seems that most organisations believe they have identified which processes and couplings they would eventually need to explore. Many, but not all have also applied formal FEP identification procedures. However, it seems that most processes and coupling needs have been identified long before these formal exercises were undertaken.

A3.1 FEPs analyses

Quite a few of the responding organisations have applied formal structured procedures for FEP recognition such as interaction matrices (RES), influence diagrams (PID) or simply audit against different (international) FEPs-list. There are examples of a structured approach of developing the repository concepts starting from general design requirements (ensure safety while preventing over-conservatism, taking into account the required functions of barriers, achievable technologies and existing geological environments) to select suitable repository concepts (especially the EBS). Analyses of the long-term integrity of the EBS and the integrated systems are conducted. The key issues concerning T-H-M in PA/SA are selected by using FEPs and Process Influence diagrams. However, according to other respondents formal FEP exercises did not reveal processes or issues not already known to be important.

Compilation of answers

JNC developed design requirements so as to ensure safety while preventing over-conservatism, taking into account the required functions of barriers, currently available engineering technologies and technological advances expected in the near future, as well as economic feasibility. In developing the design requirements, the characteristics of the geological environments of Japan and their relationship with the performance assessment of the geological disposal system are also taken into consideration. Thus, the design requirements are sufficiently flexible to be tailored to these considerations. Design requirements relating to specifications for each component of the EBS and the disposal facility are selected from the foregoing design requirements, and combinations of these design requirements are logically made following a unified strategy to ensure safety of the integrated repository system. In determining each specification, the design scheme is improved and rationalized based on realistic design analyses of the various combinations. Specifications that are determined to meet the design requirements based on the design strategy may have a certain range of permissible values. Example specifications of the EBS and the disposal facility are discussed, recognizing the diversity of geological environments and natural phenomena in Japan, the uncertainty of data and the need for sufficient safety margins for system performance. In addition, analyses of the long-term integrity of the EBS must be conducted. The results of these analyses are integrated into the safety assessment and must be reflected in the specifications of the EBS and the disposal facility. Next, the key issues concerning T-H-M in PA/SA are selected by using the FEP and PID, as follows; Phenomena of engineered barrier with resaturation, Deformation of near field due to rock creep and

overpack corrosion expansion, Overpack sinking, seismic-stability of engineered barrier, Gas migration in buffer, Extrusion of buffer in fracture of rock.
Nirex used a FEP database structured into a master directed diagram and simplified onto a two dimensional RES-like FEP Interaction Matrix to identify interactions between FEP groups (Bailey and Billington 1998; NEA 1999). A RES analysis was performed to consider importance of depth, cavern orientation with respect to stress axes and cavern span on repository layout / design and groundwater flow patterns affecting the long-term safety programme (Nirex 1997a). Systematic modelling was performed to scope impact of repository design, layout, siting, lithostratigraphy and depth on the excavation disturbed zone (EDZ) (Nirex 1997b). These analyses did not reveal any previously unknown processes.

OPG note that in the earlier years, the identification and study of T-H-M issues was largely based on expert opinion and reviews of experience in similar international programs. This approach included structured elements, though not within a formal framework. For instance, in the early 1980's, a series of semi-annual workshops were organized, drawing together experts from across the country and from other countries. Some of these workshops covered a variety of issues, while others were focussed on specific questions, such as the effect of transitional (geologically short-lived) processes on the geosphere (Heinrich 1984). A more formal FEP procedure was introduced in the late 1980's (Goodwin et al. 1994b). This procedure provided a mechanism to mix together expertise across many disciplines. For the most part, the FEP procedure confirmed the importance of T-H-M issues that had already been identified. In addition, however, the procedure identified a few "new" FEPs and raised the awareness in other FEPs that required further evaluation.

SKB have applied the basic element of the RES approach, the Interaction Matrix, as a tool for FEP recognition. /Pers et al., 1999/. The matrices cover FEP's relevant to engineered barriers as well as to natural barriers and to the interaction between barriers. All FEP's are categorised with respect to their estimated importance for safety assessment. Based on the Interaction Matrices, T-H-M-C diagrams intended for direct use in safety assessment studies have been constructed. The matrix off-diagonal elements represent binary interactions between repository components/parameters, while most processes of importance for safety analysis are chains of such interactions.

STUK's TEAM notes that POSIVA has carried out an exercise with the RES methodology (Vieno et al. 1994). Processes and couplings considered have been audited against FEPs lists (Andersson and King-Clayton 1996, Vieno and Nordman, 1997). The audits were used as arguments for the completeness of the TILA-99 safety assessment. The audits did not reveal any significant "previously unknown" processes or FEPs.
USDOE applied a structured process for FEP recognition, evaluation and analysis. The FEP analyses did not reveal new issues.

Some organisations have not applied formal structured procedures for FEP recognition (CNSC, USNRC). However, USNRC has reviewed USDOE FEPs analyses and conducted its own independent assessment to identify significant T-H-M processes.

A3.2 Other procedures

There are several means of identifying important processes and needs for coupled analyses. These include:

- past experience, established scientific facts, judgement and expert reviews
- confirmation by some small scale tests and full-scale tests in laboratory and in-situ,
- precedence study of existing underground structures,
- analysis of groundwater system in terms of evidence of the effects of coupled processes,
- assessing relevance of seismic transients,
- searching for evidence of past ice-sheet loading cycles,
- review of safety assessments and other studies carried out for similar disposal concepts in other countries,
- requirement in regulations,
- developing site characterisation plans,
- carefully documenting and exploring existing scientific/technical understanding of already identified processes and interactions,
- through the public review process, including thorough and rigorous independent review by learned groups providing a basis to re-examine the relative importance and treatment of T-H-M issues in future PA/SA undertakings.

In fact, it may seem that these procedures identify more focussed interaction or processes than the formal approaches. Still, the formal approaches are considered essential for checking and confirming completeness of identification

Compilation of answers

Past experience, established scientific facts, judgement and expert reviews are important means of identifying needs for coupled analyses (CNSC, JNC, Nirex, STUK, OPG, USDOE, USNRC).

JNC confirmed processes/issues by some small scale tests and full-scale tests in laboratory and in-situ.

Nirex made a precedence study of existing underground structures to reveal details of span and constructability as functions of rock type, fracture state, in-situ stress and depth etc (Nirex 1997c). They analysed the groundwater system in terms of evidence of the effects of coupled processes (Nirex 1997d). They searched for evidence of past ice-sheet loading cycles, pump test evidence of H-M coupling during hydrotesting (Nirex 1997e) and observational evidence of relationships between hydraulically active fractures and in-situ stress state (Lunn 1997).

OPG note that the technical feasibility of the disposal concept and its impact on the environment and human health were published in an Environmental Impact Statement (EIS) in the 1990's (AECL 1994a,b). Subsequently, a Second Case Study (SCS; Wikjord et al. 1996) was also published. A Federal Panel (CEAA 1998) subjected the EIS and SCS to a public review. Through the public review process, the EIS and SCS (and supporting documentation) were subject to thorough and rigorous independent review by learned groups including the panel appointed Scientific Review Group (SRG 1995), the Nuclear Safety Commission (formerly the Atomic Energy Control Board), Environment Canada, Natural Resources Canada, NEA/OECD (NEA 1995), Canadian Geoscience Council and TAC (Technical Advisory Committee). These technical review comments provide a basis to re-examine the relative importance and treatment of

T-H-M issues in future PA/SA undertakings.

In addition to the systematic RES screening, SKB has compiled extensive descriptions of processes, i.e. individual binary interactions or chains of binary

interactions, in a specific process report /SKB 1999a/. The format of the process report is that of a background report to the recently issued safety analysis report SR 97 /SKB 1999b/. As opposed to the interaction matrices, the process report (present version) does not by itself assure complete coverage of all issues/processes.
STUK'S TEAM notes that POSIVA explored safety assessments and other studies carried out for similar disposal concepts in other countries, especially studies performed by SKI and SKB on the KBS-3 concept. Also analyses of some FEPs, e.g. a large (postglacial) rock movement intersecting the repository, are specifically required in the draft regulations.

The Site Characterization Plan for Yucca Mountain and the execution of the site characterization plan identified issues, sometimes outside of the formal PA FEPs process (USDOE).

A3.3 Completeness in identification

Most organisations believe they have identified most processes/issues (i.e. FEPs) where they potentially need to consider T-H-M-couplings for the currently considered waste disposal concepts. (If concept changes there will be a need to reconsider, i.e. new FEPs analyses to be conducted). However, some teams note that there is still a need to evaluate to what extent potentially important processes or couplings actually needs to be included in an assessment.

For example, in the context of coupled T-H-M issues, a geosphere model capable of simulating long-term flow system evolution in response to external changes may be considered an important gap in the modelling technology. Such evolution includes the transient response of the geosphere to cyclic hydraulic-mechanical loading that may occur during glacial and inter-stadial periods.

Compilation of answers

All organisations (CNSC, JNC, Nirex, OPG, SKB, STUK, USDOE) believe they have identified most processes/issues where they potentially need to consider T-H-M-couplings. However, some teams note that there is still a need to evaluate to what extent potentially important processes or couplings actually needs to be included in an assessment.

Nirex suggest they would have to reconsider the importance of processes if their remit was expanded to include significant heat generating HLW.

OPG note that, in some cases time and resources did not allow the necessary analyses to be completed (i.e. to meet EIS/SCS schedule). Most or all such issues are documented in references that directly support the EIS (Davis et al. 1993; Davison et al. 1994a,b; Goodwin et al. 1994; Johnson et al. 1994a,b; Simmons and Baumgartner 1994) and in a second safety assessment presented to the Panel (Baumgartner et al. 1996; Goodwin et al. 1996; Johnson et al. 1996; Stanchell et al. 1996; Wikjord et al. 1995; Zach et al. 1996). In addition, some issues are noted in the various technical review comments on the EIS (CEAA 1998; SRG 1995). These review comments are currently being reviewed and evaluated in the DGRTP (Deep Geologic Repository Technology Program) at OPG. In particular, in OPG's 1998 Safety Assessment Plan (Russell et al. 1998) identified gaps in the DGRTP's safety assessment technology (methods, models and codes) existing at that time. The report recommended a series of near-term improvements and additions to the methods, models and codes, along with suggested supporting experiments, studies and demonstrations to address these safety assessment gaps. In the context of coupled T-H-M issues, a geosphere model capable of simulating long-term flow system evolution in response to external changes is considered an important gap in the modelling technology (Russell et al. 1998; Jensen and Goodwin 1999). Such evolution includes the transient response of the geosphere to cyclic hydraulic-mechanical loading that may occur during glacial and inter-stadial periods. According to SKB, the interaction matrices and the T-H-M-C diagrams are believed to cover all processes/issues, although this cannot be strictly proven.

STUK's TEAM notes that the FEPs and couplings affecting the KBS-3 disposal system in the Fenno-scandian shield have been identified in a great detail. The Process report of SR 97 (SKB 1999b) provides a thorough compilation of the present state-of-art.

USDOE consider the T-H coupling to be of most significance with respect to a potential repository at Yucca Mountain for high level nuclear waste. Because the waste will be emplaced in unsaturated rock, the heat transfer mechanism is conduction dominated, and the role played by T-H coupling is primarily that of two-phase exchange, particularly in the vicinity of boiling temperatures. Because the rock is highly fractured, the impact of T-M-H and T-C-H couplings are considered to be of lower significance (USDOE, 1998, Section 3.1.1 and 3.1.3, TSPA/VA Technical Basis Document).

In 1992, the Center for Nuclear Waste Regulatory Analyses (CNWRA), sponsored by U.S. Nuclear Regulatory Commission, (NRC) conducted a state-of-the-art literature review (Manteufel et al., 1992) of coupled T-H-M-C processes to identify the processes considered relevant to the U.S. repository program based on the design described in the DOE Site Characterisation Plan. The design has since evolved and changed a number of times. The relative importance of the processes and issues changed as the design concept changed.

A3.4 Documentation

Some organisations have clearly documented which couplings and processes they consider there is a need to address. For other organisations this information can only be found indirectly in different reports.

Compilation of answers

JNC have systematically checked the comprehensiveness of the FEP list by reviewing the matrix shown in a hierarchical FEPs matrix table. This review is documented. Nirex have documented all FEPs and interactions in Nirex's Master Directed Diagram and FEP Interaction Matrix and associated documentation (Baily and Billington, 1998, NEA 1999). OPG note that a "list of issues/processes" and the authors' rationale for scenario selection has been documented (Goodwin et. al. 1994b). SKB has documented the systematic FEP screening and the process descriptions in SKB Technical Reports (Pers et al. (1999) and SKB, 1999a). USDOE discusses and documents the issues in TSPA/VA (USDOE, 1998, especially section 6.4 of vol. 3). The next edition of discussion/documentation will be in TSPA/SR and its supporting documents which will be published late this year (2000) or early next year. The issues and processes determined by USNRC/CNWRA to be relevant to the U.S. repository program are documented in reports called Key Technical Issue Resolution Status Reports (IRSRs).

The IRSRs address T-M, T-H, and M-H couplings. Some organisations (CNSC, STUK) have not assembled an explicit list of processes and couplings.

A4. Couplings evaluated in the safety assessment context

There are several T-H-M couplings considered in the safety assessment context.

A4.1 Thermo-hydraulic couplings

Table A4.1 lists thermo-hydraulic couplings considered. The different issues are further discussed in the following subsections.

***Table 4.1**: Thermo-hydraulic couplings considered*

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA?
Thermal buoyancy in saturated systems with moderate heat input. Heat transport by convection	T-H coupling in steady-state analysis (Nirex) Density dependent flow model (STUK). Coupled transient flow and heat transport including temperature-dependent density and viscosity (OPG). Density dependent flow and heat transport modelling (SKB).	Impact on the groundwater flow path (Nirex, SKB) Impact on heat transport and impact on groundwater flow (OPG)	No a low order effect compared with density variations induced by salinity changes (Nirex). Considered to be of fairly minor importance as compared to the driving forces caused by topographical gradients, salinity variations and land uplift at the coastal sites (SKB, STUK). Heat transport is conduction dominated in low permeable rock. Impact on flow negligible for cases studied (OPG. SKB)	Capturing the time-varying component of the system (Nirex) Geometrical structure of the subsurface and hydraulic properties (permeability and porosity) of the rock mass and their distribution (OPG)	Yes to maintain scientific credibility (Nirex) No, not included in TILA-99 (but noted not needed in underlying analysis) (STUK). Should be mentioned but no need for new analyses (SKB). The validity of sensitivity analysis using 1D simplified SA model is site specific and must be justified with detailed coupled T-H geosphere PA modelling for each specific site and repository design. (OPG).
Vapour / water / heat migration and thermal buoyancy in partially saturated systems	The simulation (analysis) of T-H processes is quasi-static which takes into account (slow) dynamic responses. (USDOE) MULTIFLO simulating fully coupled T-H processes, including thermal buoyancy effects, re-saturation under a heat gradient, etc., for a dual continuum (i.e., fractured porous medium (USNRC)	No specific quantitative criteria are used to assess the need to consider T-H coupling. Calculated radiological risk (to the public) could be such a criterion. (USDOE) Consideration of both the effect on calculated radiological risk and the ability to understand the details of the hydrogeological or mechanical system. Saturation and temperature are the key parameters used to judge whether T-H coupling should be included in the analyses (USNRC)	Is considered to be most important for the potential repository at Yucca Mountain because T-H coupled processes may mobilize the pore water in the near-field rock in such large quantities as to reach the waste packages. (USDOE) T-H coupling inclusion into models of geologic media for above-boiling conditions is critically imperative (USNRC)	In characterizing the rock with large spatial variability of properties, especially hydrological. Simulating or modeling the consequences is the next important source of uncertainties. (USDOE) Fracture hydraulic properties and the matrix/fracture interaction coefficient. Also the long-term infiltration rate, but this could be bounded. Effects of persistent geologic features, such as fault zones or through-going fractures. (USNRC)	Yes, T-H coupling needs to be considered, simply to enhance the credibility of the process. Coupling could be treated by a bounding analysis, but it would involve major simplifications and may not always be valid. (USDOE) Yes (USNRC)

A4.1.1 Thermal buoyancy in saturated systems with moderate heat input

In low permeable saturated systems with moderate heat input, thermal buoyancy effects are generally found to be small compared to changes in density due to salinity and to other driving forces. (For high heat loads this observation is not valid, see section A0).

Compilation of answers

Nirex recognised that heat generation within the repository would alter the groundwater density introducing a buoyancy effect on the groundwater flow. This effect was modelled but found to be small compared to changes in groundwater density due to changes in salinity. It was implicitly included in the density variation in groundwater considered in Nirex 97 (Baker et al 1997). Only steady state responses were considered in Nirex 97, although it is intended to develop a time variant dynamic modelling capability. The biggest uncertainty is capturing the time-varying component of the system. The consequences can be bounded using simplifying assumptions. The coupling should be considered to maintain scientific credibility.

OPG notes that thermal buoyancy effects were investigated in detail because it might potentially increase the upward flow rate and transport from the repository to the biosphere. Detailed 2D and 3D fully coupled T-H transient finite-element analyses (Chan et al. 1986; Chan et al. 1994; Davison et al. 1994b; Stanchell et al. 1996) were performed. Results indicate that there is no sign of thermal convection cells and the temperature field calculated is approximately the same as simple heat conduction calculations. There is a slightly larger effect on groundwater flow. Thermal buoyancy effects lead to slightly higher groundwater velocities. The decrease in groundwater travel time, as determined by particle tracking, is generally 10% or less. In a sensitivity analysis with pessimistic assumptions the travel time is reduced by a factor of 2 (Chan et al. 1994; Davison et al. 1994b; Stanchell et al. 1996). For a repository in saturated low-permeability, low-porosity rock with a design temperature below 100^{o} C the buoyancy effect is unlikely to affect temperature distributions significantly. That heat transport in low-permeability, low-porosity rock is expected to be conduction dominated has been shown by relatively simple analyses (Chan et al. 1980; Chan and Jeffry 1983).

Despite these results OPG suggests the validity of sensitivity analysis using 1D simplified SA model is site specific and must be justified with detailed coupled T-H geosphere PA modelling for each specific site and repository design. Geometrical structure of the subsurface and hydraulic properties (permeability and porosity) of the rock mass and their distribution are the major uncertainties. Because of the potential sensitivity of modelling results to geometry and hydraulic properties, it would be prudent to carry out additional detailed coupled T-H modelling in a conceptual model that includes a number of discrete fractures.

STUK'S TEAM made similar conclusions. The effects of thermal buoyancy have been analysed (Laitinen & Löfman 1996, Löfman 1996) and are considered to be of fairly minor importance as compared to the driving forces caused by topographical gradients, salinity variations and land uplift at the coastal sites (Andersson et al. 1998). The effects are thus not included in the safety assessment modelling in TILA-99 (Vieno & Nordman 1999).

In the far-field, SKB categorise thermal buoyancy as important for SA/PA /Pers et al., 1999/. Yet it is found to play a minor role compared to the effects of typical topographical variations /SKB, 1999a/. This conclusion is based on results from coupled hydrothermal calculations /Thunvik and Braester, 1980/. No other handling of this process is made in the SR 97 safety analysis. In the nearfield, the process has been judged to be of no importance for SA/PA /Pers et al., 1999/. Quantitative estimates also show that heat transport by flow is negligible compared to conductive heat transport in hard rock /Thunvik and Braester, 1980; SKB, 1999a/. For these reasons, no explicit account is taken of this coupling in the SR 97 safety analysis. According to interaction matrices /Pers et al., 1999/ groundwater pressure increases caused by volumetric heat expansion may also be important, but no justification is provided.

A4.1.2 Vapour/water/heat migration and thermal buoyancy in partially saturated systems

At the unsaturated Yucca Mountain it is necessary to consider the T-H coupling where water in the vapour phase moves away from the heat source, particularly via fractures in the rock, and condenses into liquid water as it reaches cooler regions.

Compilation of answers

USDOE notes that thermal-hydrological coupling is most significant at Yucca Mountain near the boiling temperature of water, 96°C due to the elevation above sea level. At the boiling temperature, the applied heat is expended in vaporising the pore water in the rock causing a plateau in the increase of rock temperature. Water in the vapour phase moves away from the heat source, particularly via fractures in the rock, and condenses into liquid water as it reaches cooler regions. Liquid water tends to drain down by gravity; part of it returns to the region of boiling temperature and is vaporised again repeating the process. The process continues until all the water in a rock region is driven off at which time rock temperature rises again, above the boiling temperature. As the radioactive waste decays, the driving thermal power decreases, and thermal conduction plus the influx of percolation water cause the hot areas to cool and eventually rewet. Due to the T-H processes during the heating phase, the water budget available for the re-wetting will be much less than that of the ambient condition for a significant period of time.

USDOE handles the T-H coupling by dual (permeability) continuum analysis and qualitative argument. The analyses are benchmarked with laboratory tests and in-situ drift-scale thermal tests. The results are abstracted in the top level PA calculation. The simulation (analysis) of T-H processes is quasi-static, which takes into account (slow) dynamic responses. The coupling is considered to be most important since the processes may mobilise the pore water in the nearfield rock in such large quantities that a condition of a "dry" near-field may be questioned. However, the water mobilised by T-H processes drains down by gravity through the cooler cores of the pillars between the emplacement drifts, thereby minimising the possibility of seepage into the drifts. Any seepage into the drifts is prevented from contacting the waste by various components of the engineered barrier system.

No specific quantitative criteria are used by USDOE to assess the need to consider T-H coupling. Calculated radiological risk (to the public) could be such a criteria. The major uncertainties are in characterising the rock with large spatial variability of properties, especially hydrological. Simulating or modelling the consequences is the next important source of uncertainties. It may be possible to bound the consequences of T-H coupling using simplifying assumptions, sensitivity studies, etc. However, due to the complexity of T-H coupling and its effect on TSPA, it would require a great deal of simplification. Any resulting bounding analysis may or may not be valid during specific time periods and may never be completely consistent with infiltration rates and climate states, etc. used by other submodel components of TSPA. Instead, the issue of bounding the consequences of T-H coupling is approached by applying the same ranges of uncertainty in hydrologic properties and other parameters specified in the ambient unsaturated zone flow and transport model to the TSPA model. How the T-H coupled model drives processes that influence the calculated radiological risk to the public is discussed in the Repository Safety Strategy. The T-H coupling needs to be considered, simply to enhance the credibility of the process.

USNRC has analysed thermo-hydraulic couplings for the drift-scale heater test (DST) using MULTIFLO (Litchner et al., 2000). MULTIFLO is capable of simulating fully coupled T-H processes, including thermal buoyancy effects, re-saturation under a heat gradient, etc., for a dual continuum (i.e., fractured porous medium). A reference of the DST analyses is as follows: Hughson and Green (1999). The MULTIFLO code was also used to T-H processes in laboratory-scale heater tests (LST). Results of these tests are documented in Green and Prikryl (1998, 1999). Analyses of both the DST and LST indicate that T-H coupling is important to heat and mass transfer for the conditions evaluated. It is noteworthy that both scales of experiments were conducted at temperatures above boiling in media that have low matrix permeability and relatively high fracture permeability.

USNRC notes that the heat sources in both the DST and LST were variable in time. In particular, the heat source was imposed on a system that was initially at ambient conditions. The heat source vaporized water originating from two sources: matrix water and infiltrating water. After onset of heating, matrix water near the heat source was vaporized, transported away from the heat source by a gas pressure gradient, and condensed where the rock temperature was below boiling. This activity would continue until the affected medium approached steady-state temperatures. After steady-state conditions were approximated, only infiltration water entering the heated zone would participate in the vaporization/condensation sequence. However, given the relatively short duration of both the DST and LST, it is questionable whether the modeled system attained steady conditions and no additional rock water was vaporized. Therefore, the systems of both tests are considered dynamic.

USNRC concludes that T-H coupled simulations provide for more representative simulation of temperature than heat conduction-only models. In addition, mass transfer simulation is more representative of the experiments if the T-H processes are fully coupled in the simulations. The need is assessed based on the consideration of both the effect on calculated radiological risk and the ability to understand the details of the hydrogeological or mechanical system. Saturation and temperature are the key parameters used to judge whether T-H coupling should be included in the analyses. Of these two parameters, saturation was a better discriminator when comparing different models. For example, there have been cases when temperature predictions from different conceptual models (i.e., equivalent continuum versus dual continua) were qualitatively the same, whereas saturation predictions from the same models were distinctively different. T-H coupling inclusion into models of geologic media for above-boiling conditions is critically imperative.

USNRC suggest fracture hydraulic properties and the matrix/fracture interaction coefficient lead to the greatest model uncertainty in terms of T-H coupling. Also causing uncertainty was the long-term infiltration rate, however, back-calculating the infiltration using measured saturation values usually reduced this source of uncertainty. The effects of persistent geologic features, such as fault zones or through-going fractures, also lead to uncertainty.

A4.2 Mechanical and thermo-mechanical analyses

Most programmes consider mechanical stability and the mechanical impact from the heat producing waste. Table A4-2 summarises the findings from these studies. The different issues are further discussed in the following subsections.

***Table A4-2**: Mechanical and thermo-mechanical couplings considered*

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA
Stability of underground excavation including: - Rock burst - Rock failure (breakout) - Key blocks	Analytical and numerical (FEM) rock mechanical analyses considering mechanical (JNC) and thermo-mechanical (OPG, SKB, STUK) impact of tunnels. Qualitative assessment of risk for rock burst (OPG). Experiments and modelling potential for rock failure (breakout) Key block analyses (USDOE and USNRC), Inspection of URL searching for blocks (OPG).	Exploration whether excavations will be mechanically stable (displacements, stress/strength evaluation). Analyse used to design the geometry of the rooms and layout.	Excavations found-designed to be stable (JNC, SKB, STUK, OPG, USDOE). Risk very low for sudden events such as rock bursting, localised, small-scale strain bursts may occur (OPG). No unstable blocks found (OPG) Heat generated by the decay of the waste and seismicity are the major factors that could induce rock-mass instability (USNRC)	Inadequate knowledge of fracture patterns, rock-mass mechanical properties, strength properties, and thermal properties (USRNC)	Mostly a pre-disposal (i.e. engineering issue). The importance should be determined based on its effect on radiological risks
Fault shearing due to heat load	2D axisymmetric far-field thermal and thermomechanical finite-element analysis. A limit equilibrium stability analysis was performed by comparing the combined in situ and calculated thermal stresses with the Coulomb failure criterion (OPG).	Studying effect on stress field and judging impact on fracture deformation (OPG)	Reduced compressive stress above repository may lead to increased apertures in the top 150 m of rock. Some potential for shearing of a subhorizontal fault to at most a depth of about 100 m, no potential for shear failure of a subvertical fault (OPG).	Present analysis is preliminary conclusions should be checked by using more realistic models (OPG).	Possibly
Displacement of joints due to earthquakes	Assessing probability of damaging earthquakes, vibrational effects of earthquakes are expected to have insignificant impacts on the repository (OPG) Fracture and fault displacements resulting from seismic events analysed in a static DFN-model assuming frictionless fractures. Consequence of faulting analysed as a "what-if" case in safety assessment (SKB, STUK).	Likelihood of earthquakes (OPG). Displacement in deposition holes. Radionuclide release in a earthquake scenario combining estimates of earthquake frequency and resulting potential damage to canisters (SKB) ."What-if" scenario (STUK).	Risk is judged to be low (SKB) "What if" scenario one of few release possibilities. Risk of earthquake displacement very low (STUK)	Uncertainties are many; with regard to forecasting seismic activity as well as with regard to the relevance and validity of the numerical method (SKB). From the safety assessment point of view, the main uncertainties are associated with transforming and transferring the results of the T-H-M analyses into the models and input	Yes Although the safety margins inherent in the analysis are judged to compensate for all uncertainties, development of alternative, or supplementary, approaches is underway (SKB).

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA
				parameters of release and transport analyses of radionuclides (STUK).	
Effects of seismisity on rock fall	Field investigation and modelling of the effects of seismicity on rockfall in a T-M environment (USNRC)	Effect on calculated radiological risk and the ability to understand the details of the hydrogeological or mechanical system. Also the effect of rockfall on waste container integrity and ground motions. (USNRC)	Being explored. Heat generated by the decay of the waste and seismicity are the major factors that could induce rock-mass instability USNRC	Inadequate knowledge of fracture patterns, rock-mass mechanical properties, strength properties, and thermal properties (USRNC)	Potentially yes. The importance of rockfall should be determined based on its effect on radiological risks.) USNRC
Rock creep	Potential time-dependent thermal and mechanical crack growth as a creep mechanism using statistical microcracking analysis techniques developed for ceramic materials. (OPG). Analysis code is exclusive-use FEM code integrating with Okubo model. Duration of evaluation is 10,000 years (JNC). Bounding analysis Theoretically, rock creep can proceed until all shear stresses have disappeared, and the buffer has been compressed until the swelling pressure corresponds to the mean rock stress (SKB).	Assessing results of analysis Variations in creep deformation and stress state with time of rock (JNC). Comparison of resulting pressure and compressive strength of canister (SKB)	There will be no effect beyond one room diameter (8 m) for the conceptual design for a repository (OPG). Essentially no creep deformation is expected to occur for the next 10,000 years. No change over time in stress distribution. Formation of a plastic zone does not occur (JNC). Pressure is far below the canister design pressure, effects of rock creep are not considered to pose any threat to the mechanical integrity of the canisters. Rock creep may however also have consequences in the form of changed hydraulic conditions (SKB).	No rheological models seem to have been suggested and found valid for jointed granitic rock masses (SKB).	Rock creep may be disregarded in analyses, but still mentioned. SKB considers to improve the understanding of rock creep around repository openings in order to arrive at more realistic bounds to scope creep effects.
Buffer creep	Buffer is applied to Visco-elasto-plastic body (Sekiguchi-Ohta model). Analysis code is DACSAR. Duration of evaluation is 10,000 years. No rock creep deformation nor overpack corrosion swelling deformation is considered (a conservative description in view of subsidence).	Evaluation index is distance of self-weight sinking, Stress ratio of buffer JNC	The decrease in thickness of buffer due to the settlement of an overpack has a smaller impact than the expansion of overpack corrosion products. Furthermore, the stress ratio in the buffer owing to settlement is small. (JNC)	- no answer	It is concluded that the sinking of an overpack will not have a significant impact on the long-term performance of the engineered barrier system. (JNC)

A4.2.1 Stability of underground excavations including thermal effects

Most programmes study the stability of the underground excavations while considering the effect of the thermal load. (See also section A4.4.3 on the impact of T-M effects on hydraulic conductivity). Such analyses also include evaluations of the risk for rock burst, key block stability, rock failure (breakout).

Compilation of answers

JNC evaluates the stability of underground excavations for the hard rock system. Loading conditions are taken as the overburden pressure in proportion to depth. For the evaluation process, firstly, an approximate thickness of supports in the access tunnel by Oka's elastoplasticity analytical equation (Oka, 1977), with the mechanical property value and depth of rock mass, are examined. Then, the analyses on each tunnel using two- or three-dimensional finite element methods are carried out, in order to verify support thickness and obtain disposal tunnel spacing and disposal pit pitch required to secure the mechanical stability of the underground excavations. For evaluation method, firstly, the stability based on normal strain of the rock mass and the stress of tunnel support are evaluated. Next, the results are evaluated analytically, based on a distribution of local safety factors and the maximum shear strain of rock mass and the stress of tunnel support. The results of the analyses support the prediction that, for the hard rock system, underground excavations would be stable without supports at depths greater than the examined depth of 1000 m. The values obtained from the above study is used to determine the required disposal tunnel spacing and disposal pit pitch in order to ensure the mechanical stability of the excavated openings.

OPG notes that mechanical or coupled thermo-mechanical effects were analyzed in some detail for conceptual repository design (summarized in Simmons and Baumgartner 1994). Specifically, these analyses were used to design the geometry of the rooms and layout of canister holes to ensure that there is no rock failure under the combined effects of ambient in situ stress, excavation induced stress and thermal stress. A standard commercially available finite-element code, ABAQUS, was used. Standard empirical Hoek-Brown or Coulomb failure criteria were used.

SKB has performed quantitative (one-way) coupled T-M analyses of the development of thermal stresses from the heat generated by the decaying fuel (Probert and Claesson, 1997; Hökmark, 1996; Hakami et al., 1998). Quantitative analyses of intact rock failure caused by thermal stresses show that regions of potential failure are small (Hökmark, 1996). From qualitative arguments it is concluded that this process does not pose any threat to the mechanical integrity of the fuel canisters. Changes in near-field rock permeability associated with fracturing are treated separately (see section A0). Quantitative analyses of fracture deformations caused by thermal stresses show that this process does not pose any threat to the mechanical integrity of the fuel canisters, unless fractures of very large extension (several hundred meters) are allowed to intersect canister positions (SKB, 1999a). Effects on fracture transmissivities are treated separately (see section A0). In addition, SKB has performed numerous isothermal mechanical analyses to assess the stability of the repository openings for different assumptions regarding pre-mining stresses and orientations of tunnels relative to the pre-mining stresses. However, these analyses have relevance to the construction of the repository rather than to the long-term safety. In the safety analysis, stress redistribution effects and excavation damage effects on the retention properties of the near-field rock are accounted for by assuming that radionuclide escape routes exist in the initial state, i.e. after closure.

STUK'S TEAM notes that most mechanical analyses conducted by POSIVA deal with mechanical or coupled thermo-mechanical effects as regards the stability of the deposition tunnels and holes. A few TMH analyses have been performed (Tolppanen, et al 1995, Johansson and Rautakorpi, J. 2000).

In support of the upcoming TSPA-SR, USDOE conducts key block analyses based on underground mapping. The analyses include thermal and seismic effects. The lower lithophysal subunit, in which most emplacement drifts are planned, is calculated to be very stable. OPG notes that block (delineated by existing fractures and excavation boundaries) fall-out (as opposed to spalling), often encountered in civil engineering or mining excavation in fractured rock, has not been observed at the URL either in MFR or SFR. It is judged to be very unlikely in any possible Canadian site in plutonic rock and was not considered further.

USNRC notes that CNWRA also conducted modelling to study T-M effects on emplacement drift stability (Chen et al., 1998). They suggest heat generated by the decay of the waste and seismicity is the major factor that could induce rock-mass instability (see also sections A4.2.3 and A4.4.3).

OPG note that Ortlepp (1992) reviewed the risk for rock bursting based on his extensive deep mining experience and concluded that the risk is very low for sudden events such as rock bursting in a disposal repository constructed in a medium-grained granitic rock body similar to that at the URL. However, localized, small-scale strain bursts of rock slabs, as occasionally experienced in the URL, could occur.

Rock failure (breakout) due to excavation induced stress redistribution under the very high ambient in situ horizontal stresses and high stress ratios at the URL has been studied in detail experimentally at the URL (OPG). Rock rupture similar to the well-known phenomenon of well bore breakout has been observed in a Mine-by Experiment designed to observe this "notch" rupture. This has resulted in a teardrop shape cross section of an initially circular tunnel. The occurrence and geometry of failure was predicted reasonably well by a boundary-element code EXAMINE3D originally developed by Evert Hoek based on the theory of linear elasticity. More elaborate analysis is being attempted to try to predict the time evolution of rock rupture (see Section 2.5). In situ measurements of hydraulic conductivity the Excavation Damaged Zone (EDZ) were performed in one of the ruptured notches in this Mine-by tunnel and in another tunnel, known as Room 209 at the 240-m level (Martin et al. 1992).

A4.2.2 Far-field fault shearing due to heat load

There have been analyses of the potential for fault sheering, resulting from the repository heat load. Horizontal stresses above the repository may be reduced up to a certain level, which may possibly lead to enhanced aperture (and permeability) of vertical fractures.

Compilation of answers

OPG notes that to study the potential for fault shearing a 2D axisymmetric far-field thermal and thermomechanical finite-element analysis was performed (Golder Associates 1993). It was found that horizontal stress in the rock above the repository would be reduced in a zone extending from ground surface to about 300-m depth. This might possibly lead to enhanced aperture of vertical fractures. A limit equilibrium stability analysis was performed by comparing the combined in situ and calculated thermal stresses with the Coulomb failure criterion. It was found that there is some potential for shearing of a subhorizontal fault to a depth of about 100 m but not at greater depth. There is no potential for shear failure of a subvertical fault. Since this T-M analysis is preliminary in nature the conclusions should be checked by using more realistic models.

A4.2.3 Effects of seismicity/earthquakes

Displacements in fractures intersecting the deposition hole due to a large, postglacial earthquake in a nearby, major fracture zone is considered to be one of the few, if not the only, processes which could threaten the integrity of initially intact copper-iron canisters in a properly located and constructed KBS-3 repository. If the event occurs one may need to consider that the rock movement breaks canisters, displaces bentonite, brings oxygenated glacial meltwater into the repository, and enhances flow and transport in the near-field and geosphere. However, current analyses suggest such displacements and follow on effects to be highly unlikely.

Effect of seismicity is one of the important aspects in the U.S. repository program. The potential for rock fall on waste containers, as a consequence of seismic events, is presently being explored.

Compilation of answers

OPG note that detailed site specific and design specific dynamic vibrational analysis has not been performed. Based on a study of the probability of damaging earthquakes in north-western Ontario (Atkinson and McGuire 1993) the vibrational effects of earthquakes are expected to have insignificant impacts on the repository and surrounding plutonic rock. Moreover, the growth of faults or formation of new faults is expected to have a very low probability of occurrence in stable portions of the Canadian Shield, which is among the tectonically most stable areas in the world. In addition, the siting process would avoid regions where seismic activity is known to be a problem. It is therefore excluded from any scenarios requiring quantitative evaluation.

SKB has performed earthquake risk analyses for the three generic sites considered in the SR 97 safety report. No other safety aspects than the possible mechanical damage done to canisters subjected to shear displacements along fractures that intersect deposition holes were considered. The risk analyses were based on a numerical method of computing secondary movements along repository host rock fractures given 1) the distance to a potential earthquake zone and 2) the magnitude of an earthquake occurring on that zone (LaPointe et al., 1997). The risk, expressed as the number of canisters expected to fail within the next 100,000 years, was obtained by applying the numerical method many thousand times on statistically relevant populations of canister-intersecting fractures (LaPointe et al, 1999). It was assumed that the present-day seismicity can be extrapolated far into the future and beyond the observed magnitude range. The general conclusion was that the calculated risk is too small to be a concern for safety assessment. The uncertainties are however many; with regard to forecasting seismic activity as well as with regard to the relevance and validity of the numerical method. Although the safety margins inherent in the analysis are judged to compensate for all uncertainties, development of alternative, or supplementary, approaches is underway.

STUK'S team notes that TILA-99 (Vieno and Nordman, 1999) includes a "what if" scenario where a large postglacial rock movement is assumed to intersect the repository, break canisters, displace bentonite, bring oxygenated glacial meltwater into the repository, and enhance flow and transport in the near-field and geosphere. The scenario is a response to the requirements in the draft regulatory guidance. The approach to estimating of the probability of canister failures due to earthquake-induced displacements in fractures intersecting deposition holes has been developed by LaPointe & Claduohos (1999). An application of the approach is currently underway.

Most of the analyses are (quasi-)static. In the safety assessment, all release and transport analyses of radionuclides use time-invariant boundary and in-situ conditions. The effects of time-dependent evolution of the conditions are tried to be covered by means of a large number of conservative, static variants. From the safety assessment point of view, the main uncertainties are associated with transforming and transferring the results of the T-H-M analyses into the models and input parameters of release and transport analyses of radionuclides. The current understanding is that there is basically only one process which could threaten the integrity of initially intact copper-iron canisters in a properly located and constructed KBS-3 repository within the next 100 000 years. This is displacements in fractures intersecting the deposition hole due to a large, postglacial earthquake in a nearby, major fracture zone (LaPointe and Claduohos 1999, SKB 1999a). As concerns transport of radionuclides from an initially defective copper-iron canister, the main uncertainties are related to the hydromechanical behaviour of the two-layer canister (SKB 1999a) and to deriving of flow and transport parameters (near-field flow rates, ratio of the flow wetted surface and flow rate along the migration pathway).

According to USNRC the effect of seismicity is one of the important aspects in the U.S. repository program. Sponsored by U.S. NRC, CNWRA conducted a field investigation of the effects of mine seismicity on jointed rock-mass behavior (Hsiung et al., 1992) and local hydrology (Hsiung et al. 1993), and a laboratory-scale experiment of jointed rock-mass subjected to repeated ground motion (Hsiung et al., 1999). CNWRA also conducted modeling to study T-M effects on emplacement drift stability (Chen et al., 1998) and effects of seismicity on rockfall in a T-M environment (Ahola, 1997). The need is assessed based on the consideration of both the effect on calculated radiological risk and the ability to understand the details of the hydrogeological or mechanical system. The effect of rockfall on waste container integrity due to T-M and ground motions is another parameter considered in performance assessment. For T-M coupling, inadequate knowledge of fracture patterns, rock-mass mechanical properties, strength properties, and thermal properties lead to uncertainty. Analysis is ongoing to determine if the T-M effect on H will affect the safety of the repository. It is suggested that heat generated by the decay of the waste and seismicity are the major factors that could induce rock-mass instability. Consequently, T-M coupling consideration to assess drift stability and T-H effects on permeability is very important. The stability problems and change in permeability will be substantially reduced if heat is not present.

A4.2.4 Rock creep analysis

Current analyses do question whether there will be any significant rock creep or stress changes in crystalline rock due to creep over a time period of 10 000 years.

Compilation of answers

OPG note that potential time-dependent thermal and mechanical crack growth as a creep mechanism was analysed by Wilkins and Rigby (1993) using statistical micro-cracking analysis techniques developed for ceramic materials. They concluded that there will be no effect beyond one room diameter (8 m) for the conceptual design for a repository located in SFR.

JNC analyses Rock creep. The evaluation index is variations in creep deformation and stress state with time. The rock is described by a variable compliance model (Ohkubo) and the buffer is described as an elastic body. The analysis is performed with a FEM code integrating with the Ohkubo model. The duration of evaluation is 10,000 years. The results are that essentially no creep deformation is expected to occur for the next 10,000 years. Moreover, calculations show no change over time in stress distribution, and the formation of a plastic zone does not occur.

SKB considers the possibility that the geometry of the deposition holes may change over time as a result of creep movements and that, as a consequence, canisters may be subjected to increased buffer pressures or unevenly distributed buffer pressures (SKB, 1990a). However, SKB notes that no rheological models seem to have been suggested and found valid for jointed granitic rock masses, for intact solid granitic rock or for individual rock fractures. Therefore no time-domain creep analyses have ben conducted. Instead, SKB concludes that the effect of deviatoric creep is that the rock stress state tends to be more hydrostatic over time. Theoretically, rock creep can proceed until all shear stresses have disappeared, and the buffer has been compressed until the swelling pressure corresponds to the mean rock stress, which is on the order of 20 MPa at repository depth. Since this pressure is far below the canister design pressure, effects of rock creep are not considered to pose any threat to the mechanical integrity of the canisters. Rock creep may however also have consequences in the form of changed hydraulic conditions. Because of this coupling SKB considers improving the understanding of rock creep around repository openings in order to arrive at more realistic bounds to creep scope and effects.

A4.2.5 Buffer creep

The cited analysis of buffer creep suggest that the sinking of an overpack will not have a significant impact on the long-term performance of the engineered barrier system.

Compilation of answers

In the buffer creep analysis JNC uses the distance of self-weight sinking and the stress ratio of buffer as evaluation indices. The Buffer is described as a visco-elasto-plastic body (Sekiguchi-Ohta model). The analysis code is DACSAR. The duration of the evaluation is 10,000 years. No rock creep deformation nor overpack corrosion swelling deformation is considered (a conservative description in view of subsidence). The settlement of an overpack is around 5.1 mm after 10,000 years, even in the vertical emplacement case where a heavier load is applied to the buffer. At longer times, the settlement of the overpack tends to cease. In other words, the decrease in thickness of buffer due to the settlement of an overpack has a smaller impact than the expansion of overpack corrosion products. Furthermore, the stress ratio in the buffer owing to settlement is small - in the order of 10^{-2} after 10,000 years - a value that is negligible compared to the stress change caused by the expansion of overpack corrosion products. From these observations, it is concluded that the sinking of an overpack will not have a significant impact on the long-term performance of the engineered barrier system.

A4.3 Mechanical-hydrologic couplings

Most of the analysed hydro-mechanical couplings concern mechanical impact in the hydraulic conductivity and subsequent effects. The issues considered are summarised in table A4-3. The different issues are further discussed in the following subsections.

***Table A4-3**: Mechanical-hydrologic couplings considered*

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA
EDZ in tunnels and repositories. Potentially increased permeability due to fracturing or deformation of the near-field rock.	RES was used to identify the key parameters. A modelling study to determine the extent to which the EDZ was affected by various factors. A fracture compliance model related changes in fracture aperture to changes in normal stress across the fracture, based on coupled shear flow tests (Nirex) Effect on hydrogeology and transport was assessed by representing EDZ as an EPM with practically infinite permeability (OPG). No quantitative analysis of process, but EDZ is represented by increased permeability in the Safety Assessment (SKB)	The key parameter used to assess the importance of this effect was the increase in hydraulic conductivity (PA related) and the spatial extent of the EDZ (construction aspects and PA related). (Nirex) Potential impact on flow and transport (OPG). Qualitative assessment of process. Included as increased permeability in safety assessment (SKB)	Yes (Nirex) Flow and transport modelling showed that the assumed EDZ often had little impact on performance (OPG). Potentially (SKB).	Inadequate computer codes and incomplete data on fracture compliance are the major problems (Nirex).	The effect can be described as a volume around tunnels with increased permeability along the tunnel. Modelling the processes and couplings is needed for scientific credibility (Nirex).
Shaft sinking or other construction effects	Quasi-static responses after full resaturation have been considered (Nirex). Stress analysis, followed fracture permeability calculation using normal stress-fracture normal displacement relationship. Field experiments.	The increase in hydraulic conductivity and the spatial extent of the EDZ (construction and PA) (Nirex). Fracture permeability changes during excavation were compared with measurements in two field experiments.	The analysis showed that the coupling should be considered and provided information on the nature and extent of the coupling (Nirex). Inconclusive as model predictions and field measurements did not agree.	Inadequate computer codes and incomplete data on fracture compliance are the major problems (Nirex). Two-way coupled H-M model needed. Processes other than H-M coupling may affect fracture permeability (OPG).	Yes; for scientific credibility. Can be treated with bounding assumption. (Nirex) Yes, to demonstrate understanding of processes. Perhaps sensitivity analysis assuming pessimistic parameters OK for PA.
Hydrotesting	Much of the evidence for possible H-M coupling in this environment comes from the dynamical response of fracture networks to groundwater withdrawal and recovery (Nirex).	The need was considered in terms of a requirement to understand the response of the rock mass rather than PA driven. (Nirex)	No; it was shown to be a low order effect lost in the range of uncertainties of assessing transmissivities of low permeability rocks. (Nirex)	This low order effect can be considered as captured within the uncertainty inherent in hydrotesting of low permeability rocks. (Nirex)	Yes, but only to show that it is not significant. Can be treated with bounding assumption (Nirex).
In-situ stress impact on fracture hydrualics	Studies of the variation of transmissivity of fractures as a function of orientation and depth in the Sellafield area (Nirex)	Assessment of degree of relation (Nirex)	Analysis suggested that there was evidence for such coupling (Nirex).	- no answer	Presently only indirect through interpretation of field data (Nirex).
Overpack corrosion	Elasto-plastic buffer and elastic overpack, temperature strain. ABAQUS. Axial symmetry. 10,000 years. Rock creep from results of creep analysis. Self –	Stress state and excess porewater of buffer.	Mean effective stress and shear stress increase. High in the vicinity of the overpack. Stress ratio particularly large at the peripheral area of the overpack.	- no answer	The analysis shows that the engineered barrier system attains a stable state for a long

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA
	weight is not considered (JNC)		Excess porewater increases and reaches a near maximum level after about 400 years, but becomes zero after completion of corrosion expansion (JNC).		period of time without reaching a total failure condition (JNC).
Glacial load	Steady state analyses of the H-M coupling due to glacial loading /unloading cycles. In situ stress conditions and hydraulic heads would be altered by the advance and retreat of ice-sheets in proximity to, or above, the repository (CNSC, Nirex). Coupled H-M analysis of glacial loading. Numerical analyses of the impacts of increased head gradients and water pressures (OPG). Transient models studying the effects of glacial loading / unloading cycles will probably be developed in the future (Nirex). Mechanical impact of ice-cover on canister holes. Groundwater flow resulting from high gradients (SKB)	Mechanical stability of rock and caverns. Impact on groundwater flow	Impact is important (rock stability, high groundwater flows) CNSC, OPG. Glacial loading can cause rotation of principal stresses. This has to be taken into consideration in designing tunnels for stability. Yes, simple scoping calculations have shown the need to consider glacial derived couplings, in particular the induced changes in boundary conditions and groundwater heads (Nirex). Impact judged to be acceptable, but additional studies may be warranted (SKB)	Boundary conditions at the ice/bed interface, which vary with time as the ice sheet advances or retreats (OPG). In considering couplings with glacial loading relates to the time sequence of the glacial episodes and their impact on the boundary conditions (Nirex).	Yes, changes would impact on the performance of the repository (CNSC). Yes, OPG Yes, for scientific credibility. Can hopefully be treated with bounding assumption (Nirex).

A4.3.1 H-M coupling in the EDZ around the repositories and shafts

This coupling involves changes in hydraulic properties of fractures and rock matrix due to stress changes imposed during excavation of repositories and shafts. The extent of the zone of modified hydraulic and mechanical properties is called the EDZ. Modelling studies and experimental evidence suggest the EDZ can be handled in Safety Assessments by introducing a volume with altered hydraulic properties around the excavations. The extent of the EDZ depends on the rock properties, the cavern depth, the cavern orientation with respect to stress directions (σ_H) and cavern size.
Many assessments include the effect of the EDZ in the hydrogeological analysis, but the EDZ properties are sometimes postulated rather than assessed from measurements or modelling.

Compilation of answers

Nirex addressed the EDZ using a number of approaches. A RES study was used to identify the key parameters likely to impact on the nature and extent of the EDZ across the Potential Repository Zone showing the importance of depth and cavern orientation with respect to σ_H and cavern span (Nirex 1997a). A modelling study was undertaken to determine the extent to which the EDZ was affected by repository design, layout, siting, lithostratigraphy and depth (Nirex 1997b). This used induced stress changes of 2MPa across existing fractures as an approximate indicator of the extent of the mechanical EDZ. To estimate the extent of the hydraulic EDZ, a fracture compliance model, relating changes in fracture mechanical aperture to changes in normal stress across the fracture was used based on coupled shear flow tests (CSFT). Hydraulic aperture was then estimated and related to transmissitivy using the cubic law and the transmissivity converted to hydraulic conductivity using 'Snow's Law'. The study was carried out using the code EXAMINE assuming effective stress conditions with a uniform porewater pressure. This effectively ignores changes (increases) in effective stress due to hydraulic drawdown during the operational phase of the repository and is therefore a worst case with respect to the extent of the EDZ and is consequently applicable to the post-closure phase of the repository. The model assumed elastic rock behaviour and shear displacements across existing fractures. The results of the above elastic model were compared with calculations using an elastoplastic model implemented using PHASES with a Hoek & Brown failure criteria. This showed that an elastic representation of the EDZ was conservative (Nirex 1997b). Observational evidence based on participation in the ZEDEX experiment (Emsley et al 1997) was also used.

Early PA treatments of the hydrogeological impact of the EDZ around vaults and shafts assumed that the axial and radial hydraulic conductivity increased by 100 and 10 times that of the background respectively within a zone assumed to extend for one diameter from the excavation (Atkinson et al 1994). Based on the results of modelling and experience from full-scale experiments (ZEDEX) the EDZ in the Nirex 97 PA was reduced to 8m, approximately one cavern radius, with the axial hydraulic conductivity increased to 100 times that of the background rock (Baker et al 1997).

OPG note that although no coupled hydro-mechanical modelling was performed, the possible effects of an EDZ (whether it has resulted from blast damage, thermal stress or shear rupture due to unfavourable in situ stress, tunnel shape and orientation) and the near-surface disturbed zone due to thermal stress on PA of the geosphere have been studied by detailed 3-D finite-element groundwater flow modelling and particle tracking (Chan and Stanchell 1991). The particle-tracking results indicated that an EDZ and near-surface disturbed zone (represented as an EPM with practically infinite permeability) would have little effect on groundwater travel time from the repository to ground surface. More elaborate solute transport modelling (Chan et al.1997 and Chan et al. 1999b) indicate that the results are quite sensitive to the geometry and material properties of the EDZ and material properties of the discrete fractures. An EDZ with maximum damage (based on reasonable extrapolation of experimental data) would lead to a radiological dose rate only 2 to 3 times higher than the case with a minimum-damage EDZ. However, in a very pessimistic case with an EDZ and a very conductive discrete fracture or minor fracture zone connecting the repository to a major fracture zone at a very unfavourable orientation (Chan et al., 1997), the estimated radiological dose rate (based on a deterministic 2D finite-element solute transport model of part of the geosphere followed by an approximate dose conversion factor) would be 100 times higher than the medium-value estimate for the reference EIS case study that assumes no EDZ and no discrete fractures. Sensitivity analysis showed that the large effect was caused by the very conductive discrete fracture rather than the EDZ. The orientation, location and extent of the discrete fracture in that numerical study were considered extremely unlikely by the site geologists. Sensitivity analysis was also performed in the post-closure IPA using the SYVAC3-CC3 (EIS) model by varying the Waste Exclusion Distance (WED), which is defined as the shortest distance from the edge of a repository room to a major fracture zone through SFR.

In the SKB SR 97 assessment there was no coupled analysis of the change in near-field rock permeability due to intact rock failures. Instead, near-field radionuclide escape routes are assumed to exist a priori (SKB, 1999b). Some of these are, by definition, results of mechanical processes (fracturing around openings). The estimation of the EDZ effects were partly based on the findings from the ZEDEX experiment conducted at the Äspö HRL (Olsson et al, 1996), but additional assumptions were made in order to obtain reasonable bounds to effects of this M-H coupling (Andersson, 1999).

A4.3.2 H-M coupling during shaft sinking

It would be potentially interesting to obtain experimental evidence for hydro-mechanical effects during shaft sinking.

Compilation of answers

Nirex planned to collect appropriate data to measure the coupling between stress redistribution associated with the sinking of the Rock Characterisation Facility shafts and the hydraulic response of the surrounding rock volume. The possible effects of these processes were modelled as part of the Task 1 of DECOVALEX II (Jing et al 1999). It had been hoped to compare modelling results with observation during shaft sinking but the refusal to gain permission to sink the shafts meant that this was no longer possible.

OPG reported that prior to sinking the shaft for the URL in granitic rock in Manitoba, the expected change in the permeability of discrete fractures due to stress changes were simulated using one-way coupled M-H modelling. Uncoupled mechanical stress modelling was performed to simulate redistribution of stress as the shaft advanced (Lang et al. 1987). An empirical hyperbolic normal stress-normal fracture closure relationship was then utilized to calculate the new fracture aperture, from which fracture permeability was calculated. Stresses and fracture transmissivity were measured in boreholes as the shaft advanced. The model predictions did not agree with the measurements. A similar experiment was attempted in the Room 209 tunnel at 240-m level. Again, the one-way coupled model did not correctly predict the measured fracture permeability change during tunnel excavation (Chan et al. 1993). It was concluded that 1) two-way coupled HM modelling should be attempted and 2) it is preferable to have an experiment in which the excavation does not intercept the fracture(s) to avoid processes other than coupled H-M processes affecting fracture permeability.

A4.3.3 H-M coupling during hydrotesting

Large drawdowns during hydrotesting in boreholes affects the measured hydraulic conductivities of fractrures. However, at instances the effect is considered insignificant compared with other uncertainties affecting permeability estimates.

Compilation of answers

Nirex considered that sufficiently large drawdowns imposed during hydrotesting in boreholes may be sufficient to modifiy the mechanical and hence hydraulic aperture of fractures which in turn impact on the measured hydraulic conductivity and storage of the fracture system. Modelling suggested that this mechanism was possible. However it was unlikely to be significant compared with other uncertainties in the analysis of hydrotesting results undertaken at Sellafield (Nirex 1997e).

A4.3.4 H-M coupling due to stress impacts on fracture hydraulics.

A potentially important H-M coupling is the stress (change) impact on fracture aperture and thus permeability. Such impacts may both concern understanding of current in-situ conditions and when projecting potential permeability changes resulting from future changes of the stress field (thermal load, ice load etc.).

Studies of the variation of transmissivity of fractures as a function of orientation and depth in the Sellafield area may be taken as evidence for a coupling between in-situ stress and fracture hydraulics. It would certainly be of interest to know when this coupling is significant (i.e. when changes of the stress state will make it necessary to (significantly) change initial estimates of fracture transmissivity.

Compilation of answers

Nirex consider that in certain environments in situ stress conditions could modify the transmissivity of the fracture network due to the modification of the mechanical and hydraulic aperture of the fracture network. A study undertaken as a result of the Nirex programme suggested that there was evidence for such coupling from the variation of transmissivity of fractures as a function of orientation and depth in the Sellafield area (Lunn 1997). Nirex did not explicitly include this coupling in Nirex 97 (Baker et al 1997) beyond using the observational data to parameterise the hydraulic conductivity vectors used in the modelling of the groundwater pathway.

SKB has not quantitatively explored the impact of fracture transmissivity change due to fracture deformations, although this coupled process has been analysed conceptually in numerous investigations. In the near-field, future loads are not expected to give systematic increases in fracture apertures (SKB 1999a). This is a conclusion drawn from thermomechanical stress analyses and from ice load stress analyses. However, it cannot be ruled that, around individual deposition holes, unfortunately oriented and located fractures may open. The variation in escape route transport capacity assumed in the SR 97 safety analysis is judged to provide sufficient bounds to possible effects of this coupling. In the far-field, below the ground surface, apertures of steeply dipping fractures and fracture zones will increase as a result of the thermal pulse (SKB, 1999a; Hakami et al., 1998). No explicit account is taken in the SR 97 safety analysis of this systematic increase in vertical hydraulic conductivity. The reason is that the effects do not extend deep enough to have any significant influence on the conditions around the repository.

A4.3.5 H-M: Overpack corrosion expansion analysis

Both the mean effective stress distribution and the shear stress distribution increase their values with the progress of the overpack corrosion expansion. Analysis shows that the engineered barrier system attains a stable state for a long period of time without reaching a total failure condition.

Compilation of answers

JNC analysed the overpack corrosion expansion by evaluating the stress state and excess pore water of buffer. The buffer is described as an elasto-plastic body (Modified Cam-Clay model) and the overpack is treated as an elastic body (with consideration of temperature strain for expansion). The analysis code is ABAQUS. Dimensions of analysis is axial symmetry. Duration of evaluation is 10,000 years. Rock creep deformation is described on the basis of the result of creep analysis. Self -weight is not considered. Both the mean effective stress distribution and the shear stress distribution increase their values with the progress of the overpack corrosion expansion. The distribution state of these values becomes high in the vicinity of the overpack. The maximum value of stress ratio after 10,000 years is 0.60, of which didn't reach the critical state (M=0.63). The zones in which the stress ratio is particularly large are limited to the peripheral area of the overpack. The excess porewater pressure begins to increase at the onset of the overpack deformation arising from corrosion expansion, and reaches a near maximum level after about 400 years, and the maximum value is about 2.7 kPa. After the completion of the overpack corrosion expansion, the excess porewater pressure becomes zero immediately, and the consolidation is complete. From the above considerations, the analysis shows that the engineered barrier system attains a stable state for a long period of time without reaching a total failure condition.

A4.3.6 Glacial load

In situ stress conditions and hydraulic heads would be altered by the advance and retreat of glaciers / ice-sheets in proximity to, or above, the repository. In upper layers this may lead to structural failures of the rock mass and shearing of existing fracture zones, but these effects tend to decrease with depth and distance from major fracture zones. The glacier could also induce very high hydraulic gradients around the repository. The T-H impact from glaciations needs to be explored if the impact from glaciations should be properly analysed. (Such analyses are of course only relevant in repository locations where future glaciations are a possibility.)

Compilation of answers

In studying the effects of glaciation on a nuclear fuel waste repository (Nguyen et. al 1993; Selvadurai and Nguyen, 1995) CNSC considered a full H-M coupling. The results of mathematical modelling reported here show that structural failure of the rock mass near the edge of the glacier could happen in the top 200 m. Existing fracture zones could also experience shear failure at these shallow depths. At deeper elevations, where a repository would be located, structural failure of the rock mass is unlikely. The glacier could induce very high hydraulic gradients around the repository. These gradients could reach maxima of the order of 100% (several orders of magnitude higher than normal regional gradients). CNSC concludes that a new glacial period, happening in the next 10,000-20,000 years, is a possibility. A rock mass of the Canadian Shield that would host a nuclear fuel waste repository, would experience important changes in its stress and groundwater flow regimes, similar to what happened in previous glacial periods. These changes would impact on the performance of the repository. The modelling results suggest that, as a consequence of the flow rates resulting from these gradients, an envelope of unfractured rock of at least 100 m between the wastes and a major fracture zone is desirable.

In SR 97 SKB (SKB, 1999a) discussed the mechanical impact form an ice-cover based on the calculations made in support of the SKI SITE-94 report (SKI, 1996). These analyses suggest that the glacial load would not constitute an hazard for the canisters. SKB also explored the impact of high gradients potentially resulting from sub ice streams. Temporarily very high flows may result, but the overall impact on performance was judged to be minor.

OPG notes that the hydraulic impact of a glaciation has been discussed qualitatively in some detail (Davison et al. 1994a). A main argument for not treating glaciation in detail (Davison et. al. 1994b, Zach 1996) was: “The next glacial episode will not occur until about 2 x 10^4 years from now (Eronen and Olander 1990) beyond the 10^4 - year time period required for quantitative evaluation of potential impacts (AECB 1987)”. A literature review and a simple linear elastic mechanical analysis was performed (Ates et al. 1997) under the conceptual disposal facility engineering study (Simmons and Baumgartner 1994). A potentially important effect identified is the change in surface topography leading to changes in hydraulic head distribution. Quantitative analysis was not performed in time for the public review of the EIS. Subsequently, 2D coupled H-M finite-element modelling was performed to investigate potential effects of a future glaciation on a repository located in SFR (Chan et al. 1998) using the MOTIF finite-element code. Continuum models with and without a vertical fracture zone were analysed. Cases with the repository situated beneath the interior or the front (terminus) of the glacier were considered. It was found that significant excess pore pressure (up to approximate 1/3 the ice pressure) would be generated by the consolidation effect due to mechanical loading by the glacier. The results are dependent on the assumed hydraulic boundary condition at the ice/bed interface. In one case the hydraulic gradient due to glacial loading was predicted to be greater than unity. This hydraulic gradient dissipates very slowly. Groundwater travel time from 500-m depth to ground surface was predicted to be significantly shorter than those predicted by detailed coupled flow modelling for the EIS reference case (Davison et al. 1994b). In addition to increasing the magnitude of stress in the rock the ice load also causes a rotation of the principal stresses. This has to be taken into consideration if tunnels were to be designed for stability by optimising their shape and orientation relative to the major principal stress direction. Mechanical stability was not analyzed because it was suspected that the calculated stress results might have been affected by the choice of mechanical boundary conditions. Further coupled H-M (and perhaps also T-H-M) modelling will be carried out in the context of DECOVALEX III BMT 3. Major uncertainties include the boundary conditions at the ice/bed interface and how these boundary conditions vary with time during the advance/retreat of the ice sheet.

Also Nirex have analysed the H-M coupling due to glacial loading / unloading cycles. In situ stress conditions and hydraulic heads would be altered by the advance and retreat of glaciers / ice-sheets in proximity to, or above, the repository. This has not been explicitly included in existing Nirex Safety Assessments. However the processes involved have been considered briefly and some preliminary transient scoping calculations have been undertaken.

A4.4 Full (or almost full) T-H-M couplings considered

There are few examples where the full T-H-M couplings have been considered in a safety assessment context, see Table A4-4. The different issues are further discussed in the following subsections.

A4.4.1 Heat pulse creating a hydraulic driving force and potential fracturing

It is suggested, based on scoping calculations with an almost fully coupled T-H-M code, that the heat pulse generated by the wastes has the ability to significantly perturb the groundwater and stress regimes in the host rock. According to analyses the heat pulse may create groundwater driving forces and in some extreme cases, when a low

***Table 4-4**: Full (or almost full) T-H-M couplings considered*

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA
Heat pulse creating a hydraulic driving force and potential fracturing	Scoping calculations of consequence of heat load with the FRACON code (T-dependent hydraulic conductivity, full hydro-mechanic coupling, heat conduction and thermally induced stresses and deformation) (CNSC). Two quantitative analyses based on completely different methods were performed to compare with the CNSC results : a 2D fully coupled T-H-M model using the MOTIF finite-element code and a semi-analytical solution based on the Green's function method (OPG). Comparison of results from different models (OPG).	Impact on groundwater and stress regimes (CNSC). Considered potential of thermoporoelastically induced pore pressure (from different models) causing cracks to short circuit repository to fracture zone (OPG).	Yes, the pore pressure induced by may be a significant driving force and in some extreme cases, the high pore pressure can induce tensile cracks in the rock mass (CNSC). Effect is expected to be more significant for very-low permeability sparsely fractured rock or intact rock than medium fractured rock with well-connected fractures (OPG)	Different modelling approaches yield different calculated temperatures and pore pressures. Further modelling exercises are needed (OPG).	Yes, (CNSC) Yes, at least until issue is resolved (OPG).
Engineered barrier resaturation	Model water diffusion in unsaturated clay, water movement due to the thermal gradient and the swelling pressure resulting from wetting of the buffer. Thermo-hydro-mechanical experiments at the Kamaishi mine. (JNC) Sensitivity analysis using lower thermal conductivity to represent unsaturated buffer in thermal and thermomechanical analyses. Post-EIS coupled T-H numerical analysis including convective groundwater flow and heat transport, as well as swelling stress (OPG). T-H-M calculations which aim at assessing the time scale for saturation of the buffer. The main processes are heat flow from the canister through the saturated /unsaturated buffer, flow of liquid water from the rock into unsaturated portions of the buffer, evaporation/condensation and development of a swelling pressure with accompanying redistribution of the initial buffer porosity (SKB).	Study of resaturation behaviour (JNC). Need to understand the evolution of the barrier system (SKB) Resaturation effects on maximum near-field temperature and stress.	It is found that the resaturation behavior of the near-field can be assessed (JNC). Yes a fully coupled approach is needed in the buffer. Couplings in the rock less explored. (SKB). Can be important for design of lrepository ayout (OPG).	The complexity of the saturation problem is mainly on the buffer side, and work is underway to better understand how soil suction is influenced by the developing swelling pressure and how gas pressures may affect the time scale (SKB). Model validation (OPG).	Yes
Permeability and velocity changes due to thermomechanical deformation of fractures and temperature-dependent viscocity	Fracture aperture changes due to temperature changes are used to calculate permeability changes for the YM case. (USDOE). T-M analyses are used to determine fracture permeability change and geometry of the altered zones, and T-H analysis using the results from the T-M analyses is used to determine the effect of altered zones on percolation flux. (USNRC) Fully coupled T-H-M near-field	Changes in hydrologic properties compared to the natural variability of these properties (USDOE). Effect on calculated radiological risk and the ability to understand the details of the hydrogeological or mechanical system. T-M effects on the distribution if	T-H-M effects considered to be small in relation to natural variability (USDOE) Being explored, effect is potentially very important (USNRC) Range from mild to significant	Rock-mass mechanical and strength parameters (USNRC). In situ parameters for stress-displacement constitutive	USDOE consider T-M-H effects in SR calculations Elevated percolation flux will potentially affect corrosion, waste mobilization, and transport. (USNRC)

Issue	Type of analysis	How was need assessed?	Is coupling (or process) important	Major uncertainties?	Need to consider in PA
	analyses using highly idealized geometry (OPG/AECL)	moisture percolation flux across repository axis. (USRNC). Effects on groundwater velocity (OPG/AECL)	depending on model configuration (OPG/AECL)	relationship for fractures (OPG)	Yes (OPG)

permeability is combined to a high Young's modulus of the rock mass this may induce tensile cracks in the rock mass. There is currently some uncertainty regarding the significance of the effect. It has been suggested that the effect is expected to be more significant for very low permeability sparsely fractured rock or intact rock than medium fractured rock with well-connected fractures.

Compilation of answers

CNSC have developed the FRACON code including temperature dependent hydraulic conductivity (T->H through viscosity and density), full hydro-mechanic coupling is considered via the effective stress principles in geomechanics (H->M and M->H, Biot, Terzaghi), heat conduction (T) and thermally induced stresses and deformation (T->M). The code neglects thermal convection (H->T), since flow rate is low in granitic rock mass, and mechanical impacts on temperature (M->T). The code was subjected to verification against a set of analytical solutions, prediction of laboratory experiments and prediction of field experiments.

The FRACON code was used for the preliminary assessments of the impact of the heat generated by nuclear fuel wastes on a sparsely fractured plutonic rock mass, representative of conditions that can be encountered in the Canadian Shield. The thermal, mechanical and hydrological disturbances due to these two factors were traditionally analysed by neglecting the coupling between the T-H-M processes. From the scoping calculations where this coupling is considered (Selvadurai and Nguyen, 1996), several new results were found:

- The heat pulse generated by the wastes has the ability to significantly perturb the groundwater and stress regimes in the host rock.
- The pore pressure induced by the radiogenic heat can accelerate the movement of contaminated water to the ground surface. In ten thousand years, this accelerated rate results in flow distances of tens of metres in addition to any flow distance dictated by the natural hydraulic gradient that existed prior to the thermal loading.
- Very low permeability of the rock mass will not always ensure lower groundwater flow rate since the thermally induced hydraulic gradients are higher for lower permeabilities. In some extreme cases, when a low permeability is combined to a high Young's modulus of the rock mass, the high pore pressure generated by the waste heat can induce tensile cracks in the rock mass, and the buffering distance provided between the repository and a fracture zone could be reduced.

By analyzing the thermal, stress and groundwater flow regimes of a rock mass without considering the influences of coupling between these processes, it is likely that some safety features of importance to a repository could be unwittingly omitted. It is recommended that detailed, site-specific assessment of a future repository should be conducted by taking into account the coupled nature of thermal-mechanical and hydrological processes.

According to OPG a finite-element code, MOTIF, have been developed under the auspices of the Canadian Nuclear Fuel Waste Management Program to simulate fully coupled T-H-M processes in fractured rock masses (Guvanasen et al. 1986, Guvanasen and Chan 1991 and 2000). The formulation is based on a generalization of Biot's (1941) consolidation theory to nonisothermal situations. Heat conduction, convection and dispersion are included. Fluid viscosity is temperature dependent and fluid density can vary with temperature and pressure. A nonlinear stress-fracture displacement constitutive relationship has been incorporated. The MOTIF code has been utilized to model various coupled T-H-M phenomena in a PA context.

One coupled effect that may potentially affect the safety (long term performance) of the repository is cracking of rock due to excess pore pressure generated by thermoporoelastic effect (Nguyen and Selvadurai 1995). Since water has higher thermal expansion coefficient than rock, excess pore pressure would be generated as the radiogenic heat raises the temperature of saturated rock. In very low-permeability rock this excess pore pressure can only be dissipated very slowly. The question is whether this excess pore pressure can lead to crack initiation and propagation, thus creating a fast transport path from the repository to a major fracture zone. Two quantitative analyses based on completely different methods were performed to compare with the results of Nguyen and Selvadurai (hereafter designated Model 1). The coupled T-H-M analyses performed by AECL and its consultant at the University of Minnesota were: a 2D coupled T-H-M model using the MOTIF finite-element code (designated Model 2) and a semi-analytical solution based on the Green's function method (designated Model 3). The results indicate that:

- the excess pore pressure calculated by Models 2 and 3 are approximately the same but are lower than those calculated by Model 1;
- the temperatures calculated by Models 1 and 2 are very similar but are lower than those calculated by Model 3.

Berchenko et al. (1997) subsequently investigated the conditions for unstable natural hydraulic fracture propagation. This paper, however, did not explicitly analyse thermally generated pore pressure. Further coupled T-H-M modelling is clearly necessary to address this question. This effect is expected to be more significant for very-low permeability sparsely fractured rock or intact rock than medium fractured rock with well-connected fractures.

A4.4.2 Engineered barrier resaturation

Analysing resaturation of the engineered barriers may require a fully coupled analysis. Such modelling was part of DECOVALEX II and is also studied as separate BMT (BMT1) in DECOVALEX III. The analysis is supported by experimental evidence.

Compilation of answers

In exploring resaturation of the Engineered barriers JNC consider a fully coupled T-H-M situation. The modelling of the mechanical phenomena in the engineered barrier system is extended from the coupled thermo-hydro-mechanical code developed by Ohnishi et al. (1985). This model can take into consideration water diffusion in unsaturated clay (Philip and de Vries, 1957), water movement due to the thermal gradient (de Vries, 1974), and the swelling pressure resulting from wetting of the buffer.

To acquire data relating to coupled thermo-hydro-mechanical phenomena under actual rock mass conditions, JNC conducted coupled thermo-hydro-mechanical experiments at the Kamaishi mine (Fujita et al., 1998). Heating and cooling tests were conducted and changes in the temperatures of rock mass and buffer, as well as changes in the water content of the buffer, were measured. An analysis has been made for the disposal pit method for vertical emplacement in hard rock, using the axisymmetric model. For the intrinsic permeability of the rock mass, the average value for the rock mass and the value of the rock matrix are used. The excavation of the tunnel is described by fixing a tunnel portion at atmospheric pressure. The results show that, in the analysis, the buffer would be saturated in 50 years, except for one case (porewater pressure, 0.0 MPa; intrinsic permeability of rock mass, 1.0×10^{-20} m^2. It is found that the resaturation behavior of the near-field can be assessed through an analysis that takes into account coupled thermo-hydro-mechanical effects.

OPG (AECL) discussed qualitatively re-saturation under a heat gradient as a near-field effect (Johnson 1994b and 1996) in support of the SA for the EIS and Second Case Study. The thermal conductivity of bentonite clay based buffer and backfill materials is dependent on the degree of saturation. Unsaturated buffer and backfill would have lower thermal conductivity, leading to higher canister temperature. Conservative (low) thermal conductivity was assumed for buffer and backfill materials in designing the borehole layout using heat conduction and thermomechanical calculations (summarised in Simmons and Baumgartner 1994). Subsequently, finite-element analysis was performed (Thomas and Onofrei 1996) taking coupled T-H effects into account in unsaturated backfill and buffer.

SKB has conducted numerous T-H-M calculations which aim at assessing the time scale for saturation of the buffer (SKB, 1999b). The main processes are heat flow from the canister through the saturated /unsaturated buffer, flow of liquid water from the rock into unsaturated portions of the buffer, evaporation/condensation and development of a swelling pressure with accompanying redistribution of the initial buffer porosity. All processes are interrelated and non-linear, which requires fully coupled calculations. A description of the numerical approach is given by Rutqvist et al. (2000) together with descriptions of corresponding approaches used by other participants to the DECOVALEX II project. For the time scale calculations performed for the SR97 safety report, a number of assumptions were made regarding the hydraulic conditions in the near-field rock, while the buffer parameters were kept constant. Full saturation was obtained after 12 years for typical reference conditions. The complexity of the saturation problem is mainly on the buffer side, and work is underway to better understand how soil suction is influenced by the developing swelling pressure and how gas pressures may affect the time scale. The rock experiences an increasing boundary pressure, which is small in comparison to the tangential stresses that prevail at the borehole periphery. This pressure tends to stabilise the periphery and restrict initiation and development of brittle failures in the walls of the deposition holes (SKB, 1999a) but is not judged to be crucial to safety and has no impact on the saturation time scale.

A4.4.3 Permeability and groundwater velocity changes due to thermomechanical deformation of fractures and temperature-dependent viscosity

A set of analyses conducted for the Yucca Mountain project suggest that changes in hydrologic properties due the T-M-H processes are rather small compared to the natural variability of these properties. OPG (AECL) performed generic near-field numerical studies to investigate the effects of coupled T-H-M processes on fracture aperture and groundwater velocity using bench mark tests that include either multiple fractures or a single fracture in a stiff rock with very low permeability. The results indicate a rather complex interplay of fracture closure and temperature-dependent water viscosity.

Compilation of answers

USDOE consider T-M-H effects in SR calculations. Fracture aperture changes due to temperature changes are used to calculate permeability changes. The effects are not large in preliminary calculations. Changes in hydrologic properties due the T-H-M processes are rather small compared to the natural variability of these properties across the mountain.

USNRC are currently conducting T-M and T-H analyses to evaluate T-M-induced changes in hydrological properties and drift geometry, and the effects of such changes on moisture flow. Results indicate the following: (1) Thermally induced rock failure in the roof, floor, and sidewall areas of the emplacement drifts (aided by seismically induced rockfall from the roof) would result in considerable changes in emplacement-drift geometry. (2) Significant changes in fracture permeability from fracture-network dilation associate with thermally induced fracture slip can be expected in two zones centered at the drift and at the middle of the pillars. The pillar-centered zone would be more extensive and would develop only in areas of relatively high rock-mass stiffness. (3) Lateral diversion of moisture within or above the altered zones would result in elevated moisture fluxes through the repository in certain areas and reduced fluxes in other areas. The effects of such moisture-flux redistribution on corrosion and waste mobilisation and transport need to be accounted for in PA abstractions.

OPG (AECL) performed generic near-field numerical studies to investigate the effects of coupled T-H-M processes on fracture aperture and groundwater velocity using test problems that include either multiple fractures (Chan et al. 1996) or a single fracture (Guvanasen and Chan 2000) in a stiff rock with very low permeability. The results indicate a rather complex interplay of fracture closure and temperature-dependent water viscosity. Thermally induced compressive stress causes fracture closure and concomitant reduction in fracture permeability, whereas viscosity decrease with temperature leads to increased groundwater velocity for a given fracture aperture. Velocity changes can range from a fractional increase to a decrease by a factor of 100 of the initial isothermal value. Both the magnitude and direction of the velocity change can be time dependent. These studies were conducted using highly idealized geometrical models. The complex interplay between competing factors in coupled T-H-M processes is likely site and design specific. Prior to abstracting simplified models for SA, it would benecessary to conduct fully coupled T-H-M PA models using site-specific and design-specific parameters and geometries.

A5. R&D on T-H-M in nuclear waste programmes

Coupled T-H-M processes are considered in the R&D plans of the waste management organisations and by the respective regulatory organisations.

A5.1 Numerical modelling

Most organisations are involved in some aspects of T-H-M modelling. Most results presented in chapter 4 are based on such modelling. It seems that modelling related to different DECOVALEX tasks is an important part of the modelling undertaken.

Compilation of answers

JNC has a 2-D and axial symmetry T-H-M model version considering water movement under temperature gradient. A model of the development of the swelling pressure of buffer has been modified to a 3-D version. Nirex took part in the BMT2 and BMT3 cases of DECOVALEX III task 3. As previously noted POSIVA conducts several rock mechanical analyses. Studies presently underway include mechanical and thermomechanical analyses of the stability of repository excavations (Johansson & Rautakorpi 2000) and earthquake analyses (a continuation of LaPointe & Claduohos 1999). OPG note that ongoing participation in BMT 2 (upscaling) and BMT 3 (glaciation) within DECOVALEX III can be considered numerical experiments with T-H-M relevance. To USDOE numerical simulations/analyses are an integral part of the thermal testing program. Numerical simulations of the tests are used to design the tests and to predict the measurements to be made in the tests. Actual measurements in the tests are then compared with the predictions and interpretations are made leading to refinements to the mathematical models used for making the predictions. USNRC notes that CNWRA is currently conducting numerical experiments with T-H-M relevance. Currently, the numerical analyses are restricted to T-H, but will be expanded to include M by loosely coupling T-H and M numerical model analyses.

A5.2 Site specific measurements and field tests

Most respondents have or are planning to measure T-H-M related parameters as a part of the site investigations. Measured parameters include stress field, rock strength, heat transfer properties, and of course, geological, geophysical, geohydrological and geochemical data. The site data is usually complemented with an extensive laboratory testing program for thermal, thermal-hydrological and thermal-mechanical parameters. Mechanical models usually obtain the structures (fracture pattern, fracture zones) from the geological characterisation, the mechanical properties from laboratory measurements on bore cores and stress distributions from in-situ stress measurements. There are also plans for exploring the history of faults using detailed mapping, petrographic and mineralogical investigations of fractures and fracture zones, paleohydrogeologic techniques and Apatite Fission Track Thermochronology.

Anomalies found in hydraulic head monitoring could be tested against various possible mechanisms, including glaciation and high salinity that may have led to the observed anomalies.

Some programmes have not yet selected sites or investigation areas. These programmes do not at present plan T-H-M related site measurement, but the organisations note that such measurements will be undertaken when sites are selected and explored.

In addition some organisations conduct different field tests. These include:

- the "prototype repository" and other T-H-M related experiments at the Äspö HRL,
- different heater experiments with measurement of T-H-M responses at URL Canada, and elsewhere.

Future plans include:

- 'ZEDEX'-type experiments to determine the impact of excavation technique,
- measurements of displacement, water inflow and draw down during shaft sinking, as part of a monitoring of the coupled rock response.

Compilation of answers

JNC notes that in Japan, the implementing organisation will be established in the year 2000. The detail plan to measure parameters and so on will be decided after that. T-H-M issues are considered in specifications of repository and engineered barrier, thus are treated as initial condition in PA/SA.

Nirex notes that it had been hoped to undertake a number of H-M experiments in the Nirex Rock Characterisation Facility. These would have included a 'ZEDEX'-type experiment to determine the impact of excavation technique. During shaft sinking, measurements of displacement, water inflow and drawdown would have been undertaken as part of a monitoring of the coupled rock response. In the event that Nirex constructs a RCF in future, similar experiments are very likely to be included.

Site investigations and numerical analyses conducted during the Canadian Nuclear Fuel Waste Management Program have developed and tested methods relevant to at least 2 or 3 T-H-M processes. These include: Detailed mapping, petrographic and mineralogical investigations of fractures and fracture zones on shaft and drift walls. It was concluded that there are no shear displacements that can be attributed to geologically recent events such as glaciation or neotectonic movements. Recently, paleohydrogeologic techniques and Apatite Fission Track Thermochronology have been employed to further address issues surrounding fracture/fault re-activation and displacement. Regional hydraulic head monitoring has been conducted for over 15 years. Apparent anomalous head distribution (large deviation from hydrostatic condition) have been observed. There is an ongoing project to document and reanalyse these data and to test various possible mechanisms, including glaciation and high salinity that may have led to the anomalies. There is also a project to develop and test methods for in-situ stress measurements in deep boreholes.

OPG also notes that a recently completed in situ experiment (Martino and Chandler 1999) conducted at the URL, known as the Thermal Hydraulic Experiment (THE) should have been called the THME. A small heater installed at the end of a borehole was used to raise the temperature of SFR (Sparsely Fractured Rock) at the 420-m level. Temperatures and hydraulic pressures were measured. Analytical solutions based on the

theory of coupled thermoporoelasticity was employed to back-analyze the data. After fitting the thermoporoelastic parameters the modelled and measured pore pressure and temperature changes are in good agreement. Laboratory determinations of these parameters were also carried out. Also time-dependent rock failure in the Mine-By tunnel at the URL has been modelled with some success using the PFC (Particle Flow Code) after some parameter calibration (Potyondy 1998). It was found that some further improvement is necessary to achieve detailed quantitative prediction of the temporal evolution of notch breakouts. Work is being planned to extend the capability of the PFC code to include poroelastic and thermoporoelastic effects and to apply it to model some of the experiments mentioned above, plus the TSX (Tunnel Sealing Experiment).
Past URL experiments with some T-H-M relevance have included: 1) the Room 209 Excavation Response Test at the 240-m level (Lang et al. 1988; Chan et al. 1993); 2) simultaneous measurements of in situ stress in the rock walls of a fracture zone and permeability in the fracture zone at a number of locations (Martin et al. 1988); 3) the Mine-By Experiment (Read and Martin 1996); 4) excavation stability study to investigate how the shape and orientation of tunnels relative to the principal in situ stress directions affect tunnel (or disposal room) breakout (Read 1996); 5) a heated failure test to study borehole breakout when large diameter boreholes are drilled under high in situ stress at elevated temperatures; 6) an isothermal buffer test to investigate buffer swelling and buffer/rock interaction; and 7) a buffer/container experiment to study buffer resaturation, swelling and other near-field T-H effects including elevated pore pressure due to heating.

STUK'S TEAM notes that the T-H-M parameters, which have and will be measured at the selected site (Olkiluoto) include stress field, rock strength, heat transfer properties, and of course, geological, geophysical, geohydrological and geochemical data. The data is needed for adapting the EBS to the in-situ conditions and to find the optimal location and layout of the repository within the site, and as input for forthcoming safety assessments. Presently, Posiva is participating in the experiments in the Äspö Hard Rock Laboratory and is involved in several project proposals for T-H-M studies in the 5th Framework programme of EU.

USDOE notes that T-H-M related parameters have been and are being measured in the Yucca Mountain site investigations program. An extensive laboratory testing program has been completed for thermal, thermal-hydrological and thermal-mechanical parameters. These are being complemented by a program of field testing under which three thermal tests have been or are being conducted (the Single Heater Test, the Large Block Test and the Drift Scale Test) and one more is planned. The properties are being measured from a number of samples taken from a range of locations in and around the planned repository footprint. In situ measurements at several locations are also being used. The overall objective of the thermal testing program is to gain an in-depth understanding of the coupled thermal-mechanical-hydrological-chemical processes that take place in the local rock mass around the potential repository because of the decay heat from the emplaced waste.

USNRC does not carry out site investigations, this is the task of U.S. Department of Energy. However, T-H experiments have been recently conducted at CNWRA. A third laboratory-scale experiment (LST3) has been designed and is undergoing fabrication. The LST experiments have T-H, but not T-H-M relevance. We are not conducting an in situ experiment with T-H-M relevance.

A5.3 Use of data

T-H-M data are used in relevant functional analyses and in Safety Assessments. In addition, T-H-M data and analyses have a central role in locating of the repository within the site in order to ensure constructability and stability of deposition tunnels and holes. There is a strong positive correlation between constructability, operational and long-term safety of the repository. Site characterisation, engineering design and safety assessment are made in close interaction.

It appears that many past postclosure assessment/safety assessment reports tended to be qualitative and focus on issues that had been filtered by the model working groups or among design engineers. Even if the considerations are reported, and may be viewed as part the assessment, this fact may, at first glance, convey the impression that T-H-M issues have been overlooked.

Compilation of answers

According to STUK'S TEAM T-H-M data and analyses have a central role in locating of the repository within the site. The main factors are related to geochemistry (brackish, sulphate-rich water in the upper part of the bedrock vs. more stable, but highly saline groundwater deeper), constructability and stability of deposition tunnels and holes (high stress/strength ratios deeper in the bedrock), fracture zones and flow of groundwater. There is a strong positive correlation between constructability, operational and long-term safety of the repository. Site characterisation, engineering design and safety assessment are made in close interaction.

OPG notes that site investigations, if implemented, are likely to be conducted in a phased approach initiated by non-invasive feasibility studies. The information gathered during these investigations will involve multiple disciplines and focus on the collection of data to support SA and engineering decisions. Past T-H-M modelling efforts in support of Safety Assessment and repository engineering have focused on: i) T-H coupling as relevant to groundwater velocity and temperature field distributions ii) coupled T-M (one-way T to M) response that has been considered in repository design and iii) coupled M-H effects of ice loading on repository rock stress and hydraulic head distribution. Design engineers are also beginning to explore the effects of glaciation. Coupled T-H-M processes were not quantitatively analysed in past SA models but were discussed qualitatively. The PA 'model' reports were much more thorough, and they form an integral part of the SA.

USDOE notes that the measured parameters are for supporting both repository design/engineering design and long-term safety assessment (TSPA). The measured parameters are primarily to evaluate the T-M-H models, which will be used for the long-term safety assessment. Stability of emplacement drifts in the pre-closure period and the nature, characteristics and timing of drift collapse during the post-closure period is an important consideration in repository design and long-term safety assessment. USNRC note that the results obtained from the above mentioned experiments and analyses are extracted for use in the U.S. Nuclear Regulatory Commission/CNWRA performance assessment. It is also noted that the level of importance of different site-specific parameters needs to be analyzed on site-specific and design-specific bases.

A6. How should T-H-M be treated in Safety Assessment?

There are only a few coupled T-H-M processes, which need direct analyses in a Safety Assessment. Although PA/SA is built around simplifying abstractions/assumptions, T-M-H modelling coupled with appropriate testing is still needed to understand how the hydrological system works, in order to construct the abstractions.

A6.1 What key parameters should be used to judge importance of T-H-M coupling

Calculated radiological risk or dose to the public is the ultimate parameter or criterion by which the importance of T-M-H processes is judged in a safety assessment. In most repository concepts, like the KBS-3 concept, the safety function is isolation, and the prime role of the geosphere is to provide the environment that will safeguard the integrity and performance of the EBS. Nonetheless, process models that support the safety assessment help provide an understanding of how T-M-H processes may affect local hydrological conditions.

The key impact of T-H-M processes as regards repository performance is of course disposal concept and site dependent. Examples listed by respondents include

- the water pressure or water content in buffer and rock affects from overpack corrosion should be considered,
- temperature in buffer and rock,
- the EDZ,
- T-H-M effects on parameter estimation from site or laboratory experiments,
- temperature, relative humidity, and rock fall in the emplacement drifts are three key parameters for determining the drip shield and waste package integrity over long periods, and water saturation in the invert of the emplacement drift is one of the key parameters for assessing the transport of radionuclides.

Compilation of answers

According to JNC the water pressure or water content in buffer and rock affects from overpack corrosion should be considered. Temperature in buffer and rock is important for the radionuclide migration.

Nirex consider the EDZ to be one of the most important risk-related couplings. It can be included in a PA as a simple increase in hydraulic conductivity. However, it should be based on a detailed understanding of the underlying processes.

OPG suggest that radiological risk or dose is the quantitative criterion on which the importance of T-H-M parameters should be judged. In addition, coupled T-H-M effects that influence performance measures related to radionuclide transport or repository engineering design and stability should also be considered. Potentially important coupled T-H-M effects include: reduced groundwater travel time and stress redistribution due to H-M effects of glaciation and the possibility of fracture initiation and propagation due to increased pore pressure caused by coupled T-H-M effects in a rock mass with very low permeability and very low porosity. The net effect of T-H-M processes on repository performance remains difficult to quantify, particularly, explicitly in current SA models. Challenges still remain in demonstrating the effect of time dependent T-H-M processes on repository performance.

STUK'S TEAM notes that the KBS-3 disposal concept aims at long-term, retrievable isolation of spent fuel assemblies in durable copper-iron canisters. The key issue for the isolation is the integrity and performance of the EBS. A central part of the safety assessment is the base case resulting in no significant releases of radionuclides from the repository into the geosphere (Crawford & Wilmot 1998, SKB 1999a).

USDOE notes that calculated radiological risk to the public is the ultimate parameter or criterion by which the importance of T-M-H processes is judged. Nonetheless, as indicated in the responses to the items 2 and 3 below, process models that are upstream of TSPA analyses help provide an understanding of how T-M-H processes may affect local hydrological conditions. At the subsystem level, temperature, relative humidity, and rock fall in the emplacement drifts are three key parameters for determining the drip shield and waste package integrity over long periods, and water saturation in the invert of the emplacement drift is one of the key parameters for assessing the transport of radionuclides. These subsystem parameters can be affected by drift integrity and by potential changes in seepage due to T-M-H processes.

USNRC presents the view that the relative importance of a T-H-M-parameter should be based on our understanding of the process. Without such understanding, the effect of radiological risk may be difficult to estimate. The importance of the effect of T-H-M processes on local hydrological and mechanical conditions, on the other hand, has to be considered in the context of radiological safety.

A6.2 Need to demonstrate understanding or just simplifying assumptions?

All respondents agree that considering T-H-M-(C) processes is important for demonstrating understanding. It is necessary for scientific credibility in general but also for the demonstration of the confidence in the understanding of the system. Performance and safety assessments are built around simplifying abstractions (rather than assumptions). It is necessary to acquire a knowledge base supporting an understanding of how the hydrological system works, in order to construct the abstractions. Regardless of the approach selected to PA/SA, evidence should be provided to substantiate simplifying assumptions that consider both time and space.

A PA/SA approach based on simplified assumptions likely will require the support of detailed T-H-M modelling. T-H, T-M and T-H-M models that have been evaluated with respect to analogues and field tests are a significant component of the knowledge base. Although PA/SA is built around simplifying abstractions/assumptions, T-H-M modelling coupled with appropriate testing is still needed to understand how the hydrological system works, in order to construct the abstractions. While detailed modelling may not be explicitly included in the PA/SA, it is likely to remain a key component by offering insight and guidance to define what are reasonable PA/SA simplifying assumptions. Mechanistic modelling is needed to show that abstractions are defensible.

Compilation of answers

JNC thinks that considering THMC processes is important for demonstrating understanding. However, if it is not needed for PA/SA in detail, the hydrogeological modelling may not be important. That depends on the criteria of PA/SA and of permission of closure of repository for each country. THM, THMC or THC modelling may be important for PA/SA on radionuclide migration, and it may be important when permission of closure of repository will be judged. Also permission of closure of repository may be judged based on the confidence of THMC prediction by confirming validity of THMC as well as geological characteristics (hydrology and geochemistry), because these items can be easily obtained during operational phase. Chemistry may be more important when an actual repository will be located in soft rock, since drifts and shafts will be constructed using concrete material, e.g. concrete lining.

According to Nirex considering T-H-M is important for scientific credibility. It is important to be able to demonstrate that we have an adequate scientific understanding of the processes involved.

According to OPG the understanding of the hydrogeological setting should be sufficient to put forth a technically defensible safety assessment. In this regard, the issue of whether simplifying assumptions can be used to build a PA/SA is probably site specific, a function of both the complexity of the hydrogeologic setting and the reliance of the SA on its performance. Regardless of the approach selected to PA/SA, evidence should be provided to substantiate simplifying assumptions that consider both time and space. Examples, may include the applicability of steady-state approximations for flow domains affected by glaciation, the selection of effective diffusivities to describe the uncertainty and spatial variability within the fractured flow domain, the probability that transmissive pathways may either propagate or develop and the likelihood that redox conditions will remain poised during the time frame relevant to repository safety. The rigor with which assumptions are justified will depend on the dominance of the process or mechanism in governing mass transport and the role of the geosphere in the disposal system.

A PA/SA approach based on simplified assumptions likely will require the support of detailed T-H-M modelling. Simplified PA/SA approaches benefit from the fact that they are more easily transparent and traceable. However, issues surrounding dimensionality, time dependent parameter/boundary conditions, spatial variability and parameter scale dependence are likely to influence the validity of such simplified approximations. While detailed modelling may not be explicitly included in the PA/SA, it is likely to remain a key component by offering insight and guidance to define what are reasonable PA/SA simplifying assumptions. Developing confidence in the performance of a used fuel repository requires a coordinated multidisciplinary effort. This includes the derivation of conceptual flow domain models that underlie and serve the basis for development of mathematical models in geosphere PA.

STUK'S TEAM notes that T-H-M-C analyses have a central role in the assessment of the performance and safety of the repository.

USDOE notes that PA/SA is built around simplifying abstractions (rather than assumptions). It is necessary to acquire a knowledge base supporting an understanding of how the hydrological system works, in order to construct the abstractions. T-M and T-M-H models that have been evaluated with respect to analogues and field tests are a significant component of the knowledge base. Although PA/SA is built around simplifying abstractions/assumptions, T-M-H modeling coupled with appropriate testing is still needed to understand how the hydrological system works, in order to construct the abstractions.

USNRC notes that use of simplified model abstractions in a performance assessment are critical to the success of the assessment, otherwise, the fully inclusive model would become too complex to be effective. However, it should be noted that these abstract models should be developed based on process-level models that adequately represent the physical system. Without such a physically based understanding, a realistic performance assessment would not be achieved. There remains the need for process-level models since important processes can be identified and associated uncertainties determined only through the detailed T-H-M-modelling.

A7. Conclusions

The current compilation summarises the treatment of coupled thermo-hydro-mechanical processes in performance and safety assessments of deep repositories in hard (strong) rock formations, available at the time of the start of DECOVALEX III. The answers were provided between January 2000 and February 2001. The report can thus be used as reference when assessing lessons learnt from DECOVALEX III.
Most organisations already apply standardised procedures for identifying processes and couplings to be considered in assessments. However, it seems that these procedures more would be a means of stating the confidence in that all relevant (T-H-M) processes are indeed considered in the safety assessment rather than as tool for identifying previously non-considered processes or couplings. Providing a motivated statement of confidence is indeed a crucial part of a safety assessment report, and here the formal approaches are indeed valuable. However, judging from answers the impression is that most THM issues are already identified. One should not expect dramatic surprises if applying such procedures. (It is rather the means of analysing the couplings that needs to be discussed.) But the current conclusion depends on the material of the EBS. When concrete material is used, chemical influence against the performance of the EBS is not negligible.

There are several identified problems where T-H-M couplings are shown to be important or are judged to be potentially important to be considered directly in a safety assessment context. Examples of such problems given by the different respondents to the questionnaire include:

- One of the more important pure hydro-thermal couplings concerns the migration of vapour, water and heat in partially saturated systems. These systems seem very hard to describe without considering this coupling.
- Most programs evaluate the mechanical stability of the underground excavations before and during construction. Most analyses can be limited to only consider mechanical processes such as rock burst, rock failure (breakout) and fallout of key blocks. After disposal the thermal effect on rock stability needs to be assessed in the near field, and potentially also in the far-field.
- The potential for and the effect of rock creep is studied in some programs. Even if analyses seem to suggest that creep would be limited and its impact small, the process is not discarded from consideration in the safety assessment context.
- Mechanical effects such as rock fall or fracture shear displacements resulting from earthquakes have been analysed and found to be potentially significant to consider. There seems to be fewer studies on the impact on permeability or hydrology in general.
- A potentially important hydro-mechanical coupling concerns the understanding and modelling the formation and resulting hydraulic properties of a disturbed zone (EDZ) around tunnels. Many safety assessments make assumptions on the EDZ based on limited experimental data. A better understanding of the EDZ may affect parameters used in the Safety Assessment and would at any range improve the confidence in the description of the near-field rock.
- There is less clear evidence as to what extent there is a real need to consider stress and stress change impact on fracture hydraulics. There are some field studies indicating such impacts, but it has not really been studied if these effects would be important in a safety assessment context.

- The consequences of a glacial ice cover is another area where hydro-mechanical couplings are potentially very important to consider. Important questions include proper formulation of both hydraulic and mechanical boundary conditions, resulting hydraulic and mechanical response of the rock mass and impact of transients.
- Full thermo-hydro-mechanical couplings, including all such interaction between buffer and near-field rock, need to be considered when analysing the resaturation of the buffer. On a longer time perspective also the chemical interactions need to be considered, for example from the volume changes resulting from the formation of corrosion products.

There are other problems suggested, such as heat pulse driven rock fracturing and permeability changes due to theromechanical deformation of fractures, where a full thermo-hydro-mechanical analysis is potentially needed. So far, such effects have not been included at any depth in safety assessments.

There are also some areas where it is well established that no further modelling is needed and the coupling can be handled by a simplifying abstraction in the Safety Assessment. Still also these processes and couplings should be mentioned in the safety assessment, with reference to the underlying work showing their limited impact on safety.

T-H-M issues are considered in repository R&D, both as regard modelling, field experiments and repository design. Even if there are only a few coupled T-H-M processes, which need direct analyses in a Safety Assessment.

Full thermo-hydro-mechanical couplings, including all such interaction between buffer and near-field rock, need to be considered when analysing the resaturation of the buffer. On a longer time perspective also the chemical interactions need to be considered, for example from the volume changes resulting from the formation of corrosion products or high-pH effects of concrete.

Although PA/SA is built around simplifying abstractions/assumptions, T-M-H modelling coupled with appropriate testing is still needed to understand how the hydrological system works, in order to construct the abstractions.

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Attachment to Appendix A: The Questionnaire

Below follows the specific questions asked to the participants. Introductory text tec are removed.

AA1 Context

Describe the repository concept that exist or is planned in your country (type of waste, waste form, type of bedrock, vault design etc.)

AA2 Means of identifying T-H-M issues to be considered in PA/SA

How have you identified T-H, M, T-M, H-M and T-H-M issues to be considered in safety/performance assessment of the repository concepts considered by your country/organisation?

- Have you applied “structured procedures for FEP recognition” (RES, PID, audit against FEP-list)? If so did these analyses reveal processes/issues not “already known?
- Did you apply other procedures for identification of processes/issues (experience, “tradition”, something else)?
- Do you think you have identified most processes/issues where you potentially need to consider T-H-M (or T-H, M-H, H-M) couplings?
- Have you documented your “list of issues processes” (If yes how and where?)

AA3 Overview of identified issues/processes

If possible please provide an overview of how you handle the identified T-H-M (or T-H, M-H, H-M) couplings, by presenting a list of all couplings and for each coupling address the following:

- Short description of the coupling (few words).
- How do you (or how do you intend) to handle the coupling (quantitative analysis, bounding analysis qualitative arguments, no current plan).
- If a judgement has been made not to further consider the coupling, could you please indicate the arguments for this judgement

(Note, in the next set of questions you will be asked to provide much more detailed information on the issues you have analysed in more detail).

AA4 Details of the coupling evaluated in the safety assessment context

The following set of questions concern your experience in modelling/assessing (or in reviewing modelling or assessments) of TMH processes/issues in a safety (performance) assessment context. Please, provide examples (with references) were you have analysed if/how

- thermo-hydraulic couplings (e.g. the thermal buoyancy effects, re-saturation under a heat gradient)
- mechanical or coupled thermo-mechanical effects (e.g. thermo-cracking in vaults, rock burst, block fall-out, vault creep, faulting, effects of changed external conditions, glaciations),
- hydro-mechnical effects (e.g. permeability changes due to water pressure changes, changes of rock stability (see above))
- full hydro-mechnical couplings (water flow close to the heat-producing vault, …)

affect the safety (long term performance) of the repository. Please consider both "near-field" and "far-field" issues.

For each example discuss the following:

- Describe the coupling and when you have judged it to be potentially important.
- Have you considered dynamic responses – or is the analysis only (quasi-)static?
- Did the analysis show that you need to consider the coupling
- How was the need assessed? (What key parameter is being used to judge how important a THM-parameter is? Is it simply the effect on calculated radiological risk, how a THM process may affect local hydrological conditions, or more generally your ability understand the details of the hydrogeological or mechanical system)
- Where are the major uncertainties? Is it in knowing the boundary conditions (e.g. glaciation sequence, plate techtonincs,…), in characterising the rock (e.g. structures, properties, spatial variability,..), or in modelling (e.g. resource demanding codes, numerical convergence, accuracy/verification, …) the consequences? Or in all?
- Can the consequences be bounded using simplifying assumptions, sensittivity studies etc.?
- Do you think you need to consider the coupling (motivate)?

AA5 Experimental evidence

Are you currently performing in-situ experiments with T-H-M relevance? Please provide details (objectives, principle setup, expected results)?

Are you currently performing numerical experiments with T-H-M relevance? Please provide details (objectives, principle setup, expected results)?

AA6 Site investigation programmes, site selection and repository design

T-H-M related issues are evidently needs to be considered when constructing a repository. The following set of questions concern to what extent THM is being (or is planned to be considered) in site investigation programmes, in site selection and in repository design. The questions also wish to explore to what extent the (planned) focus is on engineering constructability issues or if the (planned) focus is on long term safety issues.

- Do you – or do you plan to – measure T-H-M (or T-H, T-M or H-M) related parameters in your ongoing/planned site investigation programme (try to be specific)?
- Are the parameters (planned to be) measured primarily to support engineering decisions, to adopt the repository design or to provide input data to the (long term) safety assessment?
- Will any site of the specific TMH related properties impact on a siting decision? (If possible be specific)?
- Are safety relevant T-H-M issues considered in repository design (be specific if possible)?
- Is any of the above information (planned to be) mentioned/discussed in your PA/SA reports (or in review of such reports)?

AA7 Your views on how THM should be treated in Safety Assessment

The previous questions concerned your actual consideration of THM in SA/PA applications. The following set of questions concern your view on how TH; should be considered in PA/SA

- What key parameters should be used to judge how important a THM-parameter is? (Is it simply its effect on calculated radiological risk or something more detailed, such as how a THM process may affect local hydrological conditions?)
- Is it important to be able to demonstrate that you understand the detail on how the hydrogeological system works or is it adequate to build PA/SA around simplifying assumptions?
- If you PA/SA should be built around simplifying assumptions is there still a need for detailed THM-modelling?
- Any other comment

AA8 Previous DECOVALEX status reports

Do you have comments concerning the content of Andersson (1999) or Stephansson et al., (1999) not already covered in you previous answers – please provide them here.

AA9 Any other comment

Do you have any other comment to the questionnaire?

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