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**CHARACTERISATION AND REPRESENTATION OF THE EXCAVATION DISTURBED OR  
DAMAGED ZONE (EDZ)**

**LESSONS LEARNT FROM A SEDE TOPICAL SESSION**

**Meeting held on 24 September 1998, Paris-France**

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## Foreword

The assessment of the response of host geological environments to the excavation of underground openings and the potential impact of the response on the flow of groundwater and gas, on radionuclide transport and on the design of repositories have been, and continue to be, a topic of relevance to the analysis of the long-term safety of deep repository systems for long-lived and/or high-level radioactive waste.

In that regard, national and international work which has already been documented in international fora has mainly been focused on:

- understanding the fundamental processes of excavation response (mostly from a geomechanical point of view);
- development of instrumentation and measurement methods for characterisation purposes;
- minimising the excavation response;
- full-size testing of mining techniques in representative conditions within Underground Research Laboratories (URLs); and
- modelling the excavation response (and testing the results of this modelling).

This work has been mainly carried out in hard crystalline rocks and to a lesser extent in rock salt. However, the effects of excavation on radionuclide transport and the relationship with repository design, including potential couplings with thermal effects and the design of sealing systems, have not been fully investigated. This has often led to an oversimplified and very conservative treatment of the roles and impacts of the excavation disturbed (or damaged) zone (EDZ) in performance assessment exercises by, for example, representing the EDZ as a continuous high-permeability zone around galleries and shafts.

In this framework, it was considered timely and of mutual benefit to organise a Topical Session on the “Characterisation and Representation of the Excavation Disturbed Zone (EDZ)” along with the ninth annual meeting of the NEA Co-ordinating Group on Site Evaluation and Design of Experiments (SEDE). This Topical Session was held in OECD HDQ in Paris, France, on 24 September 1998. This Topical Session was not intended to cover all national waste management programmes, concepts, geological media or site specific features, but rather to provide some examples of current practices and experiences as a starting point for discussion.

This document reflects the material that was presented at the Topical Session and provides an overview of its main outcomes regarding the EDZ in order to help Member countries define further relevant work in this area.

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## Executive Summary

The assessment of the response of host geological environments to the excavation of underground openings and the potential impact of the response on the flow of groundwater and gas, on radionuclide transport and on the design of repositories have been, and continue to be, a topic of relevance to the analysis of the long-term safety of deep repository systems for long-lived and/or high-level radioactive waste.

National and international work in this area, which has already been documented in international fora, has mainly been focused on:

- understanding the fundamental processes of excavation response (mostly from a geomechanical point of view);
- development of instrumentation and measurement methods for characterisation purposes;
- minimising the excavation response;
- full-scale testing of mining techniques in representative conditions within Underground Research Laboratories (URLs); and
- modelling the excavation response (and testing the results of this modelling).

The majority of this work had been carried out in hard crystalline rocks and to a lesser extent in rock salt. The effects of excavation on radionuclide transport and the relationship with repository design, including potential couplings with thermal effects and the design of sealing systems, have not, however, been fully investigated. This has often led to an oversimplified and very conservative treatment of the roles and impacts of the excavation disturbed (or damaged) zone (EDZ) in performance assessment exercises by, for example, representing the EDZ as a continuous high-permeability zone around galleries and shafts.

In this framework, it was considered timely and of mutual benefit to organise a Topical Session on the “Characterisation and Representation of the Excavation Disturbed Zone (EDZ)” along with the ninth annual meeting of the NEA Co-ordinating Group on Site Evaluation and Design of Experiments (SEDE). This Topical Session was held at the OECD HDQ in Paris, France, on 24 September 1998.

It was not intended that this Topical Session should cover all national waste management programmes, concepts, geological media or site specific features, but rather should provide some examples of current practices and experiences as a starting point for discussion. Management programmes, concepts, geological media or site specific features, rather to provide some examples of current practices and experiences as a starting point for discussion.

The Session considered EDZs in three rock types: argillaceous rocks, crystalline rocks and rock salt. All members of the SEDE Group participated in this Topical Session and the report provides a compilation of both the presentations and the intensive discussions that took place during this meeting.

## Terminology

It appears that a variety of meanings of the term EDZ exist due to the fact that EDZs have been studied in different types of rock. There is no universally agreed definition of the EDZ, nor is there agreement as to what precisely the acronym EDZ means, however these differences are probably not important as they are related to the slightly different use of terms such as *disturbed* and *damaged*. **In crystalline rocks**, the **Damaged Zone** is limited mainly to that part of the rock mass closest to the underground opening which has suffered **irreversible** deformation. The **Disturbed Zone** lies further into the rock mass in which only **reversible** elastic deformation is assumed to have occurred. **In plastic rocks**, such as the Boom Clay or the Zechstein salt at Asse, it is assumed that it is not possible to distinguish between these two zones and the term **Excavation Disturbed Zone** is currently used.

It is recommended that the subdivision of an EDZ needs to be retained for use in the future in any rock types where it is warranted.

## Role of the EDZ

The various rock types of interest for the deep disposal of radioactive waste are associated with EDZs that vary in their extent and properties. The problems associated with the development of an EDZ may be greatest in indurated clay. This rock type suffers from the fact that it is sufficiently brittle to allow the development of fractures within the EDZ but is also more chemically sensitive than crystalline rocks. It is commonly subject to more rapid and more substantial chemical changes, such as oxidation, than is the case in an acidic crystalline rock.

In addition, there are problems in characterising an EDZ. It is difficult to make measurements, in particular hydraulic measurements, close to underground opening as the rock here may be only partially saturated. Solute transport within the EDZ is even more difficult to determine, as transport, unlike groundwater flow, is determined by the presence and properties of all the fractures within the EDZ, together with the intervening matrix.

The importance of an EDZ with respect to radionuclide releases is very dependent on the assumptions made regarding its properties. Such assumptions in performance assessments (PAs) have varied from those where the EDZ has been assumed to be critical for safety to those where it has assumed negligible importance. The role of seals and the type of backfill used in tunnels or vaults are intimately associated with the assessment of EDZ. Their long-term stability needs to be taken into account when considering the time-dependant development of an EDZ. The effects of EDZ can be minimised by, for example, the use of appropriate excavation techniques and by preventing any U-tube effect by limiting waste emplacement to the least permeable parts of the rocks mass.

In conclusion it is required that:

- The treatment of the EDZ in PA needs to be an integral part of the repository system and not something independent of it;
- Adequate sealing techniques and suitable repository designs and construction methods can be demonstrated;
- A good understanding of the EDZ, regarding its evolution, its properties and any self-healing tendencies it may possess can be demonstrated, as this will improve the confidence in the results of a PA.

## Pre Existing Information

Information prior to this SEDE Topical Session was available from four main sources:

- The NEA Workshop held in 1988 in Winnipeg (NEA, 1989):
 

For repositories in clays it was concluded that excavation effects, if properly managed, would have no adverse influences on long-term safety, due to the self-healing characteristics of the clay. For repositories in salt, whilst it was felt that some short-term safety assessment concerns could exist, excavation effects were not considered to be an issue for the repository's long-term performance. However, it was noted that a better understanding of the combined effects of excavation, pressure, heat and radiation was required, as they influenced long-term creep phenomena. For repositories in crystalline rocks, excavation effects were not considered important for their short-term performance; however, it was felt that the implications for long-term safety had yet to be fully assessed.
- The CNS Conference also held in Winnipeg in 1996 (CNS, 1996):
 

The Workshop showed there was a general lack of information about the radionuclide transport properties of the EDZ pathway, particularly with respect to values of its effective transport porosity, in particular its flow-wetted surface area, its dispersion and diffusion characteristics and its chemical sorption properties. The Workshop concluded that more work was needed in these areas before the importance of the EDZ as a radionuclide release pathway could be properly understood and sealing methods could be developed to eliminate it effectively. It was also concluded that work was needed to determine if such seals would be required to ensure or significantly enhance long-term repository performance.
- The review of the previous work on EDZs carried out as part of the planning for the ZEDEX project at Äspö (Emsley et al., 1997):
 

The ZEDEX experiment gives indirect evidence that the damaged zone around the drift has to be considered in PA as a potential pathway of significantly increased hydraulic conductivity.
- The treatment of the EDZ in performance assessments (e.g. Kristallin-1, AECL-94, SR-97):
 

Based on the results of ZEDEX a base case with no hydraulic significance of the EDZ and a conservative variation case with a 100 times increase in Darcy velocity in the EDZ has tentatively been included in the SR-97 assessment. The ZEDEX project has contributed to more realistic performance assessment models.

## The EDZ in Different Rock Types

### *EDZs in hard rocks*

In the context of **the ZEDEX project at the Äspö HRL**, the term EDZ is taken to mean the disturbed zone that is assumed to include the failed and damaged zones closest to the wall of the underground opening, which is likely to vary depending on the excavation method used. A link between the level of damage and the excavation method has been demonstrated, although no difference in terms of damage could be detected between the two drill and blast methods used. As predicted, the damage observed around the Drill & Blast (D&B) drift was greater than that observed around the TBM drift. It was concluded from this research that:

- The damaged zone is characterised by changes in state (e.g. the state of *in situ* stress, chemistry, *etc.*) and in its properties, with the latter being dominant;
- The disturbed zone is characterised by elastic displacements, changes in state (most significantly the *in situ* stress) and no induced fracturing.

Consequently, as regards any implication for performance assessment, the **results from ZEDEX indicate that the role of the EDZ as a preferential pathway to radionuclide transport is limited to the damaged zone**. The greatest extent of this zone, as determined from the AE (Acoustic Emission) results, was at most 1.0 m around the D&B drift and this figure is therefore considered to be conservative. The results of the ZEDEX project were used in SKB's most recent PA, SR-97.

Since 1996, the programme in the Canadian URL has established a series of initiatives to allow a better integration of the EDZ in PA by carrying out tracer tests, sensitivity analyses and sealing tests. A 3D transport model MOTIF for the movement of <sup>129</sup>I was used, with fracture zones as fast pathways. The results showed that the assumption of a high permeability EDZ leads to earlier releases of <sup>129</sup>I, but at a rate only three times higher than when minimum damage to the rock mass within the EDZ is assumed. The 3D model also demonstrated the significant dispersion and diffusion that takes place in the EDZ pathway.

### *EDZs in salt rock*

Salt is currently the preferred rock for the disposal of long lived, heat-emitting waste in Germany. In the long-term safety assessment of a repository in rock salt, the hypothetical case of an inflow of water or brine into disposal boreholes or repository vaults needs to be considered.

The EDZ is being studied under project ALOHA, which is being carried out at the Asse salt mine near Braunschweig, Germany. As part of this project, gas injection tests have shown that the permeability in the undisturbed rock salt is approximately  $10^{-21}$  m<sup>2</sup> or lower, whereas in the disturbed zone permeabilities around  $10^{-17}$  m<sup>2</sup> are obtained. Liquid injection tests confirmed the results of the equivalent gas tests and the results of these and electrical conductivity measurements showed that the injected brine did not spread evenly, but followed preferential pathways through the salt.

Future investigations as part of this programme will concentrate on the relation between the stress state in the rock salt and its hydraulic behaviour, in order to allow predictions to be made of the possible extent of healing within the EDZ.

### ***EDZs in argillaceous rocks***

Two distinct types of argillaceous rocks, plastic and indurated, are being considered for the deep disposal of long-lived radioactive waste.

Whereas plastic clays, such as the Boom Clay being investigated at Mol, have an essentially plastic response to large changes in applied stress, indurated clays, such as the Opalinus Clay in Switzerland and the Jurassic clays being studied by IPSN in southern France, are far more likely to respond to the same stress changes by fracturing.

As regards the ***Boom Clay***, the extent and properties of the EDZ need to be taken into account in the assessment of its long-term performance, as, even in this plastic clay, it is possible that changes in the properties of the clay within this zone could be significant. An extensive measurement programme, known as the Mine-by-Test, was launched to answer a number of questions concerning the rheological behaviour of the Boom Clay around a newly excavated gallery.

The measurements around the Test Drift have proved to be most helpful and the experimental data have allowed the geotechnical model calculations to be validated. In addition, the analysis of the hydromechanical and hydraulic behaviour of the clay surrounding the galleries has resulted in a validation of the calculational and analytical methods and an improvement in the excavation methods applied in order to reduce the extent of the EDZ. The experience gained in the Boom Clay has shown that, due to its elastic visco-plastic behaviour and self-healing properties, its geomechanical and hydraulic properties are likely to recover to their pre-excavation values after a sufficient time. The extent of the EDZ and the time for this recovery will depend on the excavation techniques used.

**Indurated** Toarcian and Domerian (Lower Jurassic) clay formations have been investigated at ***Tournemire***. Due to the presence of an old tunnel and new galleries at the site and the availability of several different investigation techniques, it has been possible to compare the EDZ development over different timescales and in different geological settings.

The relatively abrupt transition between intact rock and the EDZ in the tunnel is observed at a depth of about 1.30 to 1.50 m (resulting in an actual thickness for the EDZ of approximately 0.9-1.0 m).

The EDZ around one of the experimental galleries is less pronounced and smaller in extent than that around the tunnel. Evidence from fracturing in the borehole cores suggests that the depth of the EDZ is >40 cm, whereas changes in the sonic and hydraulic properties can be observed for depths of between 0.5 - 1 m.

Convergence measurements following the excavation of the galleries has shown that deformation of the clay is still occurring; though at an ever-decreasing rate, after more than 500 days, i.e. the EDZ is evolving with time. The majority of the mechanical evolution within the EDZ around the galleries seems, however, to have been completed and the current difference between the extent of the two EDZs could be due primarily to geometrical differences and to the different modes of excavation.

The first investigations made on an EDZ in this type of formation confirm that it is significant in terms of its hydraulic properties and suggest that further research is required concerning the evolution of such an EDZ with time.

### **Main Conclusion of the Topical Session**

Since the CNS Workshop (CNS, 1996), considerable work has been carried out in rocks other than crystalline rocks.

This Topical Session has provided a summary of the anticipated level of the significance of EDZs in different rock types and the difficulty in characterising and modelling them. It was concluded that the significance of the EDZ in terms of repository safety has declined over the last two decades, as our level of understanding of EDZs has increased.

There is now sufficient confidence in our understanding of the EDZ in crystalline rocks, plastic clays and rock salt not to require additional large-scale R&D programmes to study its effects. It is still likely to be necessary to carry out site specific investigations of EDZs at potential repository sites, so to provide site-specific data on their properties and to aid in the design of sealing systems. Residual problems and uncertainties associated with EDZs in indurated argillaceous rocks are likely to be resolved over the next few years, as more *in situ* work is carried out in these types of rocks.

## 1. BACKGROUND

The assessment of the response of host geological environments to the excavation of underground openings and the potential impact of the response on the flow of groundwater and gas, on radionuclide transport and on the design of repositories have been, and continue to be, a topic of relevance to the analysis of the long-term safety of deep repository systems for long-lived and/or high-level radioactive waste.

National and international work, which has been extensively documented in international fora, e.g. NEA (1989) and CNS (1996), has mainly been focused on:

- understanding the fundamental processes of excavation response (mostly from a geomechanical point of view);
- development of instrumentation and measurement methods for characterisation purposes;
- minimising the excavation response;
- full-size testing of mining techniques in representative conditions within Underground Research Laboratories (URLs); and
- modelling the excavation response (and testing the results of this modelling).

This work has been mainly carried out in hard crystalline rocks and to a lesser extent in rock salt. The effects of excavation on radionuclide transport and the relationship with repository design, including potential couplings with thermal effects and the design of sealing systems, have not been fully investigated. This has often led to an oversimplified and very conservative treatment of the roles and impacts of the excavation disturbed (or damaged) zone (EDZ) in performance assessment exercises by, for example, representing the EDZ as a continuous high-permeability zone around galleries and shafts. Work has, however, been undertaken more recently that follows a more integrated approach to the analysis of the EDZ within the framework of performance assessment (e.g. Emsley *et al.*, 1997).

## 2. PURPOSE OF THE REPORT

This report is aimed at reflecting the material that was presented at the Topical Session of the NEA Co-ordinating Group on Site Evaluation and Design of Experiments (SEDE) of the NEA that took place Paris in September 1998 and providing an overview of its main conclusions.

This report is designed to be applicable to a larger audience than that of the SEDE members, and is also aimed at putting the outcomes of the Topical Session in a wider perspective, in order to help Member countries define further relevant work regarding the EDZ. It is also designed to place these recent discussions within a broader framework by also reviewing the conclusions of the two previous international initiatives on the EDZ, namely the 1988 NEA Workshop and the 1996 CNS Conference (NEA, 1989; CNS, 1996).

### 3. ORGANISATION AND OBJECTIVES OF THE TOPICAL SESSION

Immediately before this Topical Session the SEDE had added to its focus the topic *Characterisation of the Near-Geosphere in the Presence of the Excavation and in the Perspective of the Repository*. Whereas it is very difficult to characterise the geosphere on a regional scale in order to achieve a high level of confidence in the detection of all relevant features and processes, the near-geosphere<sup>1</sup> is more amenable to detailed characterisation resulting in a more reliable description of this part of the rock mass in models and assessments. This does not necessarily imply, however, that it is easy to characterise the rock mass close to the repository and the extent to which our increased knowledge of the near-geosphere has been incorporated into safety assessments has also been somewhat limited to date. Many repository concepts derive a large part of the geosphere barrier function from the rock that immediately surrounds the excavation. It is of importance, therefore, to see the characterisation of the near-geosphere in the context of the excavation and the future engineered barrier system, as it is the part of the rock mass that is most disturbed by excavation and investigation and by the presence of the repository.

In this framework, it was considered timely and of mutual benefit to organise a Topical Session on the *Characterisation and Representation of the Excavation Disturbed Zone* along with the 9th Annual Meeting of the SEDE. The Topical Session, held in Paris, in September 1998, was aimed at:

- exchanging information on recent developments within national waste management programmes;
- identifying the possible effects that could be caused by excavation and by characterisation work, and their extent and duration;
- identifying available methodologies for characterising these effects, and for minimising them;
- identifying the related parameters for use in performance assessment; and
- determining the confidence/reliability of the information.

It was not the intention in this Topical Session to cover all national waste management programmes, concepts, geological media or site-specific features but rather to provide some examples of current practices and experience, as a starting point for discussion.

The members of the SEDE Group that took part in the Topical Session and the titles of the presentations that were given are listed in Annex 1. This report is based on the texts that were presented. There has been a substantial amount of *in situ* experimental work on EDZs since the date of the Topical Session, however, the results of this later work are not included in this report, although they are occasionally referred to in order to place the discussions at this Topical Session in the current context.

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1. The term *near-geosphere* can be used to refer to the rock which is assumed to have been affected by the construction of the repository (the extent to which the rock might be affected and the distance from a repository can vary with rock type and with the type of effect under consideration, i.e. whether chemical or mechanical). It can also be used to refer to the rock mass that is within a certain, fixed distance from a repository, e.g. perhaps 10 m.

#### 4. TERMINOLOGY AND CURRENT UNDERSTANDING OF THE EDZ

The acronym EDZ has a variety of meanings which are, however, relatively similar in their description of what has taken place in the rock mass due to the construction of an underground opening. These different meanings have developed because EDZs have been studied in different types of rock, where effects can be markedly different, and in different geological environments but within the same types of rock. The latter is the situation for crystalline rocks which have been studied in very different structural terrains, for example, in the Canadian Shield (at AECL's URL site at Pinawa) and in the Alpine basement rocks of southern Switzerland (at Nagra's Grimsel Test Site). The granitic basement at Pinawa at depths of more than a few hundred metres has an extremely low fracture density and unusually high *in situ* stresses. These have had a considerable influence on the extent and form of the EDZ compared with those developed at Grimsel and Äspö. The essential elements of the EDZs in all these crystalline rocks (e.g. increased diffusivity, increased effective porosity and increased permeability) are, however, similar.

There is no universally agreed definition of the EDZ, nor is there agreement as to what precisely the acronym EDZ means, however these differences are probably not important, as they are related to the slightly different use of terms such as disturbed and damaged. This current variance in the use of this terminology does not seem to have caused any problems to date, either in investigating EDZs nor, in the way in which they have been treated in performance assessments.

The various ways in which the term EDZ is or has been used are listed below:

- **In Canada** the terms Excavation Disturbed Zone or Excavation Damage (or Damaged) Zone (both EDZ) were originally used synonymously, although it was understood that the spatial and temporal changes in the EDZ were important and these were taken into account in performance assessment calculations. In the USA and Canada the term Disturbed Rock Zone (DRZ) has also been applied. Fairhurst and Damjanac (1996) make no distinction in their use of these terms and state that they are all synonymous.
- **In Sweden and Switzerland** the Excavation Damaged Zone is distinguished from the Excavation Disturbed Zone. The Damaged Zone is limited to the part of the rock mass closest to the underground opening which has suffered irreversible deformation and **where** fracture propagation and/or the development of new fractures has occurred. This is distinguished from the Disturbed Zone, which is further into the rock mass, and in which only reversible (recoverable) elastic deformation has occurred.
- 1 and 2 above are both concerned with the development of EDZs in crystalline rock. The **development** of an EDZ in a plastic rock, such as a soft (plastic) clay or rock salt is somewhat different from that in an essentially brittle, crystalline rock.
- **In both the Boom Clay (Belgium) and the Zechstein salt at Asse (Germany)** the term Excavation Disturbed Zone is used. In both these rocks the macro response of the rock is essentially plastic, however, this disguises the fact that the large changes in stress accompanying the development of an underground opening produce dilatancy and microfracturing in the salt, which is modelled as an elastic-viscoplastic material. In contrast, it has been assumed for a considerable time that the deformation around underground openings in rocks such as the Boom Clay could adequately be modelled assuming perfect plasticity. Recent experience at Mol suggests, however, that this may be an oversimplification<sup>2</sup>.

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2. This re-evaluation took place after the Topical Session reported here.

- The EDZ developed in indurated clays, **such as the Jurassic clays (or shales) at Tournemire and the Opalinus Clay in Switzerland**, is more like the EDZ developed in crystalline rocks. In the short term the two are likely to be similar in extent and possible also in character. In the long term, however, an EDZ in an indurated clay may heal or partially heal, whereas the same seems less likely in the more brittle and stronger crystalline rock. The main difference between the EDZs developed in these two types of rock may be related to the chemical changes that takes place within them. This subject is discussed later in the report in Section 8.2.

The terminology used in this document is in line with that used in crystalline rocks, in that a distinction is made between an *Excavation Disturbed Zone* and an *Excavation Damaged Zone*. In rocks such as the Boom Clay or the Zechstein salt at Asse it is assumed that it not possible to distinguish between these two zones, and the term *Excavation Disturbed Zone*<sup>3</sup> is used, in line with its current usage at both sites. It is also recommended that this subdivision of the EDZ is retained for use in the future in any rock types where it is warranted.

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3. It may be that these two zones do not exist in these types of rock, in particular in plastic clay. Conversely, it is also possible that, although the Boom Clay can be modelled adequately as a perfectly plastic material, in phenomenological terms it does possess these two zones. Even if this were to be the case, it is likely to be difficult to distinguish between these two zones in such material and the possibility of their existence may have no impact on the role of the EDZ in relation to the long-term performance of a repository.

## Acronyms

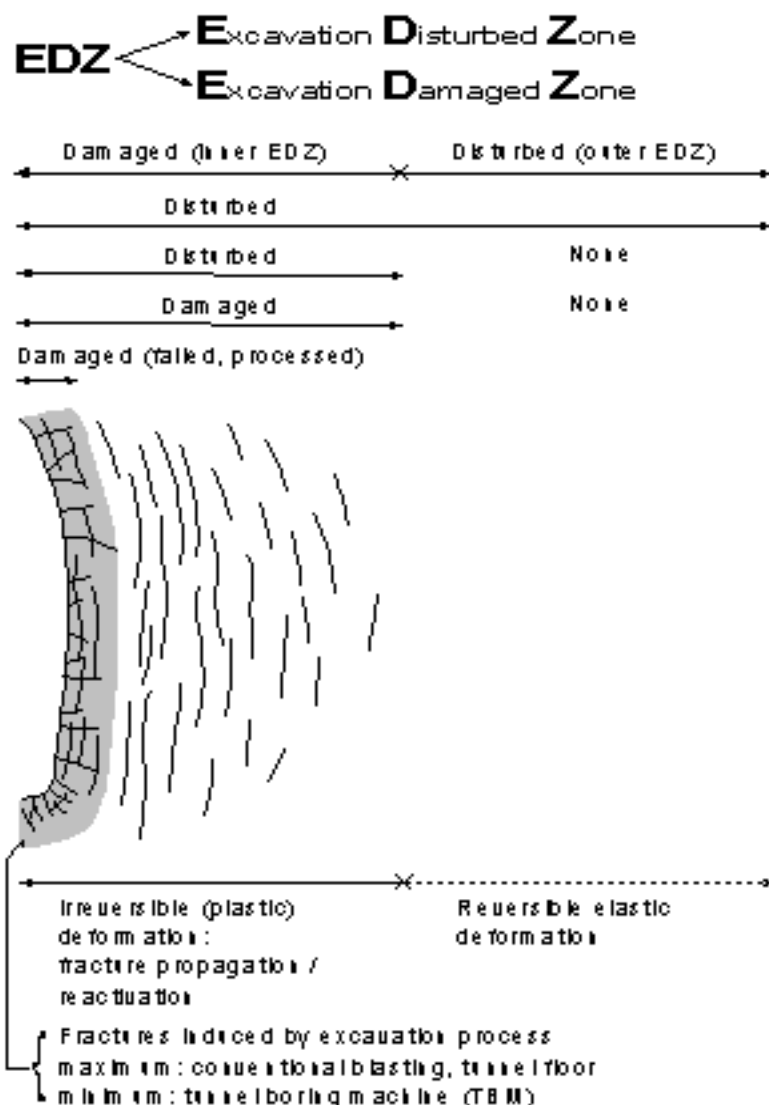
The numerous acronyms used in this report are defined here:

AE	Acoustic Emission
ANDRA	Agence nationale pour la gestion des déchets radioactifs (French waste management agency)
AECL	Atomic Energy of Canada Limited
D&B	Drill and Blast
DRZ	Disturbed Rock Zone (equivalent to the EDZ)
EBS	Engineered Barrier System
EC	European Commission
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EDZ	Excavation Damage(d)/Disturbed Zone (See Figure 1)
ENRESA	Empresa Nacional Residuos Radioactivos SA (Spanish waste disposal agency)
GRS mbH	Gesellschaft für Anlagen- und Reaktorsicherheit (German company for reactor and facility safety)
GTS	Grimsel Test Site (Nagra's underground research facility)
HRL	Hard Rock Laboratory (at Äspö, Sweden)
HADES	High Activity Disposal Experimental Site (the name given to first phase of the URL at Mol, Belgium)
HLW	High Level Waste
IPSN	Institut de protection et de sûreté nucléaire (French Institute for Protection and Nuclear Safety)
ISAG	The <i>In Situ</i> Advisory Group (the precursor to the SEDE)
MFR	Moderately Fractured Rock
NAGRA	Nationalen Genossenschaft für die Lagerung Radioactiver Abfälle (Swiss waste disposal agency)
ONDRAF/NIRAS	L'organisme national des déchets radioactifs et des matières fissiles enrichies/De nationale instelling voor radioactief afval en verrijkte splijtstoffen (Belgian agency for radioactive waste and enriched fissile materials)
POSIVA Oy	The Finnish waste disposal agency
PRACLAY	(the name given to the most recent phase of the URL at Mol, Belgium)
SCK/CEN	Studiecentrum voor Kernenergie / Centre d'étude de l'énergie nucléaire (Belgian nuclear energy research centre)
SEDE	The NEA Co-ordination group on Site Evaluation and Design of Experiments
SFR	Sparsely Fractured Rock
TBM	Tunnel Boring Machine
UK Nirex Ltd	The UK waste management agency
URL	Underground Research Laboratory
WIPP	The Waste Isolation Pilot Plant (New Mexico, USA)
WRA	Whiteshell Research Area
ZEDEX	Zone of Excavation Disturbance Experiment (at the HRL)

### 5. PRESENTATIONS AT THE SEDE TOPICAL SESSION

The Topical Session commenced with an introduction to the subject of the EDZ from Andreas Gautschi (Nagra). He described the role of the EDZ in different rock types and also its role in performance assessment. Figure 1 provides an illustration of the general ideas associated with the EDZ concept, an indication of the terminology used and the features and processes associated with an EDZ. The discussion below, which is based on this presentation, is followed in the next Section of this report by a short summary of the results of previous workshops concerned with the EDZ and also with the review work that was included in the planning of the ZEDEX Project at Äspö (Emsley *et al.*, 1996).

Figure 1. The various terminologies which have been applied to the description of and features and processes associated with the EDZ.



## 5.1 Introduction

As described above, the various rock types of interest for the deep disposal of radioactive waste are associated with EDZs that vary in their extent and properties. Table 1 summarises the types of changes that are associated with the development of EDZs in the rock types of interest. The discussion above concentrated on the physical attributes of EDZs, in particular the fracturing or microfracturing that is associated with them. There are, however, also possible chemical changes which could be of significance, depending on their magnitude, which is likely to be dependent on the time over which any underground structure remains open, on the type of backfill used (its mineralogy and its deformation characteristics) and on the temperature regime of the repository. Indurated and plastic clays appear likely to suffer the largest chemical changes, although it is still unclear whether such changes, even in these rocks, will be significant with respects to long-term safety. The extent of self-healing is also of interest. In plastic clay and rock salt it would appear that self-healing is likely. The extent of this self-healing is, however, somewhat unclear. In the Boom Clay the indications are that self-healing is likely to be complete<sup>4</sup> within a relatively short period of time (see Section 8.1), the kinetics of the healing process in the salt at Asse suggest that healing takes longer to achieve in this type of rock. Experiments are to be carried out at Asse to examine the extent of healing over several decades (see Section 9).

## 5.2 The EDZ in indurated clays

The rock type about which least is known in this regard and where the problems associated with the development of an EDZ may be greatest, is indurated clay. This rock type suffers from the fact that it is sufficiently brittle to allow the development of fractures within the EDZ but also more chemically sensitive than crystalline rocks, with the result that it suffers from chemical changes, such as oxidation, to a considerable greater extent than does an acidic crystalline rock. In addition, it is unclear at present the extent to which self-healing will take place in this type of rock and what the kinetics of the process might be. It is possible that the rate of both these may be determined by the mineralogy and, in particular, by the percentage of expandable clays. Underground experimental work, such as that described below in Section 6, is rapidly increasing our understanding of the EDZs in such rocks.

## 5.3 Characterisation of the EDZ

EDZs are a problem to characterise, as can be seen below in the descriptions of the *in situ* experimental programmes presented in Section 6. It is difficult to make measurements, in particular hydraulic measurements, close to an underground opening as the rock here may be only partially saturated. In addition, what is often of most interest in performance assessment is the effective permeability of the EDZ parallel to a tunnel or vault, whereas it is far easier to drill boreholes normal to the tunnel and to take spot measurements. It is subsequently difficult to determine the effective hydraulic interconnectivity of fractures or microfractures within the EDZ. This then poses a question: "Are there practicable field experiments to address the information needs of performance and safety assessment or must alternative (predictive) methods be used to illustrate the role of the EDZ in repository performance?" It is hoped that the work on the different rock types described below, together with the synthesis of the main conclusions of the Topical Session, will provide at least a partial answer.

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4. The extent of this self-healing is unclear, i.e. it is uncertain whether perfect self-healing occurs. This is a subject which is to be investigated by the NEA "Clay Club".

Solute transport within the EDZ is even more difficult to determine, as transport, unlike groundwater flow, is determined by all the fractures present within the EDZ, together with the properties of the intervening matrix. The reactivation of fractures or possibly the generation of new fractures within the Damaged Zone may result in fractures which have different characteristics from those in the intact rock, in terms of their matrix diffusion and colloid filtration characteristics.

Table 1. **A summary of the potential changes that commonly are found within the EDZ in various rock types. This table is based on the level of understanding of the effects of EDZs at the time of the Topical Session and may have to be modified as more work is carried out, in particular on indurated clays.**

Rock type	Fractures	Changes in Permeability*	Chemical Alteration**	Self-Healing***	Remarks
<b>Crystalline or Volcanic</b>	fracture reactivation, creation of new fractures	orders of magnitude	minor (oxidation), salt accumulation	none	negligible role at Yucca Mountain
<b>Plastic Clays</b>	None (normally), also self-healing	minor (less than factor of 2)	oxidation, sulphide, salt accumulation	extremely fast (plastic flow)	transition "plastic" to "indurated"
<b>Indurated Clays (Shales)</b>	new fractures + reactivation	orders of magnitude	oxidation, sulphide, salt accumulation	depends on swelling capacity	
<b>Rock salt</b>	newly-formed fractures	orders of magnitude	none	yes (plastic flow) but kinetics?	? rock-salt dissolution by inflowing water

\* with respect to undisturbed rock (this change in permeability needs to be put into context – this subject is discussed below)

\*\* during the operational phase (up to 100 years) (additional geochemical alteration may occur during the post-closure phase due to cement-porewater interaction)

\*\*\* post-closure

#### 5.4 Factors that affect the EDZ

Other factors that need to be taken into consideration when determining the potential significance of the EDZ are:

- any assessment of the significance of the EDZ needs to consider the roles of seals and backfilling materials,
- the combination of measures to minimise the extent or effects of the EDZ (e.g. excavation methods, liners, seals, *etc.*) need to be taken onto account; and
- the existing measures to reduce the impact of the EDZ are often conservatively neglected in most PAs - is this, however, the most sensible route to follow?

The importance of an EDZ with respect to radionuclide releases varies from negligible, in what might be termed a “realistic” performance assessment, in which effective sealing and some form of self-healing in appropriate rock types is assumed, to critical in unrealistic/disruptive cases (e.g. where the EDZ is modelled as a continuous high permeability zone around the excavation and failure of the seals takes place). Further *in situ* work on seal emplacement and examination of the effects of self-healing is likely to allow a more realistic overall assessment of the effects of an EDZ on repository performance.

## 5.5 The role of seals and tunnel backfill

The role of seals and the type of backfill used in tunnels or vaults are intimately associated with the assessment of EDZs. Such an assessment needs to consider why seals and backfill are used in a repository and how they might influence the formation and future development of an EDZ. Any assessment should also examine the significance of the EDZ in the context of the entire disposal system. This is necessary to illustrate that boundary conditions and spatially and temporally variable system properties, which will govern transport processes, have been adequately captured. The main purpose of seals and backfill are:

- to provide some protection against human intrusion;
- to provide low permeability plugs;
- to provide additional sites for radionuclide sorption; and
- to provide mechanical support for the underground openings.

Their long-term stability also needs to be taken into account when considering the time-dependent development of an EDZ. The elements of a seal and the principal components of flow in and around a repository tunnel are shown in Figure 2 (from Nagra).

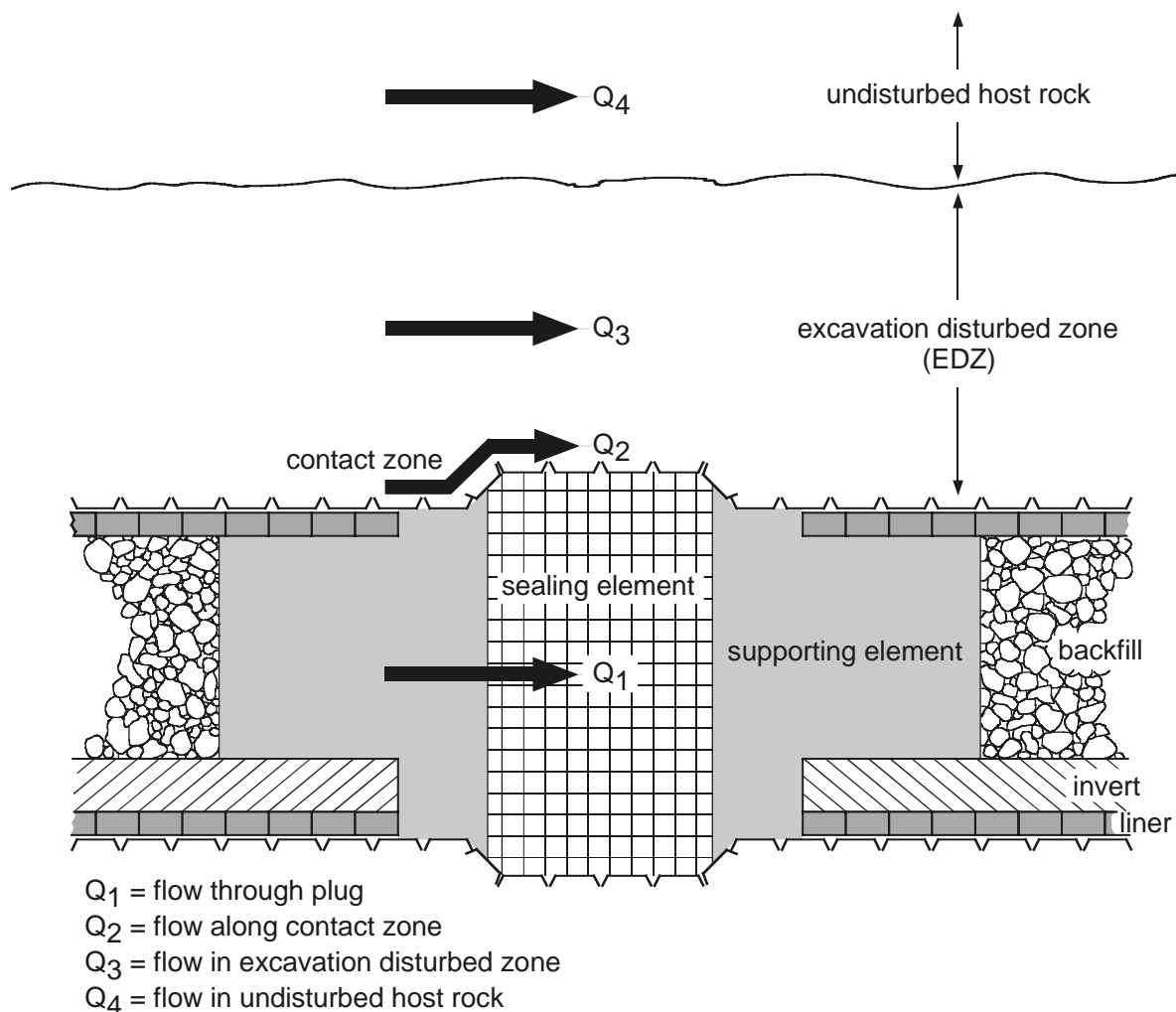
## 5.6 How should the effects of an EDZ be minimised?

The effects of an EDZ are sometimes conservatively neglected in a performance assessment, however, it is still good practice to try and minimise any such effects and there is believed to be a good chance that such efforts will be rewarded. The effects of an EDZ can be minimised by:

- the use of appropriate excavation techniques;
- the early emplacement of rock support systems, tunnel liners, *etc.* (especially in key zones) to minimise dilatant effects;
- similarly, the use of grout and/or resin injection in key zones to minimise changes in hydraulic conductivity and chemical changes;
- the excavation of the EDZ in key zones before emplacing seals;
- effectively resurising the EDZ by the use of expandable backfill or by mechanical means;

- designing the repository so as to minimise the effects of the EDZ on groundwater flow and radionuclide transport, *e.g.* by preventing any U-tube effect<sup>5</sup>, by limiting waste emplacement to the least permeable parts of the rock mass, *etc.*;
- by the use of highly sorptive porous tunnel backfill.

Figure 2. **Elements of a seal: the principal components of flow in and around a repository tunnel (from Nagra).**



## 5.7 The significance of the EDZ for radionuclide release

The significance of the EDZ with respect to the release of radionuclides from a repository is very dependent on the assumptions made regarding its properties. Such assumptions in performance assessments have varied from those where the EDZ has been assumed to be critical for safety to those where it has assumed negligible importance. The assumptions associated with these two situations are listed in Table 2.

5. This could occur if the EDZ were sufficiently transmissive and if it provided a continuous permeable pathway from the surface, through and from the repository.

Table 2. Assumptions associated with two ways of including an EDZ within performance assessment calculations: the PA realistic case and the critical case.

PA realistic case	Critical case
Need to take into account: <ul style="list-style-type: none"> <li>• <i>in situ</i> measurements of hydraulic conductivity (increase in K often less than expected from modelling)</li> <li>• high quality seals</li> <li>• self-healing processes operative (where appropriate)</li> </ul>	Assumptions often associated with: <ul style="list-style-type: none"> <li>• conservative/robust treatment in PA</li> <li>• alternative scenarios (<i>e.g.</i> complete failure of the sealing system)</li> <li>• introductory chapters in research proposals</li> </ul>
<b>Conclusions:</b> What is required: <ul style="list-style-type: none"> <li>• Treatment of the EDZ as an integral part of the near-field and not independently</li> <li>• Demonstration of adequate sealing techniques and suitable repository design and construction</li> <li>• Good understanding of the EDZ: evolution, properties, self-healing, <i>etc.</i></li> </ul>	

Open issues associated with the current understanding of the EDZ are generally assumed to be:

- what is the effective hydraulic conductivity of the EDZ? and
- what determines the transport properties of the EDZ and how can these be determined?

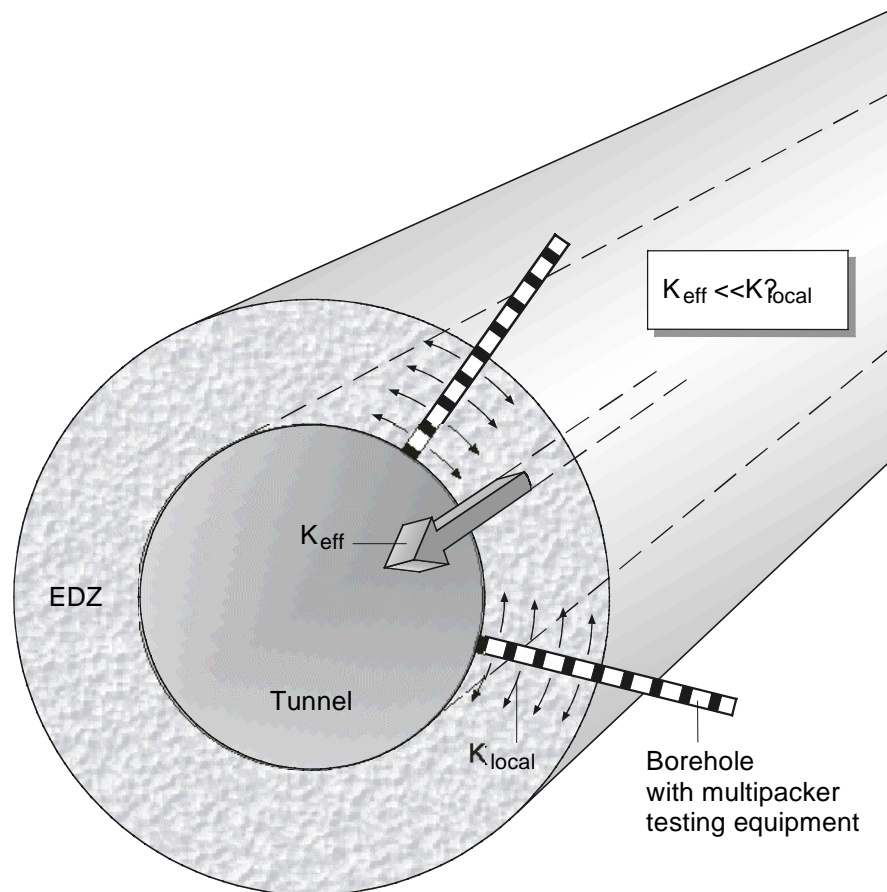
The effective hydraulic conductivity of the EDZ is related to be interconnectivity of its fractures. The issue is illustrated in Figure 3 where the effective conductivity ( $K_{\text{eff}}$ ) is contrasted with local measurements of conductivity ( $K_{\text{local}}$ ) carried out in radial boreholes. It is currently believed that  $K_{\text{eff}} \ll K_{\text{local}}$ , since it is considered that there is limited connectivity of the fractures (either induced fractures or extended existing fractures) within the EDZ. This problem of scale-dependence is common to many areas of the *in situ* measurement of rock properties, but it particularly acute when considering the EDZ as it difficult to carry out measurements at varying scales.

The transport properties of the EDZ are determined by its following attributes (some of these are intrinsic properties of the rock mass, whereas others are more related to the conceptual understanding of the processes involved):

- fracture density and fracture connectivity;
- sorption;
- matrix diffusion; and
- colloid filtration.

Some of these are discussed in the reports of the various *in situ* experimental programmes that are presented in Section 7 and others are discussed later in the Synthesis of the Main Conclusions (Section 10) where the overall understanding of the EDZ in different rock types is presented.

Figure 3. The effective hydraulic conductivity of the EDZ compared with the locally determined values of the hydraulic conductivity in radial boreholes.



## 6. PRE-EXISTING INFORMATION

Information prior to this SEDE Topical Session was available from four main sources, although biased towards the situation in hard rocks:

- The NEA Workshop held in 1988 in Winnipeg (NEA, 1989).
- The CNS Conference also held in Winnipeg in 1996 (CNS, 1996).
- The review of the previous work on EDZs carried out as part of the planning for the ZEDEX project at Äspö (Emsley *et al.*, 1997).
- The treatment of the EDZ in performance assessments (e.g. Kristallin-1, AECL-94, SKB-97).

At the time of the NEA Workshop in 1988 it was considered that, at least in hard rocks, the EDZ was likely to be of great significance for performance assessment. At that time there had been only limited research into the development of EDZs in clays whereas, in rock salt, there had been

extensive experimentation, both underground and in the laboratory, on the effects associated with underground excavations. The results of the ZEDEX Project are discussed in Section 7.3.

## 6.1 The 1988 NEA Workshop

In 1988 a workshop on excavation response was held in Winnipeg organised by the NEA ISAG (The In Situ Advisory Group), a forerunner of the SEDE (NEA, 1989). A review had been conducted by the ISAG of current requirements for in situ research and a primary topic identified concerned the excavation response, that is the effects that could be induced in the rock mass by the construction of a repository. Specifically, it was noted that residual stresses, creep or subsidence and induced fracturing, possibly leading to an increased potential for groundwater flow, were phenomena that required analysis to determine their influence on the safety of a repository and on the design of its engineered barriers.

It was considered at the time that the boundary between the engineered vault and the host geological environment was conceptually one of the least well understood components of the disposal system. There were many questions relating to the implications of excavation effects and damage in this zone for the performance and design of repositories, and this was believed to apply to all rock types. The aspects of the excavation response that were considered to require explanation were thought to include:

- the importance of excavation response to the design and safety of a repository;
- the type of *in situ* tests and measurements conducted; and
- the conceptual and mathematical models that had been developed.

The validation of the latter was thought to be of particular importance if they were to be used in support of performance assessment.

The objectives of the workshop were to:

- review the influence of excavation effects on the engineering design and performance of repositories;
- develop conclusions and recommendations on ways of accounting for excavation effects in clay, rock salt and crystalline rocks; and
- provide a forum for discussions between scientists conducting *in situ* studies and measurements and those developing predictive models for use in safety assessments of repositories.

Five key considerations emerged from the presentations and discussions at the workshop:

- the relevance or importance of excavation response and damage to performance assessment;
- the extent to which fundamental processes or the physics of excavation response were reliably understood;
- the future needs for the development of instrumentation and measurement methods;

- appropriate strategies for model development and validation<sup>6</sup>; and
- implications for repository design and engineering.

Differences in priorities emerged from the studies of the different rock types being studied with respect to the relevance of excavation effects to performance assessment. For repositories in clays it was concluded that excavation effects, if properly managed, would have no adverse influences on long-term safety, due to the self-healing characteristics of the clay<sup>7</sup>. For repositories in salt, whilst it was felt that some short-term safety assessment concerns could exist, excavation effects were not considered to be an issue for the repository's long-term performance. However, it was noted that a better understanding of the combined effects of excavation, pressure, heat and radiation was required, as they influenced long-term creep phenomena. For repositories in crystalline rocks, excavation effects were not considered important for their short-term performance, however, it was felt that the implications for long-term safety had yet to be fully assessed.

## 6.2 The 1996 CNS Workshop

The 1996 CNS Conference Workshop on the EDZ was held in Winnipeg, Canada in 1996, with its main objective of providing a forum for informal and frank discussions of international work performed since 1987 on characterising and modelling the EDZ in hard rock environments. The focus of the 1996 EDZ workshop was related to the design-related aspects of the EDZ, such as methods of minimising the EDZ during repository development and methods that could be used to seal the EDZ to eliminate it as a pathway for the release of radionuclides from a repository.

A keynote introductory presentation was given by Dr. C. Fairhurst of the University of Minnesota (CNS, 1996) and numerous case studies and examples were drawn from *in situ* studies of EDZs in hard rocks at AECL's Underground Research Laboratory, PNC's Kamaishi Mine, Nagra's Grimsel Facility, SKB's Äspö HRL and POSIVA's research tunnel at Okiluoto. The presentations covered the current state-of-the-art in:

- methods for characterising the location and geometry of the EDZ in hard rocks;
- methods for modelling rock mass response to predict the location and extent of the EDZ in hard rocks;
- methods for designing excavations in hard rocks to minimise the EDZ; and
- methods for sealing the EDZ.

The workshop concluded that significant progress had been made since the 1988 NEA Workshop in methods that could be used to characterise and measure the extent of the mechanical damage surrounding excavations in hard rocks. In particular, the acoustic emission-microseismic monitoring technique (AE/MS) was shown from examples in AECL's URL and SKB's Äspö facility to be extremely useful in revealing the extent of damage that develops around excavations during construction. The workshop also revealed that good progress had been made in advancing some rock mechanics models to the point of being able to predict the location and extent of the EDZ around openings in hard rocks. Examples were shown to illustrate how this knowledge and the models could be used to design opening with better construction methods (such as improved blast designs),

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6. Reference here is more to geotechnical and geochemical models and not so much to safety assessment models.

7. Assuming that the clay is sufficiently plastic.

geometries and orientations that could significantly reduce and almost completely eliminate the EDZ. Examples were also given to illustrate how this knowledge could be used to design seals that could effectively cut off the EDZ pathways around underground openings in hard rock.

The CNS workshop did reveal however, that there was still a general lack of understanding regarding the significance of the EDZ as a potential pathway for the release of radionuclides from hard rock repositories. The workshop showed that little work had been done to date to represent the EDZ as a transport path in models being used to assess the long-term performance of repositories. Furthermore there was a general lack of information about the radionuclide transport properties of the EDZ pathway, particularly with respect to values of its effective transport porosity, in particular its flow-wetted surface area, its dispersion and diffusion characteristics and its chemical sorption properties. The workshop concluded that more work was needed in these areas before the importance of the EDZ as a radionuclide release pathway could be properly understood and sealing methods could be developed to eliminate it effectively. It was also concluded that work was also needed to determine if such seals would be required to ensure or significantly enhance long-term repository performance.

### 6.3 A review of EDZ studies

In order to plan the ZEDEX Project at Äspö a review was carried out of the then (1994) understanding of the EDZ and the previous work that had been performed (Emsley *et al.*, 1997). A summary of this review, which provides an indication of the level of knowledge regarding the EDZ in crystalline rocks at that time, is presented below.

In the United States *in situ* experimental work, involving the characterisation of the EDZ for radioactive waste programmes, has been performed by USDOE in the Climax Mine and in the Edgar Mine. The main objective of the Spent Fuel Test-Climax (SFT-C) was to assess experimentally the suitability of granite for the retrievable storage of spent fuel and to assess the rock mass response to the thermal load of a simulated repository. Measurements were made of the mechanical response to the excavation of a tunnel between two previously excavated drifts (Henze, 1981). Model calculations of the thermal and mechanical responses of the rock mass were performed for each stage of the experiment: excavation, heating and cooling. Calculations of the mechanical response were initially made with continuum models and later with discrete joint models. The models predicted expansion of the pillars between the rooms, whilst the measurements performed *in situ* showed contraction. Results of modelling of the temperature field as a function of time showed good correspondence with *in situ* data. It was also shown that available finite difference codes could accurately simulate temperature conditions that would be present in future test areas and full scale repositories. The geological structure (heterogeneity) appeared to cause more disturbance during the excavation phase than during the heated phase (Patrick, 1986).

The experiments carried out at the Edgar Mine by the Colorado School of Mines (CSM) had the objectives of developing and evaluating blast rounds in order to minimise damage to the rock mass surrounding underground openings and to develop techniques for characterising the nature and extent of the excavation response in the rock. The characterisation showed that the controlled blasting had limited the extent of blast damage to 0.5-1 m from the wall of the room. The stress models applied adequately predicted the trend and magnitude of measured stresses, but did not account for the variability in the measured data and this was attributed to non-elastic movements. Discontinuous deformation analysis techniques were employed in the subsequent analysis to fit distinct block movements in order to account for measured displacement vectors. Ubbes *et al.* (1989) concluded that

when determining the properties of the EDZ the actual number of fractures is less important than whether or not they are open.

At Stripa, Sweden a number of experiments have been performed over the years. Whilst these did not necessarily have the characterisation of the EDZ as a primary experimental objective, they did nonetheless require the EDZ to be addressed in order to explain the experimental results. These experiments included the Macro-Permeability Test (MPT), the Buffer Mass Test (BMT), the Site Characterisation and Validation Experiment (SCV) and the Rock Sealing Project (RSP). The MPT was undertaken to assess the bulk permeability of a large volume of rock and showed that a skin zone with a hydraulic conductivity about one third of the bulk rock hydraulic conductivity had to be assigned in order to match the model to the pressure data measured in the radial boreholes. The Buffer Mass Test was performed to study water uptake in highly compacted bentonite and later, the Rock Sealing Project was carried out in an enclosed part of the same drift to evaluate the hydraulic properties of the EDZ and the ability to seal the EDZ by grouting (Börgesson *et al.*, 1992). The results of the experiment and associated modelling indicated that the hydraulic conductivity of the part of the EDZ (0.0-0.8 m from drift wall) which is directly affected by blasting is of the order of  $1.10^{-8} \text{ ms}^{-1}$ , whilst the conductivity in the floor is twice that in the wall. This effect was attributed to the use of higher energy explosive charges. The part of the EDZ which was affected by stress redistribution (extending approximately from 0.8-3.0 m from the drift wall) was given a hydraulic conductivity of  $3.10^{-9} \text{ ms}^{-1}$  with an anisotropy ratio (radial:axial) of 1:40. In the SCV experiment (Olsson, 1992) it was shown that the inflow to the drift was affected by the presence of a low conductivity skin.

At the AECL Underground Research Laboratory (URL) research directed at understanding the factors and the mechanisms controlling rock mass response to excavation has been the focus of two major experiments. The Room 209 test was performed to determine the hydraulic and mechanical response of a rock mass containing a narrow zone of permeable fractures, to estimate the mechanical and hydraulic properties of the rock mass and to assess the ability to model the hydraulic and its mechanical response (Simmons, 1992). It was found that the tunnel floor was more damaged than the rock in the wall and the roof and that the extent of damage in the floor was found to be at least 1 m, which was attributed to a higher charge density and explosive energy used in the floor blast holes. The results of hydraulic conductivity tests indicated that the blast-induced fractures were not hydraulically connected and that there was no significant axial conductivity along the tunnel (Martin *et al.*, 1992). Modelling of the rock mass response was performed and it was concluded that the mechanical response of the rock mass (without the fractured zone) was adequately simulated by the elastic two- and three-dimensional models used (Simmons, 1992). The hydraulic response of the fractured zone was not well simulated by the models used in predictions of the response to tunnel advance.

The main objective of the Mine-by Experiment performed at the 420 m level of the URL was to show that safe construction was possible at this depth in highly stressed granitic plutons (Read and Martin, 1991). Specific objectives were to improve the understanding of *in situ* rock mass behaviour and failure mechanisms, to evaluate the excavation damage around underground openings and to contribute to studies on the viability of the borehole alternative for emplacement of waste containers. The first phase of the experiment, the Excavation Response test, was to excavate a circular test tunnel in an orientation selected to maximise the in-plane stress ratio in order to promote development of excavation damage. A notch developed in the crown and floor of the tunnel by progressive failure and an understanding of the failure process was reached through the use of both monitoring and laboratory testing.

ANDRA was involved in a smooth blasting experiment carried out in 1991 at the URL in Canada. The main result of the experiment showed that it was possible to reduce the extent of the damaged zone significantly (from >1 m to 10 or 20 cm) using gas energy explosives combined with appropriate blast designs. A compilation of the experience of EDZ-related studies performed at the URL is given by Read (1996).

In the research performed within the Grimsel Test Site, an experiment on the extent of excavation effects was performed in 1983 that included measurements of the excavation response around a 30 m long, 3.5 m diameter TBM drift. Changes in the measured parameters, in particular the permeability, were attributed to elastic deformation of the excavated rock mass and to changes in hydraulic boundary conditions due to the construction of the drift (Lieb *et al.*, 1989).

During 1991 SKB performed an experiment to study the extent and character of the disturbed zone at the Äspö HRL. The aim of this experiment, the “Blasting Damage Investigation”, was to study the extent of the zone damaged by blasting for three different drill and blast schemes. The experiment showed that the damage in the floor of the drift was more extensive than in the walls for all drill and blast schemes used (Pusch and Stanfors, 1992). The distribution of the induced fractures was mainly controlled by two parameters: the precision in contour hole drilling and the local geology (Christiansson and Hamberger, 1991). The three blasting schemes resulted in the following sizes of damage zones: Scheme 1: 0.3 m in the wall and 1.7 m in the floor; Scheme 2: 0.3 m in the wall and 0.6 m in the floor; Scheme 3: and 0.5 m in the wall and 2.1 m in the floor.

#### **6.4 The treatment of the EDZ in performance assessments**

This subject was not discussed in detail during the Topical Session, although the way in which the EDZ has been modelled and the importance attached to it in understanding repository behaviour, was reviewed in Section 4 [plus it may be included in Alan Hooper’s text].

### **7. EXCAVATION DAMAGE ZONES IN DIFFERENT ROCK TYPES**

#### **7.1 Introduction**

EDZs have been studied most frequently in crystalline rocks. This is partly due to the fact that the majority of early work in URLs was carried out in this rock type and partly because an EDZ is more obviously visible in this type of rock than it is in less competent rocks, such as clays and rock salt.

EDZs have been most frequently studied in crystalline rock in Canada and Sweden, at the Canadian URL at Pinawa and at both Stripa and Äspö in Sweden. They have also been investigated at the Grimsel Test Site in Switzerland and, more recently, at Kamaishi, in Japan. Work started on EDZs quite early in URL programmes, as it was considered that an EDZ could have a considerable influence on the performance of a repository in crystalline rock. This is because its formation could result in the production of a more permeable pathway parallel to a disposal tunnel, which could result in the more rapid transport of radionuclides in the rock mass immediately adjacent to the repository. This part of the rock mass is now commonly referred to as the near-geosphere, i.e. what is often termed the intact rock lying between the repository and the nearest fracture zone. This part of the rock mass is significant, as it is often provides an important component of the geosphere barrier in performance assessments.

Such more permeable pathways could also provide connections between the faster natural pathways in the rock mass, which are normally associated with fracture zones. Such increased connectivity could result in a hydraulic cage effect, in which a component of the groundwater flow bypasses the waste disposal tunnels or vaults, which could be potentially advantageous, as it reduces the flux of groundwater through the repository. However, the potential for increased flow immediately outside the Engineered Barrier System (EBS) results in the possibility of lowered solute concentrations in the EDZ, thereby increasing the potential flux of radionuclides through the EBS, because the concentration gradient through the EDZ is increased<sup>8</sup>.

In other rock types, notably clays and rock salt, the problems caused by the formation of an EDZ have always been considered to be less acute. There has commonly been an assumption of self-healing within an EDZ in both plastic clays and rock salt, although it is only recently that it has been possible to demonstrate the actual extent of this process over many years, for example at Mol. The possible extent self-healing process in rock salt is discussed further in Section 6.4.

More indurated clays pose possibly a greater problem. There was initially less interest in the potential of such rocks for the disposal of long-lived wastes and it has only been in last few years that there has been an increased level of investigation of these rock types, notably at Tournemire, France and Mont Terri, Switzerland. Complex couplings are believed to exist, in which the deformation of these clays is linked to geochemical and other processes, and these types of rocks display short and long-term creep properties and aspects of brittle behaviour that are difficult to understand and investigate *in situ*. In addition to the lower level of understanding of the phenomenological factors associated with the deformation of such clays, compared with crystalline rocks, it is currently believed that an EDZ in such rocks may be more significant than one in a plastic clay or in rock salt. It would appear that the emphasis of any research into EDZs needs to be placed in this area.

## 7.2 EDZs in hard rocks

All crystalline rocks and also hard, volcanic rocks, which are not always considered under the category of crystalline, and included in this discussion.

This section of the report is based on the following presentations at the Topical Session:

- the reports on the results of the ZEDEX Project by Olle Olsson (SKB) and Alan Hooper (UK-Nirex Ltd);
- the work associated with the research on the EDZ at AECL's URL site (Chan *et al.*, AECL); and
- the summary of the EDZ workshop held in Winnipeg in 1996 (Cliff Davison, AECL).

## 7.3 The ZEDEX Project at Äspö (Olle Olsson, SKB)

The most comprehensive underground examination of the EDZ in hard rock to date has taken place at Äspö and is known as ZEDEX (Zone of Excavation Disturbance EXperiment). The results of this experimental programme are presented in detail in Emsley *et al.* (1997).

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8. This is most applicable to the situation where spent fuel or HLW is surrounded by a low permeability barrier, which is normally compacted bentonite. It is, however, also applicable to other waste disposal applications in saturated rock.

ZEDEX was undertaken as a joint project by ANDRA (France), UK Nirex and SKB (Sweden) with significant contributions from BMBF (Germany) and Nagra (Switzerland). The objectives of the project were to understand the mechanical behaviour of the EDZ with respect to its origin, its character, the magnitude of property changes within it and its extent and dependence on the excavation method. Supporting studies to increase the level of understanding of the hydraulic significance of the EDZ and to test equipment and methodologies for quantifying the EDZ were also carried out. The ZEDEX project was carried out at the Äspö Hard Rock Laboratory (HRL), Sweden, between April 1994 and July 1996.

The rationale for undertaking this project was that it was considered that the scale and properties of the EDZ could affect the efficiency and effectiveness of plugs placed to seal underground openings and provide enhanced hydraulic conductivities which could have deleterious consequences for repository performance.

The site for the study was located in the Äspö HRL at a depth of 420 m. Changes in rock properties caused by the excavation of two drifts, one excavated by conventional drill and blast and one by a Tunnel Boring Machine (TBM), were investigated through measurements in boreholes before, during and after excavation. Two different drill and blast methods were used: low-shock energy smooth blasting and normal smooth blasting. The cross sectional form of the blasted drift was designed to be circular with a flat floor and with the same diameter (5 m) as that of the TBM drift. A number of boreholes were drilled axially and radially relative to the test drifts to assess the properties and extent of the EDZ. These boreholes were used to undertake a range of measurements that included seismic tomography, borehole radar, hydraulic testing and acoustic emission monitoring.

The ZEDEX Project results support a division of the zone around an underground opening into the following three parts:

- a *disturbed zone* in which the material behaviour is essentially unchanged, but the stress state is perturbed by the opening;
- a smaller *excavation damaged zone* characterised by changes in both the pre-excavation stress state and in the material behaviour of the rock mass; and
- a *failed zone* in which rock slabs detach completely from the rock mass as a result of progressive failure.

In the context of the ZEDEX project, the term EDZ is taken to mean the disturbed zone that is assumed to include the failed and damaged zones closest to the wall of the underground opening produced by the excavation method.

### **7.3.1 Conceptual understanding of the Damaged and Disturbed Zones**

The characteristics of the damage to the rock caused either by blasting or by excavation by TBM are quite similar. There is normally a zone of crushed rock around the blast hole and the TBM groove, *i.e.* the trace of the steel disc that breaks the rock, from which radial cracks extend. The extent of the cracks is however significantly different, being some tens of millimetres for a TBM excavation compared to some tens of centimetres in the case of blasting. The crushed parts of the rock and the parts with induced fractures constitute the damaged parts of the rock. In the ZEDEX experimental programme the extent of the damaged zone was taken to be the distance to which induced fractures extended from the drift wall.

Crushing and stress-induced cracking may also occur if the presence of the void causes stress concentrations in excess of the breaking strength of the rock. This did not occur during the ZEDEX experiment due to the low level of *in situ* stress in comparison with the strength of the rock.

In the disturbed zone, beyond the damaged zone, the stress redistribution caused by the presence of the void is likely to cause block movements and changes in the aperture of natural fractures and/or elastic deformation of the rock. Changes in material properties of this zone, such as seismic velocity, Young's modulus *etc.*, are expected to be insignificant. Changes in the hydraulic properties of the rock mass within this zone depend on changes in the aperture of natural fractures and hence on their orientations, size and connectivity.

### 7.3.2 Summary of main findings

The link between damage and the excavation method has been demonstrated, although no difference in terms of damage could be detected between the two drill and blast methods used. As postulated, the damage observed around the Drill & Blast (D&B) drift was greater than that observed around the TBM drift. A visual inspection of the rock close to the drift walls indicated that most of the newly developed connected cracks had been introduced by the excavation process. Results indicated that significant damage is caused by misfires or partially failed rounds and the resulting subsequent reblasting required. For example, misfires and partially failed rounds resulted in larger amounts of radiated seismic energy into the rock compared to successful rounds, illustrating the importance of designing a blast pattern that will result in a full pull<sup>9</sup> in order to reduce the risk of damage to the rock. A modified design of the cut and a consistent use of electronic detonators with precise firing times could reduce damage significantly. Simultaneous detonation of all the contour holes has also been shown to reduce damage significantly, compared with detonation of the contour holes at different times, as was used in the ZEDEX experiment.

The damaged zone around the drifts, in particular the D&B drift, was seen to be controlled, to some extent, by lithology; with the more brittle rock types sustaining more damage. As expected, the changes in rock properties induced by the change in *in situ* stresses and those induced by relaxation are very small in magnitude and were mainly detected by the Acoustic Emission (AE) measurements. The results have enabled the subdivision of the EDZ into damaged and disturbed zones with the interpreted boundary between these zones being based on the acquired data.

The damaged zone, caused by the excavation methods applied, has been identified using several measurement techniques. Monitoring of AE events was the most sensitive method and may therefore produce a conservative estimate for the extent of the damaged zone, that would indicate minor damage due to crack opening and slip. Sparse AE activity is not expected to correspond to measurable changes in rock properties. However, a large number of AE events, as observed around the D&B drift, indicates intense microcracking and is expected to produce a macroscopically detectable increase in crack density. Significant AE activity in the D&B drift was observed up to 1 m from the drift wall, whereas the corresponding extent for the TBM drift was a few tens of centimetres. Seismic velocities are related to crack densities and changes in velocities were in agreement with the AE data. The dye penetration tests performed in the slots cut from the drift showed the extent of macrofracturing that extended to about 50 cm in the floor of the D&B drift. The hydraulic measurements performed in the damaged zone showed little change in permeability of the rock matrix, the larger permeabilities observed being associated with the induced and pre-existing fractures intersecting the boreholes. The damaged zone can, therefore, be characterised by changes in

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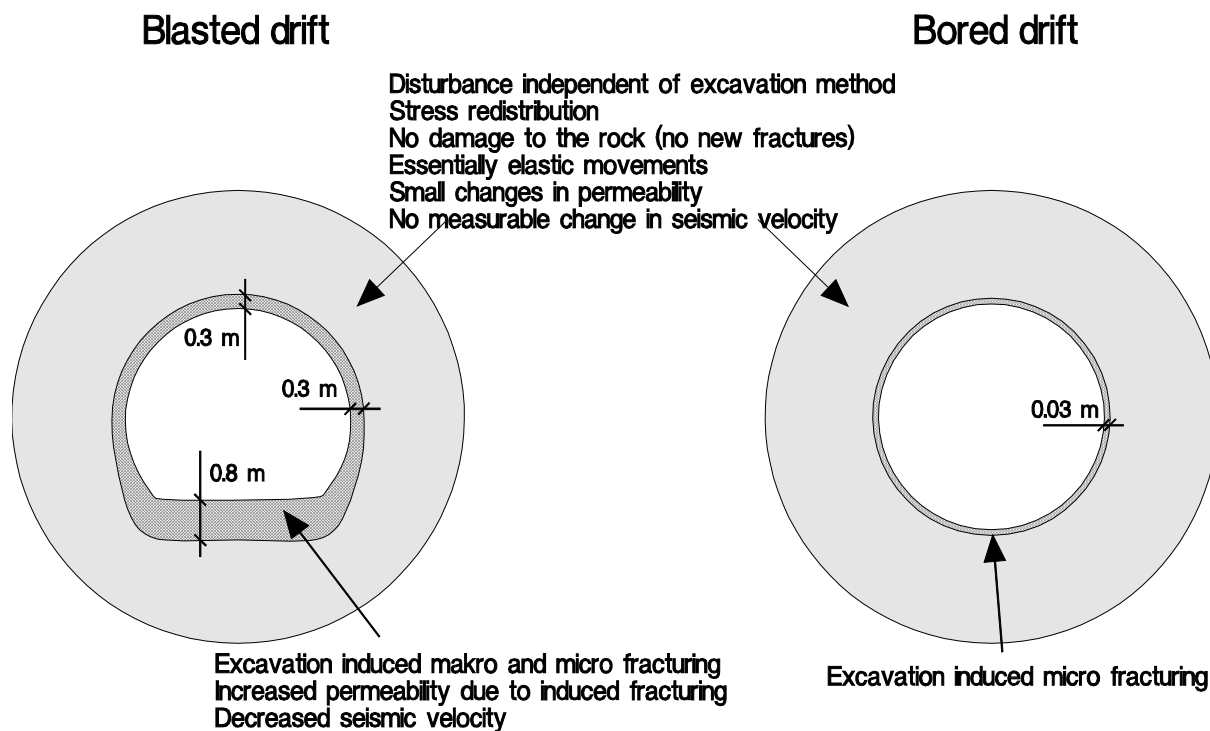
9. i.e. all the rounds fire successfully.

state (*e.g.* the state of *in situ* stress, chemistry, *etc.*) and in its properties, with the latter being dominant.

The disturbed zone is characterised by elastic displacements, changes in state (most significantly the *in situ* stress) and no induced fracturing. In this zone only a very few AE events were observed, with a similar event density for both the TBM and D&B drifts. The source mechanisms suggested that the sparse events resulted from shear-slip on existing fractures. The high-resolution seismic tomography results showed no changes in seismic velocity and the displacement measurements indicated elastic behaviour. The hydraulic tests performed before and after excavation revealed no significant changes in hydraulic properties due to excavation. From these observations it was concluded that the disturbed zone could be characterised by changes in state, which could be considered to be reversible.

The current view at Äspö of the characteristics and extent of the damaged and disturbed zones are shown in Figure 4. The extent of the damaged zone is significantly greater around the drift excavated by blasting compared to the drift excavated by the TBM. The extent of the damaged zone around the TBM drift is limited to about 3 cm from the drift wall. In the D&B drift the damaged zone extends to about 30 cm into the wall and about 80 cm into the floor. It is characterised by irreversible changes in properties due to excavation-induced macro- and micro-fracturing, resulting in a decreased seismic velocity and an increased permeability. Outside the damaged zone there is a disturbed zone where no, or only very limited, changes in properties have been observed. The disturbed zone is characterised by elastic displacements, changes in state and no induced fracturing. No measurable changes in seismic velocity have been found.

Figure 4. Summary of the main findings of the ZEDEX Project. The extent of the damage zone is significantly greater in the drift excavated by blasting compared to the drift excavated using a Tunnel Boring Machine (TBM).



### 7.3.3 Implications for performance assessment

The results from ZEDEX indicate that the role of the EDZ as a preferential pathway to radionuclide transport is limited to the damaged zone. The greatest extent of this zone, as determined from the AE results, was at most 1.0 m around the D&B drift and this figure is therefore considered to be conservative. The clearly demonstrated link between the extent of the damaged zone, which is the hydraulically significant part of the EDZ, and the excavation methodology, indicates that the damaged zone can therefore be limited through the application of an appropriate excavation method.

The damaged zone around a blasted drift can also probably be reduced by further development of blast designs. The limited extent of the damaged zone, even in the blasted drift, should also make it feasible to block any pathways in the damaged zone by plugs placed at strategic locations.

An important aspect of the EDZ in performance assessments is the assumption that a zone of significantly increased permeability exists along the drift; however, limited evidence in support of this hypothesis exists. The results of the ZEDEX Project have shown that there is little change in matrix permeability in the damaged zone close to the drift walls and that the larger permeabilities are the result of intersecting pre-existing or induced fractures. There appears to be no experimental evidence

in support of an increased permeability in the disturbed zone affected by the stress redistribution caused by the void. The stress redistribution will of course lead to changes in fracture aperture, with both increases and decreases taking place. In a normal three-dimensional fracture network it is unlikely that fractures would open and connect in such a way that a permeable path opened along the drift. The risk of such a connected pathway would of course be greater if drifts were oriented parallel to one of the main fracture sets.

The ZEDEX experiment provides indirect evidence that the damaged zone around a drift in hard rock has to be considered in a performance assessment as a potential pathway of significantly increased hydraulic conductivity. As the hydraulically active part of the damaged zone consists of induced fractures it is not meaningful to describe its hydraulic properties in terms of its hydraulic conductivity. Attempts should instead be made to estimate the transmissivity of the damaged zone for the entire drift cross-section. Unfortunately, the ZEDEX experiment did not include measurements that would allow a value of the transmissivity to be determined.

The results of the ZEDEX project are also used in SKB's current work on the SR-97 Performance Assessment (SKB, 1999). The main conclusions with respect to SR-97 are that:

- it is not clear that the presence of an EDZ will necessarily imply changes in the permeability of the rock mass;
- only minor hydraulic impacts can be expected in full face bored (TBM) tunnels (i.e. there is minimal development of an EDZ and only a small change in hydraulic conductivity); and
- for a conventional tunnel, excavated by drilling and blasting, a conservative assumption could be to assume a 100 times increase in hydraulic conductivity within a 1 m deep zone below the floor of the tunnel.

A base case with the EDZ having no hydraulic significance and a conservative variation case with a 100 times increase in Darcy velocity in the EDZ was subsequently included in the SR-97 performance assessment, based on the results from the ZEDEX project (SKB, 1999). It is concluded that the ZEDEX project has thereby contributed to more realistic performance assessment models.

## **7.4 The use of information from the Äspö ZEDEX Project in an assessment of long-term repository performance (Alan Hooper, UK-Nirex Ltd)**

### **7.4.1 Introduction**

The United Kingdom concept for the disposal of intermediate-level wastes, in particular long-lived "transuranic" wastes, envisages that the waste would be emplaced in stacks in horizontal vaults having cross-section of order 16m. x 16m. excavated at a depth of order 500m below the ground surface. Much of the research and assessment work undertaken by Nirex had been directed to evaluation of the suitability of locating such a facility in strong, fractured rocks of the Borrowdale Volcanic Group found at a suitable depth near Sellafield in West Cumbria.

In its most recent post-closure performance assessment, "Nirex 97" (Baker et al, 1997), Nirex wished to test the significance of potential disturbance of the hydraulic properties of the host rock surrounding the excavated vaults. Initially the intention was that the numerical models developed for this purpose would be tested subsequently in a process of validation, by undertaking measurements

of rock and groundwater responses in a proposed Rock Characterisation Facility at the site near Sellafield.

The presentation to the SEDE Group Topical Session gave a simple description of the groundwater flow modelling used for this aspect of the Nirex 97 assessment and of the role played by participation in the ZEDEX Project in building confidence in parameter selection.

#### **7.4.2 Groundwater Flow Modelling**

The approach to groundwater flow modelling to obtain key parameters for the post-closure performance assessment was to use a two-dimensional continuum porous medium model in association with the verified, physical NAMMU program (Hartley et al, 1996). This can be applied to give output of key parameters such as groundwater flux through repository vaults, and the length, location and water velocity of pathlines for return of water from the repository to the surface. The validity of using a two-dimensional continuum porous medium model was tested by comparing outputs with those obtained from three-dimensional models.

The parameters used in the model are "effective parameters" that give a good representation of the behaviour of the system, with an appropriate level of detail, when used in models that are computationally practicable. The effective parameters are calculated by the process of upscaling on the basis of data on smaller length scales (Jackson and Watson, 1997). For a fractured rock, such as the Borrowdale Volcanic Group, the calculation of effective regional-scale permeability takes account of the presence of flowing fractures and the lengthscales over which they are connected.

An explicit representation of the repository vaults was included in the two-dimensional continuum porous medium model. This is shown in Figure 5 where the black shading represents the backfilled stacks of wastes, the grey shading represents high permeability "crown space" above the waste stacks, the darkest green represents the EDZ in the host rock, and the other shades of green represent subdivisions of host rock undisturbed by excavation of the repository.

A key factor in this approach was to assign the extent and hydraulic properties of the EDZ. It was decided that the EDZ would be represented as extending out from a vault to a distance of 8m. (being approximately half the vault diameter). In this region, the component of the effective regional-scale permeability in the direction along the axis of a vault was taken to be greater by two orders of magnitude than the effective regional-scale permeability of the undisturbed rock. The components of permeability perpendicular to the vault were unchanged.

Initially, this was viewed as a conservative approach, in terms of leading to an overestimation of the response of a generalised rock mass, following Pusch and Stanfors (1992). Nirex gained confidence that this was indeed the case from the results from the ZEDEX Project at the Äspö HRL, which are summarised in the preceding section. Although recognising that site-specific information will always be necessary to test model parameters, it was noted that the stress field and mechanical properties of the rocks at depth at Äspö and of the BVG at Sellafield were very similar and that the response to excavation might reasonably be expected to be similar also. At Äspö, only small changes in permeability were measured outside a very limited "damage zone" where excavation induced macro and micro fracturing occurred.

As noted in the preceding section, it was concluded that for a conventional tunnel, excavated by drilling and blasting, a conservative assumption could be to assume a 100-times increase in hydraulic conductivity within a one-metre zone below the floor of a tunnel. In Nirex 97, the same increase was assumed to occur within an eight-metre zone all around a vault.

A formal "bias audit" was conducted on the groundwater flow modelling in Nirex 97 to determine the sensitivity of key performance-assessment parameters (groundwater flux through the vault and travel time to the surface) to the calculated effective permeabilities. The parameters were not found to be sensitive to the calculated permeability of the EDZ, although clearly this might change, for flux through the disposal vault, if the EDZ were modelled as extending considerably further into the host rock.

### **7.4.3 Discussion of Findings**

The red arrows in Figure 5 are the groundwater flow field vectors calculated by NAMMU. This shows that, in the model, the EDZ is acting to divert groundwater flow away from the waste in the disposal vault. Therefore, in ensuring that the risk from radionuclide migration is not underestimated, it may not be conservative to define the EDZ around a vault of this design as having the extent and changed hydraulic properties used in Nirex 97 although the bias audit did not show this to be a major issue. The selection of properties for use in assessments therefore requires careful consideration of the design concept and the likely consequences of changes in properties of the near-geosphere.

It was also considered that assigning a higher permeability in the rock immediately surrounding the vault would alleviate the potential problem of over-pressurisation by gas generated from the wastes and their containers. Nirex 97 had shown the benefit of requiring a relatively small "entry pressure" for gas to enter the fractures of the host rock. Again, care would be required in modelling gas-water two-phase flow that seemingly conservative parameters for the EDZ were so.

Finally, it was noted that coupled mechanical-hydraulic effects might not be the most significant disturbance. The reaction of the groundwater/mineral system on exposure to air and/or to the altered geochemistry of near-field groundwater (following resaturation) might cause far greater effects on the hydraulic and radionuclide transport properties of the disturbed zone. The Nirex concept envisages a cementitious near field, and detailed research has shown the potential for long-term reduction of hydraulic conductivity through the formation of new minerals from rock-cement-water reactions.

## **7.5 Research into the EDZ in the Canadian URL (Tin Chan, AECL)**

### **7.5.1 Introduction**

The Canadian concept for the disposal of nuclear fuel waste envisages that fuel waste packaged in corrosion-resistance containers will be emplaced in an engineered repository at a depth of 500 m to 1000 m within the plutonic rock of the Canadian Shield. In illustrating the disposal concept, Atomic Energy Canada Limited (AECL) completed two Safety Assessments referred to as the Environmental Impact Statement (EIS) case study and the Second Case Study (SCS). In the former, the assessment considered the repository to be located at a depth of 500 m within a hypothetical Shield setting, with hydrogeological characteristics consistent with those observed at AECL's Underground Research Laboratory (URL) in the Whiteshell Research Area (WRA). The EIS revealed the most effective of all the engineered and natural barriers to be an enclosing region of sparsely fracture granitic rock ( $k = 10^{-19} \text{ m}^2$ ) 50 m or more in thickness. In part because of the pivotal role played by this natural low permeability barrier, referred to as the waste exclusion zone, and a desire to illustrate the robustness of the disposal concept, AECL completed the SCS. The SCS considered a fictitious hydrogeological setting with the same geometry as the EIS, but with a waste exclusion zone 100 times more permeable. Within the SCS, an in-room emplacement design and more durable corrosion-resistant containers were used to compensate for the diminished waste exclusion zone barrier. The

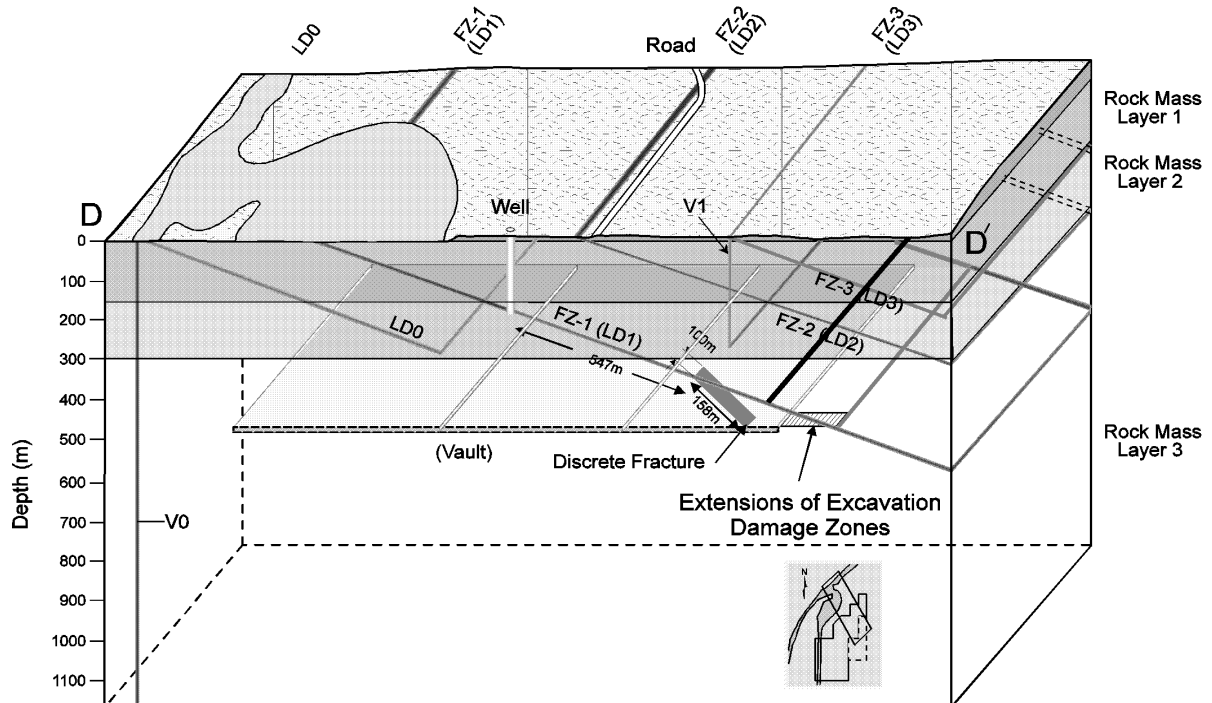
results of the long-term environmental assessment indicated that a case for safety could be made for the SCS, in part because the more effective engineered barriers compensated for a less effective waste exclusion zone in the geosphere.

As a natural extension to the EIS and the SCS safety related issues associated with the integrity of the waste exclusion zone and the role of bulkhead seals in retarding solute migration were examined through numerical sensitivity analyses. In the first of these studies (Numerical Study 1), Chan *et al.* (1996) used deterministic means to predict changes within the EIS flow field and mass transport affected by the extension of a discrete fracture and/or EDZ through a waste exclusion zone to more transmissive flow paths. In a second study (Numerical study 2) Chan *et al.* (1999), examined the performance of a used fuel repository set within a simplified crystalline rock flow domain. This analysis, which considered both in-room and in-floor emplacement methods, strived to remain faithful to the 3-D geometry of the problem. In both modelling studies the 3-D finite element code MOTIF was applied. Implications for safety were judged by predicting the transport of  $^{129}\text{I}$ , a radionuclide for which the dose outcome was found to be sensitive in both the EIS and the SCS. The results of these modelling studies, described in more detail below, provide useful insight into the predicted effect of an EDZ on repository performance and aspects of site characterisation programmes that may best advance understanding in this area.

### 7.5.2 Numerical Study 1

In numerical analyses performed by Chan *et al.* (1996) several alternative realisations of the 3-D EIS site-scale saturated groundwater flow model and the corresponding 2-D solute transport model were considered. As previously described, the simulations were performed using the finite element code MOTIF, which has special planar elements and line (pipe) elements for explicit representation of discrete fractures in 3-D or 2-D models. For the purpose of mass transport simulations the processes modelled included advection, dispersion, diffusion, matrix diffusion and radioactive decay. The simulations considered the central portion of the EIS groundwater flow domain, which encompasses a volume of 10 km x 9 km x 1.5 km in depth, as depicted in Figure 5. The flow domain is discretized into approximately 35,400 3-D hexahedral elements and 10 planar quadrilateral elements. The background rock mass was idealised as three layers of equivalent porous media with permeabilities of  $10^{-15}$ ,  $10^{-17}$  and  $10^{-19}$  m<sup>2</sup> and porosities of 0.005, 0.004, and 0.003 for layers 1, 2 and 3, respectively. The major vertical and low-dip fracture zones are all 20 m thick, with a permeability of  $10^{-15}$  m<sup>2</sup> and a porosity of 0.1. Within the model the receptor is assumed to be a water supply well, which intersects LD1 (depth 200 m) and is pumped at a constant rate of 1330 m<sup>3</sup> a<sup>-1</sup>. The vault is represented as a horizontal 5 m high slab approximately 3 km<sup>2</sup> in area with hydraulic properties obtained by averaging backfill and host rock properties. The model also includes a 1 m thick EDZ that forms an envelope around the vault and a discrete fracture, or a narrow fracture zone modelled as a discrete fracture, that connects the vault to fracture zone FZ-1 (LD1) (Figure 5). The EDZ has a permeability of  $10^{-18}$  m<sup>2</sup> above and  $10^{-17}$  m<sup>2</sup> below the vault. The discrete fracture, shown in Figure 5 is approximately 158 m long, 100 m wide, dips at 45° and has an effective hydraulic aperture of 10 mm or, in the case where it represents a narrow fracture zone, an aperture of 80 mm.

Figure 5. Conceptual model of local scale EIS groundwater flow domain and principal features considered in the EDZ/Discrete Fracture numerical sensitivity study at Whiteshell, Canada.



The 2-D solute transport model is located along vertical section D-D' and covers an area approximately 2450 m long by 620 m deep bounded by fracture zones V0 and FZ-1 (LD1) (Figure 5). It is discretised into approximately 11,800 2-D quadrilateral elements and 20 line elements. The maximum element size is approximately 10 m. Head values calculated by the 3-D flow model are projected onto the 2-D section and used as the input flow field for the transport model. The rate of  $^{129}\text{I}$  transport into fracture zone FZ-1 (LD1) and the resultant dose outcome assuming well water ingestion by a critical group are estimated over a period of 100 000 years. Both flow and transport simulations were performed for twelve variant cases which explored the influence of discrete fracture orientation and aperture, an enclosing vault EDZ and an extension of the EDZ from the vault to the fracture zone FZ-1 (LD1), on repository performance.

Figure 6a, 6b: **EDZ Numerical Sensitivity Analyses**

- a) **Influence of intersecting discrete fracture, fracture aperture and vault EDZ on total  $^{129}\text{I}$  transport rate; and**
- b) **Influence of an extended EDZ on total  $^{129}\text{I}$  transport rate.**

Figure 6a

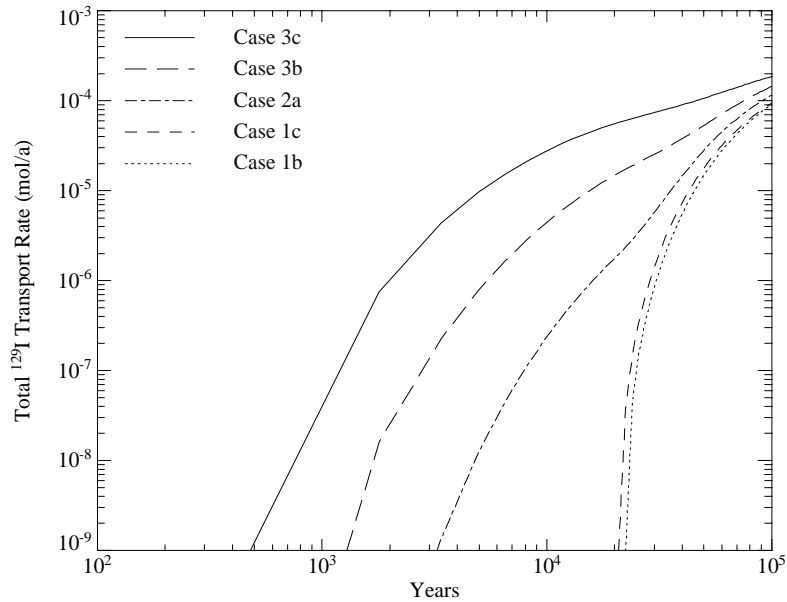
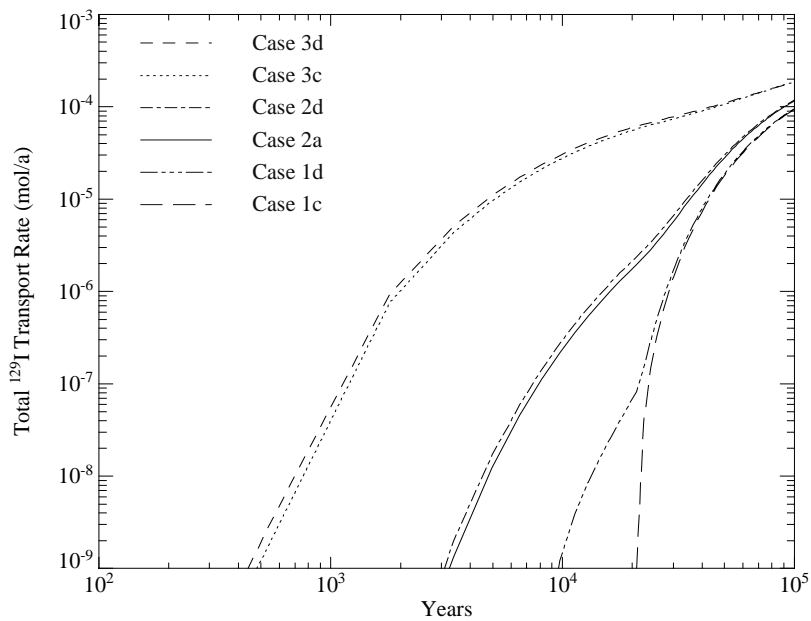


Figure 6b



A summary of the principal findings from the numerical study is as follows:

- The presence of single discrete fracture intersecting a waste exclusion zone and its aperture significantly effect the arrival time and rate of  $^{129}\text{I}$  transport. This effect is perhaps best illustrated by comparison of model simulation 1c (no discrete fracture, EDZ) with 6a (10 mm discrete fracture; EDZ) and 3c (80 mm discrete fracture; EDZ) as shown in Figure 6a;
- The presence of a vault EDZ, as represented in the numerical study appears to exert only a minor influence on the  $^{129}\text{I}$  transport rate. This is observed in simulations 1b (no discrete fracture; no EDZ) and 1c (no discrete fracture, EDZ); and simulations 3b (80 mm discrete fracture; no EDZ) and 3c (80 mm discrete fracture; EDZ) (Figure 6a).
- The extension of the vault EDZ to FZ-1 (LD1) has only a minor effect on the arrival time and  $^{129}\text{I}$  transport rate. This is shown in Figure 6b by a comparison of simulations 1c (no discrete fracture; EDZ) and 1d (no discrete fracture; extended EDZ); 2a (10 mm discrete fracture; EDZ) and 2d (10 mm discrete fracture; extended EDZ); 3c (80 mm discrete fracture; EDZ) and 3d (80mm discrete fracture; extended EDZ).

In the latter case of the EDZ extension, study results, particularly those for series 2 and 3 simulations, may appear counter-intuitive. It is evident, however, that the flow field in the vicinity of FZ-1 (LD-1) is oriented horizontally toward the vault. As a consequence, while extension of the EDZ may have a tendency to enhance dispersive and diffusive transport, it does not significantly increase the advective component. This modelling exercise reveals the importance of understanding both the geometry and boundary conditions of the near- and far-field geosphere when assessing the significance of an EDZ as a potential contaminant pathway. It is noteworthy, that estimated dose outcomes were well below the *de minimis* regulatory limit of 50 mSv  $\text{a}^{-1}$  in all simulated cases to  $10^4$  years and in most cases at  $10^5$  years.

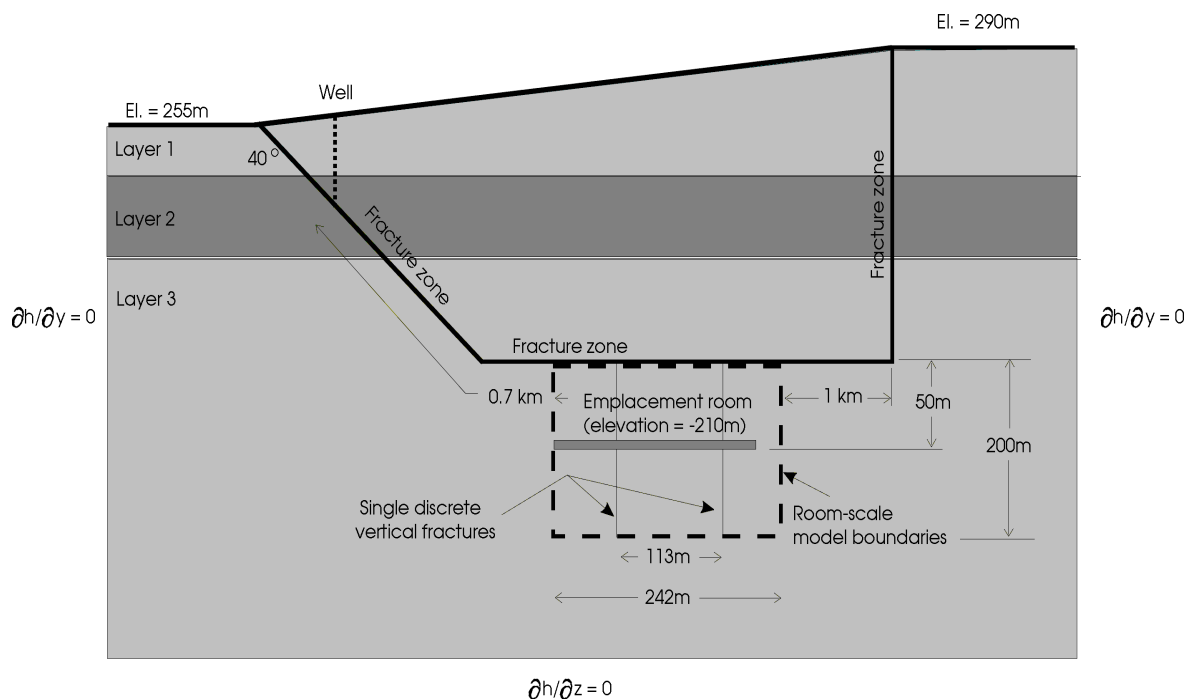
### 7.5.3 Numerical study 2

Chan *et al.* (1999) document a second study in which the effect of an EDZ on radionuclide migration was examined in more detail. The approach involved the development of a 3-D nested repository model comprising a stylised site-scale groundwater flow model and an inner 242 m x 90 m x 200 m (deep) block that discretised three disposal rooms and the immediate environs. A sectional diagram illustrating the features of the site-scale flow model and positioning of the inner room scale model is shown in Figure 7. As illustrated in the vertical section, the site-scale model includes three connected major fracture zones and a domestic water-supply well pumping from a fracture zone that was connected to the vault 50 m below by a pair of vertical discrete fractures. The undamaged rock at vault level was assumed to be either sparsely fractured rock (SFR) with  $10^{-19} \text{ m}^2$  permeability and 0.003 porosity or moderately fractured rock (MFR) with  $10^{-17} \text{ m}^2$  permeability and  $10^{-4}$  porosity. In the SFR, the EDZ hydraulic properties ranged from a minimum-damage case of  $10^{-18} \text{ m}^2$  permeability and 0.005 porosity to a maximum-damage, stress-relief notch of failed rock case - based on URL experience - with  $10^{-13} \text{ m}^2$  permeability and 0.03 porosity. In MFR, the EDZ permeability varies from a maximum-damage case of  $10^{-15} \text{ m}^2$  to no damage. Discrete fracture apertures ranged from a median-value case of 25 mm to a pessimistic case of 80 mm. Well demand ranged from zero through a median value of 1 330  $\text{m}^3 \text{a}^{-1}$  to a maximum of 18 000  $\text{m}^3 \text{a}^{-1}$ . The site-scale model block was discretized using 21,619 3-D solid elements, 60 planar elements and 21 line elements. The line elements representing the disposal rooms have equivalent properties calculated from those of the backfill, buffer and EDZ.

The flow field calculated by the site-scale flow model is used to determine the head boundary conditions for the room-scale flow model. In the transport model  $^{129}\text{I}$  is assumed to be

released from a pinhole defect in a container located 10 m from a discrete fracture. The room-scale model for in-room (IR) emplacement is divided into 56,084 3-D (hexahedral or triangular prism) solid elements and 1046 (quadrilateral or triangular) planar elements. Element size ranges from about 0.04 m to 50 m. for in-floor borehole (BH) emplacement the room-scale model is divided into 46,565 3-D (hexahedral) solid elements and 958 (quadrilateral) planar elements. Element size ranges from about 0.06 m to 58 m. In both discretisation schemes the mesh Peclet number ranges from 0.1 to 10.

Figure 7. **Excavation Damage Zone Sensitivity Study: Sectional Diagram of Site- and Room-Scale Models (Chan *et al.*, 1999).**



Great care has been exercised to match the finite-element mesh to the geometry of the rooms, the discrete fractures, the EDZ, the backfill, buffer and the container. Eighteen different cases are simulated to investigate the effects of the EDZ under various assumptions associated with the amount of rock damage, the method of container emplacement (in room or in borehole), well pumping rate, discrete fracture properties and buffer and backfill properties.

Study results from Chan *et al.* (1999) indicate that:

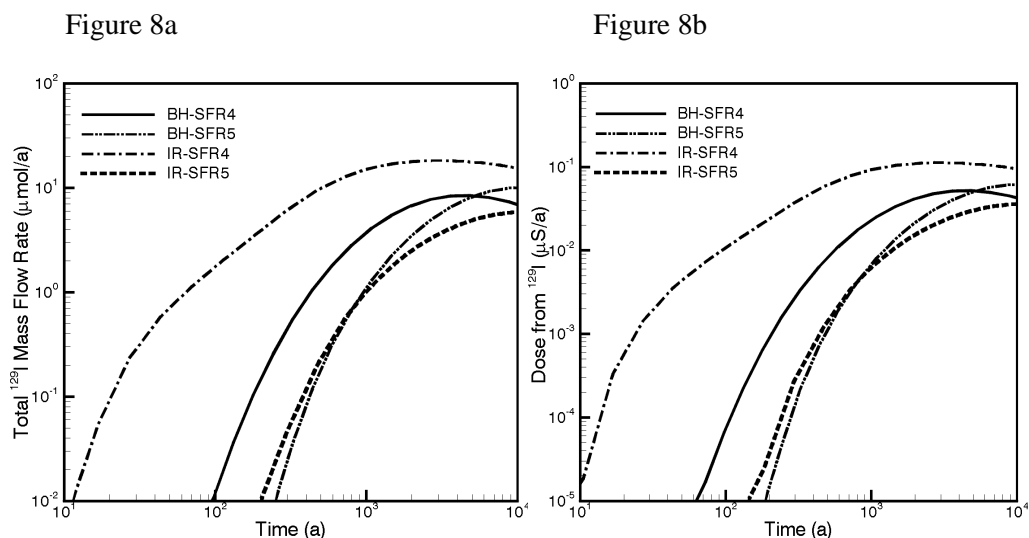
- although a highly permeable EDZ would lead to earlier release of  $^{129}\text{I}$  to the fracture zone, at  $10^4$  years after vault closure, the maximum-damage EDZ cases (Figure 8a - BH-SFR4 and IR-SFR4) would lead to an  $^{129}\text{I}$  release rate only about three times higher than the minimum-damage cases (Figure 8a - BH-SFR5 vs. IR-SFR5);

- the estimated annual dose based on ingestion in an extremely pessimistic case with a maximum-damage EDZ, maximum-demand well (18 000 m<sup>3</sup> per year), pessimistic discrete fractures (80 mm aperture) and pessimistic buffer and backfill properties was estimated to be approximately 0.12 mSv a<sup>-1</sup> in SFR and 0.16 mSv a<sup>-1</sup> in MFR, a factor of 400 or 300 below the de minimis regulatory limit of 50 mSv a<sup>-1</sup> (Figure 8b) and
- transport of <sup>129</sup>I to the fracture zone occurs primarily through the discrete fracture 10 m downstream of the defective container, but an inspection of the evolution of concentration contours reveals that the radionuclide is also diffusing and dispersing from the EDZ and the discrete fracture into the rock and the backfill.

Figures 8a, 8b: Excavation Damage Zone Sensitivity Study:

**8a: Total mass flow rate of <sup>129</sup>I against time (note: The maximum mass flow rate in the most pessimistic case, with maximum assumed damage within the EDZ, is shown by curve IR-SFR4.);**

**8b: Estimated Ingestion Dose from <sup>129</sup>I (mS a<sup>-1</sup>) (The maximum dose in the most pessimistic case, with maximum assumed damage within the EDZ, is shown by curve IR-SFR4). (Chan *et al.*, 1999)**



Storage of the radionuclide in the pore water of the backfill and the rock is likely responsible for its delayed migration. Consequently, assessment of the effects of the EDZ and discrete fractures on repository performance based solely on calculation of groundwater flux by flow modelling or travel time calculation by particle tracking could be quite misleading.

In both numerical studies matrix diffusion is found to significantly retard radionuclide transport from the vault to the nearby major fracture zone. In the most pessimistic case, Chan *et al.* (1996) estimated average linear water velocities in the discrete fracture varying between 1 and 7 m a<sup>-1</sup>. This would indicate groundwater travel times of approximately 100 years or less from one end of the discrete fracture to the other. In Chan *et al.* (1999), the most pessimistic case predicts groundwater velocities on the order of 20 m a<sup>-1</sup> in the most severely damaged portion of the EDZ and about 100 m a<sup>-1</sup> in the discrete fracture. This would imply a groundwater travel time of about a year. In both cases, however, the <sup>129</sup>I mass flux is predicted by the transport models to be insignificant at the

corresponding times. The transport models also showed in Chan *et al.* (1996) that once the radionuclide had diffused into the matrix, migration continued toward FZ-1 (LD1). Therefore, depending on the geometry of the transport problem, model realisations that assume solute diffuses into the rock matrix where it either remains or can only diffuse back into the discrete fracture, may not be conservative.

## 8. EDZ'S IN ARGILLACEOUS ROCKS

Two distinct types of argillaceous rocks, plastic and indurated, are being considered for the deep disposal of long-lived radioactive waste. This distinction is significant in terms of their geotechnical and hydrogeological properties and, of particular importance for the study of the EDZ, is their response to changes in stress. Whereas plastic clays, such as the Boom Clay being investigated at Mol, have an essentially plastic response to large changes in applied stress, indurated clays, such the Opalinus Clay in Switzerland and the Jurassic clays being studied by IPSN in southern France, are far more likely to respond to the same stress changes by fracturing<sup>10</sup>. This distinction is brought out below in the descriptions of the studies that have been carried out at Mol and Tournemire and in the comparison of the EDZs in the four rock types of interest for disposal purposes in Sections 4 and 7.

### 8.1 Plastic clays - the Boom Clay at Mol (Martin Put, SCK/CEN)

#### 8.1.1 Introduction

The characterisation of the EDZ in the Boom Clay has been carried out by an analysis of the hydromechanical and hydraulic behaviour of the clay surrounding the galleries at Mol. In order to carry out this analysis an extensive measurement programme has accompanied the construction of the underground laboratory HADES and its subsequent extension (PRACLAY). The work is described a series of papers by Labiouse and Bernier (1996, 1997a, b), Bernier and Volkaert (1997), Ferring *et al.* (1995), Bernier (1997), de Bruyn and van Caeteren (1997), Volkaert *et al.* (1998) and Barnichon (1998).

The extent and properties of the EDZ need to be taken into account in the assessment of the long-term performance of this type of clay, as the fractures that could develop in this zone, even possibly only in the short term, might create preferential pathways for the migration of water, gas and radionuclides, and thereby reduce the effectiveness of the geological barrier.

#### 8.1.2 Measurements around the Test-Drift

An extensive measurement programme, known as the Mine-by-Test, was launched to answer a number of questions concerning the rheological behaviour of the Boom Clay around a newly excavated gallery. The objectives of this programme were to determine the extent of the disturbed clay mass around the Test Drift (Figure 9), to study the interaction between the tunnel lining and the clay and to validate the geotechnical modelling of gallery construction. The Test Drift has an internal diameter of 1.5 m, a length of 67 m and its centre line is located at a depth of 222.9 m. The Mine-by-Test was carried out under several contracts from the European Community (EC) and the Belgian Waste Management Authority (ONDRAF/NIRAS).

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10. The Jurassic clays being investigated at the Meuse/Haute Marne URL site by Andra are also far more indurated than those at Mol

A number of monitoring devices, comprising three settlement devices and three series of piezometer nests, were installed in the clay before the start of the excavation in order to monitor the influence of the excavation process on its hydromechanical behaviour. Figure 10 shows the location of these instruments around the Test Drift.

A total of seven lining sections with associated instrumentation were installed in that part of the Test Drift that had concrete lining. Stress measurements were carried out to measure the pressure build-up during construction and to monitor its long-term evolution. Convergence measurements were carried out in order to follow the convergence of the lining with time and to assess the extent of its non-circularity.

The measurements around the Test Drift have proved to be most useful and the experimental data have allowed the geotechnical model calculations to be validated. Although the construction of the Test Drift has demonstrated the feasibility of excavating at depth in the Boom Clay, it was carried out without any mechanised techniques and no particular attempt was made to minimise the extent of the EDZ. Significant displacements have been recorded around the Test Drift (10 cm at a distance of 5 m from the Test Drift axis and 5 cm at a distance of 7 m), which relates to a plastic radius of about 8 m when a linear elastic, perfectly plastic response for the clay is assumed (Barnichon, 1998).

Figure 9. **The extension of the underground (HADES) laboratory at Mol to include the PRACLAY facility.**

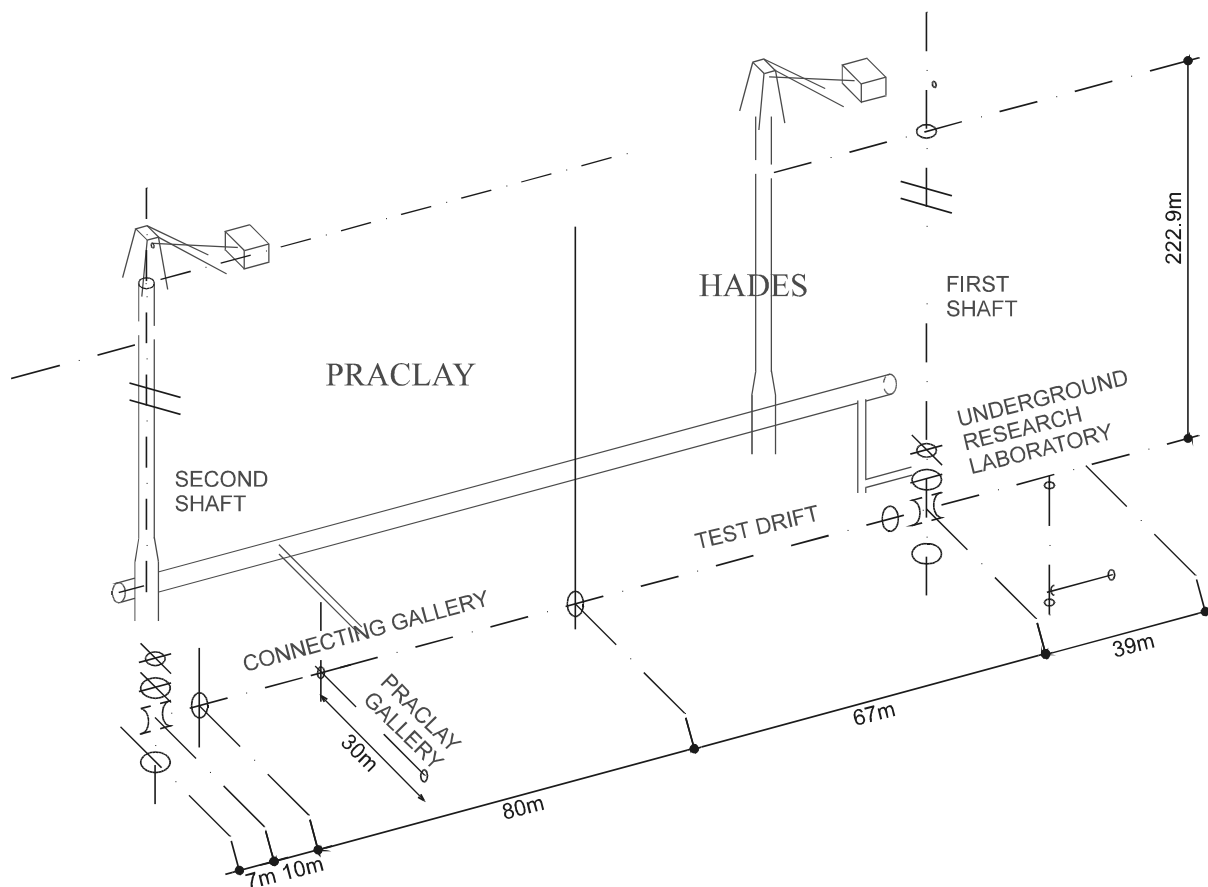


Figure 10. **Instrumentation programme around the Test Drift in the Boom Clay at Mol.**

[requires new version of figure]

### 8.1.3 *Reduction of the EDZ*

The construction of a gallery in the Boom Clay results in decompression of the clay and the creation of an EDZ. During the construction of a repository it is important to reduce the extent of this EDZ as much as possible, and the knowledge acquired since the beginning of the construction of the HADES facility in 1980 has resulted in the development of improved techniques to reduce significantly its extent. It has been demonstrated that the EDZ can be minimised by:

- increasing the excavation speed, thereby minimising additional convergence due to time-dependent deformation phenomena (whose rates are controlled by the rate of diffusion of fluids and by and viscosity of the clay);
- reducing the excavation diameter, as the plastic radius ( $R_{pe}$ ) is directly proportional to the excavation radius ( $R_i$ );
- reducing the extent of over-excavation (or the initial gap between the lining and the excavation wall);
- reducing the distance between the last installed lining element and the excavation front; and
- the use of a stiff liner.

### 8.1.4 *Measurements around the connecting gallery (CLIPLEX)*

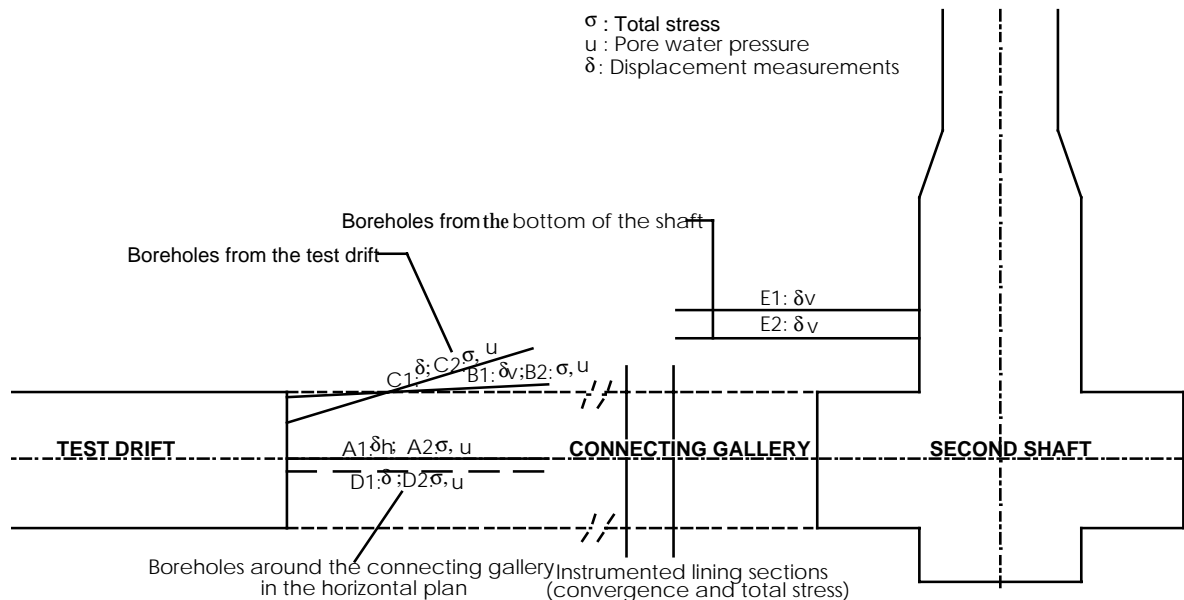
The extension of the underground laboratory consists of the construction of a second shaft and a 90 m long Connecting Gallery (Figure 9). To reduce the extent of the plastic zone created by the tunnelling process a partly-mechanised technique is being used. The over-excavation will be reduced to a minimum (about 2 cm) and the liner will be installed behind the excavated face as soon as is practical, in order to minimise the radial movement of the tunnel wall. A final decision on the excavation method and the type of liner has not yet been made.

The construction of the second shaft and the 90 m long connecting gallery by EIG PRACLAY (Economic Interest Grouping between NIRAS/ONDRAF and SCK/CEN) commenced in June 1997 and is planned to be completed before 2000. The CLIPLEX project involves the installation of an instrumentation programme for this extension and a comparison of the measurements made with blind predictions from five modelling teams. The CLIPLEX project is supported by the EC and is a joint project of EIG PRACLAY, who are acting as the co-ordinator, with ANDRA and ENRESA acting as main contractors and G3S (France), GEOCONTROL (Spain) and UPM (University Politechnique Madrid) acting as associated contractors.

The CLIPLEX instrumentation programme (Figure 11) will allow an assessment to be made of the performance of the mechanised excavation technique and the corresponding anticipated reduction in the extent of the plastic zone. For the first time in the Boom Clay, the displacements ahead of the face of the advancing tunnel will be measured, allowing monitoring of the initial convergence which

occurs ahead of the excavation front. The instrumentation programme includes the measurement of total stress, pore water pressure and displacement.

Figure 11. **The CLIPEX instrumentation programme in the Test Drift at Mol (not to scale).**



### 8.1.5 Evolution of the hydraulic properties due to excavation

Numerous single and multi-component piezometers have been installed around the HADES underground facility to monitor the hydraulic properties (pore water pressure, hydraulic conductivity and storage coefficient) of the Boom Clay. The presence of the underground installation with a water-permeable liner creates a very high pressure gradient and, therefore, drainage towards the galleries. The pressure distribution around the underground facility shows that the flow is Darcian. The evolution of the pressure distribution as a function of the distance to the lining and of time shows that reconsolidation of the clay is taking place within the EDZ. The measured hydraulic conductivities decrease towards their initial values, a process that takes more than ten years. No potentially preferential flow paths caused by expansion-induced hydrofracturing have been observed.

## Conclusions

This analysis of the hydromechanical and hydraulic behaviour of the clay surrounding the galleries has resulted in a validation of the calculational and analytical methods and an improvement in the excavation methods applied in order to reduce the extent of the EDZ. The experience gained in the Boom Clay has shown that, due to its elastic visco-plastic behaviour and self-healing properties, its geomechanical and hydraulic properties will recover to their pre-excavation values after a sufficiently long time. The extent of the EDZ and the time for this recovery will depend on the excavation techniques used.

## 8.2 Indurated clays – the Toarcian and Domerian clay formations at Tournemire (Jean-Yves Boisson, IPSN)

### 8.2.1 Introduction

The excavation of two galleries at the Tournemire tunnel site through Jurassic shales and marls in 1996 by the French Institute for Nuclear Protection and Safety (IPSN) has provided an opportunity to carry out an *in situ* research programme on the development of an EDZ in such material. The site has allowed a comparison to be made between the EDZ developed around a 100 years old tunnel and that around recently constructed galleries, and also an evaluation of the impact of such excavations on the solute transport characteristics of the EDZs and on their possible evolution with time.

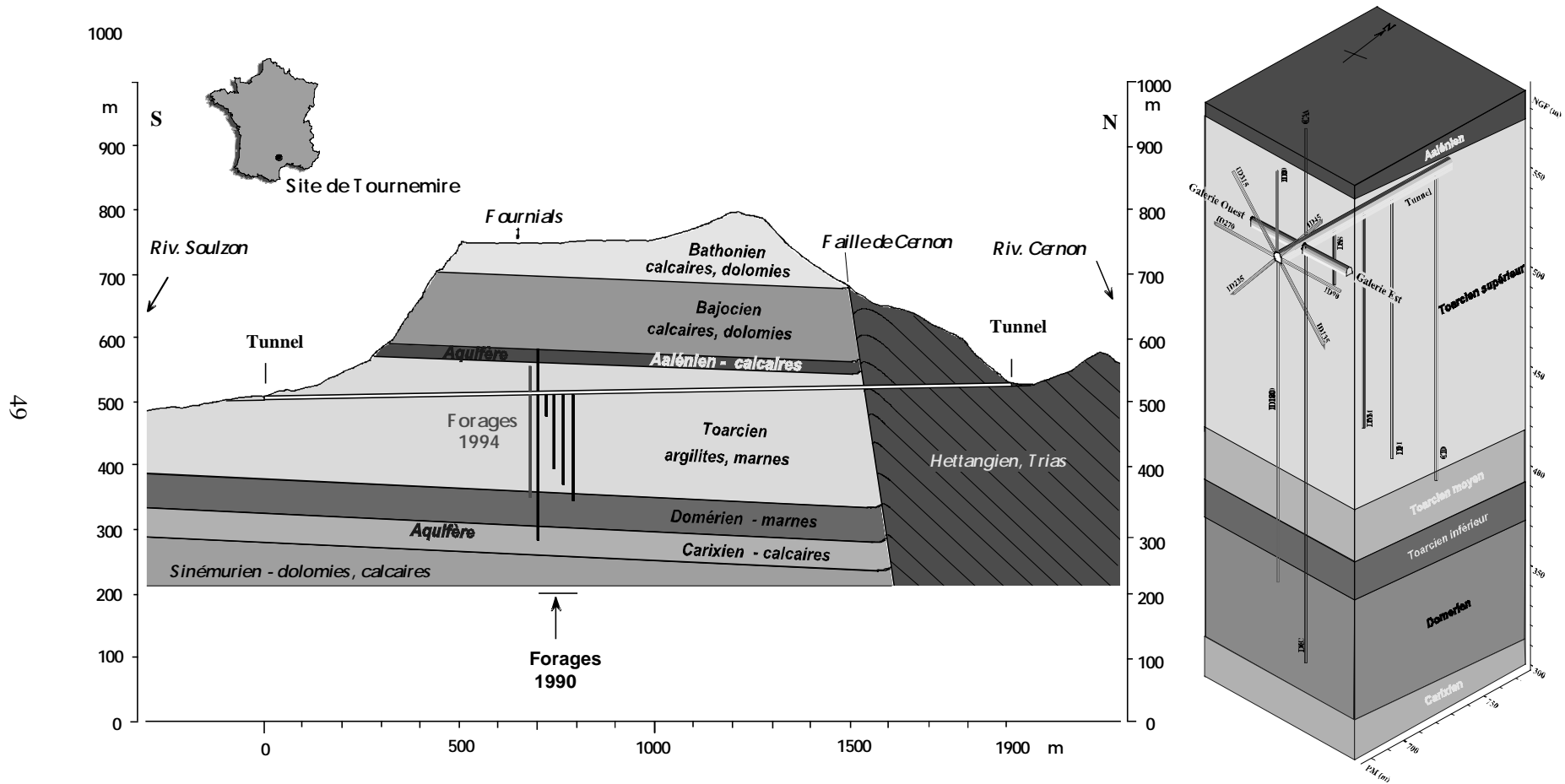
### 8.2.2 Study site

The study site (Figure 12) is located close to Millau, in southern France and consist of an old railway tunnel which intersects thick Toarcian and Domerian (Lower/Middle Jurassic) indurated clay formations (shales) which are overlain by 270 m of limestone, so that the geotechnical and hydrogeological conditions in the tunnel can be considered to some extent to be representative of those of a deep repository (Figure 12). The research programme is designed to investigate the processes associated with the movement of fluids and the transport of solutes in such formations, over different timescales and distances. Details of the geological characteristics of the site and the experimental programme which has been performed can be found in Barbreau & Boisson (1994) and Boisson *et al.*, (1998a,b).

The Tournemire tunnel itself is an old railways tunnel excavated probably mainly by hand one century ago (1884-88), with an approximate cross sectional area of 25 m<sup>2</sup> (height: 5.70 m, width: 4.6 m). The tunnel walls are protected by a continuous facing of limestone blocks which do not display any damage, e.g. fracturing, crushing, except near the floor of the tunnel.

In 1996 IPSN excavated two galleries from the tunnel (each 30 m in length and cross sectional area of 12 m<sup>2</sup>) in order to carry out new experiments. The galleries were constructed using a rotator head without recourse to water or explosives. Tunnel liners and bolts were not used, but some weeks after the excavation, steel ribs were installed every two meters to support a metal grid on the roof of the galleries in order to prevent any rock falls. These ribs do not play any mechanical role in tunnel support

Figure 12. Geological cross section and isometric model of the tunnel and two galleries at Tournemire, France.

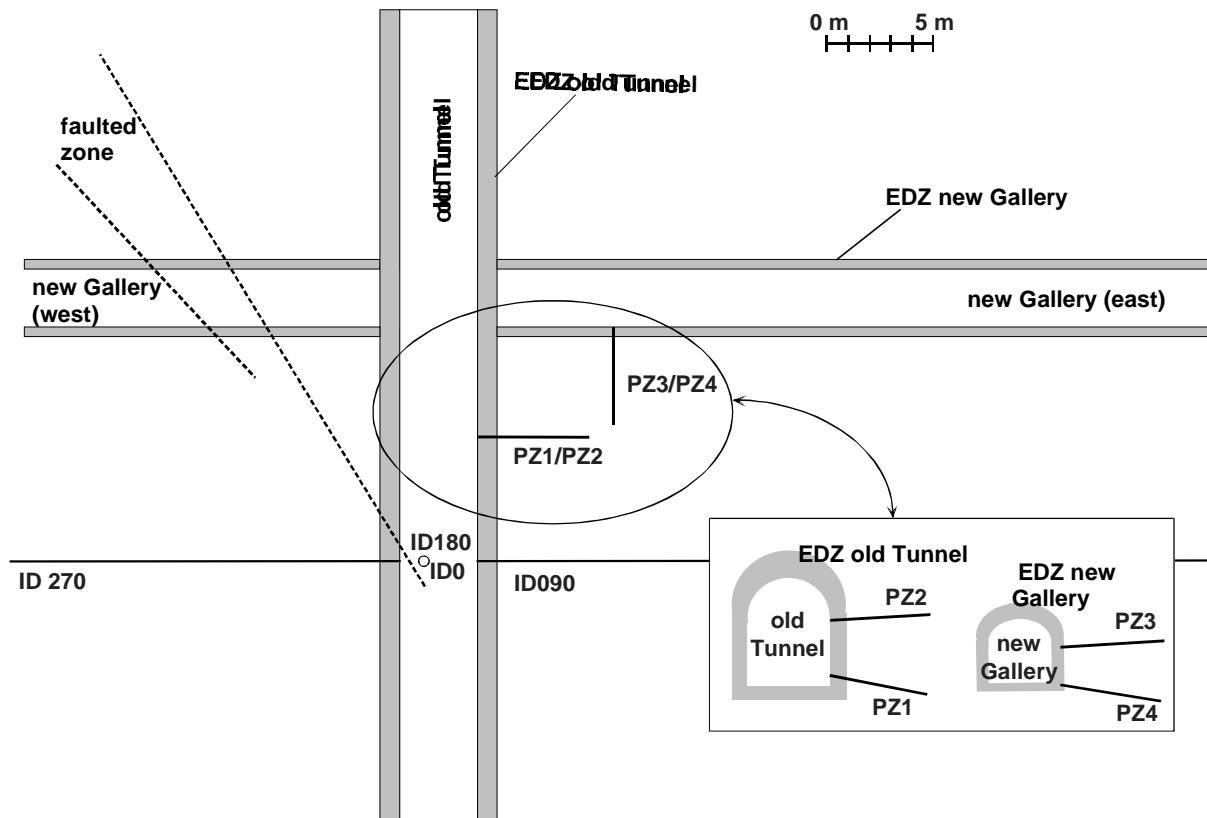


### 8.2.3 *EDZ investigation methods*

The excavation of the new galleries has provided an opportunity to develop an EDZ investigation programme which has examined the properties of the EDZs associated with both the original tunnel and with the new galleries (Figure 13). Various methods have been used to examine these EDZs, including visual observations, radar tomography and displacement measurements. Seismic wave velocities and hydraulic properties have also been determined in boreholes drilled from the original tunnel and from one of the new galleries. Figure 13 shows the location map of the tunnel and the position of the radial boreholes PZ1 and PZ2 in the old railway tunnel and PZ3 and PZ4 in the new gallery. The measurement programme is summarised below:

- **Relative deformation measurements (SIMECSOL measurements)** instrumented sections have been installed along the whole lengths of the two galleries, in order to investigate time-dependent changes following its construction. These have consisted of convergence and levelling measurements;
- **Observation of the evolution of the tunnel walls** of the new galleries to look for the development of new fractures, observation of the EDZ associated with the tunnel, via the excavation of the new galleries, and observation of the EDZ around the tunnel and the new galleries from boreholes drilled from both;
- **Petrophysical evolution of the rock** with respect to the distance from the excavations (*e.g.* natural radioactivity, neutron porosity, changes in moisture content, *etc.*). No really relevant observations regarding the EDZs have been made in this area, due probably to the techniques having too low a sensitivity;
- **Radar surface reflectometry (GEOSCAN measurements)** have been carried out along profiles in the tunnel and the galleries using conventional RADAR SIR 10 (Geophysical Survey Systems Inc.) with central frequencies of 400 and 900 MHz. This has allowed the capability of this technique for detecting changes in the EDZ to be examined;
- **Permeability measurements: the hydraulic properties** of the EDZs have been assessed by applying successive pulse tests carried out using a small packer interval of 5 cm (the ENSG-SEPPI probe) in the boreholes at up to 6 m from the tunnel walls;
- **The distribution of seismic wave velocities around the tunnel and the galleries** has been measured along boreholes using the BGR mini-sonic probe, under the same conditions as those for the SEPPI tests, in order to compare these parameters, by using interval (10 cm) velocity measurements of P and S waves, amplitude curves and amplitude ratios to image the velocity distribution.

Figure 13. Outline of the EDZs developed in the tunnel and the two galleries and the investigation boreholes drilled from the tunnel (PZ1 and PZ2) and from the eastern gallery (PZ3 and PZ4).



## 8.2.4 Results of the EDZ assessment

### 8.2.4.1 Indications from in situ mechanical response of the clay

After one year of convergence measurements from the initial excavation of the two galleries, it has been possible to arrive at certain conclusions regarding the mechanical evolution of this kind of indurated clay. The significant implications regarding EDZ development are:

- The deformation measurements indicate strongly contrasting behaviour between the western gallery, which passes through part of the rock mass that has been affected by tectonic events, and the eastern one, in which such deformation is absent and where major fracturing is not present. The main results of these measurements are summarised Figure 14, which shows that after more than 500 days, the maximum convergence is about 5 mm in the eastern gallery, whereas it is 23 mm in the western gallery, which exhibits a maximum deformation ratio of 4.

- An analysis of the deformation results has been carried out using an inverse method in order to obtain horizontal and vertical displacements at each instrumented point along the gallery wall. These displacements allow a comparison to be made with the results of numerical modelling, using the code CESAR-LCPC, in which an anisotropic linear elastic law has been adopted. This allows some general remarks to be drawn:
  - it seems that  $K_0 < 1$ , possibly indicating an anisotropy in *in situ* stresses;
  - analysis of the deviatoric stresses shows that they are most important in the zones in the footwalls of the openings and, in particular, in the railways tunnel, as is confirmed by evidence of continuous destruction of the rock at this locality;
  - Convergence of the galleries is still evolving after 500 days and it is apparent that the rock is subject to significant long-term creep behaviour, which represents, to date has accounted for about 70% of the total deformation (Figure 15);
  - Various deformation models were tested, in order to analyse this behaviour and a viscous flow model appeared to be the most appropriate. Estimates of the maximum convergence at infinite time, using the assumption of viscous flow, are about 5 mm for the eastern gallery and 30 mm for the western one;
  - It is planned to carry out continuous convergence measurements in order to confirm these observations and to adjust the parameters of the deformation laws. In order to validate these laws, it is proposed to carry out a stress measurement programme to provide an accurate measure of the stress field around these galleries and also an appropriate programme of geotechnical laboratory testing.

Figure 14. Values of the maximum convergence measured in the galleries at Tournemire over a period of two years

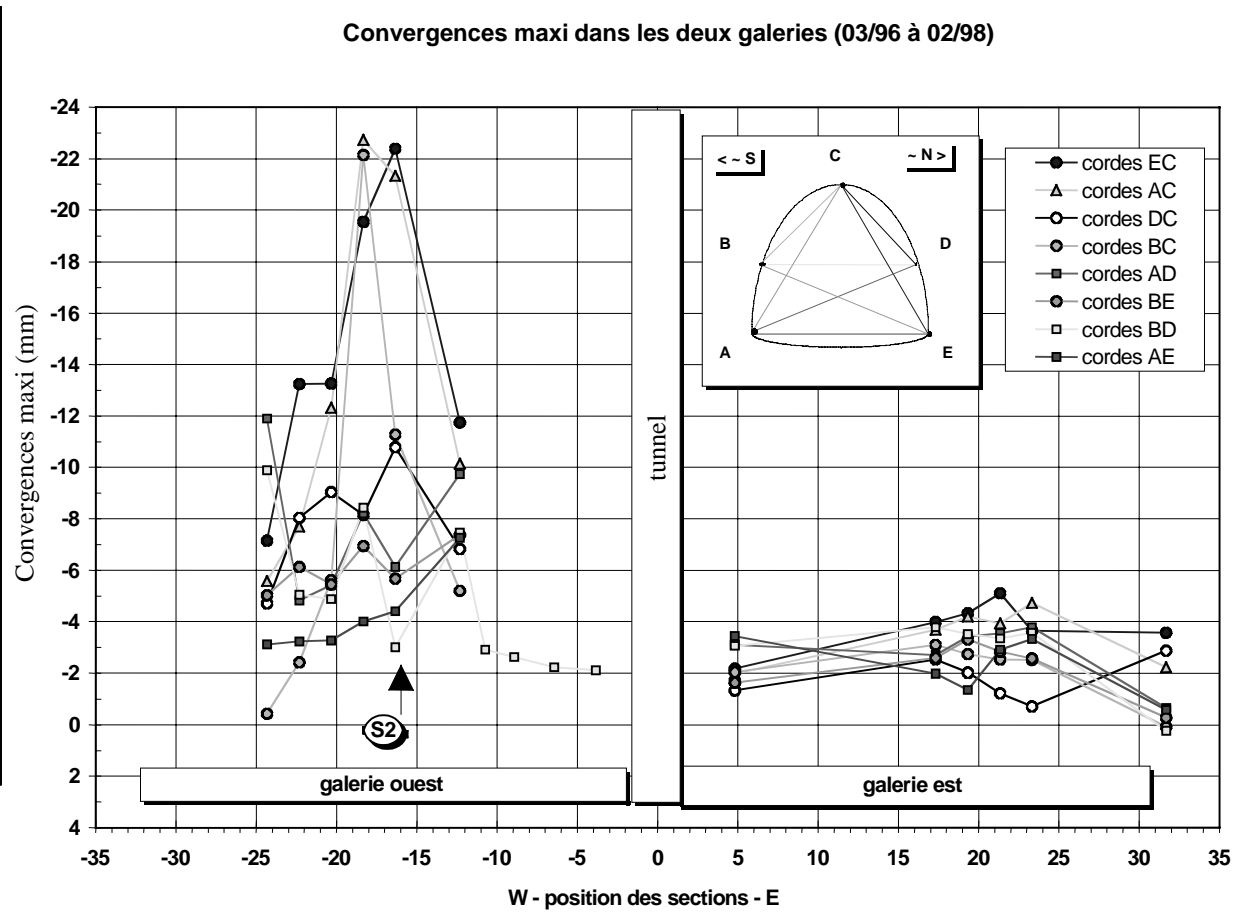
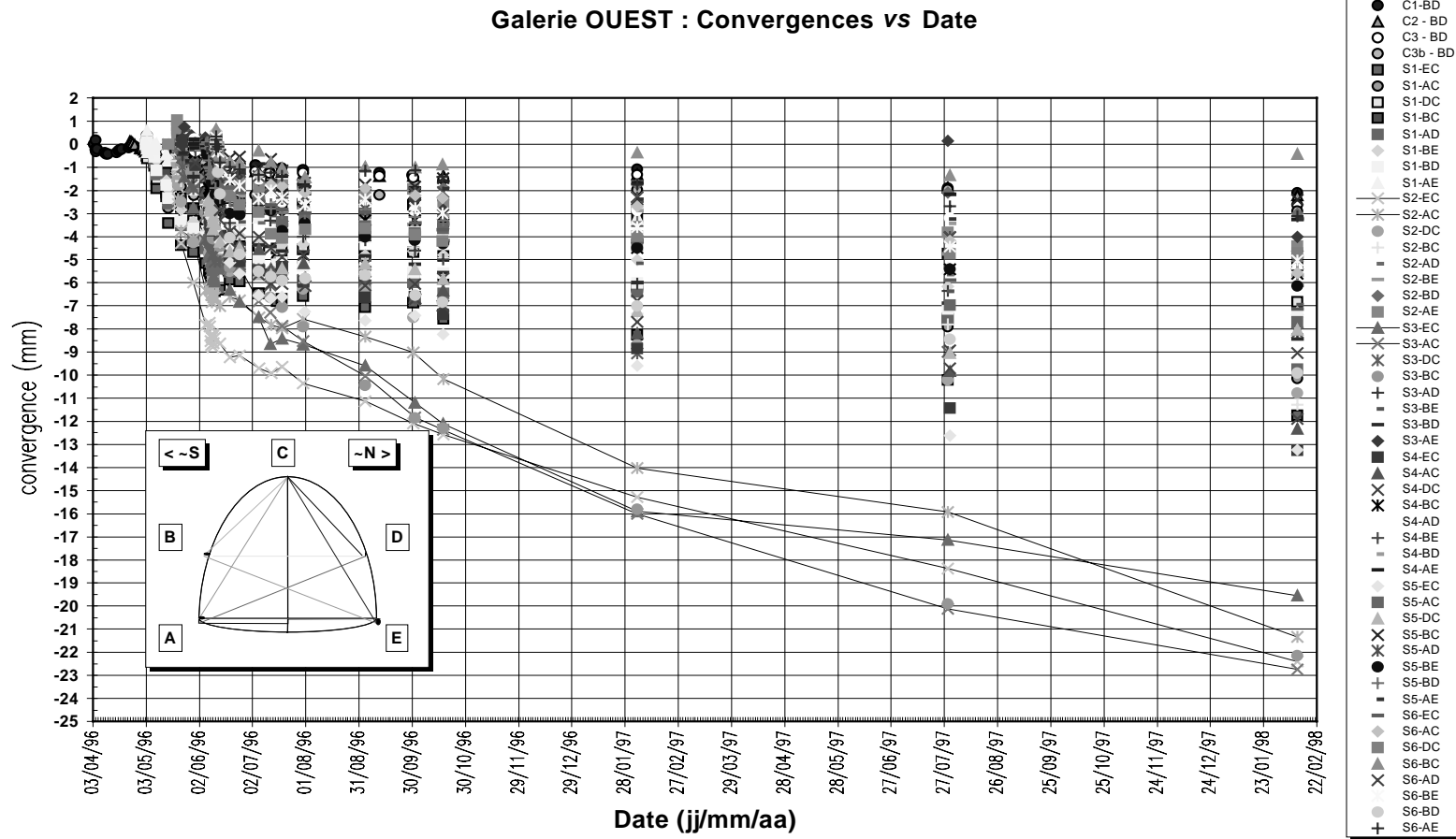


Figure 15. Values of the convergence against time for the western gallery at Tournemire.



#### 8.2.4.2 *Direct observations*

The first set of observations concerns the evolution of the walls of the galleries. A regular fracture network is present across the whole surface of the galleries, with one dominant fracture orientation apparently controlled by the bedding. The development of these fractures, in particular their lengths and apertures, seems strongly linked to the relative humidity and temperature variations prevailing in the galleries. It is important to appreciate the possible relationships that are likely to exist between the development of such fracturing and the development of the EDZ, knowing the significant coupling that exists in this type of rock between its mechanical behaviour and its moisture content (Daupley, 1997). A distinction needs to be made between such changes and those associated with the changes in *in situ* stress that accompany the excavation process and the effects that these have on the level of fracture development.

It has been possible to make the following direct observations of the EDZ in the galleries and the tunnel:

- The extension of the tunnel's original EDZ caused by the excavation of the two galleries is less than 2 m in extent for its eastern wall and consists of the development of vertical fracturing. There is a sharp transition observable between this fractured zone and the unaffected rock mass. The development of the EDZ on the western side of the tunnel is somewhat different, with a less regular development of fractures and a smaller extension of the EDZ. The only apparent difference between the two walls of the tunnel is related to the presence of a faulted zone in the immediate vicinity of this western EDZ, but no conclusions have yet been drawn as to any link that might exist between this faulted zone and differences in the development of the EDZs on the eastern and western sides of the tunnel;
- Four 6 m boreholes have been drilled, two from the tunnel (PZ1, ~15° downward and PZ2 horizontal) and two from the eastern gallery (PZ4, ~15° downward and PZ3 horizontal) and these have allowed a check to be made of the extent of fracturing associated with the EDZ for each excavation (Figure 13). Fracturing associated with the EDZ can be seen up to 1.35 m from the tunnel wall, but less than 0.60 m in the case of the gallery. Apart from the presence of two or three thin calcite-filled fractures, the core material is very homogenous, due possibly to the fact that the boreholes are oriented close to the plane of the bedding.

These direct observations have allowed valuable comparisons to be made between observations and the results derived from indirect, non-invasive techniques, which are discussed below.

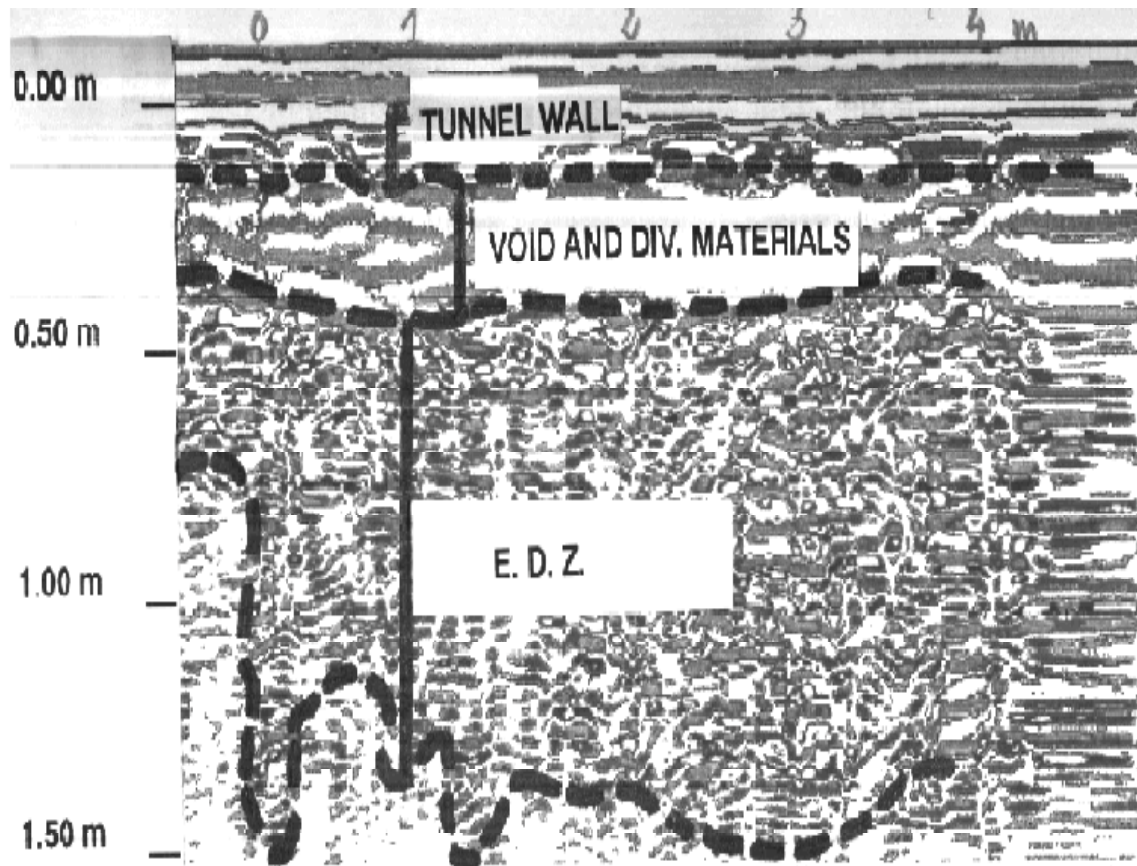
#### 8.2.4.3 *Radar surface reflectometry*

Two 5 m profiles have been carried out along the walls of the tunnel and also along the two galleries in order to check the performance of the radar tool. The results obtained using this off-the-shelf radar technique indicate (Figure 16) that:

- the technique provides a good visualisation of the tunnel structure and the possibility of detecting an EDZ with open fractures (*i.e.* in the tunnel walls); and
- this technique does not provide any useful information concerning the structure of the more recent EDZs associated with the galleries.

This technique, therefore appears promising, but will certainly require improvements if it is to prove useful for research purposes.

Figure 16. Results of the investigation of the EDZ around the tunnel at Tournemire using radar surface reflectometry (using a SIR 10 G.S.S.Inc system at 900 MHz).



#### 8.2.4.4 Permeability measurements (SEPPi probe)

The SEPPi probe was initially conceived for use in crystalline rocks (Bauer *et al.*, 1995; Homand *et al.*, 1995), and it has proved difficult to apply the technique in these indurated clays.

In general, it has proved rather difficult to interpret the tests carried out in horizontal boreholes (*i.e.* Borehole PZ2 for the tunnel, and Borehole PZ3 for the gallery), in particular when applying the classical Papadopoulos interpretation method, even when used in its modified form (Black, 1985). By using the Ramey method (Ramey *et al.*, 1975) it has been possible, however, to provide some qualitative hydraulic values which are not in disagreement with the results from the inclined boreholes (Figure 17).

Measurements performed in the two inclined boreholes (*i.e.* Borehole PZ1 for the tunnel, and Borehole PZ4 for the gallery) give interpretable results associated, in each case, with a well-defined EDZ (Figure 17). These tests show that there is a marked increase in permeability over a distance of >1.50 m (up to 2.50 m if the fracture at ~2.10 m is included) from the tunnel wall, with a sharp boundary to the EDZ<sup>11</sup>. The results of tests within the eastern gallery suggest that the permeability be enhanced over a distance of approximately 0.5m, but that there is in addition a transition zone of approximately 1 m between the EDZ and the unaffected clay.

Results from the testing in Borehole PZ1 led to an approximate permeability of the clay in the range of  $2 \cdot 10^{-20}$  to  $5 \cdot 10^{-19} \text{ m}^2$ , which is in good agreement with previous results from *in situ* tests made within the formation (Boisson *et al.*, 1997). The conclusion of this testing is that the permeability increase due to the presence of the EDZ appears to be  $\geq 5$  or 6 orders of magnitude.

The tested zones with the highest permeabilities, around 2.00 m from the tunnel wall in Borehole PZ1 and around 1.15 m in Borehole PZ4, are associated with fractures that are visible in the core.

### Distribution of seismic wave velocities

The extent of the EDZ can be measured accurately by means of seismic interval velocity measurements in boreholes. The EDZ is not only characterised by a decrease in seismic velocities, but also with a decrease in seismic amplitudes due to the increased attenuation of seismic energy.

The extent of the EDZ determined from the interval seismic velocity measurements is in good agreement with the distribution of logged fractures in borehole cores.

The P-wave interval velocities ( $V_p$ ) for the intact rock lie in the range 3800 to 4200  $\text{m s}^{-1}$  (Figure 18) and the S-wave velocities ( $V_s$ ) in the range 1600 to 1700  $\text{m s}^{-1}$  (Figure 19). The  $V_p / V_s$  ratio is relatively high, with values >2, but the highest values of 2.5 were obtained in the horizontal boreholes.

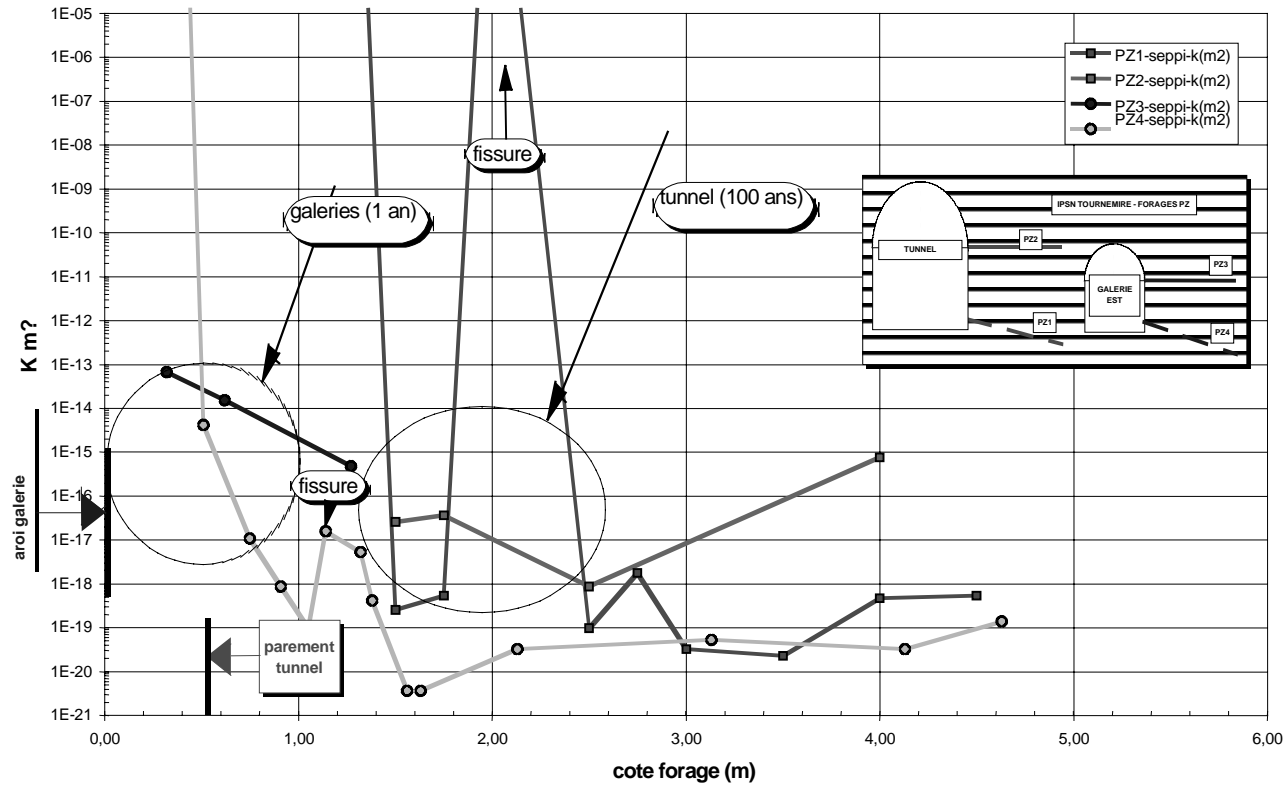
Based on the results of the seismic velocity measurements, the EDZ around the tunnel extends up to 1.35 m and 1.31 m in Boreholes PZ1 and PZ2 respectively. The transition from the EDZ to intact rock is very abrupt in both boreholes. In contrast, the extent of the EDZ in the eastern gallery is approximately 30 cm in Borehole PZ3 and approximately 40-50 cm in Borehole PZ4.

The seismogram sections and, in particular, the amplitude curves show that the interval velocity within the EDZ is considerably reduced and the seismic energy is strongly attenuated. The velocity reduction within the EDZ is more important for the tunnel than for the eastern gallery. This could indicate that the development of the EDZ around the gallery was incomplete and that it could evolve in time to resemble that currently present around the tunnel.

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11. With reference to Figure 16, the radar image of the tunnel wall, shows that approximately 40-50 cm needs to be subtracted from this value to obtain a correct value for the thickness of the EDZ. A similar value needs to be subtracted from all the other quoted figures of distance from the tunnel wall in the remainder of the text when considering the EDZ for the tunnel.

Figure 17. Permeability characteristics of the EDZ determined using the SEPPi Probe for the tunnel and for the eastern gallery at Tournemire.



The analysis of an isolated fracture at a depth of 2.12 m in Borehole PZ1 demonstrated that such fractures could be detected more easily by considering seismic amplitudes rather than seismic velocities.

#### 8.2.4.5 *Discussion and preliminary conclusions*

Due to the presence of an old tunnel and new galleries at the site and the availability of several different investigation techniques it has been possible to compare the development of EDZs over different timescales and in different geological settings.

Direct observations and investigations have allowed the EDZs to be precisely delineated, although the current radar technique requires some further improvements if it is to be applicable to newly constructed excavations.

The relatively abrupt transition between intact rock and the EDZ in the tunnel is observed at a depth of about 1.30 to 1.50 m (resulting in an actual thickness for the EDZ of approximately 0.9 - 1.0 m). It has been possible to measure the changes in sonic and hydraulic properties of this EDZ over its complete thickness.

The EDZ around the eastern gallery is less pronounced and smaller in extent than that around the tunnel. Evidence from fracturing in the cores suggests that the EDZ has a depth of >40 cm, whereas changes in the sonic and hydraulic properties can be observed for depths of between 0.5 - 1m.

Convergence measurements following the excavation of the galleries show that deformation of the clay is still occurring, though at an ever decreasing rate, after more than 500 days, i.e. the EDZ is still evolving with time. This is confirmed by the interval velocity measurements, where the reductions in  $V_p$ ,  $V_s$  or amplitude are less pronounced for the EDZ around the eastern gallery than for that around the tunnel. The majority of the mechanical evolution within the EDZ around the galleries seems, however, to have been completed and the current difference between the extent of the two EDZs could be due primarily to geometrical differences and to their different modes of excavation.

The first investigations made on an EDZ in this type of formation confirm that it is significant in terms of its hydraulic properties, and suggest that further research is required concerning the evolution of such an EDZ with time.

Figure 18. EDZ interval sonic velocity characteristics ( $V_p$ ) for the tunnel and eastern gallery.

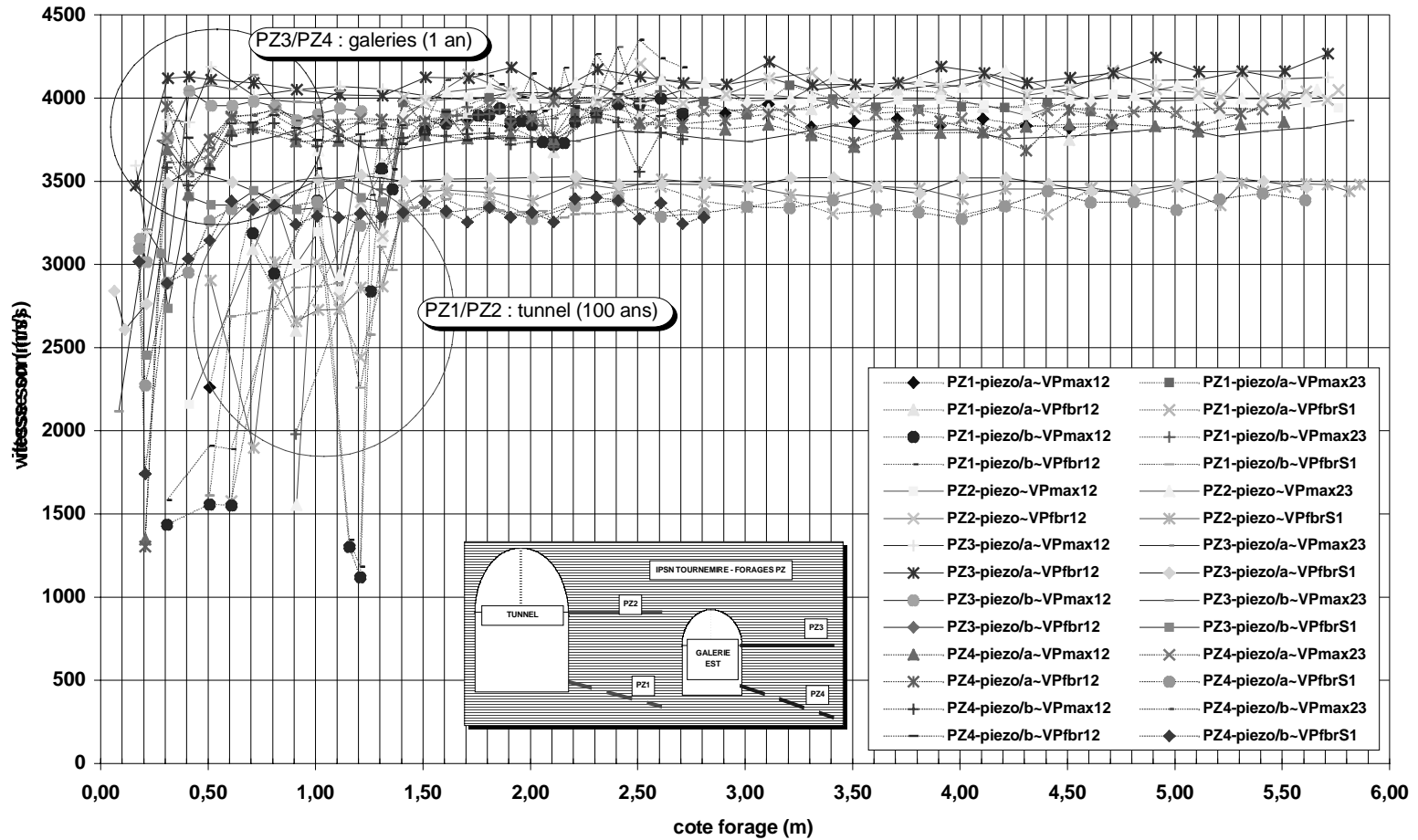
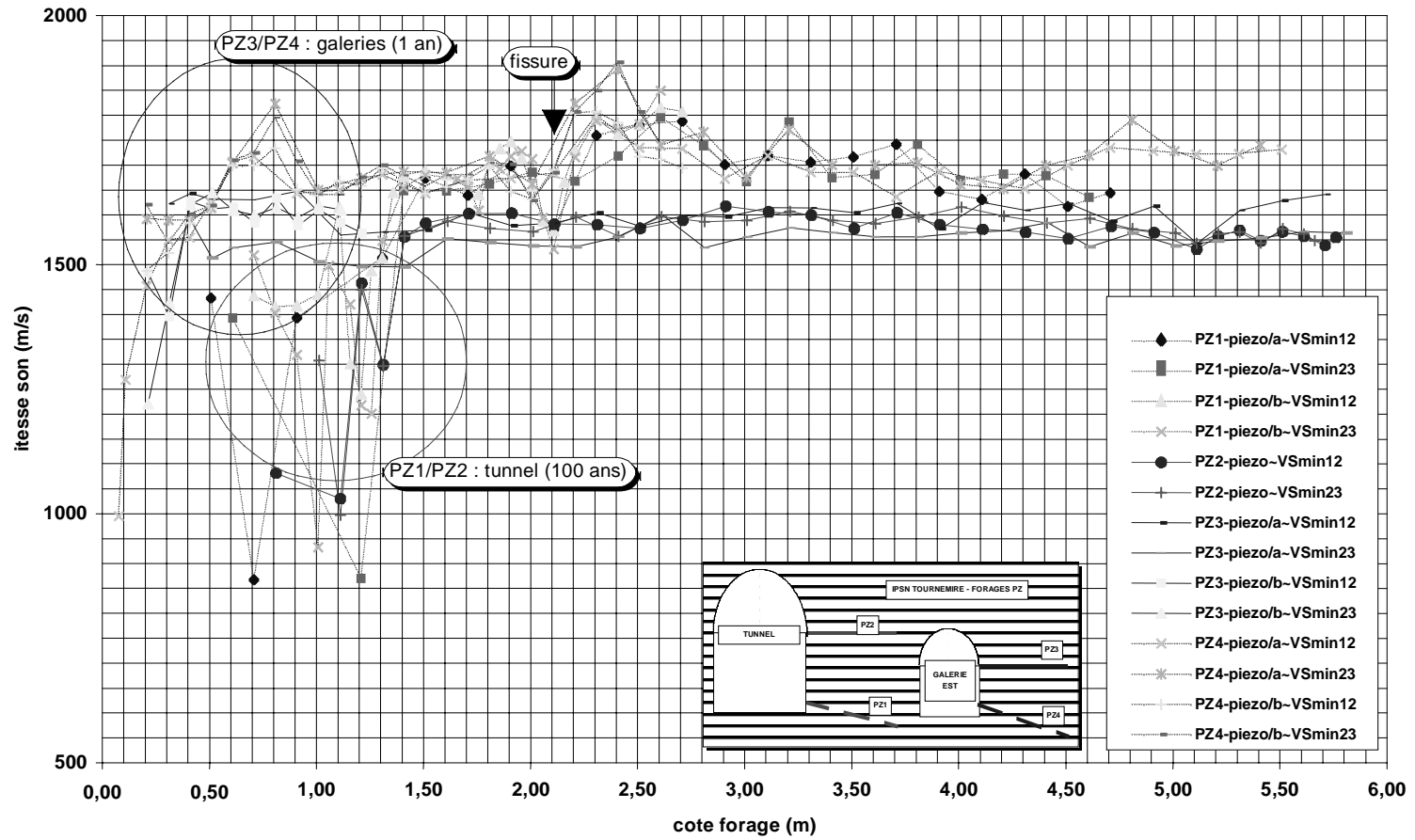


Figure 19. EDZ interval sonic velocity characteristics ( $V_s$ ) for the tunnel and eastern gallery.



## 9. THE EDZ IN ROCK SALT (KLAUS WIECZOREK, GRS)

### 9.1 Introduction

Rock salt is currently the preferred rock type for the disposal of long-lived, heat-emitting waste in Germany. In comparison with crystalline rock, salt has the advantage of exhibiting viscoplastic behaviour which prevents the formation of extensive fractures, and its permeability is low (usually approximately  $10^{-20}$  m<sup>2</sup> or less). It is, however, known from various investigations both in the bedded salt at the WIPP site (Beauheim *et al.*, 1989; Borns & Stormont, 1989) and in German domal salt (Miehe *et al.*, 1993), that EDZs develop during the excavation of drifts and chambers in rock salt. The hydraulic properties of these zones may differ significantly from the properties of the undisturbed formation.

EDZs in rock salt develop during and after the excavation of openings as a consequence of stress redistribution and related convergence. Near the opening, dilatancy occurs which changes the hydraulic behaviour of the rock. The extent and properties of the EDZ are expected to depend on the size, the geometry and the age of the openings.

In the long-term safety assessment of a repository in rock salt the hypothetical case of an inflow of water or brine into disposal boreholes or repository vaults needs to be considered. Radioactive material could then be transported preferentially within the EDZ if it is present as a zone of enhanced conductivity. The EDZ is also of significance when considering the development of enhanced gas pressures, produced as a consequence of corrosion of waste produces and/or the EBS, since they could be a driving force for groundwater flow. For this reason, not only single phase but also two phase flow systems need to be considered.

The most important hydraulic parameter, the permeability, is usually determined by packer tests in boreholes. Such tests in the water saturated rock salt at the WIPP site led Stormont *et al.* (1991) to conclude that the EDZ can be divided into a more disturbed zone, in which microfracturing and dilatancy occurs (leading to an increase in permeability), and also a less disturbed zone, which is characterised by a decrease of pore pressure. In the relatively dry domal salt of northern Germany the EDZ reduces to a dilatant zone, but only a small amount of information has been obtained so far on the change that can take place in the hydraulic properties of the salt due to the formation of an EDZ (Miehe *et al.*, 1993).

The EDZ is being studied under the project ALOHA (Untersuchungen zur Auflockerungszone um Hohlräume im Steinsalzgebirge), which is being carried out at the Asse salt mine near Braunschweig, Germany. The issues investigated during the first phase of the project, which has been completed, were the spatial extent of the EDZ and its hydraulic behaviour, in terms of its permeability, porosity and two-phase flow parameters (relative permeabilities, capillary pressure). Another important issue for the assessment of long-term safety is the development of the EDZ with time, in particular its possible healing following the emplacement of support within the excavation, *e.g.* backfilling a tunnel or the construction of a bulkhead, *etc.* This process cannot be investigated directly, however, since the time necessary for complete healing is too long, even in rock salt. As healing is a process driven by stress, the anticipated outcome of this programme will be the derivation of a relationship between permeability and the *in situ* stress which can be used to provide useful input for safety assessment calculations for repositories in rock salt.

Phase 2 of the ALOHA programme, which has been running since mid-1998, includes:

- an investigation of the hydraulic properties of the salt in the immediate vicinity of the excavations (within distances of 1 m); and
- an investigation of the healing of the EDZ around supporting structures, such as bulkheads and backfill, with time.

The ALOHA Phase 2 work programme consists of:

- electrical conductivity mapping of the test sites;
- laboratory testing on samples from the test sites (their mechanical properties and permeability);
- *in situ* stress measurements);
- *in situ* permeability measurements by gas injection testing (in several boreholes at each test site);
- the development of permeability testing method for the immediate vicinity of the drifts;
- modelling of the mechanical state of the test sites; and
- comparison of the mechanical state of the rock and its permeability and the derivation of a stress-permeability relationship.

## 9.2 Experimental Programme

The ALOHA phase 1 concentrated on the investigation of the permeability and the spatial extent of the EDZ. The experimental programme included several *in situ* investigations that were augmented by laboratory testing and modelling. The *in situ* measurements made were:

- the measurement of the rock salt permeability by gas injection at different distances from a drift; and
- the injection of liquid (salt brine) into the rock salt and tracking of the spreading brine using electrical resistivity measurements.

The investigations were performed in a 10 year old test area at the 875 m level at Asse (Figure 21). Two vertical boreholes in the drift floor were used for injection testing with gas and liquid, respectively. The liquid injection borehole is surrounded by five additional boreholes that contain cemented electrodes for the electrical resistivity measurements. More electrodes are arranged in three profiles on the drift floor (Figure 21). Additional gas injection tests were performed in a horizontal borehole in a pillar between two drifts at the 800 m level.

Laboratory tests were aimed at the determination of two-phase flow parameters (relative permeabilities, capillary pressure) of rock salt which cannot be determined *in situ*, but which are important for flow processes in partially saturated rocks. Modelling comprised hydraulic calculations and mechanical finite-element calculations for comparison with the results of the permeability measurements and the *in situ* stress. During the ALOHA phase 2 experiments additional gas injection tests over different length scales and with different symmetries will be performed in the vicinity of various excavations. These experiments will be coupled to the respective stress states by stress measurements and mechanical modelling. A special test site is located at the 700 m level of the Asse mine where a cast steel bulkhead was placed in a drift in 1914. Here, partial healing of the EDZ might have already taken place and could be detectable.

Figure 21. The ALOHA test drift in the Asse salt mine.



### 9.3 Extent and hydraulic properties of the EDZ

The results obtained from *in situ* testing in the drift on the 875 m level of the Asse mine are presented below.

#### 9.3.1 Gas Injection Tests

In gas injection testing a part of a borehole, the test interval, is sealed off by packers. Gas is injected into the test interval and the pressure development during the injection phase and the subsequent shut-in phase is recorded and, from the flow rate and the pressure curve, the permeability of the rock is derived. For these tests a four-packer probe and a test interval of 800 mm was used, with

two observation intervals of 300 mm length being located above and below. The test gas was nitrogen with a maximum injection pressure of between 2- 3 MPa and the flow rate was in the range of 500 to 550 ml min<sup>-1</sup>.

The gas injection tests were evaluated using the commercial code Weltest 200 that was originally developed for oil field testing. It optimizes certain formation parameters, especially permeability, on the basis of a chosen "reservoir model". The following assumptions were made:

- the formation is homogeneous and unlimited and has a porosity of 0.2%;
- partial water saturation is neglected; and
- the borehole has a finite radius (0.56 mm) and a storage capacity according to the test interval volume.

Depending on whether the flow into the formation is regarded as one-dimensional (horizontal) or two-dimensional (with upward and downward components), different permeability values are obtained. The results are summarised in Figure 22, which shows the permeability results at different depths below the floor. The heights of the rectangles in the figure represent the test interval lengths and their widths the ranges of the measured permeabilities.

A sharp transition from the undisturbed to the disturbed zone can be seen at about 1.5 m depth. The permeability in the undisturbed zone is in the range of 10<sup>-21</sup> m<sup>2</sup> or lower, whereas in the disturbed zone permeabilities around 10<sup>-17</sup> m<sup>2</sup> are obtained. No information is available from 0.8 m immediately below the floor, due to the length of the upper packer seals. Effort will be made in the second phase of the project to develop a measuring system for injection testing in the immediate vicinity of the excavations. Additional gas injection tests in a horizontal borehole showed that the EDZ extended for < 1 m from the drift wall, in contrast to its depth of 1.5 m below the floor.

### **9.3.2 *Liquid injection tests and electrical conductivity measurements***

Liquid injection tests with saturated salt brine were performed in a second borehole (see Figure 21) with a borehole probe similar to the one for gas injection. The liquid injection tests confirmed the results of the gas injection tests regarding the extent and permeability of the EDZ. A total of 7.5 l of brine was injected at 1 m depth during two injection phases at a maximum injection pressure of 1.5 MPa. The electrical conductivity measurements (described below) showed, however, that the brine did not spread evenly, but followed preferential pathways through the salt.

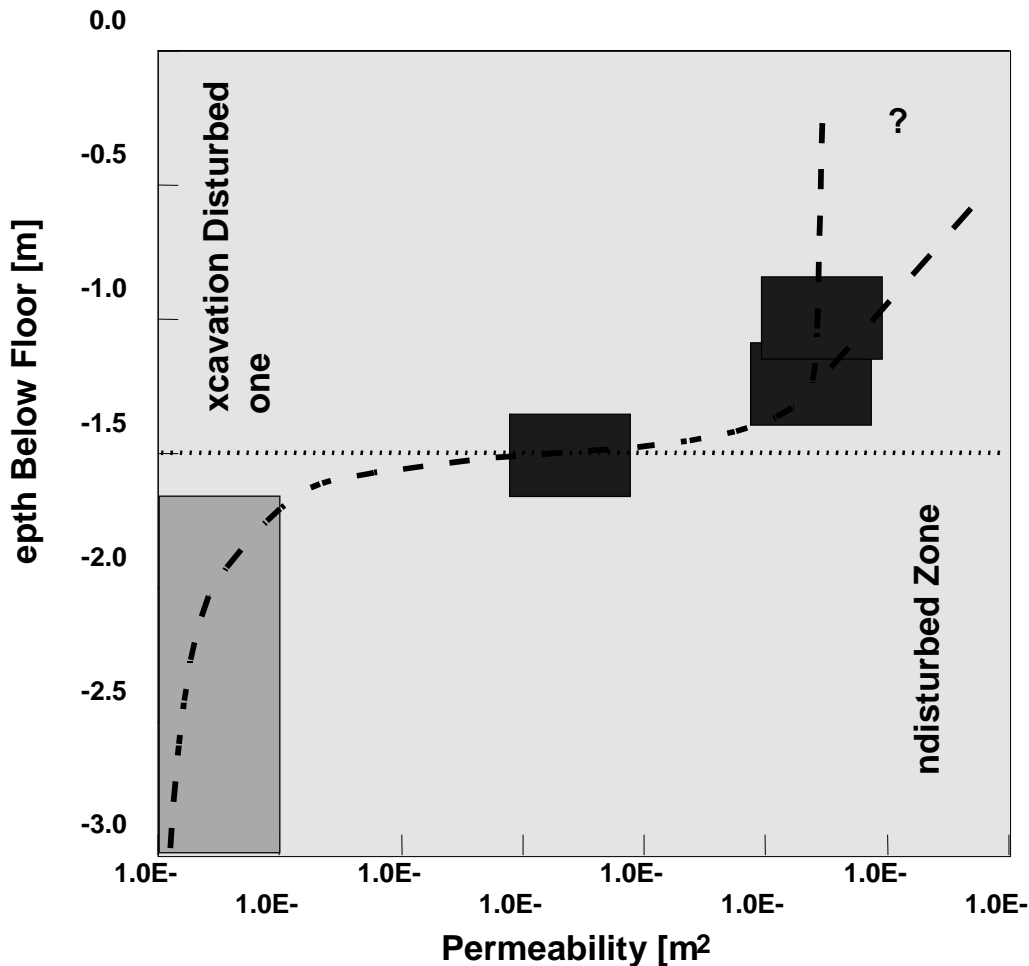
The calculated permeability to brine was 10<sup>-14</sup> m<sup>2</sup>, which is much higher than the permeability to gas found in the gas injection borehole at the same depth. To study this issue in greater depth the liquid injection borehole was overcored to a diameter of 400 mm and the core inspected. The presumed pathway was found to be a sulphatic layer several millimetres in thickness. To improve the comparison between the gas and the liquid injection tests an additional liquid injection test was performed in the gas injection borehole at 1m depth. The permeability to brine evaluated from this test was in the range of 10<sup>-17</sup> m<sup>2</sup> and, therefore, similar to the gas permeability. At a depth of >2 m no significant amount of brine could be injected into the formation (at a maximum injection pressure of 6 MPa), which is in agreement with the results of the gas injection tests.

The liquid injection tests were accompanied by electrical resistivity measurements, which measure the resistivity distribution in the rock by injecting a current via a pair of electrodes and measuring the resulting potential differences between another pair. The measured resistivity can be

correlated to the moisture content of the rock salt using a correlation function which is known from numerous laboratory tests (Kulenkampff and Yaramanci, 1993; Yaramanci & Flach, 1992).

As expected, no changes in the resistivity distribution were found during the liquid injection tests at  $\geq 2$  m depth. A different result was obtained after the injection tests at 1 m depth. Figure 23 shows the resistivity distribution in the planes between the electrode boreholes, with the injection borehole located at the intersection of these planes. It can be seen that the resistivity around 1 m depth is significantly lower than at greater depth. The value of 200 to 1000  $\Omega\text{m}$  represents a water content of 0.3 to 0.5% by volume. It is, however, also observable that the resistivity in the direction 51-53 is much lower than in the perpendicular direction 52-54 (Figure 23). This is probably due to the uneven spreading of the brine along selective pathways, a process that was discussed above. As the gas injection borehole lies outside the borehole electrode array, the additional liquid injection test performed in this borehole could not be monitored using electric resistivity measurements.

Figure 22. Permeability distribution in the upper 3 m below the drift floor.



### 9.3.3 Relationship between hydraulic properties and mechanical state of the salt

The permeability increase in the EDZ is caused by the dilatant behaviour of the rock salt in the immediate vicinity of the excavation, which is a response to the change in *in situ* stress. Several dilatancy criteria have been proposed by various authors:

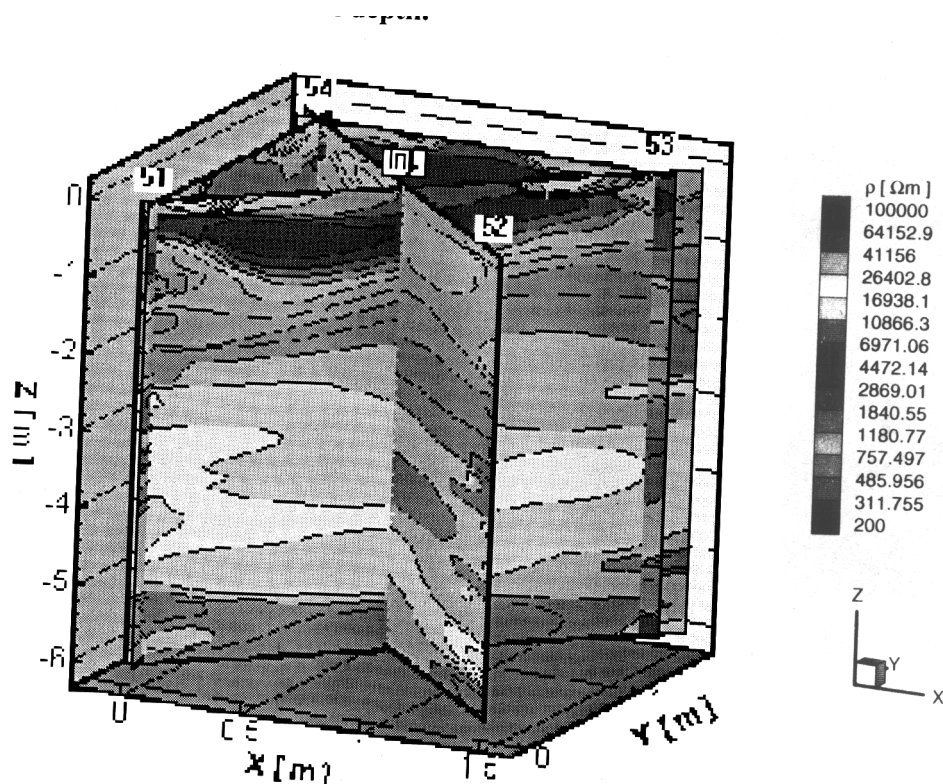
$$\sqrt{J_2} \geq 0.83 \cdot \sigma_m + 1.9 \quad (\text{Spiers } et al., 1988)$$

$$\sqrt{J_2} \geq 0.81 \cdot \sigma_m \quad (\text{Ratigan } et al., 1991)$$

$$\sqrt{J_2} \geq 0.86 \cdot \sigma_m - 0.0168 \cdot \sigma_m^2 \quad (\text{Hunsche, 1992})$$

with  $\sigma_m$  being the mean stress and  $J_2$  the second stress invariant.

Figure 23. Distribution of electric resistivity in the planes between the electrode boreholes after liquid injection at 1 m depth.



All equations have in common the assumption that a prerequisite for dilatancy is a high deviatoric stress (*i.e.* a large difference between the principal stresses ( $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ )). Mechanical modelling was performed using the finite-element code ANSYS in order to compare the results of the permeability tests to the stress state of the rock salt around the excavation. An axisymmetric model of the drift and a single injection borehole was considered sufficient. The model consisted of a sphere

with a radius of 100 m containing 611 elements with 1940 nodes. The actual history of the excavation of the drift and the borehole drilling were taken into account. The initial *in situ* stress prior to excavation was assumed to be 14 MPa at the level of the drift floor, based on stress measurements at other locations in the Asse salt mine, and to change both upwards and downwards according to the density of the rock salt of 2180 kg m<sup>-3</sup>.

The rock salt was modelled as an elastic-viscoplastic material, with the viscoplastic component including only secondary creep, according to the following equation:

$$\dot{\epsilon} = A \cdot \sigma^5 \cdot \exp\left(-\frac{Q}{R \cdot T}\right)$$

with the creep rate  $\dot{\epsilon}$  and a structural parameter A.

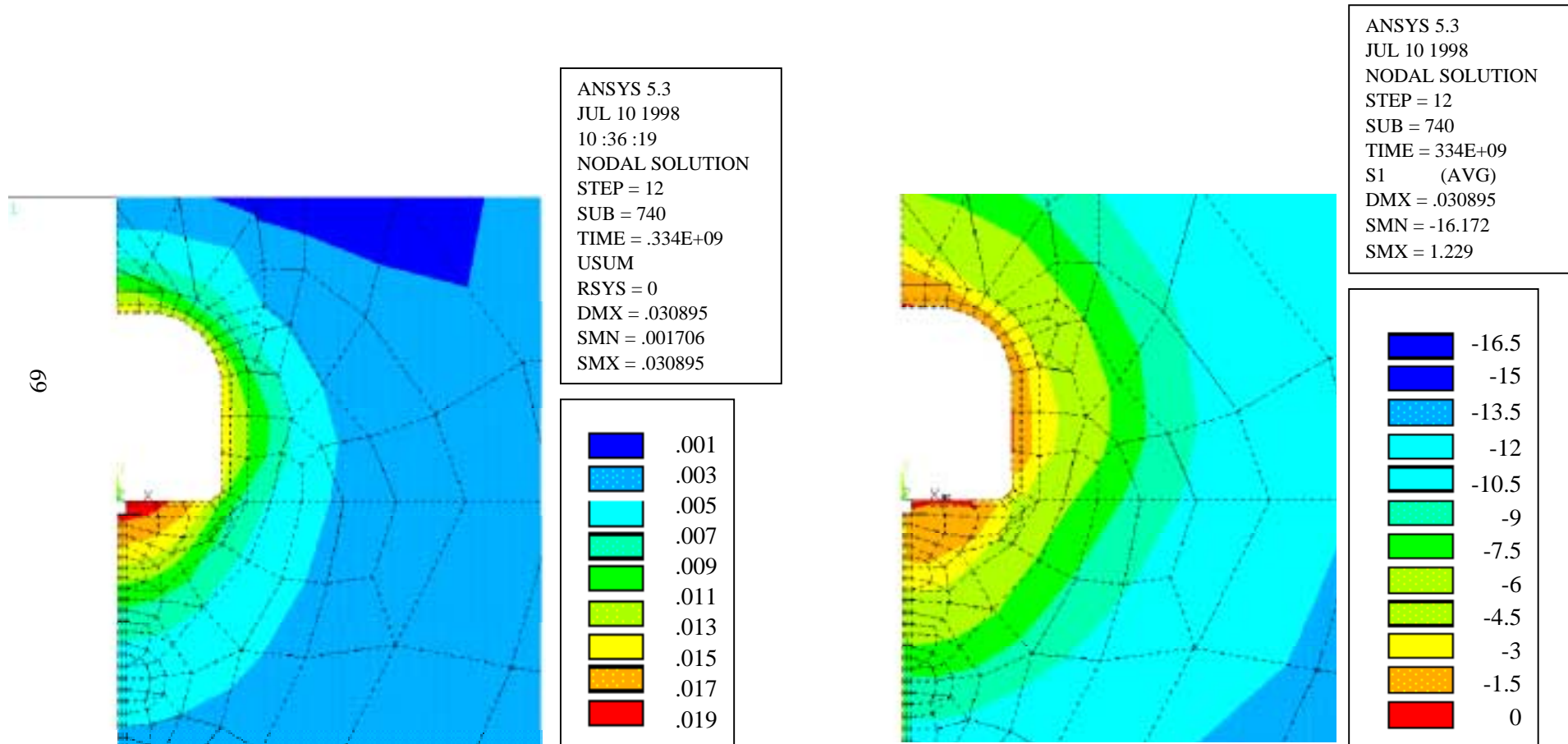
Figure 24 shows the total deformation and the distribution of the least principal stress around the drift at the end of the calculation period. The drift height is approximately 4 m and its radius 2.25m.

It can be seen that the largest deformations occur in the zone below the drift floor, whereas less deformation is observed in the walls and the roof of the drift. Consequently, the stress release is more pronounced in the floor than in the wall and the roof. A small value for  $\sigma_3$  implies a high deviatoric stress and hence a high dilatancy. Several conclusions can be drawn from the Figure 24:

- a small zone of tensile stress exists in the floor;
- a zone of diminished  $\sigma_3$  (as low as 1.5 MPa) extends about 1.5 m into the floor; and
- the extent of this zone into the wall is only about 0.5 m.

These results are in good agreement with the permeability tests. In particular, the smaller thickness of the EDZ in the wall compared with that in the floor is well reproduced. Further evaluation of the modelling results, for example in terms of where a dilatancy criterion is fulfilled, has not been carried out, since reliable measurements of the initial stress state were not available. More concise mechanical modelling, coupled to stress measurements, will be performed in phase 2 of the ALOHA project.

Figure 24. Calculated total deformation (left) and least principal stress (right) in the vicinity of the drift and the upper 5 m of the gas injection borehole at the end of testing.



#### 9.3.4 *Future work*

Future investigations in the frame of the ALOHA project will concentrate on the relation between the stress state and the hydraulic behaviour of the rock salt in order to allow predictions to be made of the possible extent of healing of the EDZ. Various sites including drifts, as well as large chambers, have been chosen for investigating this effect. A site of particular interest in this regard is an 85-year-old cast steel bulkhead in the Asse mine. The planned *in situ* investigations comprise permeability testing by gas injection and stress measurement using the overcoring method, with evaluation by finite-element modelling. Laboratory investigations on intact, disturbed, and possibly on healed salt samples and modelling with new codes that can take into account dilatancy will be carried out in cooperation with Sandia National Laboratories. An additional objective is the development of special equipment for measuring permeability in the close vicinity of openings (within a distance of <0.5). Measures have to be taken to obtain the component of the permeability parallel to an opening, as the permeability in this zone may be highly anisotropic. This is of potential interest with regard to flow around seals in galleries in a repository.

## Synthesis of the main conclusions

Timo Äikäs (Posiva) provided a synthesis of the main conclusions of the Topical Session. His general conclusions were as follows:

- (i) Experimental work in different rock types:
  - the majority of the work has been carried out in crystalline rocks; and
  - little work has been carried out in indurated clays
- (ii) Characterisation of the EDZ:
  - suitable characterisation methods exist and have been tested in various URLs;
  - the geometry of the EDZ in all rock types is sufficiently well known;
  - it is difficult to determine the hydraulic characteristics of EDZs; and
  - it is even more difficult to determine radionuclide transport characteristics of the EDZ.
- (iii) Level of understanding of EDZs:
  - the mechanisms of EDZ formation are understood in crystalline rocks;
  - the mechanisms are also relatively well understood in plastic clays and in rock salt, however the extent of self-healing and the time over which it may take place is less clear (chemical changes in clays are also likely to be more significant than those in crystalline rocks and rock salt);
  - the mechanisms of EDZ formation are less well understood in indurated clays, due to the uncertain levels of self-healing processes, the period over which they may take place and the effects due to chemical changes in the clays; and
  - the effects on the repository system due to the formation of the EDZ may not all be negative and may not, in any case, be very significant.
- (iv) Solute transport:
  - little is known about radionuclide transport in the EDZ, but it is anticipated that an EDZ should have similar properties to those of the host rock (in terms of its sorption capacities, extent of matrix diffusion, *etc.*); and
  - in order to demonstrate the validity of this premise, it is considered important to carry out experiments on the transport characteristics of fractures within an EDZ and to compare them with existing fractures in the host rock.
- (v) Modelling:
  - EDZs are frequently represented and modelled overconservatively as active hydraulic units;
  - if an EDZ is treated in such a manner in the performance assessment of a spent fuel/HLW repository, its role is significant as it maximises the rate of diffusion in the bentonite backfill (*e.g.* in SKB's KBS-3 concept); it is important to represent the EDZ in a more representative and, therefore, less conservative manner in order to avoid this artefact;

- an EDZ should not be modelled in isolation, as its significance depends upon its relationship and interactions with the other components of the repository (*e.g.* the types of seals and backfill, the presence and form of any tunnel lining, *etc.*);
- the presence of a lining or other forms of support, such as shotcreting, may be very interesting from an EDZ point of view (in, for example, effecting its rate of self-healing, *etc.*) but difficult to accommodate within a PA (as new potential interactions are introduced); and
- the effects of time-dependency in the growth and possible recovery of an EDZ have not normally been considered.

(vi) Elimination and/or reduction of an EDZ:

- methods exist to limit the extent of an EDZ (*e.g.* the use of a TBM in crystalline rocks and possibly in other rock types, the importance of lining design and seals with swelling capacities in soft clays, *etc.*);
- lining backfill designs can be tailored to minimise the post-excavation growth of an EDZ (*e.g.* by maximising the support provided to the rock and by preventing or minimising time-dependent dilatancy);
- minimising the development of an EDZ should also be viewed in relation to the operational programme for the repository (*e.g.* in a crystalline rock the ease of bentonite block emplacement in relation to the excavation method applied).

(vii) The ways forward and priorities (future research targets):

- the extent of self-healing in indurated clays needs to be examined;
- the relationship between the effective permeability (*i.e.* along a tunnel, taking into account the interconnectivity of EDZ fractures) vs. the local permeability (*i.e.* the permeability measured normal to the tunnel in radial boreholes);
- radionuclide transport within the EDZ (*e.g.* sorption in EDZ fracture vs. fractures in the host rock, access to matrix diffusion, fracture connectivity within the EDZ, colloid filtration, *etc.*);
- coupling of processes within the EDZ (*e.g.* effects of heat, clogging of fractures),
- the extent of long-term evolution of the EDZ (*e.g.* self-healing in indurated clays, maintenance of the hydraulic cage effect, *etc.*);
- at Yucca Mountain, fracturing of the host rock is so intense that the EDZ does not appear to represent an important issue;
- planned experiments of relevance to understanding the EDZ are: tracer testing in the Canadian URL; testing of seals at Äspö and Mont Terri.

(viii) Overall conclusions

- a distinction is now made between disturbed and damaged zones within an EDZ;
- large differences exist between rocks that self-heal (if only partially) and those that do not;
- the conclusions of the 1988 workshop (NEA, 1989), in which the EDZ was considered as providing a highly permeable conduit parallel to galleries are no longer considered generally valid;
- since the CNS workshop (CNS, 1996), considerable work has been carried out in rocks other than crystalline rocks.

A summary of the anticipated level of significance of the EDZ in different rock types and the difficulty in characterising and modelling them is provided in Table 3. The overall conclusion of the Topical Session was that the significance of the EDZ in terms of repository safety has declined over the last two decades, as our level of understanding of EDZs has increased. There is now sufficient confidence in our understanding of the EDZ in crystalline rocks, plastic clays and rock salt not to require additional large-scale R&D programmes to study its effects. It is still likely to be necessary to carry out site specific investigations of EDZs at potential repository sites, so to provide site-specific data on their properties and to aid in the design of sealing systems. Residual problems and uncertainties associated with EDZs in indurated argillaceous rocks are likely to be resolved over the next few years, as more *in situ* work is carried out in these types of rocks.

Table 3. A summary of the general level of significance and understanding of different aspects of the EDZ in various rock types.

<b>Rock type</b>	<b>Difficulty of characterisation</b>	<b>Level of understanding</b>	<b>Difficulty of modelling</b>	<b>Relative importance of EDZ</b>
<b>Crystalline</b>	high	high	high	medium
<b>Rock salt</b>	high	high	high	low
<b>Plastic clays</b>	high	high	high	low
<b>Indurated clays</b>	medium	medium	medium	high but should tend towards medium*

\* Note: the actual impact of an EDZ in indurated clays may, in many cases, be rather limited due to the potential for self-sealing (due probably to the presence of expandable clays and the rock's long-term creep properties). There is currently, however, insufficient understanding of the processes active in the EDZ in such rocks to be confident about the extent of such self-healing and the time over which it might be expected to occur.

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*Annex 1*

**PROGRAMME OF THE SEDE TOPICAL SESSION**

**Characterisation and Representation of the Excavation Disturbed Zone**

Chairman: T. Äikäs (Posiva Oy, Finland)

**Introduction**

Roles of the Excavation Disturbed Zone in different host rocks and in performance assessment

A. Gautschi (Nagra, Switzerland)

**Argillaceous Media**

Preliminary EDZ investigations in argillaceous rock from tunnel and new galleries at the Tournemire IPSN Site (Aveyron - France)

J-Y. Boisson (IPSN, France)

EDZ in soft clay and its representation in performance assessment

M. Put (SCK-CEN, Belgium)

**Crystalline Rocks**

Summary of September 1996 EDZ Workshop Designing the Excavation Disturbed Zone for a Nuclear Repository in Hard Rock, held in Conjunction with CNS Conference on Deep Geological Disposal of Radioactive Waste

C. Davison (AECL, Canada)

Sensitivity analysis of effects of an EDZ on <sup>129</sup>I Transport from a used CANDU fuel waste disposal repository

T. Chan (AECL, Canada), M. Jensen (Ontario Hydro, Canada) and C. Davison (AECL, Canada)

The Äspö ZEDEX project (Zone of Excavation Disturbance Experiment): Final results and use in the SR-97 performance assessment

O. Olsson (SKB, Sweden)

The use of information from the Äspö ZEDEX project in an assessment of long-term repository performance

A. Hooper (UK Nirex Ltd)

**Rock Salt**

Stress fields and development of EDZs in rock salt

K. Wiczorek, Th. Rothfuchs and U. Zimmer (GRS, Germany)

**Synthesis and Conclusions**

General discussion, synthesis and recommendations vis-à-vis the SEDE Programme of Work  
Animated by T. Äikäs (Posiva, Finland)

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