Submitted to
International Journal of Rock Mechanics and Mining Sciences
June 2004

Geohydromechanical Processes in the Excavation Damaged Zone in Crystalline Rock, Rock Salt, and Indurated and Plastic Clays

Chin-Fu Tsang,[1] Frederic Bernier,[2] and Christophe Davies[3]

[1]Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California, USA

[2]European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment (EIG, Euridice), B-2400, Mol, Belgium

[3]European Commission EC-DG RTD/J.4, B-1049 Brussels, Belgium.

Abstract

The creation of an excavation disturbed zone or excavation damaged zone is expected around all man-made openings in geologic formations. Macro- and micro-fracturing, and in general a redistribution of *in situ* stresses and rearrangement of rock structures, will occur in this zone, resulting in drastic changes of permeability to flow, mainly through the fractures and cracks induced by excavation. Such an EDZ may have significant implications for the operation and long-term performance of an underground nuclear waste repository. Various issues of concern need to be evaluated, such as processes creating fractures in the excavation damaged zone, the degree of permeability increase, and the potential for sealing or healing (with permeability reduction) in the zone. In recent years, efforts along these lines have been made for a potential repository in four rock types—crystalline rock, salt, indurated clay, and plastic clay—and these efforts have involved field, laboratory, and theoretical studies. The present work involves a synthesis of the ideas and issues that emerged from presentations and discussions on EDZ in these four rock types at a CLUSTER Conference and Workshop held in Luxembourg in November, 2003. First, definitions of excavation disturbed and excavation damaged zones are proposed. Then, an approach is suggested for the synthesis and intercomparison of geohydromechanical processes in the EDZ for the four rock types (crystalline rock, salt, indurated clay, and plastic clay). Comparison tables of relevant processes, associated factors, and modeling and testing techniques are developed. A discussion of the general state-of-the-art and outstanding issues are also presented. A substantial bibliography of relevant papers on the subject is supplied at the end of the paper..

1. Introduction

Management of high-level, long-lived radioactive waste is an important environmental issue today for all nuclear-power-generating countries. Deep geologic disposal of these wastes is one of the promising waste-management options. Potential rock types being considered for geologic disposal include crystalline rocks, salt, indurated clay, and plastic clay. An essential feature that needs to be considered for the long-term safety of a high-level waste underground repository is the excavation disturbed zone and/or excavation damaged zone near the repository, and their hydromechanical and geochemical evolution with time.

The creation of an excavation disturbed or damaged zone is expected for all man-made openings in geologic formations. Macro- and microfracturing, and in general a rearrangement of rock structures, will occur in this zone, resulting in drastic increases of permeability to flow, mainly through the fractures and cracks induced by excavation. The implications of such high permeability and its time evolution under various repository scenarios need to be evaluated as part of waste repository safety assessment. Various issues, such as processes creating fractures in the excavation damaged zone, the degree of permeability increase, and the potential for sealing or healing (with permeability reduction) in the zone, all need to be part of the evaluation.

In recent years, efforts along these lines have been made for a potential repository in four rock types—crystalline rock, salt, indurated clay, and plastic clay—and these efforts have involved field, laboratory, and theoretical studies. There are commonalities and differences in behaviour among the four rock types, and it has been recognized that an in-depth discussion among researchers will, in general, be beneficial for (a) enhancing our understanding of the excavation damaged zone and (b) improving modeling techniques to simulate its behaviour. Both aspects are essential for evaluating the impact of an excavation damaged zone on operational safety during construction of a waste repository, and on long-term safety in terms of waste isolation.

Studies are ongoing in underground research laboratories around the world to better characterize the fracturing process in the zones around excavations and, for certain formations, to assess the self-healing capacity of the rock. The previous international events on the subject date back to 1996 and 1998; more specifically, a workshop on "Designing the Excavation-Disturbed Zone" was organised at the conference on deep geological disposal of radioactive waste by the Canadian Nuclear Society on September 26, 1996 [1], and a topical session on "Characterisation and Representation of Excavation-Disturbed Zone" was organised during the 9th OECD NEA SEDE meeting on September 24, 1998 [2]. The latest international conference on the subject was held in Luxembourg, November 3–5, 2003, organised by the European Commission (EC). It was the CLUSTER Conference on "Impact of the Exacavation-Disturbed or Damaged Zone (EDZ) on the Performance of Radioactive Waste Repositories," with CLUSTER standing for CLub for Underground Storage, TEsting and Research facilities for radioactive waste disposal [3].

This paper presents a synthesis of the ideas and issues that emerged from presentations and discussions at the 2003 CLUSTER EDZ Conference [3]. First, definitions of excavation disturbed and excavation damaged zones are proposed. Then, an approach is suggested for the synthesis and intercomparison of the processes in the EDZ for the four rock types (crystalline rock, salt, indurated clay, and plastic clay). Comparison tables of relevant processes, associated factors, and modeling and testing techniques are developed. A discussion of the general state-of-the-art and outstanding issues will also be presented. A bibliography of relevant papers on the subject is supplied at the end, preceded by a list of references used in the paper.

2. Defining Excavation Disturbed and Excavation Damaged Zones

The CLUSTER EDZ Conference Proceedings [3] contains a record of the discussions of four working groups (for the four rock types) concerning definitions of the excavation disturbed zone and the excavation damaged zone. Because of the different properties of these four rock types, the groups' definitions of the terms also take different emphases. In this section, we attempt to find a set of common definitions that can be equally applied to these four rock types. For convenience of discussion in this section, we shall use the initials, "EdZ" and "EDZ" for excavation disturbed zone and excavation damaged zone, respectively.

Table 1 summarizes the main points from the discussions in the 2003 CLUSTER Conference [3], under the headings of crystalline rocks, rock salt, indurated clay and plastic clay. As can be seen from the table, the definitions of EDZ versus those of EdZ proposed by the groups are influenced by the rock types of concern. Thus, for crystalline rock, the EDZ is simply a zone with irreversible deformation involving fracture creation and propagation, whereas the EdZ is a zone with reversible processes. There is no significant tendency for self-healing or self-sealing in the EDZ, as in the case of salt or clays. On the other end of the spectrum is plastic clay, which is soft material without high cohesion, and in this case the usual "familiar" concept of microcracks and shear fracturing, etc., may not be able to describe the evolution of its microstructures. In particular, the separation of reversible and irreversible deformations are not so clear because of potential for self-healing in this rock type. Hence, the plastic clay group defined EDZ as the zone in which geomechanical and geochemical modifications may have a negative effect on operational and/or long-term safety, and in contrast, the EdZ as the zone whose property evolution has no negative effect.

While the definitions provided by the plastic clay group are clear and probably applicable to the other rock types, it seems to be too problem-specific and too much dependent on the results of performance assessment. For instance, there is the possibility that EDZ and EdZ domains will have to be redrawn if the performance measures used in performance assessment are changed in the future, or if the "negative" level is changed because of new information (e.g., the new rock surfaces exposed by microfracturing turn out to be very effective for radionuclide sorption and retardation).

Hence, we suggest EdZ and EDZ to be defined more along the lines proposed by the indurated clay group, as follows:

- The Excavation Disturbed Zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties.

- The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in flow permeability.

The use of flow and transport properties as a key element in these definitions corresponds to the issue of safety assessment used by the plastic clay group. It is also a key concern for the indurated clay and rock salt group, and is a direct consequence of fracture creation and propagation emphasized by the crystalline rock group.

3. Approach to Synthesis

A synthesis of the current state of knowledge of the EDZ for the four rock types (crystalline rock, rock salt, indurated clays, and plastic clays) is based on the many similarities (notwithstanding some differences) in the EDZ evolution and processes within these rock types. For some processes, the behaviour of one rock type represents the extreme-parameter case of another. Observations, concepts, testing methodologies, and numerical models are often transferable. Thus, consideration of EDZ evolution in all four rock types simultaneously provides us with deeper insight and higher confidence in our understanding of one particular rock type of interest. Further, the enhanced insight allows us to identify important open scientific and technical questions, as well as pinpoint "bottleneck" EDZ issues of significance for the performance and safety assessment of a nuclear waste repository.

Tables 2 through 7 summarize the key processes, parameters, and technical issues for an EDZ in the four rock types side by side. Tables 2 through 5 identify the main processes and events according to stages of repository development: the excavation stage, the open drift stage, the early closure stage (which includes resaturation and heating phases), and the late closure stage (which includes cooling and self-sealing phases). They also indicate the property and design parameters that play a controlling role in these processes. Some important technical factors involved are also shown in these tables. Table 6 briefly indicates the field experiments that have been conducted to study the EDZ and the numerical models being developed to simulate its behaviours. Some open technical questions are also listed in that table. Finally, Table 7 identifies the scientific issues in long-term waste isolation and in repository design that need to be addressed, as well as bottleneck issues concerning repository safety assessment. The information in these tables was extracted from papers, both invited and contributed, and discussions at the 2003 CLUSTER EDZ Conference [3]. More detailed and specific data may also be found in the papers listed in the Bibliography at the end of the paper.

In the sections below, we shall present a comparative discussion for the four rock types based on the six tables, Tables 2–7. Emphasis will be on common points and differences among the four rock types; the details given in the tables will not be repeated. Some overall technical comments and recommendations will conclude this paper.

4. Excavation Stage (Table 2)

During the excavation stage, basically three sources of damage may be involved. First, there is the potential for damage caused by the excavation method itself; second, there are mechanical changes caused by stress redistribution around the newly excavated opening; and, third, there are the effects of back-pressure on rock deformation by emplacement of drift support. For hard and brittle crystalline rocks, the excavation activity could by itself induce significant damage, depending on the excavation method used. Thus, if drill and blast methods are used, the EDZ could extend 0.1 to 0.75 m into the rock, increasing permeability by two or three orders of magnitude. If a tunnel boring machine (TBM) is used, the EDZ could be about 1 cm thick, with permeability increased by one order of magnitude. In contrast, such direct excavation damage is not so significant in the other three rock types, especially where a TBM is used. However, an interesting phenomenon was observed to occur during excavation in plastic clay: As a tunnel was being excavated at a depth of 230 m at the Mol (Belgium) underground testing facility, fractures were formed ahead of the excavation face, and pore pressure was found to be atmospheric for about 4 m, indicating a communication between the fractures in this 4 m zone and the drift. Further, pore pressure was found to respond (although with much less magnitude) 60 m ahead of the excavation face. Similarly, pore pressure effects were measured at greater depths than the affected permeability when these types of measurements were made in salt at the Waste Isolation Pilot Plant (WIPP) in New Mexico. This phenomenon probably results from pore-size changes caused by mechanical deformation under undrained conditions, because of the low permeability of the medium. Nevertheless, permeability was found to remain close to the intact rock value. Modeling studies so far have not been able to reproduce the data.

The stress redistribution created by the excavated tunnel or drift is the key cause of the EDZ in all four rock types, giving rise to tension, compression, and shear or deviatoric stresses in different parts of the rock around the opening. The responses of the different rock types to these stresses depend on their properties and structure. For the harder crystalline rocks with natural occurring fractures, permeability is very sensitive to the rock strength relative to the new stress state. If the rock does not fail, tangential compression occurs near the opening, thus reducing its radial permeability by about a factor of five. However, the permeability parallel to the drift wall is increased by one order of magnitude, because of radial tensile stresses working to open existing fractures. Shear stresses also act to open fractures or create new ones through shear displacement and dilation. The effect is largest at the drift wall and extends about one drift radius into the rock. For the much softer indurated clays, owing to their bedding structure, the responses are different in the side walls compared to the ceiling and floor. Above the ceiling and below the floor, there is a predominant opening of bedding planes, while on the two walls, layers of vertical fractures are formed. The EDZ is generally about one drift radius thick, with permeability increased by as much as six orders of magnitude.

There is much less substantial structure in rock salt and plastic clays. Thus, in these rock types, deviatoric stresses give rise to strain localization, forming bifurcation points where new fractures are created. For salt, the EDZ is found to be about 0.5 to 1.5 m into the rock, with a permeability increase of 4 to 5 orders of magnitude. For plastic clays, because of anisotropy, the induced fractures form an eye-shaped set of curved fractures, much like onion skins, around boreholes. However, many of the fractures are not hydraulically conductive. Thus, a 4.8 m drift in plastic clay may have fractures extending several metres beyond its wall. After a few weeks, however, piezometric measurements indicate that open fractures do not extend beyond a zone of about 1 m.

It is interesting to note that all four rock types have an undisturbed rock permeability of ~10^{-19} to 10^{-21} m^2 (for crystalline rock, this range represents the permeability of the rock matrix). Crystalline rock contains a network of naturally occurring fractures, so that its permeability before excavation of the drift is about 10^{-17} m^2. The estimated increase in permeability for the EDZ in crystalline rock is one or two orders of magnitude, meaning the crystalline rock EDZ would have a permeability of ~10^{-15} to 10^{-16} m^2—about the same as the permeability values in the EDZ around a drift in salt or clays.

It was observed that rock salt often obeys a bimodal $k-\phi$ relationship, where k and ϕ are permeability and porosity, respectively. Laboratory data are found to have a trend corresponding to a relationship $k = \phi^n$, with two regimes. At low porosity values, n equals ~4, but for high porosity values, n is ~0.2, a much weaker correlation. The tentative explanation is that at low values, any increase in porosity increases fracture connectivity, which has a strong impact on permeability; but at large porosity, a porosity increase enhances fracture aperture but not connectivity. This phenomenon is especially clear when laboratory samples are examined. Very low levels of volumetric strain are required to ensure fracture connectivity, after which the fracture apertures increase. Such behaviour is, however, not yet observed for the other rock types.

The third component of excavation activity is the emplacement of support, which is of particular importance for plastic clay. Much consideration has been given to minimise the over-excavation gap between the shield and the excavated rock wall, and to emplace an expanded lining system as soon as possible. In this way, a back-pressure quickly develops and prevents further wall convergence and larger EDZ development. Similarly, a back-pressure from a rock support system can help to limit EDZ development in indurated clays. This would probably also apply, though to a smaller extent, to rock salt and crystalline rocks.

5. *Open-Drift Stage (Table 3)*

Once the drift is constructed, an EDZ still evolves under the stress-strain conditions for plastic and indurated clays and for salt. However, the EDZ for crystalline rock should have been mechanically stabilized. During the stage before repository closure, the drift is ventilated as the waste canisters are received into the repository. It is also at this stage that the rock support system is emplaced (if not already done as part of excavation procedures), and methods for cutting off and sealing EDZ can be implemented.

Ventilation reduces drift humidity and dehydrates the rock near the drift surfaces. This dehydration has a significant effect on clay and salt properties, but probably less on crystalline rock. Thus, for indurated clay, dehydration strengthens the rock so that it may be self-supporting at the drift wall. But it also causes contraction and thus could induce tensile fractures. For plastic as well as indurated clays, ventilation changes suction, changing in turn the clay creep properties and retarding self-sealing. For rock salt, dehydration also similarly reduces salt creep rate and thus influences EDZ evolution. In the case of crystalline rock, dehydration probably does not affect mechanical properties. However, air entering the rock results in an oxidizing, two-phase flow condition in the EDZ. This oxidizing condition may cause potential chemical and biological activities and a possible clogging effect, whereas the two-phase flow implies a reduction of the effective water-permeability values. In general, ventilation is an important factor in clays and possibly also in salt, whose mechanical properties are sensitive to moisture content. This is a dynamic dependence, because humidity varies from the time of drift excavation all the way through the repository waste heating and cooling cycle.

Mechanically, rock creep is a significant process for plastic clay, indurated clays, and salt, but not for crystalline rock. Where support has been emplaced, the rock moves against the support, which provides a back pressure. In plastic clay, unsupported axial movement at the front of a drift can be as much as 10 cm per year. Further, its deformation, coupled with its low permeability, can result locally in larger pore sizes, with an enhanced suction even without desaturation. For rock salt, room convergence of 30 cm in 10 years has been observed for a 7 × 10 m drift. Detailed results show a time-dependent convergence rate, the variation of which indicates that the main EDZ generation phase is limited to early time after excavation. Later on, the convergence rates become stationary, indicating limited EDZ evolution. In the first WIPP disposal panel, room (4 × 10 m) closure amounted to one metre in twelve years. Because of the nature of salt creep, typical bolting does not change the creep rate appreciably. Therefore, control of the EDZ during the operational period continues to be a challenge for support system design.

During the open-drift period, methods to cut off the EDZ at certain locations along the drift can be implemented. This would prevent the EDZ from becoming a high-permeability continuous flow path for solute to bypass the bulk of the geological barrier. A number of design studies have been made, but further work on this subject needs to be conducted. Such work for one rock type can benefit from what has been learned from the others.

6. Early Closure Stage (Table 4)

At this stage, backfill is in place and the repository is closed. Humidity will rise in the drift, and resaturation of the EDZ (and the backfill) will probably occur in granite and clay, with water from the rock. However, this is modified by heat release from the emplaced waste, which will tend to dry the rock and backfill close to the waste canister, and cause the vapor to flow outward and condense in the cooler region away from the heat source. These transient changes in water content, associated with the interplay between resaturation and temperature gradient, would have significant dynamic impact on the behaviour of theEDZ, especially in clays and rock salt, where the rock strength is a sensitive function of water content. Simulations using numerical models have been made; however, much work remains to be done to evaluate the effects. For the crystalline rock system, the backfill and buffer in a drift of crystalline rock often involves bentonite, whose swelling properties also strongly depend on degree of saturation. Considerable work has been done for such a crystalline rock-bentonite system, and lessons learned are probably transferable to the other rock types.

With the swelling of the backfill, a back-pressure is applied to the rock that will tend to close fractures in the EDZ for all rock types. For certain repository designs in plastic clay, a nonswelling backfill is sometimes chosen to avoid such reloading, since one can depend on rock creep to close up the fractures. Similarly in rock salt, where the nonswelling backfill (crushed salt) is the most likely backfill material, the same is achieved by the rock creeping onto the backfill.

For indurated clay, data suggest that the largest permeability values are not found at the drift rock surface, but at about 0.6 m into the rock, probably as a result of the back-pressure. Similarly for salt, the expression of the EDZ around a room at WIPP assumes an ovoid shape, wherein the largest fractures occur at a nominal depth, as noted for the indurated clay. At the backfill-rock interface, there is also a subtle effect involving the capillarity of the rock versus that of the backfill, based on the local saturation in the two media. In this instance, water exchange between the two will occur through suction. The implications of this dynamic process, with the associated potential change in rock strength, are yet to be studied carefully. Here, we have used the word *backfill* in a general sense to include both bentonite buffer and a seal to isolate the wastes.

In Table 4, a number of different temperature-related issues are listed for the different rock types. Thus, for crystalline rock, thermal conductivity may not only be a function of the media (such as EDZ, backfill, and rock), but also of the transient saturation level. For rock salt, brine pocket migration within the EDZ may be a potential process of concern. Salt creep properties are very strongly affected by temperature, whereas clay creep properties may be enhanced with temperature—but this is complicated by thermally induced moisture migration (as described above). For clays, thermal expansion under undrained conditions could cause changes in local pore pressures and effective stresses, separate from that of fluid movement.

7. *Late Closure Stage (Table 5)*

At this stage, the drift, backfill, and EDZ are fully saturated, and the temperature around the repository is slowly falling. Major processes include self-sealing, long-term chemical and biological effects, and the degradation of the support system. The main concern has been with self-sealing. Some work has been done on the long-term chemical and biological activities, and, as one would expect, research on such slow processes is not easy. For crystalline rock, there is some anticipation that these reactions may give rise to flow clogging of the fracture system. For clays, there is concern that (a) chemical reactions involving concrete may produce a high pH water plume, with negative impact on rock and backfill properties; and (b) the reactions (especially those involving canister and rock support materials) may produce gases, the pressures from which could build up in the canister deposition holes.

Concerning the degradation of the rock support system over time, we need to consider whether a gap would be formed that would induce a further development of the EDZ. Alternatively, the seal-system design could be independent of the rock support system. These trade-offs might be appropriately studied through sensitivity simulations. In some cases, consideration has been given to removing the support lining before emplacement of backfill, so that it would not play a part in chemical reactions and in creating a gap during degradation.

Self-sealing is not expected in crystalline rocks. For salt, healing of the EDZ can be by viscoplastic deformation or by recrystallization in the presence of brine. The viscoplastic healing process is slow, and it was observed in the field that, in 90 years, the permeability of EDZ at a depth of 700 m recovered to 10^{-18} m^2, from an initial EDZ value probably around 10^{-16} m^2. This is still above the expected undisturbed rock permeability below 10^{-20} m^2. Whether this two-orders-of-magnitude restoration of permeability may be enough to ensure repository safety should be evaluated in performance assessment. The healing process of pressure solution and re-precipitation, however, has been observed to be very expeditious and therefore of short duration relative to the repository performance period. Successful plugs have been placed in shafts and drifts of operating evaporite mines and in one-metre seal tests at the WIPP. Generally, the state of knowledge regarding salt EDZ healing would be greatly advanced if further measurements could be made in the proximity of rigid liners or seals in operating mines.

There is also some field information showing that the EDZ permeability for plastic clay recovers to intact rock value within 15 years, though the fracture traces can still be seen. In this case, the healing process involves not only closing up of fractures due to swelling and creep, but also volume increase around large cracks with an increasing plasticity index. For both plastic and indurated clays, changes in stress state, dilatancy, swelling, and newly formed minerals all may play a role in healing. A series of experiments are being conducted at the Mont Terri underground laboratory in Switzerland to investigate the healing of excavation-induced fractures as well as gas-pressure-induced fractures. Lessons learned from these experiments may be transferable to salt and plastic clay cases.

One issue of concern is the presence of impurities, such as anhydrites in rock salt, that may have an impact on the healing process. This issue, of course, is site specific. At WIPP, for example, anhydrite stringers are not expected to heal, and the influence of the anhydrite was accounted for in the panel closure design.

8. State of Field Information and Modelling (Table 6)

Among the four rock types, field studies of crystalline rocks are probably the most extensive. Major tests have been conducted in Stripa (Sweden), Pinawa (Canada), AEspoe (Sweden), Grimsel-FEBEX (Switzerland), and Kamaishi (Japan). These have included not only detailed field measurements and laboratory tests, but also large-scale tests in which flow through an EDZ of over ~10 m has been measured and evaluated. These large-scale measurements have the advantage of being able to account for realistic anisotropy and heterogeneity effects that are always present *in situ*. In this sense, they are better than spot measurements of EDZ permeabilities. For crystalline rock, there is a need for a comparative study of the data from all the sites, to understand the results and correlate them to local conditions and *in situ* structures and stress states at the different sites.

Major field programs have been performed at Mol (Belgium) in plastic clay, and at Asse (Germany) and WIPP (USA) in rock salt. Comprehensive sets of tests have been carried out over the last 20 years or more. Field studies of indurated clays, while initiated later than the other rock types, are now most active, with tests under way or planned for Mont Terri (Switzerland), Tournemire (France), and Meuse/Haute Marne (France) underground laboratories. There will be much new data to digest, evaluate, and apply to simulation models in the coming years.

Model development is active in all four rock types. There is considerable advantage to using the same code across all the rock types—for instance, the code CODE_BRIGHT has been applied to both indurated clay and rock salt. Such multiple uses of codes not only conserves research funding for other critical problems, but also allows model testing with multiple data sets from different rock types and thus enhances confidence in our modeling capabilities.

Generally, one of the research needs in modeling is to further understand the healing process in salt and clays, and to develop or identify longer-term data that can be used to test the models. Another need is the development of anisotropic models and measurement techniques to obtain the corresponding anisotropic field data, since nearly all the processes and all the property parameters are anisotropic, particularly for clay.

9. Long-Term Safety and Repository Design Issues (Table 7)

The assumption that the presence of an EDZ provides a fast path for the escape of solutes from the canister to the biosphere is now recognized to be an oversimplification. It may be true that the EDZ is, at least over a period of time, a zone of relatively high permeability, but whether flow can take advantage of it to transport solute to the accessible environment requires an evaluation of the total flow system. Thus, if the high-permeability zone is surrounded by low-permeability regions, or the hydraulic gradient is sufficiently low, there will be an insufficient supply of flowing water in the EDZ to negatively impact the repository performance. This may be the case for plastic clays and rock salt, and possibly also for indurated clay. This discussion also points out the critical need to consider structural impurities in the medium, which may form flow paths connected to the EDZ, and (for crystalline rock) to consider the fractures or fracture zones close to the drift.

A number of design-related decisions can be made that would improve repository performance. These include positioning the drift in an optimal orientation and depth, by considering *in situ* stress directions, fracture-network and bedding-plane orientations. In addition, excavation methods can also be optimized, including the emplacement of drift support. Further, methods to cut off the EDZ and seal the drift can be improved and implemented.

10. Some General Technical Comments

After reviewing the state of understanding of EDZ for all four rock types (crystalline rock, rock salt, indurated clay, and plastic clay), it may be useful to make some general technical comments:

- Though there are definite differences in the behaviour of the EDZ for the four rock types, there are many points of similarities, where knowledge of one rock type may find a correspondence in another or may alert a researcher to seek similar characteristics in another. An example is the observation that for a backfilled drift in indurated rock, the highest permeability in the EDZ is not at the drift wall but at ~0.6 m into the rock. Such a finding may encourage research to see if similar behaviour can be found in the other rock types. Such cross-fertilization will likely be very profitable.

- EDZ behaviour is a dynamic problem, dependent on changing conditions, such as moisture—which varies from open-drift period, to initial closure period (during which resaturation takes place), to finally the entire heating-cooling cycle of the decaying waste. All these changing conditions may affect material properties, such as rock strength and creep parameters. Self-sealing is itself a slow process, with characteristic times possibly on the order of 100 years or more. On top of these factors are the even longer-term issues of chemical reactions and biological activities. All these issues make the problem a very challenging and rich field for scientific study.

- An area that has barely been analyzed and that may require further work is the potential effect of weathering during the operation phase. Geochemical processes are likely to be accelerated by ventilation cycles, especially since excavation opens up rocks that have not been previously exposed to aerobic conditions. Thus, oxidation of minerals, such as pyrites, ought to be expected. While these reactions need not have an adverse effect on site performance, a proper understanding of these processes is needed.

- A full scientific evaluation of all conditions is not necessary for performance assessment of a repository. Certainly, a high level of understanding is required of all processes and features, including understanding of all observations. This is often needed to provide confidence in the results of performance assessment. However, one would hope that the level of understanding is high enough to ensure that good performance assessment can be made through bounding, scoping, and sensitivity studies, without accounting for all details (which would be impossible anyway). For example, the study of the EDZ has been an essential element of the WIPP performance assessment for its compliance to regulations. Nevertheless, in general, substantially more work yet needs to be done in this area.

- An area of significant weakness in EDZ studies, for all the rock types, is that of anisotropy. Processes in EDZ are intrinsically anisotropic. The intact rock is anisotropic in its properties (such as presence of bedding planes or fracture) and in *in situ* stress conditions. The stress redistribution caused by the presence of the opening is also anisotropic. Thus, the induced permeability changes in the EDZ must be anisotropic. The interplay among these different types of anisotropy need to be studied not only through modeling, but also through field observations and specifically designed *in situ* measurements that distinguish anisotropic behaviours.

- Some attention needs to be paid to evaluation of flow and transport in systems with heterogeneity, owing to the presence of structures, facies, and impurities. Such heterogeneity implies the spatial variability of permeability, which could cause flow-focusing or channeling phenomena. Thus, a channelized fast path may exist, even though geologically a discrete, high-permeability pathway is not apparent.

- Another area of need is the study of seal-rock interface and the effectiveness of drift seal and EDZ cutoff. Drift seal and EDZ cutoffs will probably be implemented in drifts of all rock types, at least as a conservative measure. Scientifically, there exists the problem of processes in the seal-rock interface, which may still be an open question. Note also that for an EDZ to have an impact, it does not need to have a significant thickness around the drift; a skin of greatly increased permeability will have an effect. In terms of engineering, one needs to consider points of stress concentration, such as at the intersections between adjacent drifts and between pillar and drift roof, and whether these points present special EDZ properties. On the design side, one needs to evaluate the optimal design of structures for cutting off EDZ at appropriate points to ensure that there are no continuous flow paths. Then, there is the question of how we can guarantee the long-term performance of such structures.

- There are also a number of more detailed and specific comments:

  – There are some apparent differences in results from the various EDZ measurements at the different crystalline rock sites. They may result from sampling or measurement methods and scales, or from local *in situ* stress and structural (e.g., fracture spacing and orientation) conditions. A comparative study of these results by correlating them with site-specific data, together with summary conclusions, will be very useful.

  – It may be useful to distinguish between connected porosity and total porosity. The latter includes porosity that may be isolated and that can still be created by extensional or deviatoric stresses. Only connected porosity is correlated with permeability, while total porosity may be relevant to solute transport (because it participates in solute transport through diffusion). This distinction may help with the understanding of, for example, the two-regime character of the permeability-porosity relationship for salt ($k = \phi^n$; with n = 4 for low ϕ values and n = 0.2 for higher ϕ values).

- In plastic clay, the unexpected field observation that pore pressure responded to drilling 60 m ahead of the excavation face needs to be evaluated, together with extensiometer data and the information that fractures are communicating with the drift 4 m into the rock. It may require an enhancement of currently available models. Though the permeability is not much larger than intact rock values and these data probably have no performance impact, an understanding of these data is important for confidence building.

- In considering solute transport in EDZ, it is recognized for crystalline rocks that EDZ transport properties (such as k_D and ϕ values) are quite different from those in the undisturbed rock, because EDZ fractures are "freshly opened." Perhaps one should watch out for this possibility in the other rock types. Similarly, in dealing with two-phase fracture-matrix systems, the role of matrix diffusion may or may not be negligible, and should be considered.

11. Overall Remarks and General Bottleneck Issues

Research concerning the EDZ of crystalline rock, plastic clay, and rock salt appears to be quite mature. While there are still a number of important open questions that need to be addressed (as discussed above), there are large amounts of data and information with which to conduct a comprehensive performance assessment accounting for the EDZ. Work on indurated clays is relatively more recent, and the rock is more complex, with characteristics of both brittle and ductile rocks. However, current research in this area is also the most active, with many ongoing field tests at Mont Terri and Tournemire underground research laboratories. Substantial research is also being done at the new Meuse/Haute Marne site. Results from these studies will be very useful for a successful performance assessment of EDZ effects. In this sense, the state of the art for all four rock types are at about the same level, and great potential exists for cross-fertilization of knowledge and tools (modeling codes and testing methods).

Among all the scientific, repository design, and performance assessment aspects discussed above, we shall just highlight three major ones that need more attention across all four rock types: they can perhaps be considered the "bottleneck" issues:

– *Need to study anisotropic behaviour in deformation and flow within the EDZ*. Rock properties, such as *in situ* stresses and existing fracture networks or bedding planes, are intrinsically anisotropic. Stress redistribution caused by drift construction is anisotropic, and permeability changes are also anisotropic. The interplay of these anisotropic behaviours is an open question, one that requires not only model development and study, but also field or laboratory tests to measure such anisotropic effects.

– *Need to study seal-rock interface and effectiveness of drift seal and EDZ cutoffs*. Since drift seal and EZD cutoffs will probably be implemented in drifts of all rock types (at least as a conservative measure), their effectiveness needs to be established. More work, both in modeling and measurement, is needed to study the processes within the seal-rock interface and skin region. On the design side, one needs to evaluate the optimal design for cutting off the EDZ at appropriate points to ensure that there are no continuous flow paths.

– *Need to conduct comprehensive performance assessment studies of EDZ*. Though a number of studies, such as the performance assessment supporting the compliance certification of WIPP, have been performed along this line, there still is the need for more work. Generally, the work includes bounding, scoping, and sensitivity analyses. In such an effort, one has to ensure that a complete set of possible conditions and scenarios are considered, that time evolution of various parts are accounted for, and that appropriate parameter ranges are chosen. Since this science depends very much on "expert" experience, discussions among researchers with a wide range of backgrounds (such as interests in the four different rock types) are critical. In this context, it would be very helpful that a workshop be conducted under the auspices of the European Commission on this topic among workers in the four rock types. All may benefit by in-depth discussions, mutual peer review, and cross-fertilization.

Acknowledgements

The authors would like to thank the participants of the CLUSTER EDZ Conference and Workshop [3], whose presentations and discussions have formed the base upon which this paper was prepared. The authors also would also like to acknowledge that the Bibliography includes not only papers known to them, but also references collected by Pierre Berest, Robert Charlier, Udo Hunsche and Pekka Särkkä, which appear also in the Workshop Summary [3]. Some versions of this paper have been reviewed by Pierre Berest, Peter Blümling, Wernt Brewitz, Jesus Carrera, Robert Charlier, Frank Hansen, Udo Hunsche, Roland Pusch, Jonny Rutqvist, Pekka Särkkä, and Xavier Sillen. Their very helpful comments are gratefully acknowledged. The EDZ Conference and Workshop was jointly organised by the European Commission (EC) and EIG EURIDICE (European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment) in the framework of the EC CLUSTER Forum. The event was sponsored by most of the European waste management agencies, as well as by leading research organizations: ANDRA, ENRESA, GRS, NAGRA, NIRAS/ONDRAF, POSIVA, SCK•CEN, and SKB. The support of these organizations is most appreciated. The first author would like to acknowledge partial support from U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Geosciences Research Program, Contract Number DE-AC03-76SF00098, through the Ernest Orlando Lawrence Berkeley National Laboratory.

References

[1] CNS, Designing the Excavation Disturbed Zone for a nuclear repository in hard rock. Proceedings of the EDZ Workshop, International Conference on Deep Geological Disposal of Radioactive Waste, Winnipeg, Canada, 20 September 1996, Canadian Nuclear Society, 1996.

[2] NEA, Characterisation and representation of the Excavation Disturbed or Damaged Zone (EDZ). Lessons Learnt from a SEDE Topical Session, 24th September 1998, Paris France. NEA/RWM(2002)1, 2002.

[3] EC, European Commission, CLUSTER EDZ, Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the performance of radioactive waste geological repositories. Proceedings of an EC CLUSTER Conference, Luxembourg, 03–05 November 2003, Nuclear Science and Technology, EUR 21028 EN, 2004 (in preparation).

Bibliography

Alonso, E.E., J. Vaunat, and A. Gens, 1999. Modelling the mechanical behaviour of expansive clays. Engineering Geology, 54(1), 173–183.

Arnould M., J.-Y. Boisson, I. P. Ivanov, 2002. Discontinuity network of sedimentary clay formations : The model of lower Cambrian Blue Clays of St Petersburg. Proc. of the Int. Meeting on Clays in Nat. and Eng, Barriers for Radioactive Waste Confinement, Reims, France

Autio, J., A. Hautojärvi and J-P. Salo, 2001. The effect of the excavation damaged zone adjacent to the walls of deposition holes on the migration of radionuclides in *Scientific Basis for Nuclear Waste Management XXIV*, edited by Hart. K.P. and Lumpkin, G.R., (Mater. Res. Soc. Symp. Proc. 663, 2001).

Autio, J., and H. Malmlund, 2003. Properties of excavation damaged zone caused by drill & blast excavation ISRM 2003–Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy.

Baldi G., M. Borsetto, T. Hueckel, and E. Tassoni, 1985. Thermally induced strain and pore pressure in clays. Proceedings of the International Symposium on Environmental Geotechnology, Allentown, Pensylvania, pp. 391-402.

Barnichon J-D., and G. Volkaert, 2003. Observations and predictions of hydromechanical coupling effects in the Boom clay, Mol Underground Research Laboratory, Belgium, Hydrogeological Journal, 11: 193-202.

Bastiaens, W., F. Bernier, M. Buyens, M. Demarche, X.L. Li, J-M. Linotte, J. Verstricht, 2003. The extension of the HADES underground research facility at Mol, Belgium, Euridice report 03-294.

Bauer, C., F. Homand, and K. Ben Slimane, 1996. Proceedings of the EDZ Workshop « Designing the Excavation Disturbed Zone for a Nuclear Repository in Hard Rock. » Winnipeg, Canada, CNS, September 1996, pp. 87–96.

Bernier, F., X.L. Li, J. Verstricht, J.D. Barnichon, V. Labiouse, W. Bastiaens, J.M. Palut, J.K. Ben Slimane, M. Ghoreychi, J. Gaombalet, F. Huertas, J.M. Galera, K. Merrien, F.J. Elorza 2004, 2003, CILPEX: Clay Instrumentation Programme for the Extension of an Underground Research Laboratory, EUR 20619.

Blümling, P., and H. Konietzky, 2003. Development of an excavation disturbed zone in claystone. In: Geotech. Measurements and Modelling, Natau, Fecker, and Pimentel, eds., Swets & Zeitlinger, Lisse, 127–132.

Börgesson, L., and R. Pusch, 1989. Rock sealing by dynamic injection; Stripa Project Phase III. Proceedings of the NEA/CEC Workshop on Sealing of Radioactive Waste Repositories at Braunschweig, OCDE/OECD, Paris.

Börgesson, L., R. Pusch, A. Fredriksson, H. Hökmark, O. Karnland, and T. Sandén, 1992. Final Report of the Rock Sealing Project—Sealing of Zones Disturbed by Blasting and Stree Release. Stripa Project Technical Report 92-21. SKB. Stockholm.

Boisson, J.Y., 2002. Indurated clays—The Toarcian and Domerian clay formations at Tournemire: Lessons learnt from a SEDE topical session. Radioactive Waste Management NEA/RWM (2002)1, January 2002, pp. 48–61.

Cabrera, J., L. Dewindt, G. Bruno, A. Rejeb, A. Genty, and P. Volant, 2000. The argillaceous indurated media as a potential geological barrier for deep radioactive waste disposal: studies at the experimental IPSN Tournemire site. Safewaste 2000, Tome 1. Avignon, 200–217.

Chandler, N., D. Dixon, M. Gray, K. Hara, A. Cournut, and J. Tillerson, 1998. The Tunnel Sealing Experiment: An in situ demonstration of technologies for vault sealing. Proceedings of the 19th Annual Conference of the Canadian Nuclear Society, Canadian Nuclear Society Toronto, Ontario, Canada.

Chiarelli, A.S., J.F. Shao, and N. Hoteit, 2003. Modelling of elastoplastic damage behaviour of a claystone. International Journal of Plasticity, 19, 23–45.

Coll, C., S. Escoffier, R.W. Hamza, A. Vervoort, P. Blümbling, B. Frieg, W. Bastiaens, P. Berest, B. Bazrgan, J. Desrues, G. Viaggiani, V. Labiouse, B. Dehandschutter, L. Wouters, Y. Vanbrabant, J. Mertens, X. L. Li and F. Bernier, 2004. State of the Art on Fracturation and Self-Healing Processes and Characterisation, SELFRAC project - Deliverable 1, EURIDICE 04-151.

Conil-Aublive, N., I. Djeran-Maigre, R. Cabrillac, and K. Su. Poroplastic damage model for claystones, Applied Clay Science (accepted for publication).

Cui, Y-J., N. Sultan, and P. Delage, 2000. A thermo-mechanical model for saturated clays. Canadian Geotechnical Journal, 37, 607–620.

Delage, P., N. Sultan, and Y.J. Cui, 2000. On the thermal consolidation of Boom clays. Canadian Geotechnical Journal, 37, 343–354.

Duveau, G., W.Z. Chen, J.F. Shao, and O. Ozanam, 2003. Modeling of plastic deformation and damage due to drying around a shaft in claystone. Proceedings of 10th ISRM Congress, 8-12 September 2003, South Africa, 267–273.

Gautschi, A., 2001. Hydrogeology of a fractured shale (Opalinus Clay): Implication for a deep disposal of radioactive wastes. Hydrogeol. J. 9, 97–107.

Giraud, A., and G. Rousset, 1996. Time-dependent behaviour of deep clays. Engineering Geology, 41, 181–195.

Guimaraes, L., A. Gens, M. Sánchez, and S. Olivella, 2001. Chemo-mechanical modelling of expansive clays. Proceedings of the 6th Int. Workshop on Key Issues in Waste Isolation Research, 28–30 November 2001, Paris, pp. 463–495.

Gunnarsson, D., L. Börgesson, H. Hökmark, L.-E. Johannesson, and T. Sandén, 2001. AEspoe Hard Rock Laboratory: Report on the installation of the Backfill and Plug Test. SKB IPR-01-17, SKB Stockholm.

Hansen, F.D., 2003. The Disturbed Rock Zone at the Waste Isolation Pilot Plant. SAND2003-3407, Sandia National Laboratories, Albuquerque NM USA. December 2003.

Horseman, S.T., 1994. The Disposal of High Level Radioactive Waste in Argillaceous Host Rocks—Identification of Parameters, Constraints and Geological Assessment Properties. Enresa Publ. Tec. Num. 04.94, Enresa, Madrid**.**

Hou, Z., 2003. Mechanical behaviour of salt in the excavation disturbed zone around underground facilities. Int. J. of Rock Mechanics and Mining Sciences, Vol. 40/Issue 5, 2003, 725–738.

Hueckel, T., and G. Baldi, 1990. Thermoplasticity of saturated soils and clays: Constitutive equations. J. Geotech. Eng., 116(12), 1765–1777.

Hueckel, T., 1997. Chemo-plasticity of clays subjected to stress and flow of a single contaminant. International Journal for Numerical and Analytical Methods in Geomechanics, 21, 43–72.

Hunsche, U., and A. Hampel, 1999. Rock salt—the mechanical properties of the host rock material for a radioactive waste repository. Engineering Geology, 52, 271–291. Elsevier, Amsterdam (Special Issue on Nuclear Waste Management in Earth Sciences, C. Talbot and M. Langer, eds.)

Hoxha, D., A. Giraud, A. Blaisonneau, F. Homand, and C. Chavant, 2004. Poroplastic modelling of the excavation and ventilation of a deep cavity. Int. J. Numer. Anal. Meth. Geomech., 28, 339–364.

Jason, J.B., 2000. A review of exacavation damage studies at the underground research laboratory and the results of the excavation damage zone study in the tunnel sealing experiment. Report No: 06819-REP-01200-10018-R00, Atomic Energy of Canada Limited, Toronto, Canada.

Jason, J.B. (editor), 2003. The 2002 International Workshop, The Excavation Damage Zone – Causes and Effects. Report No: 06819-REP-01200-10105-R00, Atomic Energy of Canada Limited, Toronto, Canada.

Lloret, A., M.V. Villar, M. Sánchez, A. Gens, X. Pintado, and E.E. Alonso, 2003. Mechanical behaviour of heavily compacted bentonite under high suction changes. Géotechnique, 53(1), 27–40.

Martin, C.D., and G.W. Lanyon, 2003. Measurements of in-situ stress in weak rocks at Mont Terri Rock Laboratory. Int. J. Rock Mech. Min. Sci., 40, 1077–1088.

Nagra, 2002. Project Opalinus Clay: Safety Report. Demonstration of disposal feasibility (Entsorgungsnachweis) for spent fuel, vitrified high-level waste and long-lived intermediate-level waste, Nagra Tech. Report NTB 02-05.

Olivella, S. and E.E. Alonso, 2003. Modelling gas flow through deformable fractured rocks. Proc. GeoProc 2003—Int. Conf. on Coupled T-H-M-C Processes in Geosystems: Fundamentals, Modelling, Experiments, and Applications. Stockholm, Oct. 2003, O. Stephansson, J. Hudson, L. Jing, eds.

Olsson, O., S. Emsley, C. Bauer, S. Falls, and O., Stenberg, L. 1996. Zedex – A study of the zone of excavation disturbance for blasted and bored tunnels- Volumes 1-3. Stockholm, Swedish Nuclear Fuel and Waste management Co (SKB), International Cooperation Report ICR-96-03.

Osipov, V.I., N.B. Nguen and N.A. Rumjantseva, 1987. Cyclic swelling of clays. Applied Clay Science, 2, 363–374.

Pusch, R., 1989. Alteration of the hydraulic conductivity of rock by tunnel excavation. Rock Mech. & Mining Sciences, 26(1), 71–83.

Pusch, R., 1994. Waste disposal in rock. Developments in Geotechnical Engineering, 76, Elsevier, ISBN: 0-444-89449-7.

Read, R.S., 1996. Characterizing excavation damage in highly stressed granite at AECL's Underground Research Laboratory. Proceedings of the International Conference on Deep Geological Disposal of Radioactive Waste, EDZ Workshop, J.B. Martino and C.D. Martin, eds., pp. 35–46, Canadian Nuclear Society, Winnipeg, Ontario, Canada, 20 September 1996.

Read, R.S., and N.A. Chandler, 1997. Minimizing excavation damage through tunnel design in adverse stress conditions. Proceedings of the 23rd General Assembly, International Tunnel Association, pp. 23–28, World Tunnel Congress '97, Vienna, Austria, Balkema, Rotterdam, The Netherlands.

Rejeb, A., 2003. Time dependent behaviour of Tournemire argilites (France). ISRM Congress 2003, Technology Roadmap for Rock Mechanics, South Africa

Sánchez, M., A. Gens, L. Guimaraes, and S. Olivella, 2001. Generalized plasticity model for THM simulations involving expansive clays. Proceedings of the 6th Int. Workshop on Key Issues in Waste Isolation Research, 28–30 November 2001, Paris, pp. 397–415.

Schulze, O., T. Popp, and H. Kern, 2001. Development of damage and permeability in deforming rock salt. Engineering Geology, 61, 163–180, Elsevier, Amsterdam. (Special Issue on Geosciences and Nuclear Waste Disposal, C. Talbot and M. Langer, eds.).

Wieczorek, K., 2002. The EDZ in Rock Salt, 2002: Characterisation and Representation of the Excavation Disturbed or Damaged Zone (EDZ). Lessons Learnt from a SEDE Topical Session 24th September 1998 Paris, OECD Nuclear Energy Agency, 2002, pp. 62–70

Wieczorek, K., and U. Zimmer (GRS), 1999. Hydraulic Behavior of the Excavation Disturbed Zone around Openings in Rock Salt. ICEM' 99: 7th International Conference on Radioactive Waste Management and Environmental Remediation, Nagoya, Japan, 26–30 September 1999, JSME/ASME International.

Table 1. Proposed Definitions of EDZ and EdZ for the Four Rock Types, Based on Discussions given in [3]

	Crystalline Rock	Rock Salt	Indurated Clay	Plastic Clay
EdZ	Region where only reversible (recoverable) elastic deformation has occurred. Note: It is theoretically impossible to define the outer limits of the EdZ.	Region with change of stress relative to initial state Note: Outer boundary not clearly delineated; effects of EdZ at great depths not likely to be important over operation period, but may be significant for long-term performance.	Region where only reversible processes (elastic strain, pore pressure changes, etc.) take place; not relevant to creation of preferential pathways for radionuclide migration.	Zone with significant modification of state (pore pressures, stresses, etc.); no negative effects on safety.
EDZ	Region of Irreversible deformation with fracture propagation and/or development of new fractures. Note: Strong transient behaviour; depends on construction methods, as well as stress redistribution.	Region of considerable property change by micro-fracturing; significantly changed hydraulic properties. Note: Extent and quality of EDZ may change over time, depending on stress-strain conditions.	Microcracked zone with damage and failure, and with weakly connected microcracks. A zone in which permeability increases by several orders of magnitude, owing to newly formed connected porosity – may become an issue in safety assessment. Note: EDZ is not the same as plastic or yielded zone	An evolving zone with geomechanical and geochemical modifications of state and material properties, which might have a negative effect on operational and long-term safety.

Table 2. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Excavation Stage (construction damage; stress redistribution)

	Crystalline Rock	**Rock Salt**	**Indurated Clay**	**Plastic Clay**
Processes and Events	• Excavation procedure giving rise to EDZ – Drill-and-blast: Δk ~2–3 om; thickness ~10–75 cm – Tunnel Boring Machine: Δk ~1 om; thickness ~1 cm • Stress redistribution due to opening, causing tension, compression and shear in different parts around the drift – Δk (axial) ~1 om – Δk (radial) magnitude reduces to 1/5 original – Extent: up to 2-3 m beyond wall of a 5-m drift; thicker on floor than side and roof of drift	• Effects of excavation procedures are less significant. • Stress redistribution due to opening, causing tension, compression and shear in different parts around the drift • Microcracking at locations where dilatancy criterion is exceeded • Permeability increase with opening of microcracks; • EDZ extends 0.5 m into wall and 1.5 m into floor; Δk is 4–5 om and is anisotropic	• Stress redistribution giving rise to strongly anisotropic, deviatoric compression and/or tensile stresses, causing (a) tensile and shear fracturing along bedding planes and (b) vertical extensional or tensile fracturing in rock near side walls • Data show vertical fracture in drift walls: 10–30/m within the first m; 5–10/m in the 1-2 m and ~0/m beyond 2 m • Generally, EDZ is one drift radius from drift wall with Δk up to ~6 om • Transient pore-pressure dissipation	• Stress release at excavation (stress redistribution) leading to contractant and dilatant processes with induced fracturing; • Undrained behaviour expected in the short term; • Dilation inducing suction and pseudo-strength increase; • Shear behaviour also expected (slick and sliding); • Curved fractures with apex at front end of 4.8 m drift, extending several metres from the rock wall, but fractures closed beyond 1 m; • Evidence of extension fractures (relay fractures) for ~4 m on front of excavation; • Piezometric response far ahead of excavation front (60 m), but negligible Δk
Property and Design Parameters	• *In situ* stress, including stress anisotropy; • Rock strength (failure initiation strength); • Initial *in situ* fracture network (density and orientations), • Orientation of drift relative to principal stress directions, size and shape of drifts; • Excavation sequence, quality assurance and control.	• State of stress (depth of repository); • Dilatancy, healing and creep properties of the salt • Geometry of drift; • Procedure for rock support immediately following excavation • Lithologic heterogeneity	• Rock property parameters; anisotropy (bedding planes) • *In situ* stress state, including stress anisotropy • Drift orientation relative to bedding plane directions and to fracture directions • Drift (gallery) shape, • Methods of excavation with emplacement of support, • Moisture content in rock and transient pore pressure	• *In situ* stress-strength ratio; • Excavation and lining installation procedure to limit wall convergence • Parameters related to shear and extensional fracturing • Presence of bedding planes or planes of weakness. • Excavation shape and initial stress state

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; Δϕ = change in porosity; om = orders of magnitude

Table 2. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Excavation Stage (construction damage; stress redistribution) (continued)

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Some Technical Factors	• Difference in EDZ developed along part of the drift away from and the part near to fracture zones intercepting the drift. More studies of EDZ at drift-fracture intersections and its role may be useful. • EDZ at tunnel intersections may need special considerations • Some apparent differences in results from Stripa, Grimsel (FEBEX), Aspo and Pinawa URL; perhaps due to different *in situ* stress, drift size and drift orientation and fracture network in rock, as well as different excavation methods.	• Deviatoric stress can increase air k up to 4 om by inducing new micro cracks • Δk - Δϕ relationship shows two regimes: – Initial ϕ opening with large Δk of 4 to 5 om by increasing fracture connectivity – Later ϕ increase corresponding to crack opening after network connectivity is established, with Δk of ~2 om.	• Medium characterized by dependence on moisture content: low moisture case corresponds to harder rock and high case corresponds to ductile (soft) behaviour • Role of structures (bedding planes), weathering (drying), dissolution and oxidation; • Nonlinear stress-strain behaviour dependent on stress level, suction (water content) and weathering conditions; • Stress and strain localization: onset and propagation of discontinuity; effect of heterogeneity.	• Naturally occurring fractures are found in outcrops with spacing 0.5 to several metres; mostly extensional fractures with a small part shear fractures. However, they are not seen at depth. Confining pressure, as well as moisture content, is reason for absence of fractures.

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; Δϕ = change in porosity; om = orders of magnitude

Table 3. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Open-Drift Stage (ventilation; supports; EDZ cutoff and sealing)

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Processes and Events	• EDZ dehydration • Air entry resulting in oxidizing conditions, two-phase flow conditions (effective water conductivity decreasing), • Potential chemical and bacterial activities with possibility of clogging against flow	• Drift ventilation and salt dehydration affecting salt creep properties and hence EDZ • Room convergence (data show convergence of 30 to 100 cm in 10 years for 7 m x 10 m drifts). Thus, EDZ is still developing unless rock support is put in. • Salt creep onto support surfaces—EDZ development slows and begins to reverse.	• Rock creep; and drift (gallery) wall convergence; also floor heaving due to water during construction and operation • Ventilation-induced damage; dehydration with resulting rock strengthening and contraction; • Oxidation of pyrites-production of sulfuric acid; • Potential microbiological processes • EDZ is evolving.	• Transition from dilatant to contractant regime; creep and possible fracture closing and drift wall moves against support • EDZ is still changing. • Suction development on the wall due to dilatant (induced consolidation); meaning suction increases without desaturation • Drift ventilation and rock dehydration changing clay properties; ventilation retards self sealing • Oxidizing conditions—penetrating ~1 m into rock. However the oxidation zone is limited to a few cm when room convergence is controlled.
Property and Design Parameters	• Drift humidity condition and its variation • Fracture apertures and porosity in EDZ • Fracture density in EDZ • EDZ mineralogy	• Drift humidity and its variations • Drift support system • Preserve the requisite operational space • Special creep properties of salt Determination homogeneous parts for creep	• Drift (gallery) shape drift humidity changes; rock pore pressure changes. • Rock support, lining settling time, • *In situ* stress; depth of drift (gallery), • Drift orientation with respect to natural bedding planes, rock anistropy and *in situ* principal stress directions.	• Drift humidity and its variations • Suction as a function of dilatancy • Rock strength parameter changes • Support structure designs

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; $\Delta\phi$ = change in porosity; om = orders of magnitude

Table 3. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Open Drift Stage (ventilation; supports; EDZ cutoff and sealing) (continued)

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Some Technical Factors	Need to grout fracture zones intersecting drift prior to excavation; post-excavation grouting is more difficult due to lack of back pressure.	• Differential stress versus confining pressure: – Up to dilatancy limit (maybe a band), above which opening of grain boundary: Δk up to 2–3 om – Up to failure boundary, above which macro fracturing takes place • Δk and Δϕ relationship is an important question and is anisotropic. • Creep deformation changes with back compression from supports. • Δk in damaged salt is reversible, but full healing still needs study. • Large differences in creep properties.	• Process has 4 stages in stress-strain development 1. Closing of pre-existing fractures 2. Elastic deformation of material 3. Plastic deformation; occurrence and growth of micro cracks 4. Localization of stress strain and initiation and propagation of macro fractures • Peak of Δk is behind peak of stress as a function of strain • Effect of heterogeneity in rock property (clay content and hence rock strength not uniform). • Sealing of EDZ by emplacement of backfill after removal of EDZ damage materials or by radial cuts that are filled with bentonite—yet to be studied.	• EDZ is still changing • Fractures develop several metres in rock, but if convergence is limited, fractures can be limited to less than 1 m from rock wall. • Ventilation drying changes EDZ properties near drift wall. • Combination of low k and deformation (undrained) causes changes in suction and in apparent mechanical properties.

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; Δϕ = change in porosity; om = orders of magnitude

Table 4. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Early Closure Stage (backfill; resaturation; heating)

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Processes and Events	• Bentonite and backfill emplacement; EDZ resaturation • Wetting and swelling of bentonite and backfill; effect of swelling pressure on EDZ • Role of presence of faults with EDZ • Heating from waste canisters; effects of temperature gradients and moisture redistribution in bentonite and EDZ; thermal compression • chemical and bacterial processes (dissolution, precipitation, bacterial growth and clogging)	• Drift humidity increase affecting rock properties; • Backfill and seal emplacement and backfill support of EDZ; • Heating from canisters and effects of temperature gradients on EDZ; • Brine pocket migration in EDZ; • Chemical and bacterial processes in micro cracks of EDZ; gas generation pressure buildup and migration; • EDZ is still developing with increasing damage in certain areas where stress stays above dilatancy boundary • Creep onto support leading to compaction and $-\Delta k$	• Rock begins to resaturate and be heated by waste • Effects of swelling pressure and suction in bentonite backfill on EDZ, possibly reducing EDZ permeability; data show k in EDZ highest not at wall but at ~0.6 m into rock and is anisotropic. • Effect of transient and spatially varying temperature and saturation on rock behaviour • Effect of desaturation-resaturation cycle with corresponding pore pressure changes on rock properties • Changes as bentonite and cross-cut seals swell	• Rock begins to be heated by waste and nearby saturation is varying • Drift humidity buildup changing rock properties; • Swelling buffer materials with potential reloading of EDZ (in some designs, buffer materials without swelling capacity are chosen); • Thermal expansion in undrained conditions in the very near field near heating source; • Change in effective stress due to fracturing or sealing, • Potential increase creep rate (enhanced plasticity)
Property and Design Parameters	• Bentonite and backfill physical and chemical properties and their initial conditions • Chemically changing from oxidizing to reducing conditions • Fault or fracture zone geometry (and location) and flow properties • thermal loading and time variation; thermal conductivities of EDZ and backfill as a function of saturation	• Backfilling and sealing procedures; • Seal material properties as conditions change with time • Creep rates as a function of temperature; • Effect of temperature gradient on creep rates at different locations in EDZ • Can we design support to avoid unnecessary stress concentrations?	• Rock properties as a function of temperature and saturation; • Thermal input rate from the waste; • Seal designs	Rock strength, creep and suction properties as a function of humidity or saturation and temperature

Table 4. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Early Closure Stage (backfill; resaturation; heating) (continued)

Some Technical Factors	• Interplay between thermal compression and resaturation in EDZ • Effect of back-pressure from bentonite buffer and backfill on EDZ	• Backfill provides confining pressure. • Heating induces compressive stress in most areas, while increases differential stress in others.	• Resaturation weakens rock, enhances creep, and induces closure, especially normal to bedding planes • Resaturation is a slow process; effects of spatially and temporally varying saturation yet to understand. • Heating may cause near-field drying in EDZ, working opposite resaturation from the rock, resulting in varying wetting and pore pressures in EDZ • Effects of temperature changes on clay • Sealing bentonite provides loading on EDZ and reduces k	• Resaturation causes suction to disappear. • Open fractures start to heal. • After a few weeks, piezometric measurement indicates open fractures do not extend beyond 1 m of wall. • Temperature assists in healing; may also cause pore water pressure buildup in pores. • Temperature with saturated conditions increases creep.

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; $\Delta \phi$ = change in porosity; om = orders of magnitude

Table 5. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock: Late Closure Stage (cooling; support degradation; self-sealing)

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Processes and Events	• Rock, EDZ and bentonite/ backfill fully saturated • Decreasing temperature with smaller gradients as compared with heating stage • Chemical processes (with probably smaller effects), bacterial activities may be significant; potential decrease in permeability due to clogging of transported particles • Degradation of rock support system (rock bolts, drift lining) with its physio-chemical effects: (a)chemical reactions with backfill and bentonite; (b) high permeability paths along locations of degraded rock bolts and drift linings	• Stress redistribution; process of self healing and reduction of permeability • Stress conditions decrease below dilatancy criterion; no further micro cracking • Perhaps occurrence of cooling fractures • Healing (Asse Mine field data at 700 m show change in k in EDZ from 10^{-16} m^2 back to 10^{-18} m^2 in 90 years; not full healing yet to intact rock value of ~10^{-20} to 10^{-21} m^2)	• Cooling and fluid pressure restoring in the rock mass • Potential self-sealing due to mechanical fracture closure of precipitation of infill minerals; • Effect of fluid pressure in drift (gallery), • Lining degradation with corresponding mechanical (support) and chemical changes (e.g., high pH plume); • Gas pressure buildup generated by corrosion and waste; • Changes in bentonite buffer and cross-cut seals	• Generally, processes are much slower. • Potentially sealing on cooling • Potential carbonate transport and precipitation in the EDZ with possibility of changing rock strength or cohesion • Healing is slow; 2 kinds of processes: - closing up fractures during consolidation due to swelling and creep (data show visible fractures after 15 years, but k is at intact rock value) - volume increases around large open fractures or gaps; increasing plasticity index Gas production, pressure buildup and migration
Property and Design Parameters	• Properties and parameters related to bacterial activities • Physico-chemical properties of rock bolts and drift lining	• Parameters controlling creeping and self-healing process. • Compaction • Temperature changes • Moisture content changes	• Liner degradation introduces both mechanical and chemical changes, and causes compaction of backfill and buffer materials; • Parameters controlling gas release and buildup from corrosion and waste. • Properties of bentonite seals and cross-cut seals	• Water movements • Pore pressure changes • Clay swelling (smectite group)

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; $\Delta \phi$ = change in porosity; om = orders of magnitude

Table 5. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Late Closure Stage (cooling; support degradation; self sealing) (continued)

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Some Technical Factors	No self-sealing; however, long-term heating with thermohydrologic effects over 2,000-year time frame may lead to clay minerals in fractures, thereby clogging them.	• Effect of impurities, e.g. anhydrites • Δk (sealing) depends on time, effective stress, deviatoric stress • Healing can be by (a) viscoplastic deformation or (b) recrystallization by presence of brine • Under confining pressure, effect of healing is immediate and then progresses with time	• Sealing is a time-dependent process. – Stress state for contractancy – Dilatancy – Swelling – Newly formed minerals • With saturation, Δk of single fracture is reduced by 1 om in 1 year and Δk of fracture network reduces by factor of 50 in 110 days. • With gas injection, fracture opens. When gas depressurizes, fracture remains open and closes slowly over 5 months • Sealing needs more studies to confirm. • Lining degradation rate is considered a key factor	• Observed: k in EDZ restored in several years: (a) clay closes spontaneously against borehole casings; (b) open boreholes closed completely, and (c) clay flows into open boreholes • Fractures closed by increase in stress; swelling and creep. • Discontinuities are still present, but k restored.

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; Δϕ = change in porosity; om = orders of magnitude

Table 6. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: State of Science and Technology

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
State of Field Information (Including Natural Analogues)	• Stripa: Buffer Mass Test • Pinawa URL, Canada • Aspo: Zedex Drift • Febex Experiment (including 6-year heating and cooling) • Kamaishi Mines, Japan	• Tests in Asse Mines (ALOHA and BAMBUS II projects) • "Engineering analog" at Asse – 90-year-old bulkhead at 70-m level – 10-year old concrete dam at 900-m level • Decades of field tests at WIPP • Sealing analogs in evaporite mines	• Tests in Mont Terri (Switzerland) and Tournemire (France) underground laboratories; new tests in expected URL at Meuse/Haute Marne • Studied effects of ventilation and dehydration, heating, desaturation and resaturation • Studied self-sealing for excavation-induced fracture and gas pressure-induced fracture opening	• URF at Mol: boom clay. First shaft, 1980-1982; Test drift, 1987; Second shaft, 1997-1999; Connecting drift, 2001-2002. • HADES Project: 20 years of data on hydromechanical effect and fracture patterns around drift • CLIPEX instrument program to study effects of advancing Connecting Drift • Analog: London Underground (lower stress/strength ratio) • Analog: St. Petersburg blue clay (different stress-time history from M___
State of Modeling	• Much effort on constitutive relationships; shear stress permeability relationship still open • A large number of simulators have been developed and applied, including THAMES, ROCMAS, TOUGHFLAC codes	• Constitutive models developed for damage, dilatancy—Gens-Olivella, Hou-Lux models – BGR: CDM-model by Hunsche • Stress invariant models used with engineering judgment; applied to WIPP design and performance assessment • First simulations performed by various codes (e.g., CODE_BRIGHT, MISES 3, JIFE, percolation model) that includes creep and viscoplasticity model	• Palmer and Rice's model of stress localization, fracture initiation and propagation • Elastic and isotropic elasto-plastic model into codes CODE_BRIGHT, FLAC3D, MHERLIN, PFC • Need a threshold for onset of creep • Can model main features of EDZ development	• Model with modified CAMCLAY and Mohr-Coulomb model • Predicts well wall displacement and equilibrium pressure on lining • Cannot explain large extent of pore-pressure response (60 m) • Model of strain localization, fracturing and self-sealing is being developed.

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; Δϕ = change in porosity; om = orders of magnitude

Table 6. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: State of Science and Technology (continued)

Open Technical Questions	Understand and reconcile data and results from various field and laboratory experiments; correlate results with local conditions and drift sizes and shapes	• Need to confirm healing and study behaviour for full healing • Need constitutive model to capture anisotropy and relate damage to k, and to test them against field observations • Need to confirm reversibility of EDZ evolution by comparing results against excavation of different ages and around plugs installed long ago. Determination of dilatancy and healing • Contact between seal and host rock may be weakest zone: k can be 2 om above intact rock and concrete	• Differences exist between laboratory and field results (possibly due to sampling and coring problems) • Interactions among anisotropy of intact rock, anisotropy of EDZ stress changes and anisotropy of Δk interaction to be studied • Lack longer term experiments—self-sealing effect still not fully solved • Determination of dilatancy and healing • Design of EDZ cutoff and evaluation of its effectiveness	• Explanation for 4 m communicating fractures and 60 m pore pressure changes ahead of the excavation face. • Property parameters as a function of humidity and temperature conditions • Anisotropic modelling • Role of gas produced by reaction of water with waste canisters in EDZ

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; Δϕ = change in porosity; om = orders of magnitude

Table 7. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Overall Issues

	Crystalline Rocks	Rock Salt	Indurated Clays	Plastic Clays
Long-Term Safety Impact issues	• Potential connected fast flow paths in the EDZ; effect of EDZ on resaturation rate. • Water flow between EDZ and fracture zones intersecting drift • Role of EDZ at tunnel intersections • Assessment of THC and THB impacts	• Role of contact between seal and EDZ and host rock • Possibly EDZ only important in the first decades because of self sealing effects; need more field data and analog studies to confirm model and to test its capability for long-term prediction of self sealing (e.g., with respect to temperature and moisture changes) • Need to model anisotropic behaviours • Gas transport needs study	• On one hand, EDZ possibly a preferential pathway for gas release and reactivation of closed discontinuity, need further study • On the other hand, EDZ probably no significant effects, limited by availability of water from the low k formation, but – Confidence building – Study of sealing methods – Need bounding and scoping calculation	• Potential EDZ pathways; however, even if EDZ has high k, flow along EDZ may be limited by availability of water from the low k formation • Transport probably mainly by diffusion, need account for property changes, such as ϕ, K_d, D_l and solubility limits, • Interactions with other repository components to be simulated
Issues in Repository Design	• Improved tunnel construction and support method to reduce EDZ; • Optimal depth and orientation of tunnels relative to in situ stress condition and fracture/fault directions; • Design of methods to cutoff/interrupt EDZ; • Methods to "improve" rock-seal interface • Operational rules to reduce geochemical changes	• Make fundamental decision regarding seal locations; • Where and how effective the seal needs to be (compartmentation?) • Possibility of installing stiff liner during or immediately after excavation • How to position seal in the repository; how to remove EDZ immediately before seal emplacement • Because of creep, special measures to reduce or cutoff EDZ may not be necessary	• Optimal design of drift (gallery) geometry, • Excavation method, lining properties (stiffness, settling time), • Orientation of drift with respect to bedding planes, potential discontinuities and in situ stress direction; • Seals locations. Design of EDZ cutoffs.	• Consideration of new excavation procedures to limit EDZ formation; • Avoid or control rock desaturation during heating • Development of methods to reduce or cutoff EDZ. • New excavation methods to minimise over-excavation to reduce convergence; use of shield for drifts; put in lining as soon as possible

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; $\Delta\phi$ = change in porosity; om = orders of magnitude

Table 7. Comparison of Processes, Parameters, and Issues for EDZ in Different Rock Types: Overall Issues (continued)

"Bottleneck" Issues	• Need for establishing acceptable methodologies for complete PA scoping, bounding and sensitivity studies on effects of EDZ (including presence of fracture zones closed to drift) • Need to establish and confirm EDZ cutoff strategies and effectiveness of seals	• Understanding of processes in seal-rock interface and effectiveness of drift seals and cutoffs • Need for establishing acceptable methodologies for complete PA scoping, bounding and sensitivity studies on effects of EDZ (including sensitivity to degrees of self sealing)	• Understanding of processes in seal-rock interface and effectiveness of drift seals and cutoffs • Need for establishing acceptable methodologies for complete PA scoping, bounding and sensitivity studies on effects of EDZ (including sensitivity to degrees of self sealing)	• Understanding of processes in seal-rock interface and effectiveness of drift seals and cutoffs • Need for establishing acceptable methodologies for complete PA scoping, bounding and sensitivity studies on effects of EDZ (including sensitivity to degrees of self sealing)

NOTE: EDZ = excavation-disturbed/damaged zone; Δk = increase in permeability k; $\Delta\phi$ = change in porosity; om = orders of magnitude