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Influence of EDZ on the Safety of a Potential HLW Repository

발파교란 지역이 처분장 방사선적 안전성에 미치는 영향 평가

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Abstract

Construction of tunnels in a deep crystalline host rock for a potential High-Level Radioactive Waste(HLW) repository inevitably generates an excavation disturbed zone (EDZ). There have been a series of debates on whether a permeability in an EDZ increases or not and what would be the maximum depth of an EDZ. Recent studies show mixed opinions on permeability. However, there has been an international consensus on the thickness of an EDZ; 30 cm for TBM and 1 meter for controlled blast. One of the impacts of an EDZ is on determining the distance between adjacent deposition holes. The void gap by the excavation hinders relaxation of temperature profiles so that the current Korean reference designing distance between holes should be stretched out more to keep the maximum temperature in a buffer region below 100 degrees Celsius. The other impact of an EDZ is on the long-term post closure radiological safety. To estimate the impact, the reference scenario, the well scenario, is chosen. Released nuclides diffuse through a bentonite buffer region experiencing strong sorption and reach a fracture surrounded by a porous medium. Inside a fractured porous region, radionuclides migrate by advection and dispersion with matrix diffusion into a porous medium. Finally, they reach a well assumed to be a source of potable water for local residents. The annual individual dose is assessed on this well scenario to find out the significance of an EDZ. A profound sensitivity study was performed, but all results show that the impact is negligible. Even though the role of an EDZ turns out to be limited on overall safety assessment, still it is worthwhile to study the chemical role of an EDZ, such as a potential source for natural colloids, potential sealing of an open fracture by fine clay particles generated by the process of an EDZ, and alteration of a sorption mechanism by an EDZ in the future.

Key Words : EDZ (Excavation Disturbed Zone), High-Level Radioactive Waste Disposal, Total System Performance Assessment, Well Scenario

I. Introduction

Excavation disturbed zone (EDZ) has been an issue on the structural and post closure radioactive safety of a potential repository. According to Read[1], the zone around an underground opening can be divided into three parts:

(1) a disturbed zone in which the material behavior is essentially unchanged but the stress state is perturbed by the opening,

(2) a small excavation damaged zone characterized by changes in both the pre-excavation stress state and in material behaviour of the rock mass, and

(3) a failed zone in which rock slabs detach completely from the rock mass as a result of progressive failure.

In this paper, the term EDZ is taken to mean the disturbed zone that includes the failed and damaged zones closest to the wall that are caused by the excavation method.

There were a number of debates on the importance of the EDZ. However, the Zone of Excavation Disturbance EXperiment(ZEDEX) project resolved the most part of the issues. When the conventional controlled drill and blast (DB) is applied, then, the EDZ is confined within a meter and when the TBM is used, then, the EDZ is limited to within thirty centimeters as summarized in Table 1[2]. In Table 1, T stands for boreholes excavated by TBM and D stands for ones by DB.

Table 1. Estimated extent of the EDZ measured in the ZEDEX Project

Borehole	EDZ Extent, [cm]
RT1H	<30
RT1I	<30
RT1V	20
RD2I	65
RD3H	25
RD3I	40
RD3V	80
RD6I	80
RD6V	65
RD7H	25
RD7I	30
RD7V	50

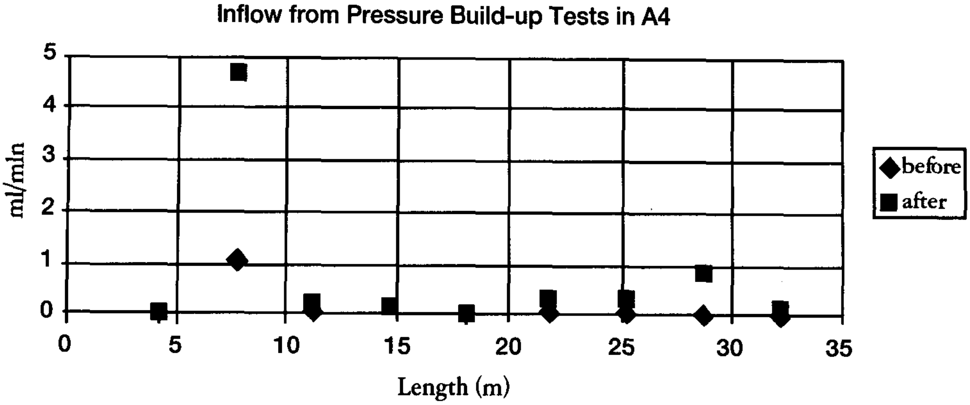
[R: Radial, T: TBM, D: Drill & Blast, H: Horizontal, I: Inclined, V: Vertical]

EDZ has been thought to increase porosity. However, whether it increases an inter-connective porosity or not is another debating issue. Sometimes a pore is clogged by the EDZ so that porosity is increased, but it does not always mean that the radionuclide pathways in the EDZ, inter-connective, increase.

Traditionally when the DB is applied, then the maximum change of porosity is increased to two orders[3]. In the field study the reduction of permeability was observed from the EDZ by TBM as shown in Figure 1. Contrarily, the opposite trend is observed for DB as shown in Figure 2.

Therefore, it is worthwhile to see the effect of the EDZ on potential radionuclide release by changing the value of porosity in EDZ from 1/10th to 100 of its original porosity[3]. To see it, the reference radionuclide migration scenario after close of a potential repository is selected. The so called well scenario is chosen to illustrate radionuclide migration from a failed waste container to a well through man-made barriers and a fractured porous medium. By drinking contaminated well water an individual sometimes might be exposed to the potential hazard of a fatal risk. Two cases, one without considering the EDZ and the one with EDZ are studied to see the effect of the EDZ.

The second issue of the EDZ is its impact on structural stability. Even though the study of it is at the early stage[4], still it will be worthwhile to state the impact and try to set the future R&D direction to understand it.



(Length = Borehole Length)

Figure 1. ZEDEX TBM Experiment: Illustrating the Reduction of Permeability after Excavation

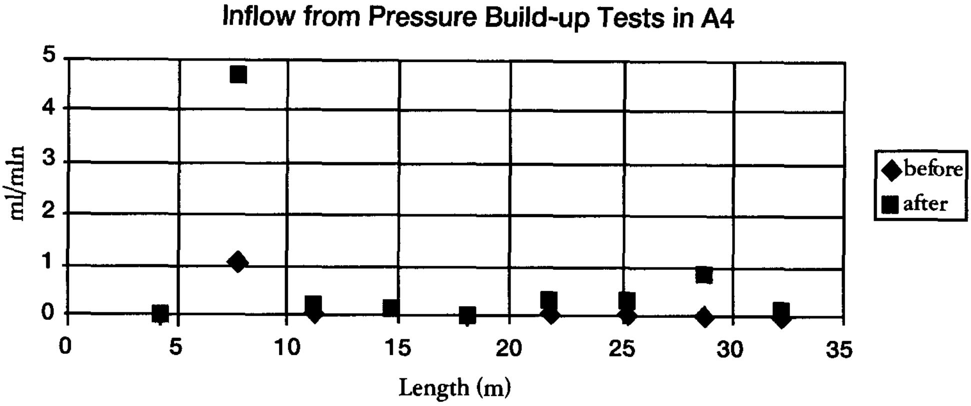


Figure 2. ZEDEX DB Experiment: Illustrating the Reduction of Permeability after Excavation

To precisely understand the role of the EDZ, it is essential to figure out the radionuclide pathways in a fractured geosphere in the vicinity of a repository. Figure 3 illustrates four potential migration pathways in a repository.

II. Role of EDZ

The impact of the EDZ has become an issue since the early stage of the OECD/NEA's Stripa study[5]. Numerous studies were done to understand the coupled processes by thermal, hydraulic, and mechanical (THM) effects of the EDZ [6-10]. Also, the role of the EDZ has been extensively examined in Canadian[11] and SKB's ZEDEX[2] studies.

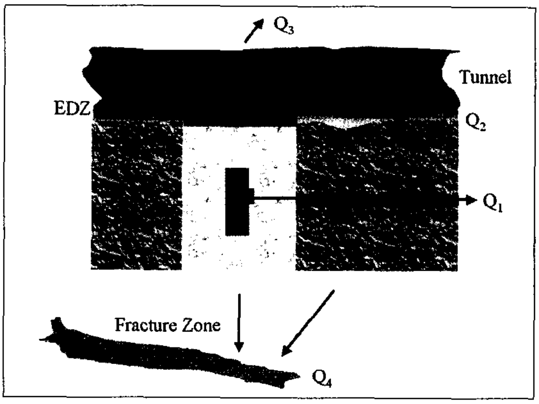


Figure 3. Potential Radionuclide Pathways in the Vicinity of a Deposition Hole

The general public is afraid whether the EDZ might open a significant pathway from a near field of a repository to a biosphere, by creating a new fractue pathway and/or by stimulating an existing fracture. However, among potential pathways shown in Figure 3, the most concerned pathway for released radionuclides is Q1. Since the transverse diffusion in a buffer is small, it will take a longer time for radionuclides to move out of a buffer region so that concentrations of radionuclides in a buffer will be reduced significantly before they reach the EDZ in the pathway of Q2. The assessment for the Q2 will be studied later. In this pathway, a radionuclide released from a failed waste container by pitting corrosion is contacted with intruding groundwater. Then the groundwater dissolves radionuclides in a uranium matrix in the solid state. Once released nuclides then diffuse through a bentonite buffer experiencing heavy retardation. Then they enter a fractured porous medium. Inside a fractured rock, the major pathway is an open fracture, because the surrounding rock is rather impermeable. The advection and dispersion carry out dissolved radionuclides to a far field. The radionuclides in a fracture diffuse to a surrounding rock matrix and it retards the migration speed in a fracture. Figure 4 illustrates the schematic view of migration of a radionuclide in this region. If the EDZ is generated, then it is the region between a bentonite buffer and an unaltered fractured porous medium. The introduction of the EDZ changes two aspects in a repository.

Firstly, it changes the thermal properties in the vicinity of an interface between a fractured rock and a buffer. If the EDZ is created heavily, then in practice a void gap can be created between a buffer and a rock. The creation of a gap will deteriorate the thermal performance of a repository, because the thermal conductivity of air is less than that of a crystalline rock. Therefore, consideration of the EDZ might widen the distance between deposition holes, six meters, based on the current thermal analysis in KAERI without any void[12]. Detailed study is required to understand the phenomena.

Secondly, the EDZ alters the aperture of a fracture. If a fracture is counted as an only practical pathway in a fractured rock, then the change in porosity can be translated into a change in an aperture. Assuming that the cubic law is valid to relate porosity to permeability, the altered aperture width by the EDZ can be estimated. Also, inside a surrounding porous medium, the porosity for diffusion migration of a nuclide is changed by the EDZ.

III. Effect of EDZ on Post Closure Radiological Safety in a Potential HLW Repository

1. Construction of Well Scenario

(1) To understand the effect of the EDZ it is required to construct the reference scenario to stipulate all important migration steps of radionuclides from a source term to intake by human beings. The so-called well scenario[13] has been a backbone of the KAERI's performance assessment. In this scenario followings are key FEP (Features, Events, and Process)'s.

(2) Radionuclides are contained in a solid matrix form, uranium dioxide.

(3) After the closure of a repository, a waste container composed of either carbon steel, stainless steel, or copper/iron starts to be corroded by impurities in intruding groundwater. Chloride and sulfide are two prime impurities under anoxic environment in deep groundwater for the corrosion of iron and copper, respectively.

(4) Intruding groundwater saturates voids in the vicinity of a repository.

(5) Pitting corrosion by impurities finally fails a waste container and the intruding groundwater

starts to dissolve radionuclides in a uranium dioxide matrix form.

(6) The container lifetime in this study is assumed to be one thousand years since initial emplacement. Some sensitivity studies[14] illustrate that small variances of the lifetime of a waste container does not affect the overall safety significantly.

(7) The release of major radionuclides in a waste matrix is controlled by the dissolution of a uranium dioxide form. Since the solubility limit of a uranium dioxide form in pore water in equilibrium with bentonite and groundwater under reducing condition is so low that the release of corresponding nuclides such as plutonium, americium, etc is limited significantly.

(8) Current analysis shows that no nuclide dissolves by its own solubility limit. Major release modes are illustrated in Figure 4.

(9) Some volatile nuclides such as Cs-135 and I-129 are in a void gap between a cladding and spent fuel matrix itself and in a grain boundary of spent nuclear fuel as shown in Figure 5. The release rates of nuclides residing in these locations are not controlled by the dissolution of the uranium matrix any more. Instead, they follow the so called instant high release mode[12].

(10) Once released into groundwater in a buffer some of the nuclides begin to precipitate and then become re-dissolved into a solute phase.

(11) Diffusion is the only way of describing the dominant transport mechanism in a buffer.

(12) Radionuclides in a buffer experience physical and chemical sorption throughout the migration process. Since the amount of radionuclides in a solute phase is limited, the assumption of the linear sorption is applied to express the relation between radionuclides in liquid and solid phases.

(13) No transport of true and pseudo- colloids is considered in a buffer due to the strong filtration of a colloid to a buffer material.

(14) Radionuclides enter a fractured porous medium. An open planar fracture is assumed conservatively. The surrounding porous rock is rather impermeable, so conservatively all nuclides migrate into an open fracture not to the surrounding medium. The network of fractures is

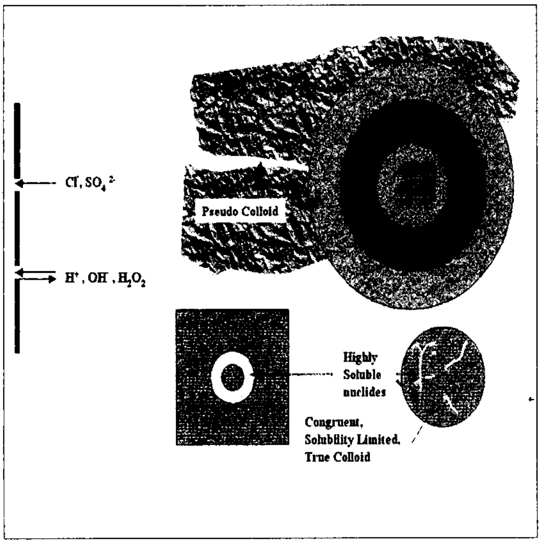


Figure 4. Major Release Modes from a Waste Form

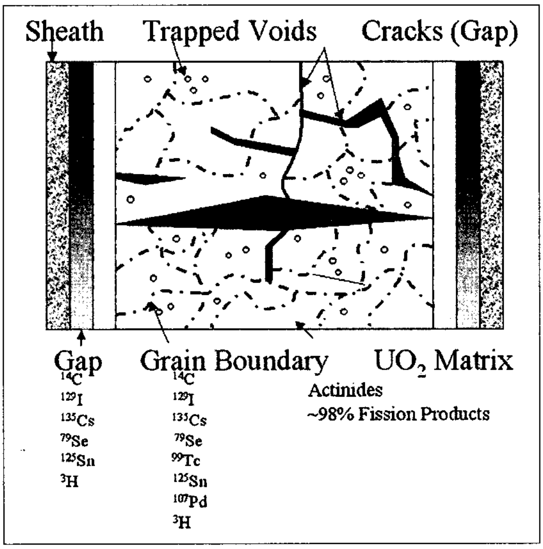


Figure 5. Nuclides in Spent Nuclear Fuel

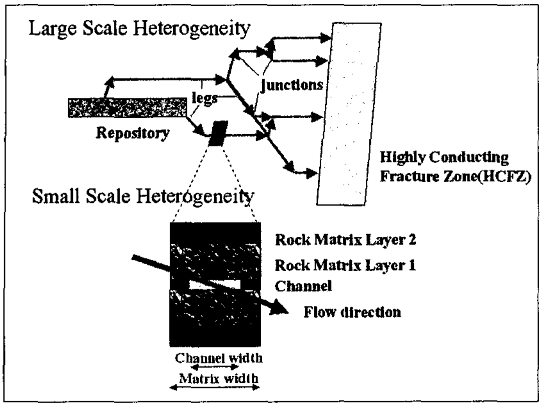


Figure 6. Schematic View of Fracture Network

illustrated in Figure 6.

(15) The radionuclides in a fracture are well mixed across an aperture because the aperture width is tiny. Since the aspect ratio of an aperture width to a fracture length is so low that the flow in a fracture is well developed except for the vicinity of the fracture inlet. In modeling practice, the potential flow theory is applied in a fracture.

(16) The dominant transport mechanisms in a fracture are advection and dispersion.

(17) In an open fracture, the sorption of nuclides occurs at the interface surface between an open fracture and a surrounding rock matrix.

(18) In reality, radionuclides migrating through a fracture diffuse into a surrounding rock matrix. To avoid any mathematical complexity only transverse diffusion is considered.

(19) Some radionuclides form pseudo-colloids when sorbed on a moving natural colloid in a fracture. They experience filtration throughout the migration.

(20) Conservatively, the depletion of a waste inventory is not considered. If needed by implementing the superposition method, the effect of the band release can be included.

(21) Radionuclides migration through a fractured rock enters an aquifer and then become diluted.

(22) A future local resident drills a well into an aquifer potentially contaminated by released radionuclides.

(23) The well is assumed to be the only source for a local resident for potable water.

(24) The appropriate dose conversion factors for drinking water is applied to convert the concentrations to doses.

(25) The annual individual doses are estimated.

The same FEP's are applied for the EDZ case also except for the following additions:

(15') The fracture aperture is altered by the creation of the EDZ. The typical cubical law is applied to correlate the aperture change with porosity change. In a practical modeling sense, the fracture region is divided into two regions, one small part representing the region created by the EDZ and the other still unaltered.

(17') The porosity and retardation coefficient whose definition includes the term for porosity by the following equation in a surrounding rock is changed:

$$R=1+\frac{1-\varepsilon}{\varepsilon}K_d\rho,$$

where R is the retardation coefficient, [-], ε is the porosity, [-], K_d is the distribution coefficient, [m^3/g], and is the bulk density of a surrounding porous medium, [g/m^3].

To perform the assessment, the MASCOT-K code, the overall one-dimensional probabilistic safety assessment code[12] is applied. MASCOT-K is based on the old Nirex's MASCOT[15], the

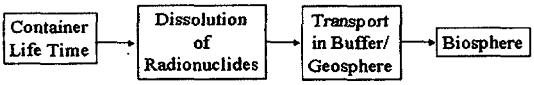


Figure 7. Connection of Sub-models in MASCOT-K

overall assessment code for the safety assessment of ILLW repositories. MASCOT-K is based on the semi-analytic solutions of radionuclide transport in a geological medium. The output signal from one module to the connecting one, physically a flux of a radionuclide is used as an input signal in the connecting module. Then the final output signal, in the well scenario, the annual individual dose to a human being, in the form of the Laplace transformed domain is numerically inverted by the Talbot theorem[16]. Figure 7 illustrates the connection of sub-regions in the MASCOT-K analysis.

Three distinct features were added to the original MASCOT, congruent release[17], highly instant release[18], and pseudo-colloid[19]. In this analysis, the credit of 1,000 years is given for a lifetime of a container.

The sub-models for congruent release and highly instant release are applied to simulate radionuclide release from a waste form to a buffer zone. The porous geosphere module in the original MASCOT is used for a buffer region. The connecting fractured medium is expressed by the fractured geosphere in the MASCOT.

Table 2. Input Parameter Values without the EDZ

Parameter	Value
Number of PWR Containers	11,375
Number of CANDU Containers	2,529
Container Area, [m^2]	16.83
Void Gap Volume in a Container, [m^3]	0.4537
Porosity of Buffeer, [-]	0.3
Porosity of Rock, [-]	0.002
Buffer Thickness, [-]	0.38
Buffer Density, [gr/m^3]	1,800
Rock Density, [gr/m^3]	2,700
Radius of Waste Form, [m]	0.4
Length of Fracture, [m]	100
Pore Water Velocity, [m/yr]	0.7
Fracture Aperture, [m]	1.0E-4
Diffusion Coefficient in a Rock, [m^2/yr]	3.15E-7
Diffusion Coefficient in a Buffer, [m^2/yr]	1.2E-3
Solubility of Matrix, [gr/m^3]	3.7E-5
Retardation in a Fracture, [-]	1
Matrix Diffusion Distance, [-]	0.5

To simulate the mixing of contaminated groundwater in an aquifer, the dilution volume ratio is applied. Using these, the radioactive toxicity in well water is estimated. To assess the annual individual dose, the dose conversion factor is used. Detailed values of input parameters are listed in the next section. Figure 8 illustrates sub-models used in the well assessment.

2. Input Data for Sensitivity Study

Two types of input data sets are used for sensitivity analysis. One is for the case without disturbance of the EDZ and the other is for the case with disturbance. Table 2 is the data without the EDZ and Table 3 is the change of parameter values for six different cases for sensitivity study.

All other data such as inventories, distribution coefficients, and dose conversion factors are given in the reference[12].

3. Numerical Results

Figure 9 illustrates the annual individual doses for nuclides embedded in a deep geological repository when the pore water velocity is increased by one order. In early time, the influence of instantly high soluble nuclides is dominant. This is due to two reasons, less retardation and high dissolution rates. Later, the effect by trans-uranium elements becomes important. In Figure 9, the early

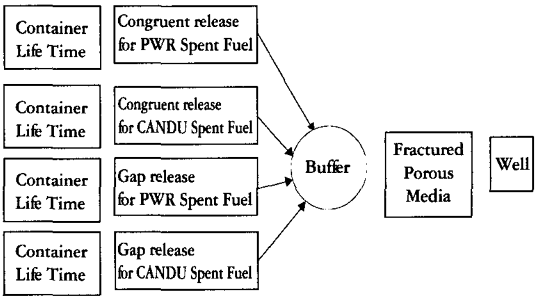


Figure 8. Sub-Models for the Well Scenario

and later peaks overlap. However, according to the other work[14], as the length of a fracture increases, two peaks become separated from each other.

Figure 10 illustrates the results from the sensitivity study. Seven different cases are compared. Case 1 is the case with the change of bulk porosity and the corresponding change in a pore water velocity by one order. In this case the extent of the EDZ is limited to thirty centimeters.

Case 2 is the one with same velocity increase. However, the perimeter of the EDZ is extended to one meter. Case 3 is similar to Case 1 for the EDZ extent. But the pore water velocity increases by 100. Case 4 is for the EDZ region of one meter with the increase of the velocity by 100. Cases 5 and 6 are the ones for the cases of the velocity reduction by one order for 30cm and one meter EDZ thickness respectively. Six Cases are compared with Case 7 without the EDZ. Figure 10 illustrates the comparison results for seven cases. For all cases, there is no difference in the annual individual doses in practice. This concludes that under the conditions given in this paper, the EDZ does not play any significant role to affect the safety of a potential HLW repository.

4. Conclusions

To understand the importance of the EDZ on the long-term post closure radiological safety, the reference scenario, the well scenario was selected. Using the overall performance assessment code, MASCOT-K, the impact of the EDZ was studied. Results illustrate that under given conditions, the EDZ does not impact the radiological safety of a repository.

IV. Other Issue

There has been a study to understand the sealing effect of a fracture by pressured bentonite.

Table 3. Sensitivity Study Case

Case	Path Length		Flow Velocity, [m]	Dispersion Coefficient, [m^2/yr]	Porosity [-]	Density [gr/m^3]
	EDZ [m]	Rock [m]				
1	0.3	99.7	7	350	0.0043	2695
2	1.0	99.0	7	350	0.0043	2695
3	0.3	99.7	70	3500	0.00928	2687
4	1.0	99.0	70	3500	0.00928	2687
5	0.3	99.7	0.07	3.5	0.00092	2701
6	1.0	99.0	0.07	3.5	0.00092	2701
Ref.	No EDZ	100	0.7	35	0.002	2700

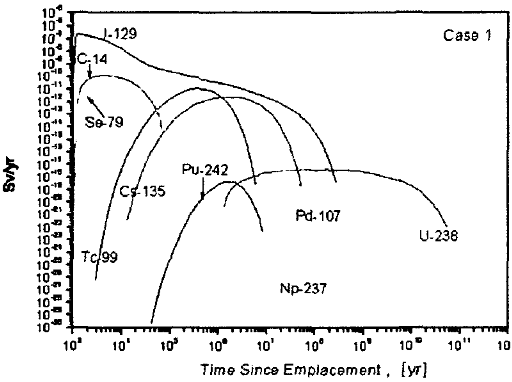


Figure 9. Annual Individual Dose for the Well Scenario

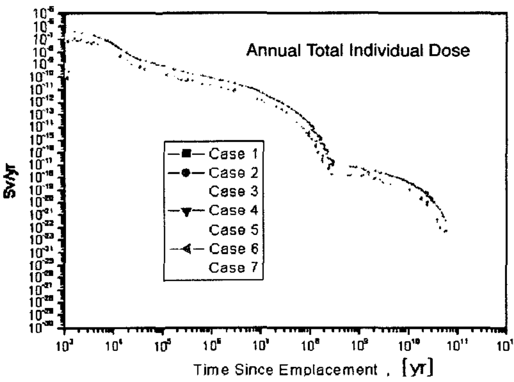


Figure 10. Sensitivity Study for EDZ Effects

In this analysis, loosened bentonite particles can penetrate into a fractured porous medium and in practice block a certain part of a fracture inlet. Then this blocked fracture region does not allow any advective transport any more. Instead, the diffusion becomes the only feasible transport mechanism in the region. The EDZ will enhance the blockage phenomena. However, in current safety assessment, conservatively, the blockage process is not considered in any modeling. If needed, it will be re-visited in the future.

V. Conclusions

The effect of the EDZ has been studied. The effect of the EDZ on the designing of a repository is issued. Qualitative assessment is given to explain the role of the EDZ for thermal calculations. More detailed studies are performed to understand the effect of the EDZ on the post closure radioactive safety assessment in a potential HLW repository.

The effect of the EDZ on the post closure safety is extensively studied. For all six cases discussed in this paper, the effect of the EDZ is limited. This statement should be true if the region of the EDZ is confined to one meter for CB and thirty centimeter for TBM. The rest of the rock, at least with a thickness of one hundred meters is not affected by the EDZ at all, so that the overall migration pathway and corresponding the annual individual doses cannot be affected.

Even though the EDZ is regarded as a prime source to speed up the radionuclide migration by the general public, scientific studies prove that the role is quite limited. To fully demonstrate its soundness to the public, when a domestic underground research laboratory is launched, proper validation experiments should be planned.

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