

PROJECT FINAL REPORT

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Name of the scientific representative of the project's co-ordinator¹, Title and Organisation:

Scientific coordinator: Patrik Sellin, Svensk Kärnbränslehantering AB, SKB

Administrative coordinator and contact person specified in Art.8.1 of the GA:

Mary Westermark, Svensk Kärnbränslehantering AB, SKB

Tel: 0046 8 5793 8720

Fax: 0046 8 5793 8611

E-mail: mary.westermark@skb.se

Project website address: www.belbar.eu

¹ Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.



Executive Summary

The BELBaR project was a collaborative project based on the desire to improve the long-term safety assessments for geological disposal facility concepts for spent fuel/ high level waste that combine a clay engineered barrier system (EBS) with a fractured rock.

Colloids may be mobile in groundwater and are thus potentially significant for safety because they have been shown to be able to sorb radionuclides and increase their effective concentration in groundwater above that which would be transported in dissolved form.

An increased understanding of the processes involved in the above aspects will have a significant impact on the outcome of future assessments. Therefore, the main aim of the BELBaR project was to increase the knowledge and reduce uncertainties with respect to the processes that control clay colloid generation, stability and their ability to transport radionuclides and reduce uncertainties in the description of the effect of clay colloids in long-term performance assessments. To meet this aim, a number of experimental and modelling activities were undertaken within the project.

A reduction of uncertainties in the understanding may lead to:

- a reduction of the assessed overall risk from a repository
- the possibility to totally neglect the colloidal processes in assessments under some circumstances
- guidance to future site selection and site characterisation programmes
- guidance in the selection of engineered barriers for a nuclear waste repository

The results from BELBaR show that the current approach for treatment of colloid in most instances is reasonable and can be justified based on sound scientific understanding. There are some areas where the current approach is unnecessarily pessimistic (e.g. an assumption of de-ionized water), while there also are areas where there are uncaptured phenomena and additional research will be needed (e.g. sedimentation in sloping fractures).

List of Contents

<i>FRONT PAGE</i>	1
Executive Summary	i
List of Contents	ii
Summary description of project context and objectives	4
1 Introduction	4
2 Structure of the project, objectives	4
2.1 WP1: Safety assessment (RWM lead)	4
2.2 WP2: Bentonite erosion (Ciemat lead)	5
2.3 WP3: Radionuclide and host rock interactions (KIT lead)	6
2.4 WP4: Colloid stability (ÚJV Řež lead)	7
2.5 WP5: Conceptual and mathematical models (Posiva lead)	8
2.6 WP6: Knowledge management, dissemination and training (SKB lead)	8
2.7 WP7: Coordination (SKB lead)	8
3 Structure of the next sections	9
4 Summary of the current treatment of colloids in Performance Assessment	9
5 Synthesis of issues	11
5.1 Erosion	11
5.2 Colloid, radionuclide and host rock interaction	16
5.3 Colloid stability	18
5.4 Conceptual and mathematical models	20
6 Summary of recommendations	22
7 Main dissemination activities and exploitation of results	24
7.1 Presentations of BELBaR work and results at international conferences	24
7.2 Meetings, workshops and training within and during the project	25

7.3	Students	26
7.4	Staff exchange	27
7.5	Peer-reviewed articles	27
7.6	The project public website	28
7.7	Relevant contact details regarding the project	28
7.8	List of Beneficiaries and contact names	28
8	Dissemination of foreground	29
	Report on societal implications	34
	References	39

Summary description of project context and objectives

1 Introduction

The BELBaR project was a collaborative project based on the desire to improve the long-term safety assessments for geological disposal facility concepts for spent fuel/ high level waste that combine a clay engineered barrier system (EBS) with a fractured rock. BELBaR partners included national radioactive waste management organisations (WMOs) from a number of countries, research institutes, universities and commercial organisations working in the radioactive waste disposal field.

The formation and stability of colloids from the EBS may have a direct impact on assessed risk from a geological disposal facility in two aspects;

- generation of colloids may degrade the engineered barrier; and
- colloid transport of radionuclides may reduce the efficiency of the natural barrier.

An increased understanding of the processes involved in the above aspects will have a significant impact on the outcome of future assessments. Therefore, the main aim of the BELBaR project was to increase the knowledge of the processes that control clay colloid generation, stability and their ability to transport radionuclides and reduce the uncertainties in the description of the effect of clay colloids in long-term performance assessments. To meet this aim, a number of experimental and modelling activities were undertaken within the project.

The primary target audience of the outcome of the project is national WMOs. The key use will be increased understanding of processes that have been shown to have a direct impact on the assessed dose/risk from disposal facilities for high-level radioactive waste or spent nuclear fuel.

In this report the focus is completely on the results and outcomes of the BELBaR project. For extensive information on the activities performed in the project please see the deliverables from the work packages 1-5 and the periodic reports.

2 Structure of the project, objectives

The BELBaR project was organised into a number of work packages. The structure and objectives of these work packages are discussed in the following sub-sections.

2.1 WP1: Safety assessment (RWM² lead)

The objectives of WP1 at the outset of the BELBaR project were to identify and synthesise the current treatment of the relevant processes in existing safety assessments. This review was used to inform the direction of the experimental and modelling programme undertaken within the framework of the BELBaR project.

At the end of the BELBaR project, the objective of WP1 was, by drawing on the results obtained within the respective work packages (as illustrated in Figure 1), to consider and where appropriate, to recommend opportunities for where WMOs could review how colloids and related phenomena are considered in the long-term safety case.

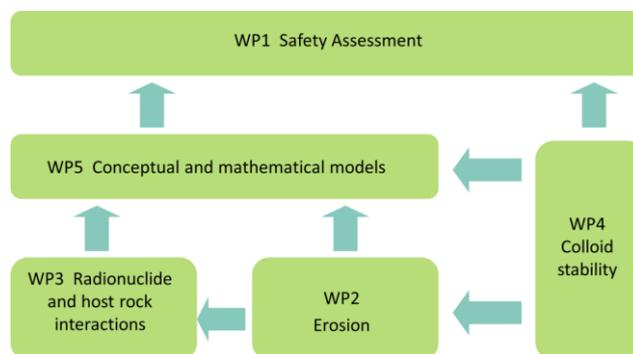


Figure 1 Information flow from BELBaR WP2-5 into WP1

² Radioactive Waste Management (RWM), a wholly owned subsidiary of the Nuclear Decommissioning Authority (NDA) was previously known as the Radioactive Waste Management Directorate (RWMD).

2.2 WP2: Bentonite erosion (Ciemat lead)

The main objective of WP 2 was to understand the main mechanisms of erosion of clay particles from the bentonite surface and to quantify the (maximum) extent of the possible erosion under different physico-chemical conditions. Figure 2 shows examples of experimental observations of bentonite erosion and attenuation of erosion under different experimental conditions.

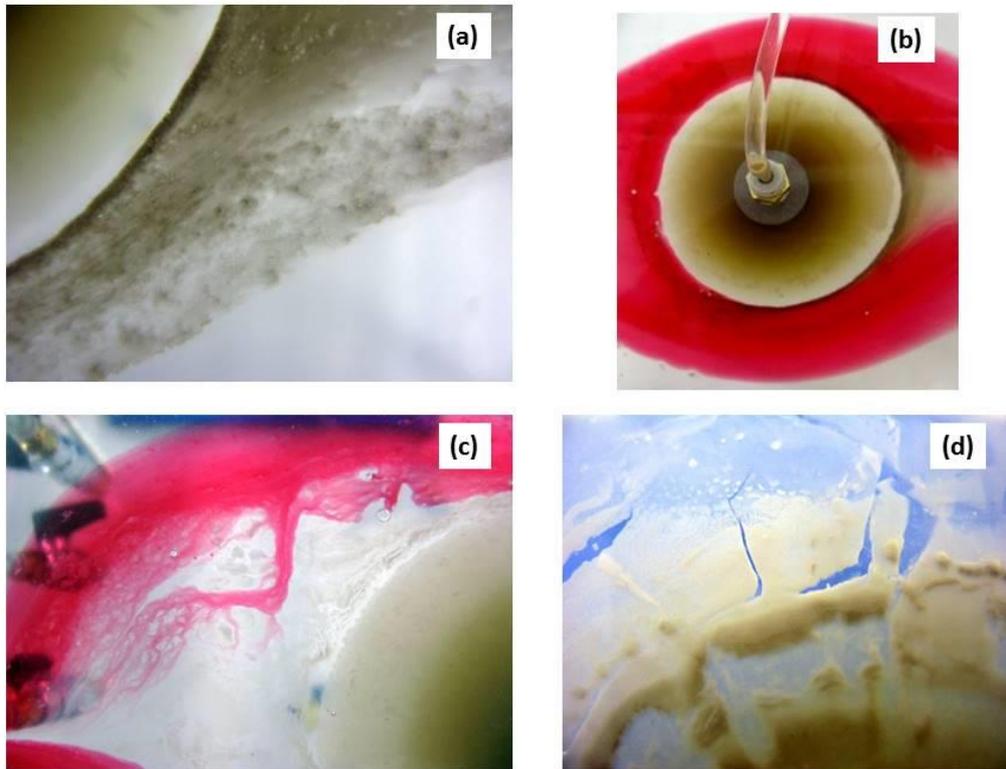


Figure 2 Photographic images showing a) the interface between the inner zone of extruded material and the outer zone of eroding material for a test with sodium montmorillonite against deionized water at 456 h, b) flow visualization of the same test highlighting the permeability of the eroding material zone and the relative impermeability of the extruded material zone, c) flow visualization of a test with 50/50 calcium/sodium montmorillonite against 4 mM NaCl indicating the semi-permeability of the eroding material zone and d) the extrusion/erosion interface from a test with 50/50 calcium/sodium montmorillonite against double strength Grimsel groundwater simulant demonstrating that the eroding material forms into extended sheets of rigid, coherent material.

2.3 WP3: Radionuclide and host rock interactions (KIT lead)

The objective of WP3 was to develop process level understanding of colloid mobility controlling processes and their appropriate description. This included radionuclide sorption and retention processes. Figure 3 illustrates the processes considered in work package 3.

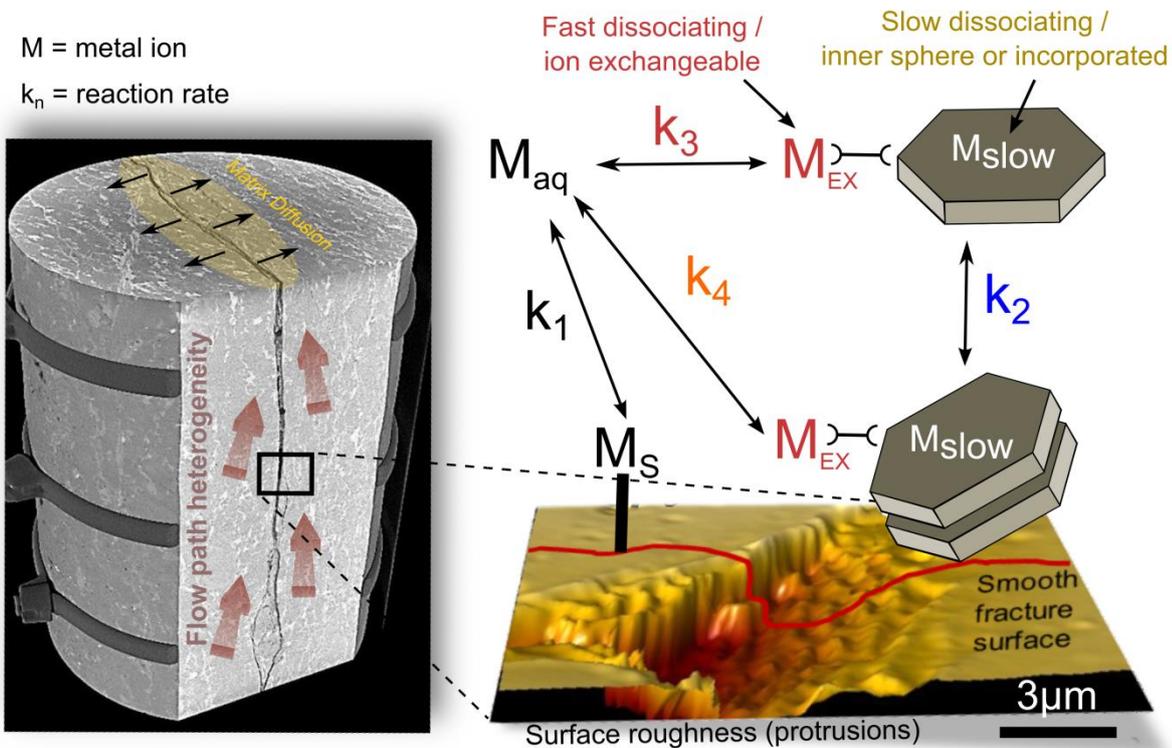


Figure 3 A schematic representation are the processes investigated within work package 3; namely (a) the radionuclide interaction with clay colloids and the observed metal-colloid dissociation rates (fast and slow dissociation step k_3 , k_4) beside the direct radionuclide fracture surface interaction rate (k_1) and the potential transfer rate from the fast dissociating to the slow dissociating mode as a function of metal-colloid contact time, (b) the mobility determining effect of fracture surface roughness and charge heterogeneity and (c) the effect of flow path complexity and matrix diffusion on colloid retention.

2.4 WP4: Colloid stability (ÚJV Řež lead)

The objective of WP4 was to understand clay colloid stability under different geochemical conditions with respect to ionic strength, pH and the influence of complexing agents. Figure 4 shows a summary representation of the underrating of the organization of smectite particles under different conditions.

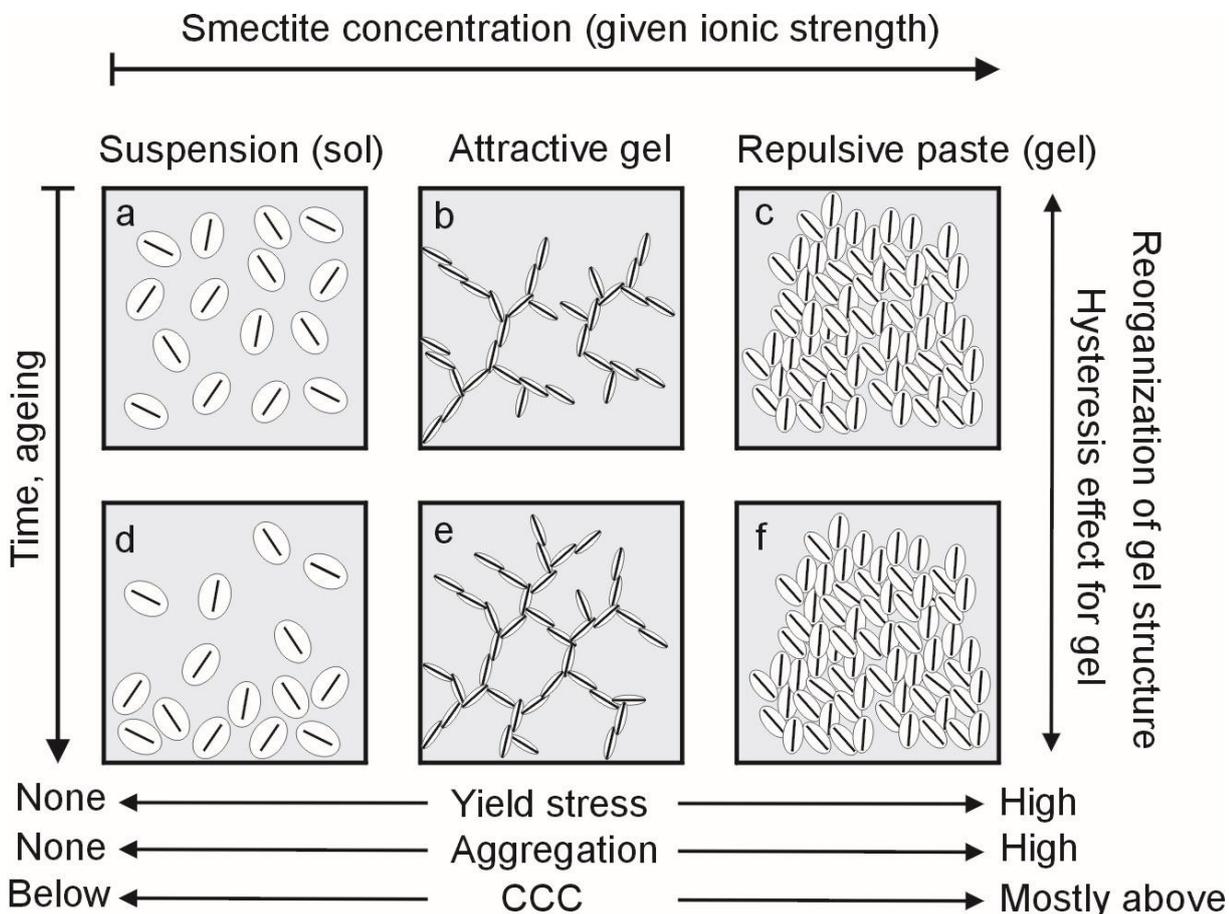


Figure 4 Schematic representation of Na-montmorillonite phases as function of montmorillonite concentration at given ionic strength investigated in WP4. a) montmorillonite particles are only weakly interacting, b) montmorillonite particles above CCC forms gel structure, c) at high montmorillonite concentration the repulsion forces dominate. Ageing d) sedimentation, e) and f) reorganization of gel structure.

2.5 WP5: Conceptual and mathematical models (Posiva lead)

The objective of WP5 was to validate and advance the conceptual and mathematical models used to predict mass loss of clay in dilute waters and clay colloid generation as well as clay colloid-facilitated radionuclide transport relevant to geological disposal of high-level radioactive waste and spent nuclear fuel.

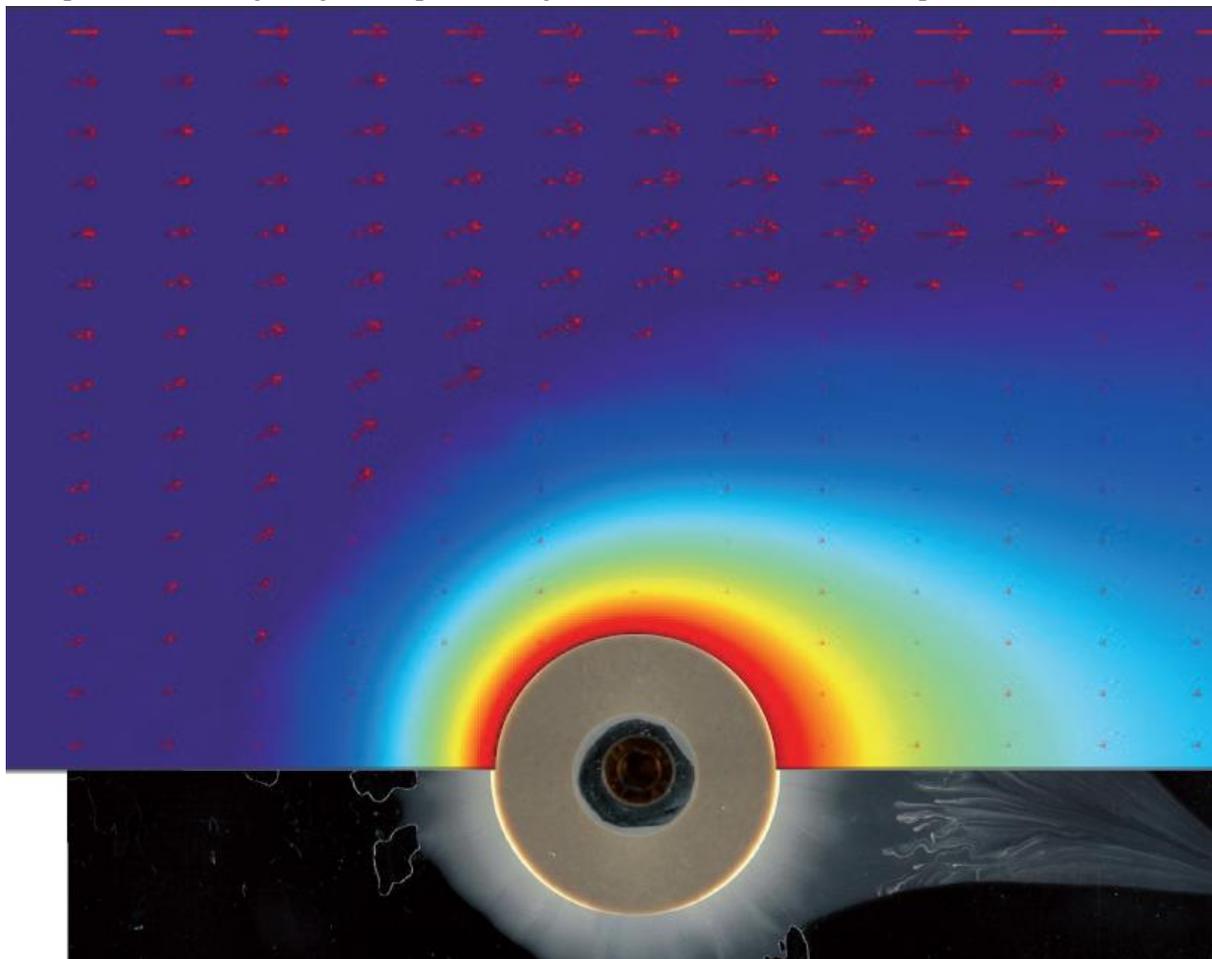


Figure 5 Examples of model results (top) and experimental observations of bentonite erosion.

2.6 WP6: Knowledge management, dissemination and training (SKB lead)

To ensure that BELBaR had the appropriate impacts, a specific work package was established for dissemination of results. BELBaR has utilised a number of avenues to disseminate knowledge including; the project website providing the primary initial interface for partners and the wider scientific community, project meetings, reports, workshops, journal publications, presentation at international conferences and training through a project coordinated professional development course.

2.7 WP7: Coordination (SKB lead)

The objective of WP7 was to provide adequate administrative, legal and financial management of the project, and documentation of scientific-technical progress through Annual Workshop Proceedings to ensure the overall function of the project work and activities.

3 Structure of the next sections

In Section 4, a summary of how each of the waste management organisations participating in BELBaR currently considers colloids in performance assessment is presented. This represented the state-of-the-art at the outset of the project.

Section 5, provides a synthesis of the issues identified at the start of the BELBaR project and on which the experimental and modelling work within the work packages was developed. Progress against these issues made throughout the course of the BELBaR project is presented, providing a demonstration of the benefit that the BELBaR project has brought to the national programmes participating in the project, with respect to the treatment of colloids in performance assessment.

Section 6, provides a summary and further recommendations based on the conclusions of Section 5.

4 Summary of the current treatment of colloids in Performance Assessment

At the outset of the BELBaR project, a State-of-the-art report was produced on the treatment of colloids and related issues in the safety assessment [i]. This report captured the limitations and uncertainties associated with the existing treatment and identified needs for additional studies of colloidal behaviour to be addressed in the BELBaR project. A summary of the treatment of colloids as reported by the participating WMOs (Posiva (Finland), SKB (Sweden) and RWM (UK)) was made in the BELBaR deliverable D1.4 Synthesis report: colloids and related issues in the long term safety case [ii] and is quoted below.

4.1.1 Finland

Colloids have received little attention in performance assessments to date. It is felt that colloid facilitated radionuclide transport has only diminutive effects on safety. In summary:

- the occurrence of deionised groundwater conditions within the buffer and backfill has not been excluded and therefore groundwater is assumed to be deionised at the repository level
- since currently, the full scale numerical model can only deal with monovalent systems, all exchanger sites in clay components are assumed to be occupied with Na^+ ions
- mass loss rate is assumed to scale with groundwater flow velocity (u) as $u^{0.41}$ since validation of a new model is pending and thus pessimistic values are chosen.
- It is assumed that fracture aperture scales with fracture transmissivity as $2b_v = 10 \cdot 0.0117 \cdot T^{0.33}$
- the formation of accessory mineral bed layers during erosion of bentonite is neglected since, although there are indications of such a process, only limited qualitative evidence exists
- it is assumed that erosion will be significant only in a few locations within the repository
- it is assumed that the radiological consequences of colloid-facilitated transport are small [iii]

4.1.2 Sweden

In SR-Site, for situations where the groundwater has a total positive charge of less than 4 mM, the loss of bentonite is calculated with the model developed [iv]. The model can be applied both to the buffer and to the backfill. However, there are a number of uncertainties associated with this treatment:

- the knowledge concerning colloid sol formation and colloid stability is good concerning the effects of mono- and divalent ions. However, modelling of the correlation effects caused by divalent ions is demanding. Since the model basically is based on monovalent ions the calculated loss should be pessimistic

- the model does not consider face to edge interactions between bentonite platelets. Not considering these interactions probably leads to an overestimation of the loss.
- filtering effects by accessory minerals could potentially limit or even eliminate the release of colloids from the buffer. However, this is disregarded in the current treatment of the process, since there is a lack of evidence that efficient filters actually form
- in the model, the expansion has been taken to be horizontal, thus neglecting gravity. Scoping calculations [iv] suggest that gravity will give small effects as, in the model, the smectite sheets have separated into essentially individual colloid particles. For gravity to have an effect the particles must be considerably larger
- the concentration limit for cation charge is only based on experimental observations

Most of the uncertainties are treated with pessimistic assumptions, leading to the conclusion that advective transport conditions in the buffer do not need to be considered in any of the deposition holes during the initial temperate period.

4.1.3 United Kingdom

RWM is currently in the generic stage of a geological disposal facility (GDF) siting process, therefore detailed studies (colloid-rock interactions) are considered more appropriate at a concept and site(s)-specific level. In the absence of any site(s) for consideration as a potential for a GDF for UK higher activity wastes, the studies undertaken by RWM are generic and consider a range of UK-relevant geologies and UK-relevant disposal concepts.

The assumption of sorption reversibility is an important issue. In some situations, to assume reversibility of sorption (onto the rock or near-field materials) is pessimistic because the radionuclide concentration dissolved in the groundwater and the amount of radionuclide that may be sorbed onto colloids may be overestimated. On the other hand, irreversibility of radionuclide sorption onto colloids could increase radionuclide mass transport. The understanding of the reversibility of sorption of radionuclides to colloid surfaces needs to be improved to allow better representation in the safety case (i.e. rates of adsorption/ desorption processes). This is likely to be conducted once a UK site(s) has been identified.

If sorption to colloids is found to show significant irreversibility and colloid particles are found to persist on a site-specific basis, then there may be a need to develop further understanding of colloid mobility and chemical stability in the near field and into the far field [v]. However, the same processes by which radionuclides may be irreversibly sorbed to colloids are also likely to occur at the surfaces of cements and rock. A key conclusion of [v] stated that in reality given that near-field colloids are expected to have limited persistence (i.e. finite lifetimes) in the geosphere, the effects of radionuclide retardation by immobilisation with solid phases are likely to outweigh the detrimental effects of transport of radionuclides irreversibly bound to near-field colloids. This is an area which will need to be investigated and understood during the site-specific stage.

5 Synthesis of issues

As explained in Section 0, colloids may be mobile in groundwater and are thus potentially significant because they have been shown to be able to sorb radionuclides and increase their effective concentration in groundwater above that which would be transported in dissolved form. Colloid facilitated transport of radionuclides may be significant if several criteria are met. The decision tree shown in Figure 6 can help to form a basis of assessing the potential importance of colloids. By answering a series of questions concerning possible colloid behaviour and considering the underpinning evidence, this can provide a framework for how colloids are treated in a particular safety assessment.

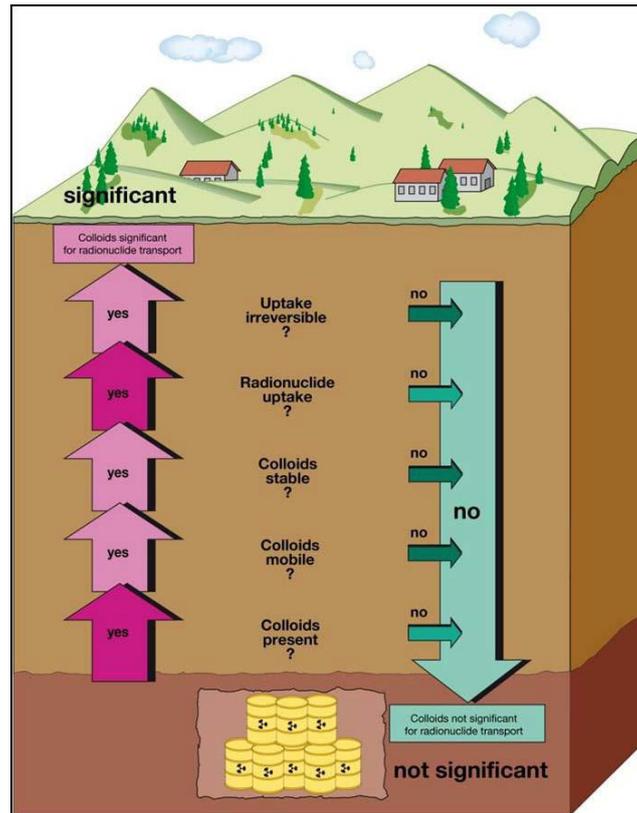


Figure 6 Basis for assessing the potential importance of colloids in performance assessment.

In Sections 5.1, 5.2, 5.3 and 5.4 of this report, progress that has been made as a result of the work undertaken within the BELBaR project against the issues is reported, along with a discussion of the extent of the potential to review the treatment of colloids in performance assessment.

5.1 Erosion

The mechanisms of bentonite erosion from compacted bentonite was investigated in WP2 to better understand the effect of erosion on the integrity of the compacted bentonite buffer in the KBS3 concept over the long-term; and the stability of colloids generated in terms of the significance of the role that they could play in facilitating radionuclide transport in groundwater. The following sections provide a summary of the issues identified at the outset of the BELBaR project, a summary of the conclusion of the experimental programme (as reported in the WP 2 Final Report [vi]) and a discussion of the potential implication of the findings for the safety assessment.

5.1.1 Mechanisms of erosion of clay particles from Bentonite

Safety case position at start of BELBaR

Erosion will cause a loss of bentonite buffer performance under some conditions.

This may lead to corrosion failures of the canisters.

Corrosion failure leads to the largest impact on risk, a less pessimistic approach may have significant impacts on the calculated risk.

The following key points reflect a summary of WP2 conclusions:

- in general, erosion/ colloid generation is rapid initially, but decreases with time and in some cases stops altogether
- in static experiments – equilibrium is reached - the maximum quantity of colloids generated depends on initial conditions but erosion is not continuous
- chemical forces driving dispersion processes are considered to be more important than mechanical forces even in the dynamic system
- there is a potential connection between flow rate and erosion when ionic strength of groundwater is below the critical coagulation concentration (CCC)

With respect to the safety assessment, these results suggest that the assumptions documented by the WMOs related to the mass loss rate's dependency on groundwater flow velocity could potentially be reviewed under no highly "erosive" conditions. The conclusions for WP2 have demonstrated that the mechanism for bentonite erosion overall is driven more significantly by chemical forces rather than mechanical forces. This may be particularly relevant when considering the differences reported in the experimentally derived, or numerical modelling derived values for n within the equation: mass loss scales with flow velocity u as $k \cdot u^n$ and that potentially the coupling between mass loss and groundwater velocity alone is over estimated in the numerical models.

5.1.2 Characteristics of Bentonite clay

Safety case position at start of BELBaR

Divalent cations have not been studied that systematically.

Should the existence and quantitative effect of divalent cations be argued, the importance of this outstanding uncertainty would reduce.

The following key points reflect a summary of WP2 conclusions:

- with higher compaction of bentonite clay, the quantity of particles produced is observed to be higher
- higher erosion is observed in Na- exchanged bentonites. In Na/Ca-bentonite (e.g. FEBEX), a quantity of Na at 20-25% is enough to favour colloid generation, comparable to that observed in a Na-homoionised clay
- low (and sometimes no) erosion observed in Ca- exchanged bentonites – even under low ionic strength conditions

- observed maximum eroded mass is thought to be related more to the montmorillonite (swelling clay) content of the clay rather than the presence of exchangeable Na. The importance of this is confirmed through observation that non-swelling minerals such as kaolinite or illite do not generate colloids. The type of clay in the smectite group is also important as saponite and beidellite do not show appreciable erosion. FEBEX clay mixed with illite showed erosion proportional to the amount of illite, but the addition of kaolinite totally inhibits erosion

These results provide an interesting insight into the effects of not only the presence of mono or divalent ions within the bentonite exchange complex, but also the effects of the presence of montmorillonite in terms of increasing the observed mass loss and non-swelling clay minerals such as illite or kaolinite in playing a role in decreasing or inhibiting mass loss.

This is an important observation in terms of the assumptions used by the WMOs regarding the composition of the clay where currently all exchanger site are assumed to be occupied by Na. Therefore the effects of the presence of a divalent ion such as Ca in the exchanger sites or the type of smectite in the clay are not considered. This leads to an overly pessimistic mass loss calculated in the numerical models. However, the modelling capability does not yet exist to take into account the complexity of modelling the correlation effects caused by divalent ions and thus within these limitations this conservative treatment is considered to be appropriate. In a natural system it may also be difficult to exclude that the sodium content in the clay will be less than 20-25%.

5.1.3 Groundwater chemistry

Safety case position at start of BELBaR

The key factor for colloid stability is the ionic strength and the content of divalent cations.

pH should have an effect, but the pH-range considered in the safety case is rather limited.

The following key points reflect a summary of WP2 conclusions:

- Ionic strength of groundwater is an important factor with respect to erosion
- In general it has been observed that increasing ionic strength, decreases colloid generation
- The presence of divalent cations in solution (Ca^{2+}) are more effective than monovalent cations (Na^+) as coagulants
- at a fixed ionic strength in a dynamic system, the presence of Ca^{2+} in solution inhibits erosion and the formation of colloids

As observed and previously recorded, ionic strength is not the only parameter that affects the formation and stability of colloids. As indicated, the presence of different cations in solution can effect coagulation, with divalent cations being more effective than monovalent ions as coagulants. This emphasises the need for appropriate site characterisation during the siting and implementation of a GDF to understand the geochemical bounds of the system to enable and understanding the impacts it will have on evolution. Given that deionised water may not be representative of a real dilute groundwater, it may be considered that the maximal zero charge limit is an overly conservative scenario. However it is considered that this assumption remains appropriate within the overall system uncertainties, particularly with regard to the need to address the potential for a change in groundwater composition, for example due to glacial meltwater.

Another assumption to consider is that mass loss ceases when groundwater salinity exceeds a stability limit of 4-8 mM NaCl for Na-bentonite. Clearly this assumption is linked to the assumed composition of bentonite as explained in Section 5.1.2 where the exchanger sites in the clay are assumed to only be occupied by Na⁺. Should the assumed composition of the clay be reviewed (and consideration given to the presence of Ca²⁺ or the smectite content) then consideration should also be given to addressing the conservatism that would be inherent in the assumed bentonite stability limit. Within the bounds of the current knowledge, however, it is considered that this assumption remains appropriate.

5.1.4 Clay-groundwater interactions

Safety case position at start of BELBaR

Changes in bentonite porewater solute concentrations can be modelled.

The related rates assumed to be limited by the availability of different porewater solutes.

Mass loss rate assumed to have hydrodynamic contribution.

The buffer and the groundwater never reach a true equilibrium.

The following key points reflect a summary of WP2 conclusions:

- groundwater evolution in the long term will affect the chemistry of the clay/ groundwater system
- it is unlikely that mechanical shear is the key mechanism to perturb a gel phase
- the hysteresis effect could enable clay to be more stable to erosion
- calcium incorporation in an open/ dynamic system could reduce/ eliminate the production of colloids

Linked to the experimental findings discussed in Section 5.1.3, it has been observed that in an open system, with a constant supply of Ca²⁺ and when the concentration of Na⁺ in the clay complex at the gel front is decreased, then colloid generation ceases. This may be an important factor in the long term, since in a system with continuous calcium supply (which would depend on the specific groundwater chemistry at a specific site) calcium saturation of the bentonite surface could result in cessation of colloid generation. Further, an observation has been made that a hysteresis effect may be relevant, that is, the history of the clay and the conditions it has experienced may affect its erosion behaviour. If the clay had previously been subject to high salinity conditions, but these were replaced with more dilute conditions, then the clay was observed to be more resistant to erosion. These types of process are not currently considered in the safety assessment. To consider the dynamic exchange of Na⁺ and Ca²⁺, a very detailed understanding of the future evolution of groundwater chemistry would be needed. The positive effect of hysteresis is a new finding that has been realised during the BELBaR project; it could potentially have a large impact on the view of gel stability. However, the experimental evidence and the conceptual understanding is still limited. Thus the current conservative treatments are considered to be appropriate.

5.1.5 Groundwater velocity

Safety case position at start of BELBaR

Groundwater velocity has been considered as a variable.

The loss of bentonite will be affected by the groundwater velocity and it is important to verify this dependence for erosion rates.

The following key points reflect a summary of WP2 conclusions:

- in tests where erosion was observed, erosion is well correlated to groundwater velocity. However, the experimental work does not give a consistent view on how the velocity affects the erosion. There are a number of studies that indicate that the velocity dependence is weaker than what has been assumed in assessment models prior to BELBaR
- tests conducted in less dilute conditions saw less mass loss, therefore potentially the use of maximum erosion rates to estimate mass loss could lead to overly conservative erosion predictions
- observed that system chemistry is more relevant than flow velocity in terms of driving erosion processes

The conclusion and recommendations noted here are strongly linked to those reported previously in Sections 5.1.3 and 5.1.4. It is important to note that when conditions are favourable such that erosion does occur, then groundwater velocity will mobilise the eroded particles, therefore water chemistry is an important factor even under dynamic conditions.

There is a time dependence aspect observed in the experimental programme that indicates that erosion rates are reduced at longer timescales, even when experimental groundwater velocity is increased. This is not currently taken into account in safety assessments.

As previously reported, the system chemistry is thought to be more relevant than groundwater velocity and even in a dynamic system, there is a maximum threshold of colloids generated given a specific set of initial conditions. The duration of the experimental programme (more than 3 years in some cases) provides additional confidence in the observed behaviour than was available previously.

This, in support of the previously reported conclusions reported in Section 5.1.3 would suggest that the current treatment and assumptions related to the correlation between erosion and groundwater velocity could be reviewed with respect to the driving mechanism controlling bentonite erosion.

5.1.6 Clay extrusion paths

Safety case position at start of BELBaR

Fractures have been assumed to be planar with a constant aperture.

Extrusion of clay into a fracture is an integral part of the current model and will have a strong impact on the mass loss.

Piping may occur before full saturation of the buffer under certain circumstances.

The following key points reflect a summary of WP2 conclusions:

- horizontal and sloped fractures display a different mechanism of mass loss. In horizontal fractures the clay is lost when colloids (or agglomerates) are transported away with the flowing groundwater. In vertical fractures the clay is lost by sedimentation and gravity is the driving force
- where all other test conditions are identical – increased slope angle leads to increased mass loss
- however, based on a limited number of tests, the effect of slope is observed to be more significant at lower angles ($0^\circ - 25^\circ$) compared to $45^\circ - 90^\circ$
- irrespective of slope, at a cation charge greater than or equal to 8.6 mEq the rate of mass loss is effectively zero. This seems to indicate that the strength of the gel is the key factor, which also confirms that the chemistry is the key factor
- extrusion of clay into the fracture also needs to be considered as a separate mechanism for mass loss

The size of the extrusion path is observed to be of primary importance in terms of the quantity of colloids generated. A smaller fracture aperture was observed to generate a significantly lower amount of colloids. This is consistent with a surface-area controlling effect on mass loss.

With respect to the angle of the fracture aperture, an interesting observation has been made that the mass loss mechanisms between a horizontal and sloped fracture are different. The first being controlled by dispersive release whilst the latter occurs through a process of structural collapse of the extruded mass and sedimentation. The acuteness of the fracture angle is also important since it was observed that as fracture angle increases, the mass loss is greater, although the effect is observed to a greater extent between 0° and 45° compared to 45° and 90° .

It is noted that the current performance assessment assumptions assume a horizontal fracture. The results observed suggest that this treatment may not necessarily be conservative. It is strongly suggested that this assumption is reviewed and potentially further work is required to account for the observed effects of slope angle/ gravity.

5.2 Colloid, radionuclide and host rock interaction

The following sections provide a summary of the issues identified at the outset of the BELBaR project, a summary of the conclusion of the experimental programme (as reported in the WP3 Final Report [vii]) and a discussion of the potential implication of the findings for the safety assessment.

5.2.1 Colloid mobility controlling processes

Safety case position at start of BELBaR

Clay colloids have not been considered radionuclide carriers due to the assumed low contribution.

Rather than attempting to develop detailed process models for colloid-facilitated transport, potential mitigating processes are ignored so as to place an upper bound on the possible effect.

The following key points reflect a summary of WP3 conclusions:

- colloid mobility is affected by:
 - fracture geometry (aperture size distribution and fracture surface roughness)
 - chemical heterogeneity induced by the different mineral phases and

- chemistry of the matrix porewater (even under the electrostatically unfavourable conditions of colloid attachment in glacial melt water, colloid retention has been observed)

Whether colloid transport of radionuclides should be included in the radionuclide transport calculations can be determined by a scoping calculation using assumed transport lengths, flow velocities and desorption rates for individual radionuclides.

5.2.2 Retention processes

Safety case position at start of BELBaR

Retardation of colloid transport in the far field, will delay the arrival of radionuclides in the biosphere.

The extent of this isn't currently taken into account.

The following key points reflect a summary of WP3 conclusions:

- it is confirmed that there is a rather strong retention of colloids in the rock
- colloid retention has been observed even at conditions where high mobility was expected, i.e. under unfavourable electrostatic conditions
- the mechanisms that contribute to colloid retention are not yet fully understood. The retention is dependent on the mineral at the fracture surface. The retention in natural rock fractures is stronger than in artificial acrylic fractures used in the erosion experiments of WP2. However, there is also a relatively strong dependence of fracture orientation (horizontal vs vertical), which may complicate a numerical description of the process
- there are experiments where no retention is observed, but that is most likely caused by too high loading of colloids or high velocities of the experimental set-up

The conclusion is that there is a significant retardation of clay colloids in a fracture in the rock. However, the uptake is not complete, which means that colloid transport needs to be considered, if colloids are present. It is clear from BELBaR that colloid retardation should be included in safety assessment calculations. However, the effect may be limited under most conditions and the process could therefore be optimistically neglected.

5.2.3 Radionuclide sorption

Safety case position at start of BELBaR

To assess the possible role of rapid reversible sorption/desorption onto colloids in facilitating transport, the following assumptions have been adopted:

1. equilibrium sorption of radionuclides onto mobile and immobile colloids,
2. equilibrium sorption of colloids onto fracture surfaces, and
3. colloid-free matrix pore space (conservative assumption, but also realistic for the small pore sizes of granitic rock).

Reversible, linear sorption of radionuclides onto colloids has been assumed.

The following key points reflect a summary of WP3 conclusions:

- the understanding of desorption phenomena has been vastly improved

- sorption of Cs onto montmorillonite is fully reversible, but not on illite
- desorption of trivalent (Eu(III)) is substantially faster from bentonite colloids than from bulk material
- pentavalent nuclides show fast desorption
- the findings about tetravalent nuclides are less conclusive. It may not be possible to assume full desorption
- the assumption of linear sorption is always valid for the concentration range that can be expected for radionuclides

It is clear that the assumption of linear sorption is valid. Sorption reversibility is nuclide specific and should possibly be treated on a case by case basis. However, for most radionuclides sorption reversibility can be assumed over repository time scales. The exception may be tetravalent elements where some caution should be taken.

5.3 Colloid stability

The following sections provide a summary of the issues identified at the outset of the BELBaR project, a summary of the conclusion of the experimental programme (as reported in the WP 4 Final Report [^{viii}]) and a discussion of the potential implication of the findings for the safety assessment.

5.3.1 Colloid stability controlling processes

Safety case position at start of BELBaR

Stability of compacted bentonite in dilute porewater conditions has been evaluated by laboratory measurements.

The controlling process is hydration of exchangeable cations limited by the availability of cation free water.

Currently the uncertainties in geochemical conditions are greater than in uncertainties in the stability limit.

Colloid stability studies have found that model colloids that possess a significant net negative charge at neutral pH, i.e. silica and illite clay, show the greatest stability under neutral pH conditions.

The following key points reflect a summary of WP4 conclusions:

- colloid stability is influenced by the differing mineralogy of different bentonites
- there is an apparent hysteresis effect where aged gels are observed to be stronger

Both the erodibility of the clay and colloid transport in the environment are related to groundwater chemistry, the intrinsic properties of the colloids and their stability. Understanding the chemical conditions that favour or do not favour stable colloidal systems helps our understanding of the likely conditions which would favour clay erosion and colloid transport. Parameters that promote the stability of colloids are also favourable in terms of clay erosion and therefore understanding stability is very important in this context.

The composition of bentonite was shown to be important to clay erodibility in WP2 (Section 5.1.2) and a theoretical basis for understanding for the effect of divalent Ca^{2+} on clay gel stability in WP4. A self-consistent, weighted correlation approximation to density functional theory was developed to describe the structural and thermodynamic properties of counter ion-only electrical double layers. The predictions

developed agreed well with the Monte Carlo simulations and show that Ca- bentonite would behave essentially as Na- bentonite where the fraction of surface charge neutralised by Na⁺ is more than 30%. This has been observed in the region 20-30% experimentally.

Linked to the recommendations given in Section 5.1.2, the effects of the presence of a divalent ion such as Ca²⁺ in the exchanger sites is not currently considered in performance assessment. This leads to an overly pessimistic mass loss calculated in the numerical models. However, the modelling capability does not yet exist to take into account the complexity of modelling the correlation effects caused by divalent ions and thus within these limitations this conservative treatment is considered to be appropriate, particularly since it remains true that the uncertainties in geochemical conditions are greater than the uncertainties in colloid stability limits.

5.3.2 Influence of other factors on colloid stability

Safety case position at start of BELBaR

Accessory minerals seem to enrich near the bentonite-groundwater interface.

Filtration has been discussed as a possible means to reduce erosion.

Colloid size, solution ionic strength and water flow rate are factors which strongly influence colloid migration.

Association of inorganic particles with natural organic compounds is an important mechanism for colloid stabilisation.

This mechanism could potentially operate to stabilise and enhance colloid populations in the near-field porewater, this remains an area of uncertainty.

The following key points reflect a summary of WP4 conclusions:

- Na and K (M⁺) and Mg and Ca (M²⁺) act in a similar way during coagulation processes
- interaction of smectite with a mineral such as kaolinite or Al₂O₃ produces aggregation of particles
- organic matter is able to stabilise colloids in NaCl electrolyte
- in MgCl₂ and CaCl₂, clay colloids undergo fast coagulation independently of the presence of organic matter

Sodium and potassium, and magnesium and calcium act in similar ways during the coagulation process; and in real systems (e.g. natural groundwater) their effect can be simplified to the effect of M¹⁺ (Na+K) or M²⁺ (Ca+Mg) cations, where M²⁺ are more effective in coagulation. The interaction of smectite with minerals like kaolinite or Al₂O₃ produces the aggregation of particles that, alone under the same chemical conditions would be stable; this means that the presence of certain minerals not only inhibits the clay colloid generation by 'dilution', but also may affect the properties of the smectite itself making the system unstable. During the investigations the effect of hysteresis was observed with attractive forces in the gels increase with aging. One week of resting produce significantly stronger gels than those tested after 24 hours.

Organic matter (like humic or fulvic acids) was demonstrated to be able to stabilise clay colloids in NaCl electrolyte. This means that in presence of organic matter more concentrated NaCl electrolyte is needed to coagulate clay dispersion (the CCC is higher).

In all the other electrolytes investigated (CaCl₂, MgCl₂) and at higher ionic strength, the clay colloids undergo fast coagulation, independently of the presence of organic matter. This is true in various aqueous media

containing different inorganic cations, showing that the ionic strength remains the key parameter. In addition, calcium ions alone are able to initiate clay colloid agglomeration even at low concentrations. The presence of this inorganic cation, even at only low concentration in natural media, is thus recommended to be considered in performance assessments, as has been highlighted previously.

5.4 Conceptual and mathematical models

5.4.1 Current model (s): Erosion of the Bentonite buffer

Safety case position at start of BELBaR

The factors considered are;

1. groundwater velocity
2. fracture aperture
3. transport resistance of bentonite gel in terms of diffusivity
4. gel cohesivity in terms of viscosity

Small-scale tests suggests groundwater ionic strength and the presence of divalent cations are the dominant factors.

Pessimistic assumptions neglecting safety promoting aspects have been used.

The following key points [ix] reflect a summary of WP4 conclusions:

- The results from the models developed within BELBaR can match the experimental results from small scale laboratory tests
- The formation of bentonite flocs in the gel/sol interface needs to be considered in a quantitative model
- The effect of gravity and the sedimentation of bentonite in fractures need to be considered in a quantitative model
- A coupled expansion/erosion model that can consider all relevant processes can be challenging to implement numerically, thus simplifications in equations as well as in assumptions may be needed.
- The models predict a large penetration distance of clay gel into fractures
- The models can be used as an upper bound in safety assessments

At KTH model development yielded a "two-region model" in which a rim area is discretised in far higher resolution than the rest of the domain and in addition the bulk of the domain is assessed by solving a set of partial differential equations while the behaviour at the rim is evaluated by an ordinary differential equation. When assuming a specific volume fraction at the rim that triggers the release of smectite particles (flocs) by diffusion (from the gel to the flowing water) $\phi_R=0.015$ as an input in the "two-region model" the match with the small-scale experimental results is very good.

The smectite loss from a deposition hole by smectite agglomerates/flocs pulled by gravity is restrained by the rate of agglomerate transport in the fracture. In fractures smaller than 0.1 mm it is found to be less than 10-100 g/a from a deposition hole in a KBS-3 type repository that is intersected by a semi-vertical fracture. This is of the same order of magnitude as the loss by erosion in horizontal fractures.

At KTH finer grids were tested as well as simplified equations together with simplifications assuming a) steady state, b) solids concentration gradient in the direction of the flow as being much smaller than that in the cross-stream direction to it (i.e. omitted), c) cross-stream velocity being much smaller than that in the stream

wise direction (i.e. omitted) and d) diffusive mass loss at the outer rim. The result was an ordinary differential equation instead of a set of partial differential equations. When comparing the results the erosion rate was some 5 % smaller in the simplified methods when compare to the full method.

When estimating the system scaling with respect to the size of the source by solving the simplified full resolution model the mass loss and the penetration depths can be estimated. According to these simulations clay mass would be lost the closer to the source the higher the water velocity. The slope in the mathematical fits is 0.31 (i.e. $\text{Flux}=0.73 \cdot (v \cdot R)^{0.31}$) suggesting relevant dependence of mass loss rate on velocity. At low velocities the penetration of the clay front into the fracture can be substantial. There are however experimental no evidences for or against clay penetrating tens of metres into fractures.

It can be stated that a new bounding estimate is proposed to be used in the safety cases to assess clay mass loss rates; loss of clay at the clay-water interface is limited by migration of newly formed clay agglomerates in fractures. This estimate can be obtained with far lesser efforts and uncertainties than used in the previous safety cases.

5.4.2 Current model(s): Radionuclide transport mediated by Bentonite colloids

Safety case position at start of BELBaR

Clay colloids have not been considered radionuclide carriers in Posiva's safety case due to the assumed low contribution.

SKB incorporated the effective transport parameters using the MARFA code.

At the colloid concentrations likely in the far field, a significant increase in risk could arise if a proportion of the radionuclides associated with colloids are irreversibly sorbed.

In that case the risk will depend on the mobility and particle lifetimes.

No further development of quantitative models for radionuclide transport mediated by bentonite colloids has been performed in BELBaR. The conclusions from WP3 are therefore valid for this issue as well. Whether colloid transport of radionuclides should be included in the radionuclide transport calculations can be determined by a scoping calculation using assumed transport lengths, flow velocities and desorption rates for individual radionuclides. It is clear from BELBaR that colloid retardation should be included in safety assessment calculations. However, the effect may be limited under most conditions and the process could therefore be optimistically neglected. It is clear that the assumption of linear sorption is valid. Sorption reversibility is nuclide specific and should possibly be treated on a case by case basis. However, for most radionuclides sorption reversibility can be assumed over repository time scales.

6 Summary of recommendations

The BELBaR project was a collaborative project based on the desire to improve the long-term safety assessments for geological disposal facility concepts for spent fuel/ high level waste that combine a clay engineered barrier system (EBS) with a fractured rock.

Colloids may be mobile in groundwater and are thus potentially significant for safety because they have been shown to be able to sorb radionuclides and increase their effective concentration in groundwater above that which would be transported in dissolved form.

The main aim of the BELBaR project was to increase the knowledge and reduce uncertainties with respect to the processes that control clay colloid generation, stability and ability to transport radionuclides; and reduce the uncertainties in the description of the effect of clay colloids in long-term performance assessments.

A reduction of uncertainties in the understanding may lead to:

- reduction of the assessed overall risk from a repository
- the possibility to totally neglect the process in assessments under some circumstances
- guidance to future site selection and site characterisation programmes
- guidance in the selection of engineered barriers for a nuclear waste repository

The synthesis report [ii] provides a synthesis of the progress that has been made as a result of the work undertaken within the BELBaR project along with recommendations for the potential to review the treatment of colloids in performance assessment.

The following points represent a summary of recommendations³:

1. With respect to the safety assessment, the results of BELBaR suggest that assumptions made by WMOs related to the dependency of mass loss rate on groundwater flow velocity could potentially be reviewed under no highly 'erosive' conditions. It has been shown that bentonite erosion overall is driven more significantly by chemical forces rather than mechanical forces and thus it is recommended that the current treatment could be reviewed with respect to the driving mechanism controlling bentonite erosion.
2. All exchanger sites in the clay are currently assumed to be occupied by Na⁺. This assumption leads to high erosion rates and overly pessimistic mass loss calculations since the current modelling capability is not able to take into account the effects of divalent cations such as Ca²⁺. However, in a natural system, it would be difficult to exclude that the Na content of clay is less than the 20-25% threshold that favours colloid generation and thus the current treatment is considered to be appropriate within the overall system uncertainties.
3. The presence of different cations in solution can effect coagulation with divalent cations being more effective than monovalent ions as coagulants. It is currently assumed that mass loss ceases when groundwater salinity exceeds a stability limit of 4-8 mM NaCl for Na-bentonite. Should the assumed composition of the clay be reviewed (Recommendation 2) then consideration should also be given to addressing the conservatism that would be inherent in the assumed bentonite stability limit. However, within the bounds of the current knowledge, it is considered that this assumption remains appropriate.

³ Recommendations may be considered most relevant to site specific assessments.

4. In terms of the ionic strength of groundwater assumed, given that deionised water may not be representative of a real dilute groundwater, it may be considered that the maximal zero charge limit is an overly conservative scenario. However it is considered that this assumption remains appropriate within the overall system uncertainties, particularly with regard to the need to address the potential for a change on groundwater composition for example due to glacial meltwater.
5. With respect to the angle of the fracture aperture, it is observed that the mass loss mechanisms between a horizontal and sloped fracture are different. Current performance assessment assumptions assume a horizontal fracture and thus the results observed suggest that this treatment may not necessarily be conservative. It is strongly suggested that this assumption is reviewed and potentially further work is required to account for the observed effects of slope angle/ gravity.
6. Significant retardation of clay colloids in a rock fracture has been observed. However, the uptake of colloids is not complete (i.e. some remain in solution), which means that colloid transport needs to be considered, if colloids are present. It is recommended that colloid retardation could be included in safety assessment calculations. However, the effect may be limited under most conditions and the process could therefore be optimistically neglected.
7. It is clear that the current assumption of linear sorption is valid. Sorption reversibility is nuclide specific and should possibly be treated on a case by case basis. However, for most radionuclides sorption reversibility can be assumed (the exception is potentially tetravalent elements where caution should be taken) over repository time scales.
8. Organic matter (humic or fulvic acid) was demonstrated to be able to stabilise clay colloids in NaCl electrolyte. In all the other electrolytes investigated (CaCl_2 , MgCl_2) and at higher Ionic strength, the clay colloids undergo fast coagulation, independently of the presence of organic matter. This is true in various aqueous media containing different inorganic cations, showing that the ionic strength remains the key parameter. In addition, Ca^{2+} ions alone are able to initiate clay colloid agglomeration even at low concentrations. The presence of Ca, even at only low concentration in natural media, is thus recommended to be considered in performance assessments (as per Recommendations 2 and 3).
9. Regarding validation and advancing the models, sufficient confidence was obtained to predict clay mass loss rate in laboratory scales using numerical simulations whereas mass loss rate predictions repository relevant scales remain to be assessed using analytically derived expressions for bounding estimates. According to the bounding estimates referred to, the agglomerate/floc migration rate in fracture is the mass loss rate determining feature.
10. The reasoning of dominant processes was succeeded considering agglomerate migration but was based only on expert judgement for clay swelling and gravity. Moreover, data needs specifications to assess the relative importance of clay swelling and gravity were raised but only when it was too late to commit experiments within BELBaR.
11. It can be stated that a new bounding estimate is proposed to be used in the safety cases to assess clay mass loss rates; loss of clay at the clay-water interface is limited by migration of newly formed clay agglomerates in fractures. This estimate can be obtained with far lesser efforts and uncertainties than used in the previous safety cases.

7 Main dissemination activities and exploitation of results

7.1 Presentations of BELBaR work and results at international conferences

The BELBaR project was presented at several international conferences

Event - web addresses etc available in D6.7	Place and Date
First period	
Clays in natural and engineered barriers for radioactive waste confinement	Montpellier, France, October 22 - 25 2012
EURADISS 2012 workshop	Montpellier, France October 25-26 2012
International Clay Conference 2013	Rio de Janeiro, Brazil 07-11 July 2013
Clay Mineral Society	Urbana-Champaign, United States, October 6–10 2013
Migration	Brighton, United Kingdom, September 8 -13 2013
Second period	
EURADWASTE	Vilnius, Lithuania, October 14-16 2013,
17th Radiochemical conference 2014	Marianske Lazne, Czech Republic, 11 - 16 May 2014
Third period	
6 th International conference on Clays in natural and engineered barriers for radioactive waste confinement 2015 http://www.clayconferencebrussels2015.com/gallery/documents/Book_of_Abstracts_ClayConferenceBrussels2015.pdf http://www.clayconferencebrussels2015.com/	Bruxelles, 23 rd -26 th March, 2015

7.2 Meetings, workshops and training within and during the project

The BELBaR project has during its four years of operation arranged several meetings and workshops. Both annual meetings, open to the public, and project internal work package meetings, have been key elements in the implementation of this collaborative project. Some main aims of these meetings:

- » Discussing the status of the work program, the different project activities, the results, work and state of progress between all project partners, and decide on next steps.
- » Providing for the detailed agreements on the work program, joint activities and training measures, including specification of type of bentonite, radionuclides and specification of type of host rock to be used
- » Ensuring the awareness of all project partners of the project objectives, work program and reporting obligations
- » The annual meetings have contributed to integration of work within the project and to communication with a broader interested community. This has been done both by invitation of external groups to the workshops and by documentation of the progress in public reports.

7.2.1 BELBaR meetings during the first period 01/03/2012-31/08/2013

- Initially in the first period of the project there was a **kick off meeting**, held in Lund, Sweden, partially hosted by the project partner Clay Technology, 7-8 March 2012. Representatives from all but one partner were present, 24 participants, and the one that was not present still had a presentation made by another representative. The objective of the meeting was to go through the plans and objectives of the project and to give it a solid start.
- In October there was a **work package meeting** in Montpellier. Mainly WP2-4 were discussed
- During the first period of the project a **first open workshop** of the project was also held, in Helsinki, March 5th-7th 2013. The workshop attracted 54 participants during three days and 24 scientific presentations were held. The contents are presented in D1.3, the published results are presented in D6.8 and the results evaluated by the End User Review Board are presented in D6.5 End User Review Board Evaluation report from the first annual meeting. The presentations made can be found in the member area of the BELBAR web www.belbar.eu. The deliverables were completed and/or submitted during the third period of the project.

7.2.2 BELBaR meetings during the second period 1/09/2013 -28/02/2015

- WP3 meeting, 11 Sept 2013 in Brighton , England
- Work meeting in conjunction with Euradwaste, 14-16 October 2013 Vilnius, Lithuania
- A topical meeting, 22-23 Oct 2013 in Rez, Czech
- WP5 meeting, 12-13 Nov 2013 in Helsinki, Finland
- The second annual meeting, 16-18 June 2014, was held in Meiringen. Switzerland. Information and the presentations made can be found in the member area on the BELBaR web www.belbar.eu The results presented at the workshop are evaluated in the public deliverable **D6.9** End User Review Board Evaluation report from the second annual meeting.
- WP2 and WP4 Meeting, 30-31 October 2014, in Prague, Czech

7.2.3 Third period 1/3/2015-29/2/2016

- The third **annual meeting** was held in Madrid during the very first days of the third period, 5th-6th of March 2015. Information and the presentations made can be found in the member area on the BELBaR web www.belbar.eu. The results presented at the workshop are evaluated in the public deliverable D6.10 End User Review Board Evaluation report from the third annual meeting.
- A **work package meeting** for WP5 was held in Helsinki in April 2015
- A **work package meeting** was held in Karlsruhe October 12-13, 2015. Information and the presentations made can be found in the member area on the BELBaR web www.belbar.eu.
- In conjunction with the WP meeting a **training course** was also held. The training course had a duration of three days, was held by 11 lecturers and gathered 18 participants from 15 organisations. The contents, the programme and a participant list are published as public deliverable **D6.11**.
- By the end of the project, **3-4 February 2016 the End conference** of the project, open to the public, was held in Berlin, Germany. It gathered 59 interested participants from over 30 organisations and 11 countries. The presentations, together with agenda and participant list are published as **D6.12** Workshop 2. Presentations can also be found in the public part of www.belbar.eu at <http://www.skb.se/belbar/news/4th-belbar-annual-workshop/>. Proceedings, including abstracts and the evaluation report from the End User Review Board can be found as the public deliverable **D6.14**.

7.3 Students

Several of the partners have supported doctoral and/or master students within the work packages to undertake aspects of their research. The number of doctoral and master students involved can be found in the section for Work statistics in the Report on societal implications at the end of this report. A few examples are:

At the University of Helsinki

- » Outi Elo made her BSc thesis in Pirkko Hölttäs group at the Laboratory of Radiochemistry at the University of Helsinki, and continued as a part time research assistant doing sorption experiments for the BELBaR project. Outi made her MSc thesis concerning neptunium sorption in the BELBaR project and continues now as a doctoral student.
- » Suvi Niemiaho made her MSc thesis (Migration of bentonite colloids and their influence on the mobility of Sr-85 and Eu-152 in granitic rock) in the BELBaR project. During their master's work, students get a scholarship from the laboratory of radiochemistry instead of a salary.
- » In addition, Valtteri Suorsa and Elina Honkaniemi have been working connected to BELBaR as part time research assistants but their salaries have paid from the overflow of my national project.

At KTH

- » Mr. Zhao Wang was working within the BELBaR project from the start of the project till June 2013.
- » Ms. Guomin Yang has been working from April 2013 till the end of the project. Both students were engaged in trying to develop the weighted correlation approach of the Density Functional Theory and apply it to study the colloidal stability of Ca-bentonite under different conditions. Mr Wang published three papers and Ms. Yang published one paper.

At JYU

- » Joni Lämsä worked between 1.10.2015 and 31.1.2016 as technical support within the "Bentonite free swelling experiments" and

- » Topi Kääriäinen worked between 1.9.-31.10.2014 and 1.2.2015-31.8.2015: with research regarding oedometric experiments

Within MSU two students were engaged in BELBaR during the third period.

- » Maria Evsyunina (in her 4th year of education) worked with sorption of cesium onto bentonite colloids at different pH values and ionic strengths and
- » Aleksey Sarantsev (in his 4th year of education) worked with sorption of strontium onto bentonite colloids at different pH values and ionic strengths, stability and size distribution of bentonite colloids under different conditions.

7.4 Staff exchange

Some staff exchange took place when Outi Elo, Research assistant/doctoral student in BELBaR, spent two periods at the institute of Resource Ecology in the Division of Surface Processes in Helmholtz-Zentrum Dresden-Rossendorf. 26.3- 29.5.2014 and 4.9.-15.11.2014, together about 4.5 months. During the first period 26.3 - 29.5.2014 she was doing the experimental work for her Master's Thesis. The work consisted of batch sorption experiments (neptunium sorption onto montmorillonite and bentonite colloids), Zeta-potential measurements (neptunium sorption onto montmorillonite) and ATR FT-IR (Attenuated Total Reflection Fourier Transform Infra-Red) spectroscopy measurements (neptunium sorption onto montmorillonite). During the second visit she did similar batch sorption experiments (neptunium sorption and desorption on montmorillonite) and conducted EXAFS (Extended X-ray Adsorption Fine Structure) spectroscopy measurements at the Rossendorf Beamline, The European Synchrotron Radiation Facility (ESRF) in Grenoble (neptunium sorption onto montmorillonite and corundum).

Worth mentioning, even though it is not a formal staff exchange, that Veli-Matti Pulkkanen worked at Aalto University during 1.8.2015-31.12.2015 on BELBaR related conceptual and mathematical modelling of bentonite. The period was funded by (Finnish) Doctoral Programme for Nuclear Engineering and Radiochemistry (YTERA).

7.5 Peer-reviewed articles

See ECAS, and Section A, Table A1.

7.6 The project public website

www.belbar.eu

7.7 Relevant contact details regarding the project

Patrik Sellin

Svensk Kärnbränslehantering AB, SKB

Box 250, SE-10124 Stockholm, Sweden

7.8 List of Beneficiaries and contact names

	Acronym	Name	Contact person
1	SKB	Svensk Kärnbränslehantering	Patrik Sellin
2	CIEMAT	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas	Tiziana Missana
3	UJV/NRI	Nuclear Research institute Rez plc	Radek Cervinka
4	KIT	Karlsruhe Institut of Technology	Thorsten Schäfer
5	POSIVA	Posiva OY	Kari Koskinen
6	VTT	Teknologian Tutkimuskeskus VTT Oy	Veli-Matti Pulkanen
7	ClayTech	Clay Technology	Magnus Hedström
8	JYU	University of Jyväskylä	Markku Kataja
9	KTH	Kungliga Tekniska Högskolan	Longcheng Liu
10	NDA	Nuclear Decommissioning Authority	Lucy Bailey
11	B+Tech	B+Tech	Tim Schatz
12	UNIMAN	University of Manchester	Francis Livens
13	HU	Helsinki University	Pirkko Hölttä
14	MSU	Lomonosov Moscow State University	Stepan N. Kalmykov/ Vladimir Petrov
15	RWM	Radioactive Waste Management	Lucy Bailey

8 Dissemination of foreground

Section A (public) This section includes two templates

- Template A1: List of all scientific (peer reviewed) publications relating to the foreground of the project. Please see also ECAS
- Template A2: List of all dissemination activities. Please see ECAS

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers ⁴ (if available)	Is/Will open access ⁵ provided to this publication?
	Montmorillonite colloids. I: Characterization and stability of suspensions with different size fractions	Norrfors et al, KIT	Applied Clay Science	Published			2015, 114, (0)	179-189		Available for free
	Effect of grain size on the sorption and desorption of SeO ₄ ²⁻ and SeO ₃ ²⁻ in columns of crushed granite and fracture infill from granitic water under dynamic conditions	Videnská et al, UJV	Journal of Radioanalytical and Nuclear Chemistry,	Published			2013		DOI :0.1007/s10967-013-2429-7.	Available but not for free
	Montmorillonite colloids. II: Dependency of Colloidal size on Sorption of Radionuclides	Norrfors et al , KIT	Applied Clay Science	Published			online 2016, January, print later 2016		doi:10.1016/j.clay.2016.01.017	Available for free
	A refined algorithm to simulate latex colloid agglomeration at high ionic strength	Christophe et al, KIT	Adsorption	Published.			2015	1-13		Available but not for free
	Accelerator Mass Spectrometry of actinides in ground-and sea-water: An Innovative method for the simultaneous analysis of U, Np, Pu, Am and	Quinto et al	Analytical Chemistry	Published.			2015, 87, (11)	5766-5773.	DOI: 10.1021/acs.	Available but not for free

⁴ A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

⁵ Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

Cm isotopes below ppq levels								analchem. 5b00980	
Influence of mineralogical and morphological properties on the cation exchange behavior of dioctahedral smectites	Delavernhe et al, KIT	Colloids & Surfaces A Physicochemical and Engineering Aspects	Published.			2015, 481	591- 599		Available but not for free
Prediction of swelling pressures of different types of bentonite in dilute solutions	Liu L.C	Colloids and Surfaces A: Physicochem. Eng. Aspects	Published.			434, (2013)	303 – 318		Available but not for free
The Swelling pressure of Na-bentonite: Study with a density functional approach	Wang Z. and Liu L.C	Chem. lett.	Published			41, (2012)	1346 – 1348		Available for free
Weighted correlation approach: An extended version with applications to the hard-sphere fluid	Wang Z. and Liu L.C	Phys. Rev. E	Published			86 (2012)	03111 5		Available for free
Counterion-only electrical double layers: an application of the density functional theory	Longcheng Liu	Journal of Chemical Physics	Published.					http://scitation.aip.org/content/aip/journal/jcp/143/6/10.1063/1.4928508	Available but not for free
A systematic comparison of different approaches of density functional theory for the study of electrical double layers	Guomin Yang and Longcheng Liu	Journal of Chemical Physics	Published.			142, (2015).	19411 0	http://scitation.aip.org/content/aip/journal/jcp/142/19/10.1063/1.4921376	Available but not for free
A weighted correlation approach of the density functional theory for an inhomogeneous fluid at an interface	Wang, KTH	Doctoral Thesis	Published					URN: urn:nbn:se:kth-diva-119776 ISBN: 978-91-7501-668-9 OAI: oai:DiVA.org/kth-119776 DIVA: diva2.612339	Available for free
Rheological Properties of Clay Material at the Solid/Solution Interface formed under Quasi-Free Swelling Conditions	Eriksson & Schatz, VTT	Applied Clay Science	Published.			108 (2015)	12-18		Available but not for free
The effect of humic acid on uranyl sorption onto bentonite at trace uranium levels	Ivanov et al, UNIMAN	J. Environ. Monit.,	Published.			2012,14 ,	2968- 2975		Available but not for free
Reversibility in Radionuclide/Bentonite Bulk and Colloidal Ternary Systems	Sherriff et al, UNIMAN	Mineralogical Magazine	Published	Mineralogical society		vol. 79 no. 6 (2015)	1307- 1315	DOI http://dx.doi.org/10.1180/minmag.2015.079.06	Available for free
Interaction of Radionuclides and Colloids Released from Materials Related to the Disposal	Hölttä et al,	2014 Waste Management	Published			Vol. 40.		ISBN (electronic) 978-	Available for

of SNF – 14273.	HU	Symposia,				2014		0-9836186-3-8	free
Actinide (Np-237) sorption on montmorillonite and bentonite colloids.	Outi Elo, HU	Master's thesis, University of Helsinki, Department of Chemistry	Published			(2014)			Available for free
Migration of ⁸⁵ Sr in crushed granite in presence of bentonite colloids	Videnská et al, UJV	Journal of the Geological Society	Accepted						Yes, open access, for free
Size distribution of bentonite colloids upon fast disaggregation in low ionic strength water	Mayordomo et al, CIEMAT	Journal of the Geological Society	Accepted						
Hydration of Febex-Bentonite observed by Environmental Scanning Electron Microscopy (ESEM).	Friedrich et al, KIT	CMS Workshop Lecture Series 2016	Accepted			2016			Available for free
Influence of the sample preparation on MX-80 bentonite microstructure	Matusiewicz et al, VTT	Clay Minerals	Accepted						Will be available for free

	Batch sorption and spectroscopic speciation studies of neptunium uptake by montmorillonite and corundum	Elo et al, HU	Geochimica et Cosmochimica Acta	Reviewer's comments received in January. Will be resubmitted before the end of April 2016	Submitted, reviewed
	Colloid erosion from confined and compacted natural bentonites	Alonzo et al CIEMAT	Applied Geochemistry		Submitted
	Transport of Uranium and Cesium in a granite fracture in the presence of bentonite colloids: effects of sorption irreversibility	Missana et al, CIEMAT	Journal of Contaminant Hydrology		Submitted
	Migration of bentonite colloids and their influence on the mobility of Sr-85 and Eu-152 in granitic rock	Hölttä et al, HU	Journal of Contaminant Hydrology/Physics and Chemistry of the Earth/ Radiochimica Acta		In preparation
2	Radionuclide sorption on bentonite colloids	Hölttä et al, HU	Physics and Chemistry of the Earth/ Radiochimica Acta		In preparation
	Uranium dissociation from bentonite colloids, a kinetic investigation	Sherriff et al, UNIMAN	Environmental Science-Processes & Impact		In preparation

	Response of montmorillonite suspensions to low frequency oscillatory shear	Eriksson & Schatz, B+tech	Langmuir	In preparation
	X-ray imaging method for monitoring one-dimensional free swelling of bentonite	Harjupatana et al, JYU	Applied Clay Science	In preparation
	Thermoreversible behaviour in smectite clay gel	Hansen and Hedström, Clay Tech	Scientific Reports	In preparation
	Colloidal pastes, gels and sols: State diagrams of three different Na-montmorillonites	Hansen and Hedström, Clay Tech	Applied Clay Science	In preparation
	Radionuclide sorption onto clay colloids	Romanchuk and Kalmykov, MO	Radiochimica Acta/Geochimica et Cosmochimica Acta	In preparation
	Summary of the findings from BELBaR	Shelton et al	MRS Proceedings	planned
	Destabilization of montmorillonite colloids by addition of Alumina Nanoparticles	Mayordomo et al, CIEMAT	Environmental Science & Technology	Planned
	Irreversibility of cation adsorption from bentonite colloids	Missana et al, CIEMAT	Applied geochemistry	Planned
	Montmorillonite colloids. III: Influence of colloidal size on the sorption reversibility of radionuclides	Knapp Karin Norrfors et al, KIT	Applied Clay Science	Planned
	Coagulation behaviour of clay dispersions in simple electrolytes	Gondolli and Červinka, UJV	Applied Clay Science	Planned
1	Results of two years erosion experiments performed on MX80 bentonite clay pellets of different compositions, under quasi-stagnant flow and glacial melt water type conditions	Bouby et al, KIT	Journal of colloids and Interface Science or Applied Clay Science	Planned
	Pu, Np, Am transport under near-natural flow conditions at the Grimsel Test Site (Switzerland): Influence of earth-tide effects	Schäfer et al, KIT	Environmental Science & Technology	planned
	Development of models for bentonite erosion within the BELBaR project	Koskinen and Kasa, Posiva	MRS Proceedings	Planned
	Chemical erosion as a function of flow velocity and size of source – scaling study by modelling	Olin and Koskinen, VTT	Applied Clay Science	Planned
	Microstructure of Na-montmorillonite	Matusewicz et al, VTT	tbd	Planned

Microstructure of Na-montmorillonite	Matusewicz et al, VTT	tbd	Planned
NMR investigation of MX-80 microstructure (tentative)	Matusewicz et al. VTT	tbd	Planned
Modelling bentonite behaviour in spent nuclear fuel disposal conditions (Dr. Sc. (Tech.) Thesis)	Pulkkanen, VTT		Planned
Rheology measurements on montmorillonite gels	Hedström & Nilsson, Clay Tech	Applied Clay Science	Planned
Erosion of colloidal clay particles in Hele-Shaw cells	Hansen & Hedström, Clay Tech	J. Colloid Interface Sci.	Planned
Modelling bentonite erosion and comparison with experiments	Neretnieks et al, KTH		Planned
Tri- and Tetra-valent actinide interactions with bentonite colloids	Sherriff et al, UNIMAN	Environmental Science-Processes & Impacts	Planned
Homo-interaction between parallel plates at constant charge: Study with the solvent primitive model	Liu, KTH	J. Chem. Phys.,	Planned, Not open access

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES *Please See ECAS and sections 7.1 and 7.2*

Section B (Confidential⁶ or public: confidential information to be marked clearly)

Part B1

N/A

Part B2

N/A

⁶ Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

Report on societal implications

A General Information *(completed automatically when Grant Agreement number is entered.*

Grant Agreement Number:

Title of Project:

Name and Title of Coordinator:

B Ethics

<p>1. Did your project undergo an Ethics Review (and/or Screening)?</p> <ul style="list-style-type: none"> If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? <p>Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 'Work Progress and Achievements'</p>	NO
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<p>2. Please indicate whether your project involved any of the following issues (tick box) :</p>	YES
---	------------

RESEARCH ON HUMANS

- | | |
|---|--|
| • Did the project involve children? | |
| • Did the project involve patients? | |
| • Did the project involve persons not able to give consent? | |
| • Did the project involve adult healthy volunteers? | |
| • Did the project involve Human genetic material? | |
| • Did the project involve Human biological samples? | |
| • Did the project involve Human data collection? | |

RESEARCH ON HUMAN EMBRYO/FOETUS

- | | |
|---|--|
| • Did the project involve Human Embryos? | |
| • Did the project involve Human Foetal Tissue / Cells? | |
| • Did the project involve Human Embryonic Stem Cells (hESCs)? | |
| • Did the project on human Embryonic Stem Cells involve cells in culture? | |
| • Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos? | |

PRIVACY

- | | |
|---|--|
| • Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)? | |
| • Did the project involve tracking the location or observation of people? | |

RESEARCH ON ANIMALS

- | | |
|---|--|
| • Did the project involve research on animals? | |
| • Were those animals transgenic small laboratory animals? | |
| • Were those animals transgenic farm animals? | |
| • Were those animals cloned farm animals? | |
| • Were those animals non-human primates? | |

RESEARCH INVOLVING DEVELOPING COUNTRIES

- | | |
|---|--|
| • Did the project involve the use of local resources (genetic, animal, plant etc)? | |
| • Was the project of benefit to local community (capacity building, access to healthcare, education etc)? | |

DUAL USE

- | | |
|---|----|
| • Research having direct military use | No |
| • Research having the potential for terrorist abuse | NO |

C Workforce Statistics		
3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).		
Type of Position	Number of Women	Number of Men
Scientific Coordinator		1
Administrative coordinator	1	
Work package leaders	3	4
	CIEMAT 2 NDA/RWM 3 UJV 2 VTT 0 Clay 1 UNIMAN 0 HU 2 KIT 1 KTH 0 SKB 0 MSU 3 JYU 0 B+tech Posiva	1 0 4 1 2 2 0 8 3 2 3 1 2 1
Experienced researchers (i.e. PhD holders)	TOTAL 14	29
	CIEMAT 1 UJV 1 VTT 0 UNIMAN 0 HU 1 KIT 1 KTH 1 MSU 2 JYU 0	0 0 2 1 0 1 1 0 2
PhD Students	TOTAL 7	7
	CIEMAT 3 UJV 2 VTT 1 HU 1 SKB 2 MSU 1 JYU 0	2 1 0 1 1 1 5
Other	TOTAL 10	11
4. How many additional researchers (in companies and universities) were recruited specifically for this project?		1
Of which, indicate the number of men:		1

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project? Yes No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective	Very effective
<input type="checkbox"/> Design and implement an equal opportunity policy	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>
<input type="checkbox"/> Set targets to achieve a gender balance in the workforce	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>
<input type="checkbox"/> Organise conferences and workshops on gender	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>
<input type="checkbox"/> Actions to improve work-life balance	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>	<input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/> <input type="radio"/>
<input type="radio"/> Other: <input type="text"/>		

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

- Yes- please specify
- No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

- Yes- please specify
- No

University students were involved in the project, workshops and training were open to them

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

- Yes- please specify
- No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

- Main discipline⁷: 1.3, 1.2, 1.4, 1.1
- Associated discipline⁷: | Associated discipline⁷:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? (if 'No', go to Question 14) Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

- No
- Yes- in determining what research should be performed
- Yes - in implementing the research

⁷ Insert number from list below (Frascati Manual).

Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?

Yes
 No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- No
- Yes- in framing the research agenda
- Yes - in implementing the research agenda
- Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs	Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid	Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport
---	---	---

13c If Yes, at which level?		
<input type="radio"/> Local / regional levels <input type="radio"/> National level <input type="radio"/> European level <input type="radio"/> International level		
H Use and dissemination		
14. How many Articles were published/accepted for publication in peer-reviewed journals?		21
To how many of these is open access⁸ provided?		12
How many of these are published in open access journals?		
How many of these are published in open repositories?		
To how many of these is open access not provided?		9
Please check all applicable reasons for not providing open access:		
<input checked="" type="checkbox"/> publisher's licensing agreement would not permit publishing in a repository <input checked="" type="checkbox"/> no suitable repository available <input checked="" type="checkbox"/> no suitable open access journal available <input type="checkbox"/> no funds available to publish in an open access journal <input type="checkbox"/> lack of time and resources <input type="checkbox"/> ? lack of information on open access <input type="checkbox"/> other ⁹ :		
15. How many new patent applications ('priority filings') have been made? <i>("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).</i>		0
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	0
	Registered design	0
	Other	0
17. How many spin-off companies were created / are planned as a direct result of the project?		0
<i>Indicate the approximate number of additional jobs in these companies:</i>		
18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:		
<input type="checkbox"/> Increase in employment, or <input type="checkbox"/> Safeguard employment, or <input type="checkbox"/> Decrease in employment, <input type="checkbox"/> Difficult to estimate / not possible to quantify	<input type="checkbox"/> In small & medium-sized enterprises <input type="checkbox"/> In large companies <input checked="" type="checkbox"/> None of the above / not relevant to the project	
19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs:		<i>Indicate figure:</i> 0

⁸ Open Access is defined as free of charge access for anyone via Internet.

⁹ For instance: classification for security project.

Difficult to estimate / not possible to quantify	X
I Media and Communication to the general public	
20. As part of the project, were any of the beneficiaries professionals in communication or media relations?	<input type="radio"/> Yes <input checked="" type="radio"/> No
21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?	<input type="radio"/> Yes <input checked="" type="radio"/> No
22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?	
<input type="checkbox"/> Press Release	<input checked="" type="checkbox"/> Coverage in specialist press
<input type="checkbox"/> Media briefing	<input type="checkbox"/> Coverage in general (non-specialist) press
<input type="checkbox"/> TV coverage / report	<input type="checkbox"/> Coverage in national press
<input type="checkbox"/> Radio coverage / report	<input type="checkbox"/> Coverage in international press
<input checked="" type="checkbox"/> Brochures /posters / flyers	<input checked="" type="checkbox"/> Website for the general public / internet
<input type="checkbox"/> DVD /Film /Multimedia	<input type="checkbox"/> Event targeting general public (festival, conference, exhibition, science café)
23 In which languages are the information products for the general public produced?	
<input type="checkbox"/> Language of the coordinator	<input checked="" type="checkbox"/> English
<input type="checkbox"/> Other language(s)	

References

- i R. Beard, D. Roberts, P. Sellin, K. Koskinen, L. Bailey, *State-of-the-art report on the treatment of colloids and related issues in the long terms safety case*, BELBaR D1.2, October 2012.
- ii A. Shelton, P. Sellin, T. Missana, R. Červinka, T. Schäfer, K. Koskinen. *Synthesis report: colloids and related issues in the long term safety case*, BELBaR D1.4, 2016
- iii M. Nykyri, H. Nordham, N. Marcos, J. Löfman, A. Poteri, A. Hautojärvi, *Radionuclide release and transport – RNT-2008*, Posiva Report 2008-06, Posiva Oy, Eurajoki, 2008
- iv I. Neretnieks, L. Liu, L. Moreno, *Mechanisms and models for bentonite erosion*, SKB TR-09-35, Svensk Kärnbränslehantering AB, Stockholm, 2009
- v S. W. Swanton, W.R. Alexander, J.A. Berry, *Review of the behaviour of colloids in the near field of a cementitious repository*, Serco Report SERCO/TAS/000475/01, Issue 2, 2010
- vi T. Shatz, R. Eriksson, E. Ekvy Hansen, M. Hedström, T. Missana, U Alonso, N. Mayordomo, A.M. Fernández, M. Bouby, S. Heck, F. Geyer, T. Schäfer, *WP2 partners final report on bentonite erosion*, BELBaR D2.11, 2015
- vii T. Schäfer, N. Sheriff, N. Bryan, F. Livens, M. Bouby, G. Darbha, M. Stoll, F. Huber, P. Hölttä, O. Elo, V. Suorsa, E. Honkaniemi, S. Niemiaho, T. Missana, U. Alonso, N. Mayordomo, K. Kolomá, R. Červinka, A. Y. Romanchuk, P. K. Verma, V. G. Petrov, S. n. Kalmykov, *WP3 partners final report on experimental results on micro- to macroscale colloid rock interaction and colloid radionuclide interaction*, BELBaR D3.11, 2016
- viii T. Misanna, U. Alonso, N. Mayordomo, A.M. Fernández, T.López, M. Hedström, E. Ekvy Hansen, U. Nilsson, M. Bouby, Y. Heyrich, S. Heck, S. Hilpp, T. Schäfer, L. Liu, L. Moreno, I. Neretnieks, J. Gondolli, R. Červinka, *Final report on experimental results on clay colloid stability WP4*, BELBaR D4.11, 2016
- ix K. Koskinen. *WP5 partners final report on development of conceptual and mathematical models within BELBaR*, BELBaR D5.3, 2016