Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Randy Arthur

Technical Note

2012:26

Initial review of chemical and erosional processes within the buffer and backfill - Chemical erosion processes

Report number: 2012:26 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Denna rapport består av en "Technical Note" inom SSM:s inledande granskning av SKB:s säkerhetsredovisning SR-Site. Syftet med denna inledande granskning av frågorna kring kemisk erosion av buffert och återfyllnad i slutförvarsanläggningen är att få en bred granskning och belysning av SR-Site och underreferenser samt att identifiera eventuella behov av kompletterande information eller förtydliganden som SKB bör tillfoga ansökansunderlaget.

Författarens sammanfattning

De dokument i SR-Site som är relevanta till detta granskningsområde bedöms vara generellt i tillräckligt hög kvalitet för att utgöra underlagsmaterial för vidare granskning i huvudgranskningsfasen av SSM:s GLS- (granskning av långsiktig säkerhet) projekt. Behov av kompletterande information eller förtydliganden har dock identifierats inom flera specifika ämnen (Appendix 2). Några specifika granskningsfrågor har också rekommenderats till fördjupade granskning i huvudgranskningsfasen (Appendix 3).

Projektinformation

Kontaktperson på SSM:
Diarienummer ramavtal: SSM2010-4230
Diarienummer avrop: SSM2011-4205
Aktivitetsnummer: 3030007-4006

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

This report consists of a Technical Note in SSM's initial review phase of SKB's safety analysis SR-Site. The aim of the initial review of issues concerning chemical erosion of buffer and backfill in a final repository is to make a broad illustration and review of SR-Site together with its subordinate references, as well as to identify potential needs for complementary information or clarification which SKB should supplement to its license applications.

Summary by the author

The SR-Site documentation relevant to this review topic was found to be of sufficiently high quality overall to justify further consideration in the Main Review Phase of SSM's PCS (Post-closure safety) project. Several specific topics for which complementary information and clarifications should be requested from SKB were also identified (Appendix 2). Specific review topics for consideration during the Main Review Phase are recommended in Appendix 3.

Project information

Contact person at SSM: Jinsong Liu

Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Randy Arthur
Intera Inc., Denver, Colorado, USA

Technical Note 8

2012:26

Initial review of chemical and erosional processes within the buffer and backfill - Chemical erosion processes

Date: August 2012
Report number: 2012:26 **SSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Contents

1. Introduction

This report summarizes the results of a preliminary review of SKB's investigations related to possible chemical erosion of the buffer and backfill in a KBS-3 repository at Forsmark. The results are intended to support SSM's initial review phase of SKB's safety assessment SR-Site. The objective of the review was therefore to determine whether the documentation in SR-Site and supporting references is reasonably complete and of sufficiently high quality to justify a more detailed review of chemical erosion processes potentially affecting the safety functions of the buffer and backfill, and in particular to identify any complementary information and clarifications needed from SKB before such a review could be carried out.

A conceptual model of buffer chemical erosion is illustrated schematically in Figure 1_1 (the basic model is also applied to the backfill in SR-Site). The figure represents a vertical cross section through a portion of a KBS-3V deposition hole that is intersected by a horizontal fracture. Free swelling of bentonite from the deposition hole outward into the fracture is resisted by friction forces acting within the bentonite and at the rock interface. The maximum penetration distance is reached when these counteracting forces equilibrate. Bentonite density and swelling pressure then decrease rapidly with increasing distance in the fracture. The rheological properties of the bentonite change accordingly from those of a solid → gel → fluid (which may also include a semi-fluid phase). Fluid properties are identical to those of groundwater at the penetration front. Clay colloids form near this front, and are lost by diffusion into the flowing groundwater. Bentonite fluids (*i.e.*, dispersions of bentonite colloids in water, not solids or gels) may also be lost by advection. More bentonite then extrudes into the fracture from the deposition hole to restore equilibrium. The resultant mass loss of bentonite from the deposition hole results in a decrease in buffer density. Erosion could adversely impact safety functions of the buffer because the corresponding safety function indicators generally depend, either directly or indirectly, on the buffer's density.

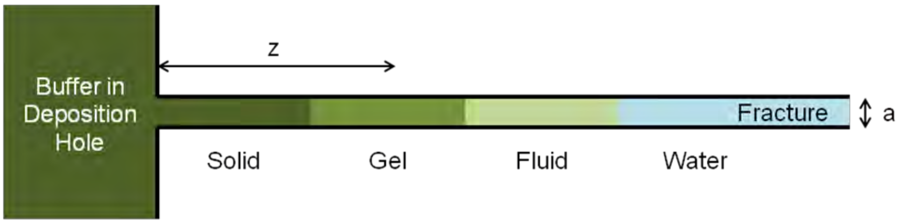

Figure 1_1: Conceptual model of buffer erosion (Birgersson et al., 2009). The swelling pressure of bentonite in the fracture decreases exponentially with increasing distance, z, and, at a given distance, with decreasing fracture aperture, a.

The preliminary review described in the present report focussed on these chemical aspects of buffer and backfill erosion. This entailed consideration of fundamental processes controlling the formation, stability and transport of colloidal smectite gels and sols over a range of groundwater flow and chemical conditions, conceptual and numerical models of processes controlling the erosion rate, factors controlling the evolution of buffer and backfill density and geometry distributions during periods of erosion, the efficacy of possible colloid-filtration mechanisms, and other chemical erosion processes described in SKB reports. Physical processes, including those controlling the so-called "piping and erosion" of buffer and backfill materials, were excluded from this review assignment. Appendix A provides a listing of SKB reports considered in the review and full bibliographic details are provided in Section 4.

2. Main Review Findings

The review was structured in terms of a number of general topics, which were considered here specifically with regard to chemical erosion of the buffer and backfill. These topics included:

- Completeness of the safety assessment;
- Scientific soundness and quality of the SR-Site safety case;
- Adequacy of relevant models, data and safety functions;
- Handling of uncertainties;
- Preliminary assessment of safety significance; and
- Quality, in terms of transparency and traceability, of information in SR-Site and associated references

An additional topic dealing with issues related to manufacturing, construction, testing, implementation, and operation (of the buffer and backfill) was not considered relevant to this review assignment. Review findings in relation to each of the above topics are described below.

2.1. Completeness of the safety assessment

The question of whether SR-Site is complete in its treatment of buffer/backfill chemical erosion was taken to concern whether there are any obviously missing pieces of information needed to carry out a more detailed review. If appropriate, such a review would be conducted during the Main Review Phase of SSM's Post Closure Safety (PCS/GLS) project (Dverstorp et al., 2011).

SR-Site is considered to be sufficiently complete in this sense, with the exception of topics discussed in the following subsections that may require further clarification and possible expansion during the Main Review Phase. SKB has developed a coherent set of arguments dealing with chemical erosion of (primarily) the buffer as a result of work carried out since the issue was first addressed in the SR-Can Interim Process Report (SKB 2004). Results of this initial analysis indicated that advective conditions in the buffer could be generated in a substantial number of deposition holes over a reasonable range of hydrogeological conditions at the Forsmark and Laxemar sites. The accuracy of the estimated erosion rates was acknowledged to be highly uncertain, however, because the calculation model was not built upon a mechanistic understanding of processes controlling colloid release from compacted buffer materials (SKB 2006). SKB therefore established the Buffer Erosion Project to address these deficiencies in understanding. The project included a number of experimental, modelling and natural analogue studies carried out in Sweden and internationally. Project results were documented in many of the reports identified in Appendix 1 and references contained therein. The treatment of buffer/backfill chemical erosion in SR-Site is largely based upon these results and indicates that 1) buffer erosion cannot be ruled out in the assessment of long-term safety, 2) there is still uncertainty with regard to modelling of colloid formation and subsequent erosion of the buffer material, and 3) erosion cannot be defensibly mitigated, e.g., by selection of alternative buffer materials (SKB 2011; e.g., Section 15.3.5). For these reasons SKB is presently engaged in a continuation of its R&D programme on buffer erosion mechanisms.

2.1.1. Numerical model of buffer erosion

The treatment of buffer/backfill chemical erosion in SR-Site lacks an adequately detailed description of the numerical model used to evaluate erosion rates (Moreno et al., 2010). The conceptual model upon which the numerical model is based accounts for forces that control the expansion of bentonite from a deposition hole into a fracture (dynamic force-balance model), and for the effects of particle and ionic concentrations on the viscosity of the expanded bentonite (viscosity model) (Neretnieks et al., 2009; Liu, 2011). The force-balance and viscosity models were combined by Moreno et al. (2010) into an overall model of buffer erosion, which accounts for both the Brownian motion of individual clay colloids into flowing groundwater and for the advection of sols that form within the fracture as the bentonite expands and becomes less dense and less viscous. The model was evaluated using an unreferenced "numerical code", but details concerning this code and associated numerical methods were not provided (Moreno et al., 2010). This information should be requested from SKB (Appendix 2).

2.1.2. SKB's R&D programme on buffer/backfill erosion

SKB has acknowledged that there are significant uncertainties in the treatment of buffer/backfill chemical erosion in SR-Site and have therefore implemented an R&D programme aimed at reducing these uncertainties. The duration of this work may to some extent overlap the Main Review Phase of the PCS project and could therefore result in new information that is relevant to SSM's evaluation of this issue. SKB should therefore be requested to provide information and periodic updates concerning the work scope, status and reporting schedules of current and planned studies in the R&D program (Appendix 2). Given the acknowledged safety significance of this issue in SR-Site and the relatively short duration of SSM's Main Review Phase it is recommended that these focussed updates be provided more frequently than SKB's traditional RD&D plan descriptions.

2.2. Scientific soundness and quality of SR-Site

The adequacy of the scientific basis underpinning the treatment of buffer/backfill chemical erosion in SR-Site was evaluated with the following questions in mind:

- Are key scientific conclusions adequately supported and justified, and
- Are necessary references provided and are they sufficiently specific?

Issues which raise doubts as to whether the first of these questions can be answered affirmatively are discussed in the following subsections. All references reviewed in this review assignment were found to be sufficiently specific, with the exception noted in Section 2.1.1.

2.2.1. Hydrogeologic constraints on erosion rates

The buffer erosion model is based on an idealized case of two-dimensional groundwater flow in a horizontal fracture intersecting a deposition hole (Neretnieks et al., 2009; Moreno et al., 2010). The model was evaluated by assuming a smooth-walled fracture with aperture = 1 mm. Bentonite was represented by a pure Na-montmorillonite and the groundwater was assumed to be a dilute NaCl solution. Groundwater flow velocities were assumed to vary between 0.1 and 315 m yr^{-1}. The Darcy flow equation, solute diffusion equations, and governing equations underpinning the force-balance and viscosity models were evaluated simultaneously (Moreno et al., 2010). Model results, shown in Table 2.2.1_1, indicated that erosion rates increase, and the length of the fracture penetrated by bentonite decreases, with increasing groundwater flow velocity.

Table 2.2.1_1. Calculated erosion rates and penetration distances of bentonite in fractures using the buffer erosion model (Neretnieks *et al.*, 2009; Moreno et al., 2010).

Water velocity (m yr^{-1})	*Erosion rate (g yr^{-1})*	*Penetration distance (m)*
0.10	11	34.6
0.32	16	18.5
0.95	26	11.5
3.15	43	7.0
31.50	117	2.1
315.00	292	0.5

The results in Table 2.2.1_1 were used to define a generalized erosion rate given by (Neretnieks et al., 2009):

$$R_{erosion} = A\delta v^{0.41},$$

where $R_{erosion}$ represents the montmorillonite release rate, δ refers to fracture aperture (m), v denotes water velocity (m yr^{-1}) and A stands for a constant (= 27.2 with units consistent with a release rate in kg yr^{-1}). The erosion rate is thus strongly dependent on localized flow conditions in fractures intersecting individual deposition holes.

The distribution of δ and v values in fractures intersecting the approximately 6,000 deposition holes in a repository at Forsmark were interpreted in SR-Site based on the results of repository-scale groundwater flow models utilizing a semi-correlated relation between fracture length and transmissivity. This relation was considered to be the most realistic among alternative approaches (fully correlated and uncorrelated models), but it is not presently possible to quantify the degree of correlation in a rigorous manner (SKB 2011; Section 12.2.2). Although such lack of rigor is a potential issue in terms of the scientific soundness of SR-Site, it probably cannot be addressed further until the repository is constructed and more direct experience is gained in characterizing fracture properties at repository depths. SSM should acknowledge this possibility and consider stipulating as a conditional requirement that characterization work aimed at improving correlations between fracture size and transmissivity should be carried out by SKB if the license application is approved.

2.2.2. Handling of the buffer erosion model in SR-Site

Several alternative cases were evaluated in SR-Site for the purpose of estimating the number of deposition holes that could experience advective conditions as a result of buffer erosion within 100,000 and 1 million years (SKB 2011; Section 12.2.2). Relative to a base case, in which a semi-correlated relation between fracture length and fracture transmissivity was used, the alternative cases assumed:

- 600 kg of buffer must be lost before advective conditions would be established in a deposition hole (instead of 1200 kg as in the base case);
- 2400 kg of buffer must be lost before advective conditions would be established;
- Deposition holes are exposed to erosive conditions 100% of the time (instead of 25% of the time as in the base case);
- A pessimistic relation between fracture aperture and transmissivity;
- A fully correlated relation between fracture length and transmissivity; or
- An uncorrelated relation between fracture length and transmissivity.

Figure 2.2.2_1 presents the results of this analysis. As can be seen, the results are bounding for each of the alternative cases individually, but do not account for the possibility that these cases could also be combined in various ways. For example, if it is assumed that only 600 kg must be lost from a deposition hole before advective conditions would be established, then it could also be assumed, in addition, that erosive conditions exist 100% of the time, that a pessimistic relation exists between fracture aperture and transmissivity, and that fracture length and transmissivity are uncorrelated. Because such combinations seem plausible, the results in Figure 2.2.2_1 may be incomplete and may be insufficiently pessimistic for propagation to an analysis of canister corrosion. SSM should seek clarification from SKB as to why various combinations among the alternative cases noted above were not evaluated in SR-Site (Appendix 2).

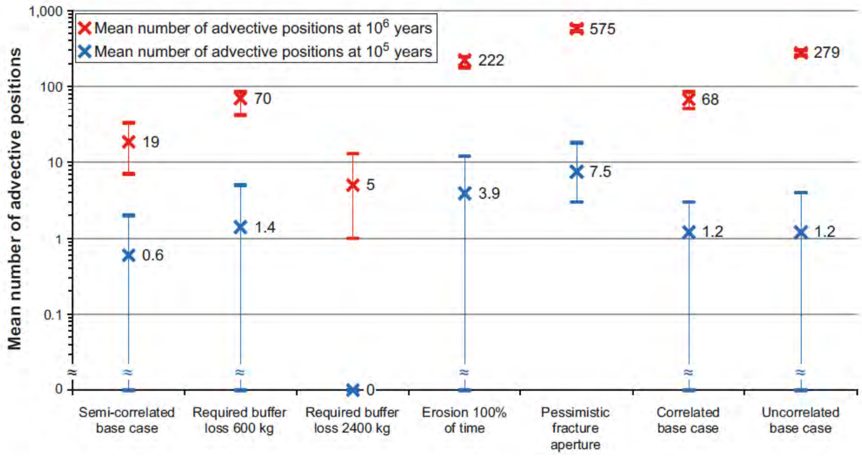

Figure 2.2.2_1. Calculated extent of erosion at 100,000 years and at 1 million years for a number of cases (SKB, 2011; Section 12.2.2). The crosses denote mean values and the bars denote the variability over the several realizations of the hydrogeological DFN model.

2.2.3. Conservatism in estimates of buffer erosion

The buffer erosion model assumes that bentonite can be represented by a pure Na-montmorillonite and that groundwater can be represented by a pure NaCl solution (Neretnieks et al., 2009; Moreno et al., 2010). These assumptions may be considered conservative, in the sense that the model over predicts erosion rates, because Cadominated clays are known not to swell as much as their Na-dominated counterparts and are therefore less susceptible to colloid formation (Jönsson et al., 2009). This view may be questionable, however, because for more realistic systems containing both Na^{+} and Ca^{2+}, the coupled effects of solute transport and ion-exchange reactions on gel/sol viscosity are largely unknown due to a lack of relevant experimental data. For this reason Neretnieks et al. (2009) concluded that reactive-transport phenomena could conceivably lead to an increase, or decrease, in model predictions of smectite loss. If so, estimates obtained using the buffer erosion model in SR-Site may not be conservative. Because this possibility appears to arise from a lack of experimental data characterizing the viscosity of montmorillonite gels/sols in Ca-bearing systems, SSM should seek clarification from SKB concerning whether such information will be obtained in its on-going R&D programme on buffer chemical erosion (include as part of Item 2, Appendix 2).

2.2.4. Backfill analysis

The analysis of backfill loss by chemical erosion is based on the same model used for the buffer (SKB 2011; Section 10.3.11). The loss rate was, however, increased by a factor of 2 to account for the increase in diameter of the interface between the fracture and deposition tunnel. No justification was (apparently) provided in SR-Site for the assumption that the erosion model is appropriate for both the buffer and backfill. This assumption may be questionable given the fact that material properties and saturated densities of these barriers will differ significantly. SSM should request clarification from SKB justifying the use of the buffer erosion model for tunnel backfill (Appendix 2).

2.2.5. Alternative models

Birgersson et al. (2009) described an alternative to the “Neretnieks” model of buffer chemical erosion (i.e., Neretnieks et al., 2009). The alternative model accounts for the rate of expansion of bentonite into a fracture restrained by friction forces at the fracture walls. A preliminary analysis using the model indicated that bentonite would penetrate a maximum distance of only a few mm into a fracture, and that the corresponding erosion rate would be independent of fracture aperture (Birgersson et al., 2009; Section 3.9). In contrast, the Neretnieks model predicts that the penetration distance would vary with groundwater flow velocity (Table 2.2.1_1) and that the erosion rate would increase with increasing fracture aperture. Although the reasons for these discrepancies are not clear, Neretnieks et al. (2009) concluded that the Birgersson et al. (2009) model was unrealistic based on an analysis of the role of wall friction on an expanding gel in a fracture. Ignoring such frictional forces was also assumed to be conservative (SKB 2010c; Section 3.5.11). This criticism was not addressed by Birgersson et al. (2009), and the present status of these conflicting points of view is unclear. SSM should seek clarification from SKB regarding its rationale for selecting the Neretnieks model of buffer erosion for use in SR-Site, and whether there are plans in SKB’s on-going R&D programme to further consider alternatives to this model (Appendix 2).

2.3. Adequacy of relevant models, data and safety functions

The following questions were considered with regard to the adequacy of models, data and safety functions used in SR-Site, specifically as they pertain to buffer/backfill chemical erosion:

- Are key datasets and data treatments (e.g., derivation of effective parameters) used in the evaluations adequately described and referenced;
- Are mathematical models sound and adequately described; and
- Are relevant safety functions, safety function indicators, and safety function indicator criteria adequately explained and justified?

Comments addressing these questions are summarized in the following subsections. All references to mathematical models reviewed in this review assignment were found to be adequately described, with the exception noted in Section 2.1.1.

2.3.1. Abstraction of buffer erosion rates in SR-Site

The abstraction methodology used in SR-Site to define the rate of buffer chemical erosion, i.e., $R_{erosion} = A\delta v^{0.41}$ (see Section 2.2.1), is based on a very limited set of modelling results (Neretnieks et al., 2009). The results are moreover relevant only for a highly simplified, though possibly conservatively bounding, model system. The rate equation was derived by regression of model results for six assumed groundwater flow velocities and for a fracture aperture (1 mm) that may be unrealistically large for Forsmark conditions (Table 2.2.1_1). Two model results at the lowest groundwater flow rates were extrapolated from the results for the 4 higher flow rates because the numerical model became unstable at the lower groundwater flow velocities (this suggests that the model may also become unstable if smaller, and probably more realistic, fracture apertures were assumed). Also noteworthy is the fact that calculated distances penetrated by the buffer in a fracture become so large at the lowest groundwater flow velocities that they greatly exceed the lengths of individual fractures that are likely to exist in a Forsmark repository (Neretnieks et al., 2009). Given the sparse, and in some cases possibly irrelevant, model results used in the regression procedure, uncertainties in estimates of $R_{erosion}$ may be large and difficult to quantify.

2.3.2. Stability of smectite gels and sols

The relative stabilities of smectite gels and sols can be interpreted in terms of environmental variables, such as total aqueous concentrations of Na^+ and Ca^{2+}, using mass-action constraints (e.g., Birgersson et al., 2009). These constraints are of fundamental importance because conditions favouring the stability of sols (and low-viscosity gels) are those for which the buffer/backfill is most susceptible to erosion. Evaluating these conditions for the case of bentonite expansion into a fracture is likely to be complicated, however, by dynamic reactive-transport processes controlled by: 1) the presence of sparingly soluble bentonite minerals, 2) ion-exchange by smectite, 3) ion diffusion in the variable-density gel and sol phases, and

4) by the mass-transfer resistance and composition of groundwater flowing in the fracture. SR-Site does not consider such reactive-transport effects on gel/sol stability because the erosion model for buffer and backfill is based on a highly simplified, and possibly conservative (see Section 2.2.3), system consisting of just pure Na-montmorillonite in contact with a simple NaCl solution. The model therefore does not account for the possible effects of ion-ion correlations that could promote gel stability in argillaceous systems containing divalent cations such as Ca^{2+}. This potentially important mechanism for inhibiting colloid formation and erosional mass losses of the buffer and backfill should therefore be evaluated further by SSM, possibly using an independent model of relevant reactive-transport processes in bentonite that has expanded into a fracture (Appendix 3).

2.3.3. Comprehensive evaluation of safety functions

The effects of buffer/backfill chemical erosion are considered in SR-Site only in relation to the effects of a loss of density on the swelling pressure (p_{swell}) and associated impacts on the safety function indicator of limiting advective transport. A loss of density could also adversely impact other safety function indicators of the buffer/backfill, however. Mass losses leading to a reduction in saturated density of the buffer could, for example, impact two safety functions (prevent significant microbial activity and ensure tightness/self-sealing) before they would impact the threshold for significant advective transport to occur. Because only the latter was considered in SR-Site, it is recommended that all potential effects on safety function indicators of buffer/backfill chemical erosion should be further evaluated by SSM (Appendix 3).

2.3.4. Buffer/backfill mass loss tolerances

The safety-relevant consequences of buffer/backfill chemical erosion depend on two quantities: 1) the erosion rate, and 2) the amount of buffer/backfill mass loss that can be tolerated before safety functions would be adversely impacted. Determination of the latter quantity is subject to considerable uncertainty. SKB's assessment that 1200 kg of bentonite can safely be lost from a deposition hole without generating advective conditions, for example, is based on a model of friction forces within the buffer and at the buffer-rock interface that are not well understood (Börgesson and Hernelind, 2006). An issue is the question whether the buffer would homogenize quickly and completely throughout the deposition hole following a loss of mass by erosion, or whether the effects of mass loss would be localized in the near vicinity of the fracture intersection with the buffer for long periods of time. SSM should carry out an independent evaluation of these modelling and data uncertainties in order to assess whether SKB's criteria for unacceptable mass losses of the buffer/backfill are credible and conservatively bounding (Appendix 3).

2.3.5. Natural Analogues

In a study of potential natural analogues of buffer/backfill chemical erosion, Puura (2010) noted that although there are examples in which natural bentonites have been exposed to infiltrating meteoric recharge, the relevance of such systems to the issue of buffer erosion may be questionable. This conclusion may be too narrowly focussed on natural bentonites, however, and does not seem to take into account relevant evidence from other natural systems indicating that clay colloids can be generated and mobilized by contact with dilute solutions. For example, experiences gained from reservoir-engineering studies of producing oil/gas fields indicate that significant reservoir damage (*i.e.*, permeability reduction) can occur when low-salinity groundwater is pumped into a reservoir (e.g., Kia *et al.*, 1987). The damage is believed to occur when clay minerals in the reservoir are dispersed as colloids as a result of contact with the dilute solutions. The colloids are transported in the groundwater until they encounter local pore constrictions along the flow path. They are then deposited in these constrictions (presumably by gravitational and friction forces), and this results in an overall reduction in reservoir permeability. SSM should consider evidence from such natural systems to help support its evaluation of models of buffer/backfill chemical erosion (Appendix 3).

2.4. Handling of uncertainties

This review topic concerns whether all known and relevant uncertainties related to buffer/backfill chemical erosion have been identified, analysed and discussed in sufficient detail. For the case of buffer (and backfill) chemical erosion such uncertainties have been acknowledged and described in adequate detail with references given to more detailed elucidations and treatments of specific topics (Neretnieks et al., 2009; SKB, 2010c; Sections 3.5.11 and 4.4.8). These uncertainties were also considered in an independent SSM review of buffer chemical erosion (Apted et al., 2010).

Conceptual uncertainties related to clay colloids were found to be sufficiently significant by SKB that attempts to account for them were abandoned in SR-Site and a highly simplified, and possibly conservative, model involving a pure Na-montmorillonite (representing bentonite) and simple NaCl solution (representing groundwater), was adopted. SKB has established an on-going R&D program to address these uncertainties and this may result in more realistic models. If so, it is unclear whether these models will have to be considered during the Main Review Phase of SSM's PCS project (Section 2.1.2). Comments addressing how various types of uncertainties were handled in the buffer erosion model adopted in SR-Site are discussed in Section 2.2.2.

2.5. Safety significance

The following questions were considered with regard to the safety significance of buffer/backfill chemical erosion in SR-Site:

- Is the overall safety relevance of buffer/backfill chemical erosion explained and justified; and

- Is the safety assessment strategy for the handling of issues related to buffer/backfill chemical erosion clearly explained?

The overall safety relevance of buffer erosion is clearly explained in Section 12.2.2 of SKB (2011), and is justified in terms of the nine erosion cases propagated to the analysis of canister erosion. Although clearly explained in SR-Site documentation, concerns related to the safety assessment strategy for handling buffer/backfill erosion issues are described in Section 2.3.1 of the present report.

2.6. Transparency and traceability of information in SR-Site and associated references

The question considered in this topic concerns specifically whether the information contained at different levels in the safety assessment (e.g., main SR-Site report, main supporting references, and other references) are internally consistent and logically subdivided. Based on the present review of buffer/backfill chemical erosion, all relevant information appears to be sufficiently consistent and adequately subdivided to justify further review of this material during the Main Review Phase of the PCS project. SKB's cross-referencing of information contained in the SR-Site report and main supporting references is adequate. As illustrated by the comment in Section 2.1.1, however, more detailed information may be needed during the Main Review Phase concerning numerical methods, computer codes, input files, primary supporting data and assumptions used to generate the results described in this documentation.

3. Recommendations to SSM

The primary objective of this initial review assignment was to determine whether the documentation in SR-Site and supporting references is reasonably complete and of sufficiently high quality to justify a more detailed review of chemical erosion processes potentially affecting the safety functions of the buffer and backfill, and in particular to identify any complementary information and clarifications needed from SKB before such a review could be carried out. The SR-Site documentation relevant to this review topic was found to be of sufficiently high quality overall to justify further consideration in the Main Review Phase of SSM's PCS project. Several specific topics for which complementary information and clarifications should be requested from SKB were also identified (Appendix 2). Specific review topics for consideration during the Main Review Phase are recommended in Appendix 3.

4. References

Apted, M.J., Arthur, R., Bennett, D., Savage, D., Sällfors, G., and Wennerström, H. 2010. Buffer erosion: An overview of concepts and potential safety consequences. Research Report 2010:31, Swedish Radiation Safety Authority, Stockholm, Sweden.

Birgersson, M., Börgesson, L., Hedström, M., Karnland, O., and Nilsson, U. 2009. Bentonite erosion. SKB TR-09-34, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Börgesson, L. and Hernelind, J. 2006. Consequences of loss or missing bentonite in a deposition hole: A theoretical study. SKB TR-06-13, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Dverstorp, B., Strömberg, B. and Simic, E. 2011. Licensing review of a spent nuclear fuel repository in Sweden. Proceedings of the International High Level Radioactive Waste Management Conference 2011, Albuquerque, New Mexico, April 10 – 14, 510-519.

Jansson, M. 2009. Bentonite erosion. Laboratory studies. SKB TR-09-33, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Jönsson, B., Åkesson, T., Jönsson, B., Meehdi, S., Janiak, J., and Wallenberg, R. 2009. Structure and forces in bentonite MX-80. SKB TR-09-06, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Kia, S. F., Fogler, H. S. and Reed, M. G. 1987. Effect of pH on colloidally induced fines migration. *Journal of Colloid and Interface Science*, 118 (1), 158-168.

Liu, L. 2011. A model for the viscosity of dilute smectite gels. *Physics and Chemistry of the Earth*, 36, 1792-1798.

Moreno, L., Neretnieks, I., and Liu, L. 2010. Modelling of erosion of bentonite gel by gel/sol flow. SKB TR-10-64, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Neretnieks, I., Liu, L., and Moreno, L. 2009. Mechanisms and models for bentonite erosion. SKB TR-09-35, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Puura, E. and OÜ, E. 2010. Impact of the changes in the chemical composition of pore water on chemical and physical stability of natural clays. A review of natural cases and related laboratory experiments and the ideas on natural analogues for bentonite erosion/non erosion. SKB TR-10-24, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Richards, T. 2010. Particle clogging in porous media. Filtration of a smectite solution. SKB TR-10-22, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB 2004. Interim process report for the safety assessment SR-Can. SKB R 04-33, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB. 2006. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. SKB TR-06-09, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB 2010a. Design, production and initial state of the buffer. SKB TR-10-15, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB 2010b. FEP report for the safety assessment SR-Site. SKB TR-10-45, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB 2010c. Buffer, backfill and closure process report for the safety assessment SR-Site. SKB TR-10-47, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

APPENDIX 1

Coverage of SKB reports

Table A:1 includes a list of SKB reports considered in the present review assignment. The list includes reports considered to be mandatory for review by SSM as well as additional relevant reports. Reviewed sections of the reports are indicated.

Table A:1 SKB reports considered in the review

Reviewed report	Reviewed sections	Comments
SKB TR-11-01: Long-term safety for the final repository for spent nuclear fuel at Forsmark	Sections 10.3.6, 10.3.9, 10.3.11, 10.4.8; 12.2	Reviewed revised versions of the main report obtained from SKB's website. Filenames: TR-11-01_VOLI_webb_ 2011-12.pdf; TR-11-01_VOLII_webb_ 2011-12.pdf; and TR-11-01_VOLIII_webb_ 2011-12.pdf (mandatory report)
SKB TR-10-47: Buffer, backfill and closure process report for the safety assessment SR-Site	Chapter 3.5.11 (Montmorillonite colloid release)	(mandatory report)
SKB TR-10-45: FEP report for the safety assessment SR-Site	Appendix 6 (buffer relevant FEPs), Appendix 7 (backfill relevant FEPs)	(mandatory report)
SKB TR-10-15: Design, production and initial state of the buffer	Chapter 6 (Initial state of the buffer)	Reviewed a revised version of the report obtained from SKB's website. Filename: TR-10-15webb_2011-12.pdf (mandatory report)
SKB TR-10-64: Modelling of erosion of bentonite by gel/sol flow	All	(relevant report)
SKB TR-10-24: Impact of the changes in the chemical composition of pore water on chemical and physical stability of natural clays: - a review of natural cases and related laboratory experiments and the ideas on natural analogues for bentonite erosion/non-	All	(relevant report)

erosion		
SKB TR-10-22: Particle clogging in porous media. Filtration of a smectite solution	All	(relevant report)
SKB TR-09-35: Mechanisms and models for bentonite erosion	All	(relevant report)
SKB TR-09-34: Bentonite erosion. Final report	All	(relevant report)
SKB TR-09-33: Bentonite erosion, laboratory studies	All	(relevant report)
SKB TR-09-06: Structure and forces in bentonite MX-80	All	(relevant report)

APPENDIX 2

Suggested needs for complementary information from SKB

[*All references cited in the following are documented in the References section of this report.*]

1. SKB should provide detailed documentation concerning the numerical code and numerical methods used to evaluate the buffer erosion model used in SR-Site (Moreno et al., 2010). The documentation should be sufficiently detailed and complete that SSM could, if deemed necessary, independently verify model results, use the model as a benchmark for alternative models, and/or evaluate the effects of alternative assumptions and parameter values on model predictions.
2. SKB should provide periodic updates concerning the status of its on-going R&D program on buffer/backfill chemical erosion. The updates should address the work scope, status and reporting schedules for current and planned studies. The documentation should be provided in a timely manner that allows for full consideration by SSM during the Main Review Phase of the PCS project.
3. SKB should provide clarification concerning why the alternative cases of buffer chemical erosion (SKB, 20011; Section 12.2.2) were considered individually and not in various combinations. For example, if it is assumed in an alternative case that only 600 kg must be lost from a deposition hole before advective conditions would be established, then, in addition, can it also be assumed that erosive conditions exist 100% of the time, that a pessimistic relation exists between fracture aperture and transmissivity, and that fracture length and transmissivity are uncorrelated? If so, what is the corresponding number of deposition holes experiencing advective conditions within 100,000 and 1 million years?
4. SKB should provide additional justification for using the buffer erosion model to estimate erosion rates for tunnel backfill despite the fact that the material properties and saturated densities of these two barriers differ significantly.
5. SKB should clarify whether alternative buffer erosion models (e.g., Birgersson et al., 2009) to that described by Neretnieks et al. (2009) and Moreno et al. (2010) are being considered in its on-going R&D programme. The documentation should include a description of the rationale for ignoring the effects of (fracture) wall friction on the erosion rate and should provide justification for assuming that this approach is conservative.

APPENDIX 3

Suggested review topics for SSM

1. Detailed review of the SR-Site chemical erosion model with a focus on the validity of underlying scientific concepts (chemical, surface-chemical and rheological) and conservatisms in the viscosity and force-balance models.
2. Periodic reviews of new information generated in SKB's on-going R&D programme on buffer/backfill erosion.
3. Reactive-transport processes controlling the thermodynamic stabilities of smectite gels and sols in fractures intersecting a deposition hole/tunnel (Section 2.3.2).
4. Potential effects of buffer/backfill loss on all relevant safety functions (Section 2.3.3).
5. Review rheological models of buffer/backfill density re-distribution and re-homogenization in response to mass losses caused by chemical erosion (Section 2.3.4).
6. Natural analogues (Section 2.3.5).

2012:26

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se