D8.15 BEACON
Bentonite Mechanical Evolution

EARB fifth annual project review

DELIVERABLE (D8.15)
Report

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Content

1 Scope of the Expert Advisory and Review Board evaluation

The Expert Advisory and Review Board (EARB) consists of experts which are representatives of organisations from outside of the project, and is in charge to advise the Technical Coordinator, and the Executive Board and the commission with critical evaluation concerning research quality and significance of outputs.

This fifth evaluation report will express the EARB's view on the new (or newly updated) deliverables that are made available to the EARB since the EARB's third annual project review report until the final workshop. This review report covers the following deliverables: D1.3, D2.3, D3.3, D4.3, D5.7 and D6.3. A preliminary summary of EARB comments on these deliverables has been presented by Jinsong Liu at the final workshop of the project.

This EARB report includes also EARB comments on the presentations during the final workshop.

2 Sources of information for the evaluation

The EARB analysed information gathered through the following sources:

- Deliverables as available after the EARB's third annual project review report and before the final workshop (between November 2020 and May 2022),
- Presentations and discussions during the final workshop of the BEACON project, 17-19 May 2022, Imperial College London, UK.

3 EARB's overall opinion on the entire project

3.1 EARB's previous review reports

During the BEACON project, the EARB has on several occasions reviewed and commented the progress of the project, through reviewing the various deliverables issued by the project as well as through participating in the kick-off meeting, the project's annual meetings and its final workshop and commenting on the presentations given during the meetings. The following review reports from the EARB have been issued:

- D8.13. First joint evaluation report prepared by the Expert Advisory and Review Board (The first EARB review at project start). 2017-09-07,
- D8.8. Second joint evaluation report prepared by the Expert Advisory and Review Board / EARB first annual project review. 2018-07-02,
- D8.9. EARB second annual project review report. 2019-08-30,
- D8.10. EARB third annual project review. 2020-11-23,
- D8.11 Fourth annual project review report prepared by the Expert Advisory and Review Board. 2021-06-30.

3.2 EARB's overall opinion on the entire project

Based on the comments from the previous review reports and the comments given in this review report (see the following sections), the EARB would like to express its overall opinion on the entire project as follows:

The EARB has the opinion that this research project has been smoothly initiated and successfully carried out. The approach of the project is systematic and the coverage is extensive. The objectives of the project have been well formulated in the beginning and achieved at the end of the project. The outcomes from this project are highly relevant to the design and the safety analysis of different types of final disposal facilities that apply bentonite as an engineering barrier in relatively large dimensions. Project achievements have been clearly documented in different deliverables and needs of additional research beyond the coverage of the project have been well identified.

The EARB will point out that compared to other similar projects, the integration between work packages has been well-organized and implemented. Moreover, disturbances by the pandemic of Covid-19 have been well handled even if the interactions between partners could not be maximised for the comparison and interpretation of the results.

The EARB acknowledges the efforts to integrate civil society (CS) representatives into CEC research projects but recommends to the Commission to carefully design objectives and means of such integration already before the projects start: Which type of project result can be addressed by CS representatives in which way? Is the involvement of CS meant to actively influence the project work or just to disseminate results? In BEACON, the course with reference to the latter question apparently changed in the middle of the project (cf. deliverable D8.9).

4 EARB's comments on the new deliverables

4.1 On D1.3 Final Assessment Report

Objective of the deliverable

The Grant Agreement states the objective of the deliverable as "*The outcome of this work package is planned to be a (hydro)-mechanical assessment of the case studies, given a range of uncertainties in the boundary conditions based on empirical and numerical evidence that, based on a probabilistic approach, would ultimately result in a set of requirements under consideration of the host rock and the repository design. For this work package three case studies were defined: the ANDRA tunnel plug, the Nagra disposal cell and the KBS-3 deposition tunnel backfill.*"

The EARB thinks that the report does not focus on the (hydro)-mechanical assessment of the case studies. The outcome of the assessment case studies are only occasionally developed in the report. The report rather gives conclusions on how lessons learned from the project can support safety cases. The report does not treat the probabilistic approach and does not set explicitly requirements under consideration of the host rock and the repository design.

In the introduction of the deliverable it is stated that the requirements regarding chemical, mineralogical and physical characteristics of bentonite developed by each waste management organisation (WMO) will be given in the last chapter. Those are however not given explicitly.

Derivation of requirements for the assessment of the heterogeneity of bentonite based buffer, backfills and seals.

The section explains that requirements on engineered barriers can be derived from safety functions by defining material characteristics to be fulfilled e.g. installed dry density. It may be possible to verify the evolution and the performance of the barriers through full scale field experiment, but predictive models are also needed to describe the long term evolution. The results from the models can then be compared with the indicators/targets to check that the safety functions are fulfilled.

The EARB thinks that this section gives a good overview how requirements can be derived from safety functions in order to be verified in the frame of the safety assessment. However the section does not treat how requirements can be defined specifically for heterogeneities at initial and final state (e.g. characteristics related to maximum technological voids, joints, minimum acceptable localised dry density, etc.).

The EARB thinks that safety verification requires to define requirements through a "safety envelope" corresponding to the range of values the characteristic has to perform to ensure safety and "the design target" corresponding to the range of values expected to be reached in the actual repository (possibly at different time frame: e.g. initial and final). As long as the characteristics stay within the safety envelope, safety should be ensured. A difference between "as-built" characteristic and "design target" could mean a decrease of the robustness.

Lessons learned from WP2

This section summarises four large-scale field tests performed before the BEACON project and draws the feedback to the safety case. These kind of large-scale tests are essential for the assessment of barrier performance. They show the complexity of the homogenisation process and the strong influence of the prevailing conditions regarding initial state, hydration and heat.

The EARB thinks that the work performed in WP2 consisting of collecting and compiling existing data and available models is quite valuable for the BEACON project itself but also for future R&D developments.

Lessons learned from WP3

This section summarises main results and conclusions of WP3 related to the development of constitutive THM models.

The EARB acknowledges the huge work performed by the modelling teams to improve the predictive capacities of their models to simulate the THM behaviour of engineered barriers during saturation and subsequent homogenisation. Despite the progress made, the transient behaviour remains difficult to understand especially because of the scarcity of experimental data to determine all parameters required by the constitutive models. The EARB therefore supports the need to increase fundamental knowledge of the basic processes underlying homogenisation and other hydro-mechanical phenomena. The quality of experimental set-ups and the care taken in carrying out the tests are essential to collect convincing data. The repeatability of the performed tests is also an issue to be considered.

See also D3.3 EARB review.

Lessons learned from WP4

This section summarises main results and conclusions of WP4 related to the experimental work.

The EARB acknowledges the huge work performed by the experimental teams. The EARB believes that performing tests to study the processes characterizing the hydration phase and the interaction between different types of bentonite barriers (e.g. blocks, and powder/pellets mixture) is essential to improve the knowledge. Especially X-ray tomography is a very valuable technique to follow and visualise the homogenisation process.

See also EARB review of D4.3 later in this report.

The three assessment cases and modelling results

These sections summarise the three assessment cases and modelling results.

The EARB notes that the modelling teams did not assign enough time to the evaluation and interpretation of the results of the assessment cases. This is partly due to the COVID situation. If more time had been given it is very likely that the results would have been more consistent.

Consequently, it is difficult for the EARB to advice on this part, which should be the core of the report. The EARB thinks that the bias related to the simplifications of the experiments set-ups done for modelling purpose deserve to be discussed more in depth. The fact that all teams are not considering the same initial and boundary conditions should be discussed and justified.

See also EARB review of D5.7 in a subsequent section of this report.

Evaluation of the modelling results with respect to safety cases

This section evaluates the modelling results with respect to SKB, ANDRA and NAGRA safety cases.

The outcome of the three evaluations are presented quite differently. It would have been interesting to understand why one WMO insists more on a specific issue than another and to know how far the conclusions drawn by one WMO are also valid for the others. It would have also been interesting to discuss how the project has improved the management of uncertainties.

Robustness of the argumentative framework

EARB thinks that this section is very valuable and treats different issues and questions the EARB raised in its last review report like the:

- homogenisation optimisation through design,
- impact of saturation rate and localized water flow,
- need to consider friction for assessing the “assessment cases”,
- impact of the geometry,
- impact of the chemistry,
- aleatoric and epistemic uncertainties.

The discussions show that several open questions remain and that R&D should continue to collect fundamental data to describe the transient hydration process and to improve predictable capabilities of the models.

4.2 On D2.3 Identification of captured knowledge of bentonite mechanical evolution gained over the duration of the BEACON project

Objective of the deliverable

This deliverable presents captured knowledge from work packages 3, 4 and 5, gained since deliverable 2.2, and summarises the key learning points from the BEACON project. The report describes also new results on bentonite THM behaviour/modelling from other projects (e.g. Decovalex, EURAD).

The EARB acknowledges the huge summarising effort and thinks that this report is valuable for the BEACON project, the external scientific community and also for future R&D developments.

Safety relevant functions of bentonite

This section remind the scope of BEACON project, relevant safety functions and main open questions raised at the start of the project.

The EARB finds that the sentence "*If the bentonite is prepared and emplaced properly, it is not expected that heterogeneities will be problematic for safety cases.*" adds nothing since it is already stated that bentonite placement (among other factors) gives rise to heterogeneities.

Captured knowledge from WP3

This section highlights important constitutive model developments and improvement adopted by the different teams.

Despite the progress made, the transient behaviour remains difficult to capture. This difficulty is attributed to the lack of experimental data necessary to derive the constitutive model parameters. To the EARB opinion this issue remains a challenge given that each constitutive model is characterised by a different set of parameters. To the EARB opinion the identification of the relevant parameters should be considered for the establishment of a systematic experimental characterisation (relevant for future R&D developments). This might be achieved if more effort is made in performing sensitivity analysis (see also the EARB comments to D1.3 in Section 4.1 under "Lessons learned from WP3" in this report).

The EARB noticed that a large part of the text 3.1.1, 3.1.2, 3.1.4, 3.15 and 3.16 was directly taken from (D3.3 2.), (D3.3, 3.10), (D3.3, 5), (D3.3, 6), and (D3.3, 7), respectively, without giving the related references. Within both documents, D2.3 and D3.3 an important statement is given: "*several modelling teams have also identified areas of constitutive model development that are deemed necessary to improve simulation capabilities. In addition, outstanding uncertainties remain concerning the detailed knowledge of some of the individual phenomena underlying homogenisation, the precise role of the different components and parameters of specific models and the actual predictive power of the formulations developed in the project.*" Which is a bit contradictory to the statement "*The models developed* *are able to reproduce what are considered to be the key features of behaviour underlying the homogenisation processes such as stress path dependency, strain irreversibility, and others."*

Lessons learned from WP4

This section summarises main results and conclusions of WP4 related to the experimental work.

The EARB acknowledges the huge work performed by the experimental teams. The EARB believes that comparing the results to large scale experiments is essential to catch on scale effect.

Specific comment: The scale should be given in Figure 3-7.

Updated understanding of bentonite mechanical evolution

This section is very valuable since it treats one of the main questions raised at the start of the project and listed in section 2: "*whether the bentonite will evolve towards a homogeneous distribution"*

The discussion pointed out the different factors that affect the degree of homogenization (hydration rate and friction). However, uncertainties remain regarding the role of friction especially at large scale. The EARB believes that this issue deserves to be investigated more in depth in future R&D.

The EARB noticed that a lot of uncertainties remain with respect to "*Whether any remaining heterogeneity will affect performance*". Consequently R&D should continue to improve predictable capabilities of the models. An upscaling approach may be interesting in this case.

Experimental and modelling uncertainties

Regarding the applicability of the results to in situ conditions, whether the teams performed or not some model calibration should be included in the paragraph " *the model were able to achieve reasonable results, despite the fact that large scale components are likely to have higher degree…(of) friction is less important*".

4.3 On D3.3 Description of the constitutive models developed in the project. Conceptual bases, mathematical description and model capabilities. Assessment of predictive power

The Deliverable presents advances in model development and improvements achieved in BEACON project.

Although general comments on the reported development are presented, the EARB thinks that additional comments on the following model improvement and how do they contributes in capturing the listed behaviour features (a, b, c, d and e) might be interesting for the scientific community:

- new water retention curve considering adsorbed and free water,
- separate micro and macro water retention curves,
- dependence on degree of saturation and pressure of the elastic compressibility coefficient for suction changes,
- water retention hysteresis (considered by three teams).

Despite the progress made, the transient behaviour remains difficult to capture. This difficulty is attributed to the lack of experimental data necessary to derive the constitutive model parameters. To the EARB opinion this issue remains a challenge given that each constitutive model is characterised by a different set of parameters. Sensitivity analysis might help to identify the key parameters.

With respect to the different transients calculated by the different models one has to keep in mind that the transients for large scale repositories could be very long due to tight host rocks, a limited/slow water in flow, etc., which has an influence on a homogeneous buffer development and related to the intended homogeneous safety function of the buffer. An estimation on "which buffer heterogeneity is safe enough" may give indications for acceptable parameter uncertainties.

Specific comment: standardize the Updated capability Tables format.

4.4 On D4.3 Experimental work on bentonite evolution in the frame of BEACON – final report of WP4

This deliverable describes the experimental work performed within the BEACON project and discusses the results.

Table 2.1 gives a clear overview of the tests performed. They are addressing:

- the influence of initial granulometry and of the hydro-mechanical path both at constant load and at constant volume,
- swelling at constant volume: pellet-scale and pellet cluster,
- binary mixtures or artificial inhomogeneities: bentonite block/pellet systems, pellet/powder mixtures and block/powder systems,
- the influence of the degree of saturation on the shearing behaviour at a bentonite.

The EARB acknowledges the huge work performed by the experimental teams. The report is well written, the tests are described in details and the results are discussed in depth.

The EARB believes that performing tests to study the processes characterizing the hydration phase and the interaction between different types of bentonite barriers (e.g. blocks, and powder/pellets mixture) is essential to improve the knowledge. Especially X-ray tomography is a very valuable technique to follow and visualise the homogenisation process.

Not all the experiments previously performed before the BEACON project were used for model simulation. The experimental work performed within BEACON provides therefore input to further model calibration or validation.

The EARB thinks that the following conclusions are important to taken into account when designing repositories and assessing their safety:

- Initial grain size distribution can influence the final state of resaturated bentonite samples. This result indicates that not only dry density, but also initial grain size distribution should be considered when analysing swelling phenomena. Future work could also focus on the final pore size distribution.

- Swelling pressure evolution in binary systems is complicated and not necessarily monotonous, especially in systems with granular material or powder. This observation is particularly important for proper understanding of the transient hydro-mechanical behaviour.
- There is an influence of different hydro-mechanical paths on the final state of the bentonite. This conclusion is very important since in a real repository the stress path followed by the bentonite is complex and can differ from one location to the other. But how can these stress paths be integrated / transferred to larger scale experiments?
- Dual density experiments showed a different evolution of swelling pressures based on the direction of saturation. A faster increase of swelling pressures followed by drop was observed on samples saturated from the high-density bases. However similar final swelling pressures are reached. The influence of the velocity of saturation has also been observed. A faster hydration results in larger final density gradients than an intrinsically slower hydration via the block or under restricted water flow. Initial saturation at low confining stress, with a high hydration velocity, leads to irreversible strains that affect the macrostructure. This shows that the hydration scheme and the hydration's velocity have a major influence on the transient hydro-mechanical behaviour. Their control are therefore an important issue to consider when designing repositories.
- Temperature around 100°C seems to increase the reached swelling pressure but a substantial drop in swelling pressure is apparent at 150°C. Influences of temperature are very important to be further investigated since the temperature around canisters could reach around 300°C.
- Salinity seems to influence the hydro-mechanical behaviour of the bentonite. E.g., at elevated salinities, clay that swelled into the void never generated significant swelling pressures during the testing period. Liquefaction was reached in some tests using saline water. Effects of salinity and processes leading to liquefaction are therefore important to be further investigated.
- Where the bentonite has minimal room for expansion, the homogenisation process is likely to take substantially longer time to occur. This conclusion is very important for the optimisation of the blocks emplacement geometry. Are interspace between blocks beneficial?
- The swelling pressure in a pellet cluster is not as homogeneously distributed as in the compacted and confined bentonite. The pellet cluster has still not been at steady state after 220 days despite being nearly instantaneously immersed in the solution. The saturation process is therefore a very long process, which could take several years or even decades.

The experimental work performed within BEACON has allowed to substantially increase the knowledge of the hydro-mechanical behaviour during the hydration process of bentonite barriers. However despite the quality of the tests performed some open questions remain. The EARB therefore agrees with the need to further increase fundamental knowledge of the basic processes underlying homogenisation and other hydro-mechanical phenomena. Especially the study of the influence of the temperature and of the chemistry is a challenge.

The EARB believes that comparing the results to large scale experiments is essential to catch on scale effect.

The quality of experimental set-ups and the care taken in carrying out the tests are essential to collect convincing data. The repeatability of the performed tests is also an issue to be considered for future projects. Discussions between experimentalists and modellers about future experiments, e.g., by performing sensitivity analysis on specific model parameters by predictive modelling, may also improve experimental set-ups – sensors at the right position, strict control of boundary conditions there where it is needed – to feed models with "improved" input parameters and boundary conditions to overcome the problem of "too many unknown model parameters".

4.5 On D5.7 Synthesis of the results obtained from all tasks in WP5 - Final report for WP5

Objective of the deliverable

As is stated in the Grant Agreement of the project, the main objective of WP5 is to demonstrate the capacity of the models to predict hydro-mechanical evolution of bentonite components in the context of radioactive waste disposal. The idea is to improve the confidence in these models by comparing them with experimental results obtained on tests at different scales and with several levels of complexity.

Three test cases (SKB tunnel backfill, Nagra disposal cell for high level waste and Andra tunnel plug) are selected to evaluate the capacity of the different models to predict the hydro-mechanical evolution of the bentonite barrier and the resulting performance of the barrier. The results can be analysed in the way to verify if the long-term performance expectations are fulfilled.

The EARB thinks that the deliverable has fulfilled the objectives set in the Grant Agreement and has produced valuable modelling results for the long-term safety analysis of the performance of bentonite barrier in relatively large dimensions (meters by meters by tens of meters) in final repositories.

In the following, relatively detailed comments are given to the modelling of the afore-mentioned three field-tests respectively.

SKB assessment case

This case has been modelled by CT, LEI, ICL and VTT.

CT uses a Hysteresis Based Material model in which the model variables are assumed to be dependent on the path of evolution. In the LEI model the Richard equation is used for the hydraulic (flow) part and the mechanical response (deformation and development of swelling pressure) is assumed to be mainly governed by the degree of water re-saturation, and is represented by elastic deformation. ICl uses an extended and modified Barcelona Basic Modelling (BBM) for clay while adopting a double-porosity structure. In this model net stress and suction are formulated as two independent stress variables. A non-hysteretic van Genuchten type water retention model is used. In VTT's coupled THM model a double-porosity approach is applied to the bentonite block while a triple-porosity approach to the pellets.

All teams assume a 2-dimensional axial symmetry for the tunnel (only half of the tunnel geometry is considered in the model) and an isothermal condition. CT, LEI and ICL have tested two types of hydraulic boundary conditions: free access to water and limited access of water. As for the mechanical boundary conditions, CT has tested by an all-roller condition and a condition of all-roller expect for the tunnel wall, where it is assumed no displacement. LEI uses an all-roller condition and ICL applied a condition of no orthogonal displacement. VTT uses a constant pressure condition for the hydraulic part of the model and roller boundary condition for the mechanical part. Moreover, VTT has presented sensitivity analysis with varying initial conditions.

As indicated in the synthesis of results for this case in the deliverable, general conclusions from the different models are

- There is a significant variation of the minimum dry density in the cases with free access of water presented by the different teams (with values ranging from 1246 to 1354 kg/m^3).
- Different teams have obtained different results regarding the influence of a restricted access of water. LEI found no change, ICL found an increasing minimum dry density, while CT found a decreasing minimum dry density.

In the synthesis of the results section, the different modelling approaches have been validated against experiment data at hand, especially the data of relation between swelling pressure and dry density. The values of final net mean stress (or effective stress) from the models are compared with the experimental data of swelling pressure at the same dry density. The comparison shows that:

- In the pellets both the LEI models and the ICL model with free access of water obtain net mean stresses that are significantly larger than those of the experimental data. This may possibly explain the extensive remaining heterogeneity with minimum dry density found in these models. The VTT model with restricted access of water predicts a lower net mean stress in the pellets. However, the CT model with limited water access predicts a larger net mean stress instead.
- The ICL model seems to overestimate the mean net stress in the bentonite block, twice as high at a dry density around 1519 kg/m^3.
- With free access of water, the final states predicted by the VTT and CT models are more consistent with experimental and the minimum dry density is more likely to lie between 1319 to 1354 kg/m^3.
- With limited access of water, the CT results are more consistent with experimental data and the remaining heterogeneity is likely to increase compared to the cases with free access of water, even though the difference is rather limited.

The synthesis of results has also discussed modelling results' implication to the safety functions of bentonite barrier in SKB's tunnel for spent fuel repository. It is shown that the requirements in the safety functions of a swelling pressure larger than 0.1 MPa can be fulfilled with the lowest dry density calculated by the different teams.

The EARB has the opinion that the model approaches in simulating this test are well performed and valuable results have been achieved. In spite of the relatively large differences in the formulation of the models, the application of different types of boundary conditions, etc., all the models seem to be able to catch the most important aspects of the evolution paths and the final state. The scattering of the modelling results has been analysed and can, to some extent, be explained when "calibrated" with experimental data.

The EARB considers that the relationship between swelling pressure and dry density is one the most important and most reliable observations. Comparison of modelling results with this relation is a reasonable choice.

The EARB agrees with the deliberations in the synthesis of results that the requirements of the safety functions (mainly a swelling pressure > 0.1 MPa) are most likely to be fulfilled according to the different modelling outcomes.

The EARB thinks that the deliverable needs to give more detailed analyses and discussions of the implication of final spatial distribution of dry density in the tunnel system to the long-term stability of the backfill material, for example, how the heterogeneity (density spatial distribution) can influence the later chemical erosion processes.

Some editorial improvements are needed. For example an end of parentheses is missing in the first paragraph of 2.2.1. Equation (5) of the ICL model needs a better typo-setting.

Nagra assessment case

This case has been modelled by EPFL, BGR and UPC.

EPFL applies an elasto-plastic model with the yield surface and flow rule developed previously in the literature. Influences of temperature on the hydraulic and mechanical processes are considered. BGR uses a coupled thermo-hydro-mechanical (THM) model with, among others, Richard approximation for fluid flow, the Camclay constitutive model for momentum balance, van Genuchten approach for water retention. The UPC model is also a coupled THM type, but double porosity structure is assumed. The micro- and macro-structural porosities are coupled through mass transfer and strain coupling. The Barcelona Basic Model (BBM) is used to represent the yield surface.

All teams apply finite element discretisation of the system. The entire cross section is the modelled geometry of the first two teams (EPFL and BGR) while UPC considers the vertical central axis as a symmetric line. All the models distinguish the properties of bentonite block in the pedestal and granular bentonite mixture (GBM) backfill around the canister.

Initial heterogeneity is modelled in different ways of the different teams: UPC has explored two configurations, one with homogenous granular bentonite material (GBM) distribution everywhere and one with a non-uniform initial density distribution of the GBM. In the BGR model, the initial dry density of the GBM is computed from measurements given in the specifications. For the EPFL approach, the initial heterogeneity of the GBM is set as distributed in different zones. EPFL considers as boundary conditions the pore pressure and temperature in the surrounding OPA clay domain before tunnel excavation as well as the measured water content of the OPA clay after the tunnel excavation. The pre-determined temperature evolution from the canister is also a boundary condition for the thermal part of model. BGR uses also Dirichlet boundary conditions for the thermal and the hydraulic processes. For the mechanical process, no displacement boundary is applied to the normal direction of the entire outer boundary (in the OPA clay) of the modelled domain. In the UPC model boundary conditions before tunnel excavation are constant pore pressure and temperature in the OPA clay, similar to that of EPFL. No displacement boundary is assumed normal to the outer boundaries of the modelled domain.

As is reported in the synthesis of results section for the Nagra assessment case, all the models of the teams predict full water saturation between 50 to 80 years. The same trend of evolution of water saturation is obtained by all three models. Influences of heating by the canister are also captured by the models. The same conclusion applied to temperature evolution.

A large discrepancy of the predicted dry density evolution at different positions (near the canister, in the host rock and in the middle of bentonite) by the different teams is observed. The discrepancy could partly be due the differences in the initial distribution of the density in the models but that is deemed not to be able to explain all the differences. The spatial distribution of the dry density, as is manifested by that along the central vertical profile, remains heterogeneous a long time (e.g. 1000 years) after water saturation.

The EARB has the opinion that the model approaches are reasonable and the obtained results are extremely valuable for the performance assessment. The most important conclusion of this modelling case is that the heterogeneity of the spatial distribution of dry density remains a long time after water saturation of the system.

The EARB also observes that the temporal evolution of the dry density at a specific point in the system may have reached a steady-state while the dry densities still differ at different points in the system (see e.g. Figure 3.4-5). The EARB thinks that the modelling teams need to further comment on this issue: Does it imply that the system will forever remain heterogeneous? If so, why further homogenisation does not proceed even though the spatial gradient of the mass distribution still exists?

The EARB thinks that the model teams need to further consider how their results imply the fulfillment of the minimum requirements formulated by Nagra for the disposal cell.

Andra assessment case

This case has been modelled by ULg, Quintessa and Andra.

EPFL applies an elasto-plastic model with linear elasticity and the van Eekelen yield surface for the Callovo-Oxfordian (Cox) host rock. Darcy's law is applied for water flow and van Genuchten approach for water retention. The BBM model is used for bentonite with an assumption of double porosity structure. The model assumes that increases of the elastic domain and of the soil stiffness are due to increases of the suction. Extended Kozency-Carman model is adapted for modelling of the evolution of water permeability.

Quintessa uses its own THM bentonite model for the simulation, simplified by only coupling the hydro-mechanical part as an isothermal process is assumed for the Andra assessment case. The model is implemented in QPAC, which is a multi-physics finite volume/mixed element code.

Andra explores a non-linear elastic approach for the mechanical model of bentonite. The model is a modified BBM-type with a single type of porosity. Andra argues that plastic behaviour is not expected in such confined conditions and is therefore not considered in the model. The clay rock is modelled with an elasto-plasticity model with a Mohr-Coulomb criterion and stress softening. Rock creep is ignored in the model. The excavation disturbed zone (EDZ) is assumed different hydraulic properties compared to other rock zones. The initial apical void (on top of the plug) is modelled with a bilinear elastic model.

All teams consider the cylindrical geometry of the system and use the central vertical profile as a symmetric line. The apical void is discretised by special interface elements. The Quintessa model uses a 2D cross-section of the bentonite, EDZ and the COx claystone. The geometry of the apical void is, however, simplified to have a “crescent” form. Andra’s model also assumes a 2D cross-section geometry, while considering even the symmetry of the modelled domain.

The excavation phase is modelled by ULg through variation of boundary conditions of confining pressure and the pore water pressure on the drilling front. In addition, the symmetric line representing the central vertical profile of the system is assumed to have no horizontal displacement and no water flux. The right and top boundaries are assumed to be subjected a constant confining pressure and pore water pressure. The bottom boundary is assumed to have no vertical displacement and have a constant pore water pressure. The saturation phase is modelled by relaxation of the fixed pore water pressure of the host rock in contact with the bentonite. Quintessa has three models with different boundary conditions: the ventilation phase, uniform bentonite (coupled EDZ and bentonite) and heterogeneous bentonite (bentonite and void only). All of the three models assume no displacement as the mechanical boundary condition. The hydraulic boundary condition is a flow rate boundary in the ventilation phase model, coupled to EDZ for the uniform bentonite model, and EDZ pressure for the heterogeneous bentonite model. The Andra model uses no flow and no displacement conditions for the vertical boundaries and constant liquid pressure and stress for the horizontal boundaries.

The synthesis of results section presents that initial heterogeneities are assumed in the different models of the different teams to have two origins: (1) an initial layered segregation (with different initial dry densities) during installation, and (2) an initial gap on the top of the bentonite plug (the apical void) due to filling defect.

The three different models show a comparable time to reach full water saturation (around 6000 years predicted by Quintessa and Andra and half the length by ULg). The discrepancy can be explained by the assumption of water permeability of the host rock. Moreover, the differences of the saturation times are small whether the top apical void is considered or not. Even the times for the closure of the top apical void are shown to depend on the water permeability of the host rock.

The results obtained by the modellers clearly indicate that after water saturation and reaching a steady-state, the dry density remains variable in the bentonite. The results are quite different between the teams. This can be partly explained by the differences of the initial dry density assumed. Otherwise the origin of the differences is difficult to understand at this stage.

The EARB would like to forward similar comments as is presented for the Andra assessment case above, i.e. the modelling teams need to have an in-depth understanding of the reasons for the long-duration of the heterogeneity in the system and its implication to performance assessment.

Additional comments from EARB

- Systematics of the report: The report jumps directly into describing the modelling approaches taken by the different teams without describing the cases themselves. After all, to the EARB opinion the teams' results should be compared and brought into context which would require a case description first. The EARB has the opinion, however, sections 2.5, 3.4 and 4.4 of the deliverable provide a systematic evaluation as expected.
- An overarching synthesis is missing for the content of chapter 6 – this varies team-by-team. Will such a synthesis be produced later?
- The "Discussion" section seems thorough and appropriate but addresses only the single teams' results. The EARB thinks that more is needed. Moreover, some of the sections in the deliverable are rather descriptive, while others are discussing strength and weaknesses of the calculations. Shouldn't there be a unified approach?
- The "Input parameters" sections vary quite a bit in nature and content – not all of this can probably attributed to the fact that different models were used.
- Why did only VTT perform sensitivity analyses for the SKB case? Is it justified to address just the 1st order linear effects? How well do they explain the overall model behaviour?
- It is unclear why the sensitivity analyses (SA) were carried out in the way they were. There are numerous approaches to, and methods for, sensitivity analyses. Why exactly these? And what type of results did they yield?

4.6 On D6.3 The BEACON Project – A Summary for Civil Society

The EARB considers that D6.3 is designed and written at a level and in a way appropriate for its purpose: The deliverable has the potential to communicate to the intended audience what BEACON was about, how the "project logic" was designed and how it worked, and what kind of results were achieved. It is written in an understandable way but does not use patronising language and is thus fulfilling the purpose of the deliverable. Perhaps a bit more weight could have been given to an assessment of the outcomes: Were the resources well-spent, did the project improve the scientific basis for safety cases? Or were there diverging opinions about this? The EARB understands that the closing paragraph of section 5.1 (which is actually a quotation from D1.3) attempts at doing so, but its meaning might not be very clear to the intended audience.

Moreover, the EARB is of the opinion that an explanation of the results (modelling and experimental) and consequences to the public is the most important part for dissemination. This should include also discussion on project aims fulfilled, additional research needed, i.e., consequences of the project results with respect to the goals.

The EARB acknowledges that its advice given in the review of D6.2 was carefully accounted for by the authors of D6.3. Hereinafter, three observations are provided which might help when preparing the final version:

- It would be good if – already in the abstract and the introduction – some more words would be spent on the functions the bentonite should fulfil in a repository. The word "buffer material" is probably not good enough for interested laypersons. And limiting "water flow, and the transport of material in the water" is only one of these functions. The issue that "clay sometimes tends to swell unevenly" is not only a challenge for modellers but it is a safety issue and basically the main reason for funding the project – this should be communicated to the audience (basically, all these issues are later addressed on p. 6, but perhaps it could be done briefly already in abstract and introduction). This advice is based on the experience that many readers will not go into all the chapters but just read abstracts, introductions and summaries.
- Not surprisingly, the word "model" is being used very often in the deliverable. It can have several meanings, though. In the deliverable, the term mostly refers to numerical and simulation models which are, however, based on phenomenological or conceptual models. It might be good to have a box in the report which briefly addresses the concept of modelling in cases like the ones addressed here, something like: That scientists experiment, observe and measure, that they then try to interpret what they see and fill this into formulas which then, together with the data, are the basis of computer simulations. These have prediction capabilities provided that they are precise and good enough, and these capabilities can be used to demonstrate safety. And basically BEACON was about testing and improving these capabilities.
- Sections 5.1 / 5.2 / 5.3: Layperson readers would probably have a hard time to grasp the meaning behind all the figures, a bit more guidance might be helpful here. Perhaps one could have lived with less figures, but added more explanation / interpretation for these. Or one could have provided all the figures but chosen one or two for an exemplary more detailed explanation and interpretation, leaving the readers the freedom to try such interpretations for the other figures on their own. "It is interesting that one group had quite a correct modelling result.": What is that supposed to mean? That this is unusual? Is it good that one group did well or is it bad that only one group did so?

Some editorial remarks are given below:

Abstract, 1st line: According to IAEA terminology, it should read „long-term disposal" rather than „long-term storage" (because the term „storage" means emplacement with the intent of retrieval).

Abstract, 2nd para, 5th line: There is one period too many.

Chapter1, p.5, 1st para: Footnote number 1 should be a superscript.

Same para: closing bracket missing.

Ensuing para, 1st and ensuing lines: sentence corrupted (one time "has been lead by" too many).

p.5 footnote 3: It is "Clausthal" (letter "h" is missing).

p. 7 5th para: "are rely".

p.9. 1st para: Footnote number 4 should be superscript.

Section 5.1, 2nd p. 18, para: Replace hyphen at end of sentence by period.

Several figure captions are missing.

4.7 The EARB general comments on the final workshop

- The EARB thinks that this final workshop of the project was well organised and accommodated. The technical challenges encountered by any hybrid meeting have been well solved during the workshop.
- The arrangement of brief presentations by the poster authors is innovative and enhances the assimilation of the wide ranges of results from the poster exhibition.
- The summaries of the WP-leaders were comprehensive with good coverage of achievements by the different WPs.
- The plenary presentations really gave chances for more in-depth and detailed information to be presented.
- The presentations by the invited speakers have been able to put the BEACON project in a larger scientific framework and are highly appreciated.
- The presentations from outside the project have broadened the horizon of the project.